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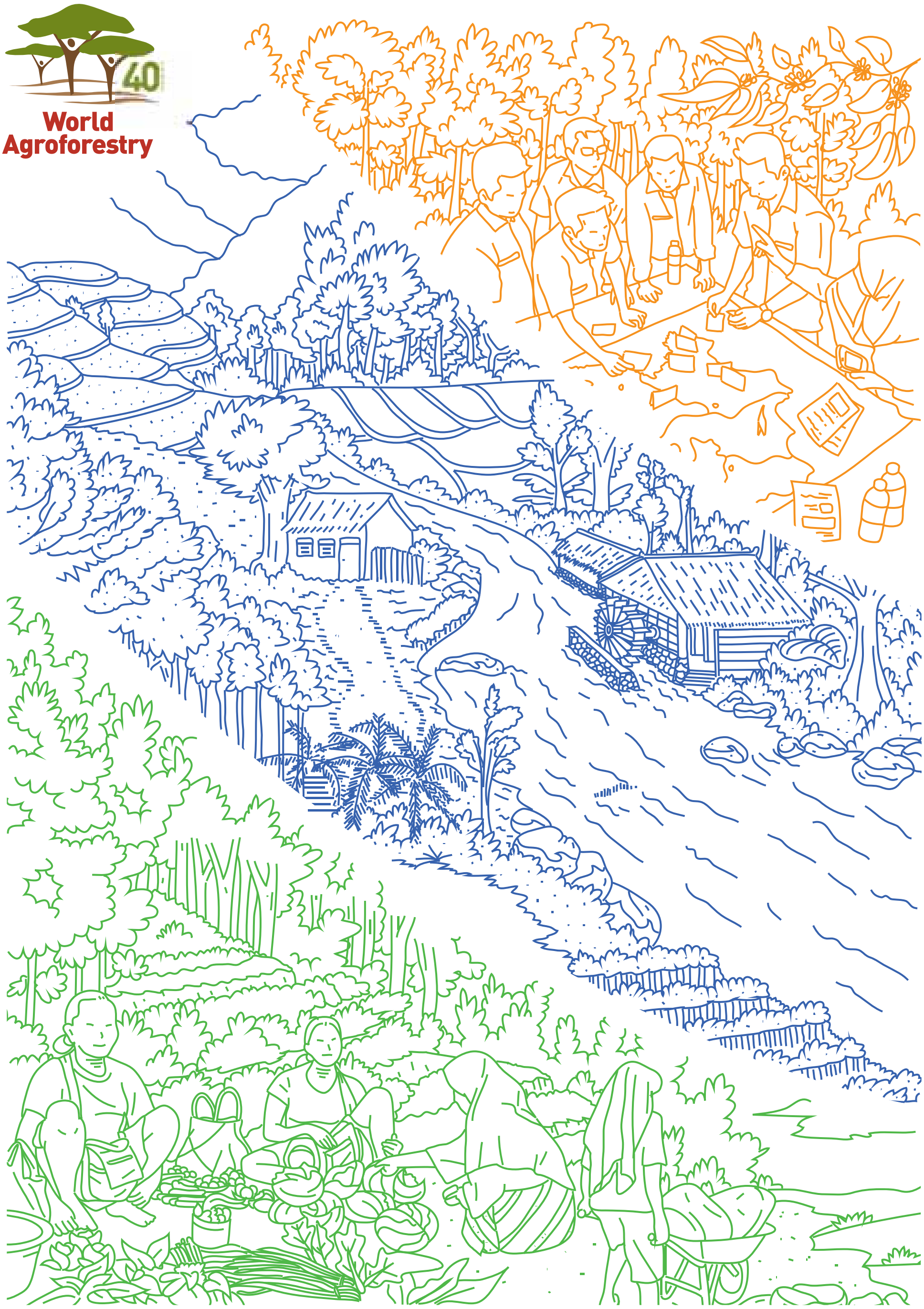

SUSTAINABLE DEVELOPMENT THROUGH TREES ON FARMS:

agroforestry in its fifth decade

Edited by Meine van Noordwijk

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Preface

As a concept agroforestry has now entered its fifth decade, as a practice it probably is as old as agriculture. This book takes stock of how concepts and practice of agroforestry have changed in the past forty years. Agroforestry started as efforts to reconcile forest restoration with farmers interest and agenda's, seeking alternatives for the then dominant form of 'green revolution' focused on a few important crops only, and bridging between traditional agriculture and forestry education and curricula to help develop the capacity of new generations of professionals, better prepared for integrated rural development.

Countless public policy issue attention cycles later[a], the starting point for agroforestry may still be as relevant now as it was then, but it is much closer to mainstream thinking. This can be attributed to institutional change and active communication that started with the establishment of ICRAF in 1978, initially hosted at the Royal Tropical Institute in Amsterdam (the Netherlands) and then moved to a new headquarter in Nairobi (Kenya)[b]. Thanks to this 40+ year history, we now have solid shoulders to stand on and can be more confident to express a vision of 'transformed lives and landscapes' with and through agroforestry – even though agroforestry itself had to be transformed and re-transformed in its own learning cycle of Diagnosis and Design. Allowing scientists to participate in farmer experiments rather than the other way around, was a radical idea, some time in the past. Conceptualization of social-ecological systems and explicit scaling has advanced. A strong commitment to action, paired to a readiness to connect the farmer scale to the global discussion and negotiation tables have helped numerous young professionals and students to make connections that last throughout their careers and lifetimes.

This book, a travelogue from the journeys of discovery, has three sections, that build up from the foundations in understanding trees, soils and component interactions in agroforestry, interpreted as field and farm level '***agroforestry1***', and trace the development of ideas to the second, landscape-level concept ('***agroforestry2***') based on direct engagement in 'learning landscapes' across the tropical continents. Rather than focusing on specific tree-based agricultural technologies, the attention shifted to issues and constraints at the agriculture-forest interface. Six chapters from Africa, Asia and Larin America provide examples of issues that needed to be resolved, for the agroforester-farmers on the ground to make progress. The final section follows this 'moving up the scales' one step further, with the ***agroforestry3*** concept of integrating the agenda of agriculture and forestry into a single 'land use'

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[a] Issues in the public attention change faster than even fast-growing trees; however, they have a tendency to come back in different guise if they weren't fully addressed previously; trees need to be resilient, and discussions to grow or harvest trees need to have foresight and be aware of longer-term risks and benefits.

[b] My personal relationship with ICRAF started when I heard about a meeting in Amsterdam in 1978 where initial workplans for ICRAF were discussed, stimulating me to visit Nairobi and the new ICRAF headquarter in 1979 when I was a young lecturer botany/ecology at the University of Juba, and in 1980 to host a visit by Peter Huxley (ICRAF) to teak intercropping projects in Yei, along the way discussing the ambitious plans for Juba to contribute to a radically new way of designing education for 'rural change agents', willing to change themselves in the process

contribution to Sustainable Development Goals[c]; boundary-work at the science-policy interface in this stage was broadened to include negotiation support in a science-policy-praxis triangle.

Many of the book chapters starting from recent review publications and ‘policy briefs’ on separate aspects; they were updated to match the overall storyline and provide references to both historical and current literature that trace the transformation of agroforestry as an idea. On behalf of the nearly 80 (co)authors, from inside and outside of permeable walls of ICRAF as a formal institution, I thank current and past ICRAF leadership for supporting and maintaining a bottom-up, participatory culture in which fierce debate on issues doesn't interfere with friendships and mutual support. In that spirit the authors hope that the work reported here for discussions at the 4th World Agroforestry Congress in Montpellier in 2019, will soon be out of date, but be still recognizable as building block from the past.

Bogor, 1 May 2019, The editor

[c] So that AFOLU (agriculture, forestry and other land uses) in the UNFCCC vocabulary can be simply replaced by ‘Land Use’

Authors list

Aida Bargues-Tobella has a MSc in Forestry from Universitat de Lleida (Spain) and a PhD in Soil Science from the Department of Forest Ecology and Management at SLU (Sweden). In her PhD project, titled 'The importance of tree cover for water resources in semiarid West Africa' she investigated the conditions under which increased tree cover leads to both higher carbon storage and better adaptive capacity to climate change, particularly through better ground-water recharge. Aida's main research interest in a secondment to World Agroforestry (ICRAF) in Nairobi is the use of trees to restore degraded lands through soil rehabilitation, with focus on dryland sub-Saharan Africa.

Alice Muchugi holds a PhD in Population Genetics, MSc in Plant Biotechnology, a Postgraduate Diploma in Education and a BSc in Agriculture. She coordinates the activities of the ICRAF seedbank in Nairobi and regional field genebanks to ensure that superior tree germplasm is available for ICRAF collaborative projects and other interested users. Her main areas of interest include conservation and use of important indigenous African tree germplasm, communicating generated scientific knowledge so that informed choices can be made in implementing science-based technologies, and mentoring young scientists, especially African women.

Andree Ekadinata is a researcher at World Agroforestry (ICRAF) in Indonesia with research experiences in land use planning, land use change analysis, quantification of ecosystem services, climate changes, REDD+ and modelling. He developed a methodology to identify complex agroforestry system using satellite image, involved in the application data generated from remote sensing such as land use changes and the drivers and quantification of the effect of land use changes to environmental services such as water, carbon and biodiversity at the landscape scale in Asia and Africa. He is currently developing a land-use planning tool to link and analyse the trade-offs between development/spatial planning at district level and the potential reduction of greenhouse gas emissions as a basis of negotiation support towards low emission development strategies at the local level.

Andrew Miccolis specializes in Agroforestry, Agroecology and participatory natural resource management and policies. Over the past 20 years he has been working in Brazil on sustainable livelihoods and conservation initiatives, including monitoring and evaluation and training of smallholder farmers and extension agents in Agroforestry and Permaculture systems using participatory approaches. In 1998, he co-founded Instituto Salvia, an NGO focusing on socio-environmental technologies, where he coordinated projects on climate change adaptation, agroforestry and land use planning. Since 2007, he has been conducting research and authored several publications on sustainable agriculture, agroforestry and land use policies in Brazil. In the last four years, Andrew has been working as ICRAF (World Agroforestry) Country Coordinator for Brazil, where he leads research-in-development initiatives aimed at forest and landscape restoration and sustainable land use, mostly in the Amazon, Cerrado, and Atlantic Rainforest biomes.

Ann Degrande is a socio-economist based at Yaoundé, Cameroon. She holds a PhD in Applied Biological Sciences (Tropical Agriculture) from the University of Gent, Belgium. Her research focus is on co-design and performance evaluation of innovative extension mechanisms. Since 2000, Ann has been coordinating projects aimed at improving smallholder livelihoods through the promotion of rural innovation in Cameroon, Nigeria and the Democratic Republic of Congo. She is also backstopping multi-disciplinary teams in the development of community approaches for the scaling of agroforestry practices throughout West and Central Africa.

Anthony A Kimaro studied forestry at Bachelors and Masters levels at Sokoine University in Morogoro, Tanzania and a PhD in forestry from the University of Toronto, Canada. Throughout his studies, he specialized in agroforestry, focusing on soil fertility management, tree-crop interactions and woodlot management. He is a scientist as well as country representative for World Agroforestry (ICRAF) in Tanzania and adjunct professor of agroforestry and soils, University of Saskatchewan. He. Despite responsibilities in the three positions, he is still able to keep his research focus and link with universities within and outside Tanzania via co-supervision of graduate students, research projects and proposal writing.

Aster Gebrekirstos is a scientist at World Agroforestry (ICRAF) and head of the Dendrochronology laboratory. Her research area focuses in the area tropical forest ecology and climate change (tree ring analysis, plant-climate interactions and its impacts and applications of isotopes to the study of plant eco-physiological / hydrological processes and global climate changes), agroforestry and restoration of degraded landscapes. She is a principle investigator, representing ICRAF, at the USAID-funded Africa RISING project and is leading and involved in several projects in Africa and Asia. She also lectures at universities in Germany and at the West African Science Service Center on Climate Change (WASCAL) PhD programme in Cote d'Ivoire. In recognition of her research and contributions, Dr. Gebrekirstos has received distinctions, notably, the prestigious AfriCAN Climate Award for excellence in research in climate change adaptation and mitigation in 2014. She is an Elected Fellow of the African Academy of Sciences since 2017. She also received the 2009 Special Award for Ground Breaking Science - African wide Young Professionals and Women in Science Competitions organized by CTA, African Technology Policy Studies Network (ATPS), Alliance for a Green Revolution in Africa (AGRA), Forum for Agricultural Research (FARA), RUFORUM and New Partnership for Africa's Development (NEPAD). She is an associate editor of the journal Dendrochronologia. She also serves on the Mountain Research Initiative (MRI) Science Leadership Council.

Atiek Widayati is a researcher and a professional on Landscape Approach and Spatial Sciences. Her major past and current experience range from land use-land cover changes, drivers and consequences, vulnerability assessments, landscape and jurisdictional HCV (High Conservation Values), and impacts evaluation. She has also been involved in and leading knowledge-to-action work through the development of Theory of Change, landscape management strategies, intervention options and outcome-oriented participatory planning. She got her PhD from the University of Northumbria at Newcastle Upon Tyne, United Kingdom. She is currently working for Tropenbos Indonesia (2017-present) and previously at World Agroforestry (ICRAF) (2001-2017).

Aulia Perdana is a researcher in value chains, markets and rural institutions with World Agroforestry (ICRAF) since 2010 and has over ten years of experience in market-related research and development activities in product value chains and marketing, and smallholder enterprise development. He has experience in managing research and development activities in Jambi, Central Java, South and Central Kalimantan, Sulawesi, Nusa Tenggara islands and Nepal. Currently he leads a four-year research project (2013–2016) on the integrated production and marketing strategy for timber and non-timber products in Indonesia. He obtained his Master of Science degree in management from Universitas Gadjah Mada.

Beria Leimona is a scientist of the World Agroforestry (ICRAF) Southeast Asia programme specializing in landscape governance, ecosystems service finance, rural development and public-private conservation investments in Asia. She has a PhD from Wageningen University, the Netherlands, with research thesis focusing on 'Fairly efficient, efficiently fair' payment mechanisms for ecosystem services. She is an Associate Editor of the Ecosystem Services Journal, and a lead author for Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES) for the Asia Pacific region, and Global Value Assessment.

Betha Lusiana is a scientist with the World Agroforestry (ICRAF) Indonesia Programme. She has a PhD from Hohenheim University, Germany, with research thesis focusing on assessing the trade-offs between agricultural development, farmers' livelihoods, and ecosystem services. Her current work focuses on implementing quantitative approach, including modelling, in developing ecological indicators for monitoring and evaluating ecosystem services condition.

Catherine Muthuri is scientist at World Agroforestry (ICRAF) where she manages the ACIAR-funded Trees4FoodSecurity projects phases 1&2. Catherine holds a PhD in plant ecophysiology from Jomo Kenyatta University of Agriculture and Technology - JKUAT / Nottingham University UK, an MSc in plant physiology and a Bachelor of Education (BEd) science degree in Botany and Zoology. She is also the cluster leader on sustainable intensification under the livelihood's systems theme of the FTA program. Catherine is the ICRAF DG Designate to the Governing Council of the African Centre for Technology Studies (ACTS) and the chair of ICRAF Staff Association (ISA). Before joining ICRAF Catherine was an associate professor at JKUAT, served as chairperson, Botany Department (2005-2009) and has 20 years' experience in research, teaching and administration at the University level. She was a board member of Kenya National trading cooperation and St Francis girls' high school. She is also a presidential award holder, the Elder of the Order of the Burning spear (EBS).

Chin Ong is a consultant to Crops for The Future, Malaysia. He has over two decades of experience in agroforestry in both World Agroforestry, Nairobi and the International Crop Research Institute for the Semi-Arid Tropic, India. He is also a special professor at the University of Nottingham, UK. He has edited several Agroforestry book, including 'Tree-Crop Interactions' with Peter Huxley and 'Agroforestry in a Changing Climate' with Colin Black and Julia Wilson.

Christian Dupraz is a senior scientist at INRA (French National Institute for Agronomical Research). He worked on fodder trees, afforestation techniques including tree-shelters, agroforestry and agrivoltaic systems. He set up agroforestry experiments in France that have been continuously monitored for almost 25 years, providing unique datasets. With his team and many colleagues from different countries he developed biophysical models of tree-crop interactions in alley-cropping systems, and evidenced the high Land Equivalent Ratio of temperate alley-cropping systems. He wrote the reference guidebook about temperate zone agroforestry entitled "Agroforestry: trees and crops" first published in 2008. Christian Dupraz was the founding President of the French Agroforestry association in 2007 and of the European Agroforestry Federation (EURAF) in 2011. He has been committed to lobby for agroforestry at the French and European levels since 1998. He is also an elected member of the Occitanie Region Parliament.

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Dennis P Garrity is a systems agronomist and research leader whose career has been focused on the development of small-scale farming systems in the tropics. He is currently Drylands Ambassador for the UN Convention to Combat Desertification, Senior Fellow at the World Resources Institute, and Distinguished Senior Research Fellow at World Agroforestry (ICRAF), Nairobi. He served as Director General of the Centre from 2001 to 2011. He is currently focusing on building an African land restoration movement and is leading an effort to perennialize global agriculture in the 21st Century by chairing the global Partnership to Create an EverGreen Agriculture. He also chairs the Steering Committee for Landcare International, a worldwide effort to support grassroots community-based natural resource management. During the 1990s he was based in Indonesia where he launched and developed the Southeast Asia Regional Programme of ICRAF. He served as the Regional Coordinator and Principal Agronomist in the Southeast Asian Regional Research Programme.

Devashree Nayak, is an Integrated Systems Specialist. She is an Agroforestry and Gender Research Scientist at World Agroforestry, New Delhi, India. Ms Nayak has been making adoption of agroforestry in particular, for over a decade. She is highly experienced in community organization, federating smallholders in legal entities, and promoting equity communities. She also works in the field of bioinformatics, focusing on the integration of bio-physical and social aspects of agroforestry research and development. Her work has been recognized and awarded at various platforms, including "Young Scientist Award" by the Odisha Environment Congress in 2014

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Edmundo Barrios was a Senior Scientist in Land and Soil Management at World Agroforestry (ICRAF) based in Nairobi, Kenya, before joining the FAO in Rome. His work focuses on understanding the ecological basis of sustainable land management in agricultural landscapes and the contribution of local knowledge systems to the capacity to adapt to disturbance and to shape change in natural resource management. A University of California at Berkeley graduate in Biological Sciences, he concluded his PhD research on biological indicators of soil quality in tropical agroforestry systems at University of Dundee (U.K.) and ICRAF in Kenya and Zambia in 1995. He is leading ICRAF's efforts to study the distribution of soil biota in agricultural landscapes of East, Southern and West Africa in collaboration with the African Soil Information Service (AfSIS), CIAT, Colorado State University and University of Colorado, Boulder. He led the recent review entitled 'Agroforestry and Soil Health: Trees, soil biota and ecosystem services' highlighting the critical role played by tree-soil biota interactions in ecosystem service provision and sustainable land management.

Elisabeth Simelton is a climate change scientist at ICRAF Viet Nam and she holds a PhD in Geography. She is the My Loi CSV team leader, CCAFS project leader, and the ICRAF's focal point on adaptation. She has widely published in the fields of climate impacts and adaptation, food security and environmental services.

Endri Martini is an Agroforestry specialist with a strong interest in ecology, forestry, and community based natural resource management. Endri conducts research and development activities on agroforestry extension to support sustainable farmers' livelihoods enhancement. Endri is a member of three professional bodies involved with ecological conservation and restoration, and is featured in at least 30 publications, having completed a Masters degree through a HICD-USAID scholarship program relating to biodiversity, conservation and natural resource management. Away from the office, Endri enjoys travelling, reading, and photography.

Fabiana Mongeli Peneireiro earned a BSc in Agronomic Engineering in 1994 and a Master's degree in Forest Sciences from the University of São Paulo (ESALQ/USP) in 1999, with a dissertation on successional agroforestry systems developed by the researcher-farmer Ernst Götsch, and concluded her PhD in Education at the University of Brasilia (UnB) in 2013 on the training of agroforestry technicians at the School of Forestry in Acre. She has been involved in agroecology and agroforestry studies and worked professionally as educator in the Amazon, Atlantic Forest, and Cerrado biomes. Fabiana collaborated on the development of the Agroforestry Education methodology in Acre and distance learning courses for the Ministry of Environment, and as an instructor in the international course on Agroforestry Systems - TCTP (Third Country Training Program). She has co-authored a series of technical-scientific texts on agroforestry and related topics, including the guidebook Agroforestry Systems for Ecological Restoration: how to reconcile conservation with production in the Cerrado and Caatinga biomes. Fabiana has been a member of the NGO Mutirão Agroflorestal since it was founded in 2003, and currently works as a consultant throughout Brazil and practices agroforestry as a Community-Supported Agriculture farmer at Altiplano Village Ecovila, where she receives volunteers and researchers.

Fergus L Sinclair leads the Agroforestry Systems science domain at World Agroforestry (ICRAF), with research into the contribution that trees can make to the productivity of farming systems and rural people's lives. This domain has two main areas of focus: soil and water productivity; and factors affecting farmer decisions about which trees they incorporate on their farms and how they manage them. He also co-ordinates the Smallholder Production Systems and Markets component of the CGIAR Research Programme on Forests, Trees and Agroforestry involving CIFOR, Bioversity and CIAT and is the ICRAF focal point for integrated agricultural research in the humid tropics led by IITA and dryland systems, led by ICARDA. Fergus is well known for pioneering development of knowledge-based systems methods for acquisition and use of local agroecological knowledge, for using participatory modelling to better harness natural resources at community level and for exploring trade-offs between the impact of farm trees on productivity and biodiversity. Recently, he has combined these interests by contributing to the development of interdisciplinary GIS tools for spatially explicit evaluation of ecosystem service synergies and trade-offs at landscape scales (Polyscape).

Gamma Galudra main work interests is forest governance, common property rights and community-based forest management. He has been actively involved in forest governance, livelihoods and community-based forest management research for 17 years. During his period working with ICRAF, he was also leading several projects related to biodiversity, community-based forest management and low emission development policies since 2010, funded by ClimateWorks Foundation, Climate Land Use Alliance (CLUA) and Margareth A. Cargill Foundation. Currently, he works for RECOFTC- The Center for People and Forests as the Director of Indonesia Country Program.

Henrique Rodrigues Marques is an environmental engineer with experience in socio-environmental projects and research in forest restoration. He has worked as a professional consultant for several governmental and non-governmental institutions in Brazil in rural development projects, socio-environmental technologies and management of protected areas. He was a research assistant at the Instituto de Pesquisa Econômica Aplicada (IPEA), identifying the limitations and opportunities of the country's forest restoration chain. At ICRAF, he is involved in the development of agroforestry solutions, training in agroforestry technologies, participatory diagnostics, landscape management and forest resources.

Hesti Lestari Tata is a senior researcher with the Research, Development and Innovation Agency of the Indonesian Ministry of Environment and Forestry (FOERDIA). She earned her doctorate from Utrecht University's Department of Plant Ecology and Biodiversity. She specializes in peatlands conservation and restoration, rubber agroforests and plantations, multifunctional agriculture and tree diversity.

Ian Dawson works within the 'Trees' Research Priority at World Agroforestry and is interested in developing new domestication and planting material delivery methods for tree species, both to support smallholder farmers' livelihoods and bring wider environmental benefits, including through forest restoration. He has a particular interest in domesticating new perennial crops.

Inder Dev is Principal Scientist (Agronomy) at ICAR-Central Agroforestry Research Institute, Jhansi, Uttar Pradesh, India. He has about 21 years of experience in research, extension and management in the field of grassland management of temperate, alpine and cold desert region of the Himalaya; Agroforestry and watershed management in semi-arid region of India. Currently he is involved in developing agroforestry based conservation agriculture practices for semi-arid regions.

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Jenny C. Ordoñez has been a researcher at World Agroforestry (ICRAF) based in Costa Rica, with a focus on generating quantitative evidence about the role of agroforestry practices for delivery of ecosystem services and improving livelihoods or rural households. With a training in agronomy, and ecology (PhD at University of Amsterdam, the Netherlands) she integrates principles of agronomy, systems analysis, functional ecology and local knowledge to assess the contribution of agroforestry practices to on-farm productivity, livelihoods, diversity conservation and ecosystem services provision. The main objective of her work is to support the design of interventions that improve the sustainability of farming systems.

Jianchu Xu is the regional coordinator and principle scientist at ICRAF-ECA, and is a professor of the Kunming Institute of Botany, Chinese Academy of Science. Dr. Xu is an internationally respected ethnoecologist whose research covers multiple aspects of coupled human-environmental systems. He has authored over 100 publications.

James M Roshetko is an agroforestry systems researcher and leader of the Trees, Agroforestry Management and Markets Unit of the ICRAF Southeast Asia Regional Program. The focus of his research is to generate and apply science-based knowledge to enhance rural development options through improved sustainable environmental management. The central theme of his work is smallholder agroforestry systems as viable components of a climate-smart, multifunctional landscape-management approach that enhances local livelihoods, protects environmental services, and achieves sustainable environmental management. He holds a doctorate in Geosciences and Natural Resource Management from the University of Copenhagen, Denmark. He obtained his master's degree in Forest Management and Agroforestry from Michigan State University, USA and bachelor's degree in Forest Resource Management from the Ohio State University, USA.

Jonathan P Cornelius specializes in agroforestry genetic resources, counting more than 25 years of experience in research, education and research management in Latin American and the Pacific. He became regional director in 2012, coming from James Cook University in Australia, where he led the Agroforestry and Novel Crops Unit. He previously worked for ICRAF as country coordinator in Peru and held positions at CATIE in Costa Rica and the UK Overseas Development Administration (now DFID) in both Honduras and Costa Rica. Born in the United Kingdom, he received his PhD in forest biology and management from the University of Alberta, Canada.

Jules Bayala is a principal scientist with World Agroforestry (ICRAF) based in Bamako in West Central Africa (WCA) regional office. He holds a PhD in Ecophysiology and Agroforestry from the University of Wales, Bangor, UK. He is currently working on establishing key directions for the agroforestry research and development programs in WCA. His research focus is on the soil-plant-water continuum, on agroforestry species physiology in the face of climate change and climate smart agriculture.

Juliana Tjeuw is a passionate plant researcher. She holds a PhD from Plant Production Systems of Wageningen University - The Netherlands, researching plant production systems of *Jatropha curcas* in Indonesia. Her Master was in plant molecular biology researching flowering genes in *Tectona grandis* while her Bachelor was in plant biology researching *Musa paradisiaca*. She has experience in oil palm plant breeding and management. She is currently an independent researcher/consultant working out of Tasmania - Australia.

Jun He holds a PhD from the University of East Anglia, and teaches Human Ecology at Yunnan University, China. Having previously worked at the World Agroforestry (ICRAF)'s China program, Professor He's current research interest lie in forest governance, value chains and environmental justice. His publications have appeared in *World Development*, *Land Use Policy*, *Human Ecology and Society & Natural Resource*, among others.

Kaushal K. Garg is a senior scientist- Natural Resource Management at ICRISAT Development center (IDC), ICRISAT. He holds a PhD in Agricultural Engineering from IIT Kharagpur, India. His expertise is in areas of hydrological modeling; water budgeting at field, watershed and catchment scale, and irrigation scheduling. He is also involved in development research of various scaling-up programs under IDC to enhance agricultural productivity.

Keith Shepherd leads the Science Domain on Land Health Decisions and serves as a Principal Soil Scientist at World Agroforestry. His research focuses on land health surveillance – an evidence-based approach to measuring and monitoring land health (including soil carbon) and associated risk factors, and improving stakeholder decision-making through Decision Analysis. Keith has pioneered a Soil-Plant Spectral Diagnostics Laboratory at the Centre for high throughput analysis of soil and plant samples using only light (infrared, x-ray and laser spectroscopy). The lab is supporting the Africa Soil Information Service and a network of spectral laboratories in national and development institutions across the tropics. Keith co-leads Information Systems Strategic Research in the CGIAR Program on Water, Land and Ecosystems has co-developed a new flagship on restoring degraded landscapes, with emphasis on land health risk assessment, monitoring and evaluation. His research on decision analysis focuses on use of Bayesian approaches and value-of-information analysis to improve development decision-making in data-limited environments.

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Lalisa A Duguma is a Scientist working on sustainable landscapes and integrated climate actions at World Agroforestry. He has over 10 years of international and regional experience in the areas of sustainable landscape management, agroforestry, natural resource management, integrated climate change actions that respond to both mitigation and adaptation objectives, climate policies analysis and other related areas.

Lars Graudal co-leads the 'Trees' Research Priority at World Agroforestry and is interested in developing new domestication and planting material delivery methods for tree species, both to support smallholder farmers livelihoods and bring wider environmental benefits, including through forest restoration. He also works for Forest & Landscape Denmark, the University of Copenhagen, Denmark.

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Malesu Maimbo has over 21 years of experience in facilitating sustainable smallholder agricultural research and development through improved land management, conservation farming, soil and water conservation, small/medium-scale irrigation and rainwater harvesting. He is currently ICRAF's Coordinator of the cross regional programme on rainwater harvesting and management referred to above and has managed several government and donor-funded projects (e.g., on Soil Conservation and Agroforestry Extension, Land Management and Conservation Farming). Mr Maimbo has much international experience working in most network countries and is recognised for his expertise in project planning, management, monitoring and evaluation.

Mary Njenga is a Bioenergy Research Scientist at World Agroforestry (ICRAF) based in Nairobi, Kenya and a Visiting Lecturer at Wangari Maathai Institute for Peace and Environmental Studies, University of Nairobi. She holds a PhD in Management of Agroecosystems and Environment and her research interest is on sustainable and efficient biomass energy production and use systems and their connections to environmental management including climate change, livelihoods and rural-urban linkages. She is also greatly interested in natural resource management in urban and rural settings, and adaptive technology development and transfer including gender integration and co-learning through transdisciplinary approaches.

Mathew Mpanda is working on the impacts of climate change on benefits and flows of ecosystem services along an altitudinal gradient on Mt. Kilimanjaro, Tanzania. His research focuses on (1) local people's perception of how climate change is impacting livelihoods, (2) soil characteristics along the altitudinal gradient, and (3) on-farm woody biomass, its availability and use. Previously, Mathew worked to understand impact of forestland tenure changes on forest cover and stocking in part of Amani Nature Reserve, Tanzania. During his undergraduate studies at Sokoine University of Agriculture, Mathew investigated household woodfuel consumption in Ilala district, Dar es Salaam, linking urban energy supply and consumption with degradation and deforestation of the adjacent coastal forests.

Meine van Noordwijk served until mid-2017 as Chief Scientist at World Agroforestry (ICRAF), based in Bogor (Indonesia) and since that time as Distinguished Science Fellow. He is also part-time Professor of Agroforestry at Wageningen University (the Netherlands). Trained as biologist/ ecologist he has experience with systems analysis and modelling of systems that range from single roots in soil, via tree-soil-crop interactions, to the understanding of water, biodiversity and greenhouse gasses at landscapes scales, and the conflicts that arise over multiple claims to landscape functions to the institutional translation of ecosystem service concepts in a comprehensive approach to land use systems.

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Ramni Jamnadass is a Kenyan scientist driven to change the lives of small holder farmers and other communities. She is the leader of Tree Genetic Resources (TGR) in CGIAR Research Programme on Forests, Trees and Agroforestry (FTA) involving ICRAF, CIFOR, Bioversity and Forest Landscape Denmark (University of Copenhagen). The TGR program aims to bridge production gaps and promote resilience by providing solutions for the more effective safeguarding, domestication and delivery of TGR by and to farmers, foresters and other stakeholders. This leads to diversified and more productive options for farming systems, to more varied diets and improved nutrition, to strengthened value chains for tree products, and to increased smallholder farm incomes. Importantly, the right TGR management decisions play an important role in enhancing the adaptive capacity of farm and forest ecosystems to cope with climate change and in countering landscape degradation. Within the TGR program she also coordinates the FTA- priorities of nutrition, orphan crops and biodiversity to support both smallholder farmers' livelihoods and bring wider environmental benefits, including through forest restoration. Within ICRAF, Ramni co-leads ICRAF's global research program Tree productivity and Diversity: Realising economic and ecological value from tree genetic resources (TREEs). This program also hosts the African Orphan Crops Consortium http://africanorphancrops.org/ which is sequencing, assembling and annotating the genomes of 101 traditional African food crops (47 trees) with the intention to improve nutritional security in Africa. The TREEs program also holds ICRAF Genebanks. Ramni has great passion in building capacities and empowering young women and men. When not at work, Ramni will be found hiking in wilderness or animal gazing in the wild African landscapes.

Ravi Prabhu joined World Agroforestry (ICRAF) as Deputy Director General (Research) in January 2012. As well as his responsibilities to oversee the whole research programme, he isalso a member of the Centre's Senior Leadership Team. According to him, ICRAF is "a Centre where focused, rigorous research provides the evidence that guides the policies of decision makers from the household through to national and global levels – the kind of decisions that help to direct investments to their most useful purposes." Ravi is an accomplished scientist in his own right: he has engaged in multi-disciplinary research and action in forested landscapes for almost 20 years. He was previously a Senior Programme Officer, Forests and Climate Change with the United Nations Environment Programme (UNEP) in Nairobi. He led the UNEP team that contributed to the UN-REDD Programme mainly by supporting countries to realize multiple benefits from REDD+, and to use REDD+ as a catalyst to transform to a green economy. Prior to that, he coordinated the Regional Plan for Collective Action in eastern and southern Africa, a joint initiative of CGIAR. He also worked in various capacities at the Center for International Forestry Research. He earned his professional degree and doctorate in forestry from the University of Goettingen, Germany. Ravi has served on numerous international initiatives and committees, including the Millennium Ecosystem Assessment where he served on the review and editorial team, and the UN Millennium Projects Taskforce 6 on Environmental Sustainability. He received the Queen's Award for Forestry at Buckingham Palace in 2005.

Richard Coe is a research methods specialist. His role in ICRAF is to support research teams, scientists, students and partners in the design of research projects and studies to improve their effectiveness. Similarly, he supports scientists in the analysis, interpretation and communication of research data and results. Ric's background is in mathematics, biometry and statistics and during his long career with ICRAF, he has increasingly concentrated on the design phase of research, with particular interest in the design of research studies that are embedded in 'development' projects. His position with ICRAF is part time and he concurrently has a post with the Statistics for Sustainable Development, based in Reading, UK. His work in the university also focuses on methods support to agricultural research projects in East and South Africa, together with increasing research methods capacity in the region. As such, it overlaps with and enhances work with ICRAF.

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Zac Tchoundjeu pioneered the participatory tree domestication approach and the development of rural resource centres at ICRAF and has led the institutes work in the West and Central Africa region.

Trees on farms: agroforestry

Agroforestry involves a wide range of trees that are protected, regenerated, planted or managed in agricultural landscapes as they interact with annual crops, livestock, wildlife and humans.

Photo: Brawijaya University/Kurniatun Hairiah

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CHAPTER ONE

Agroforestry paradigms

Meine van Noordwijk, Richard Coe, Fergus L Sinclair

Highlights

- Agroforestry as a word enters its fifth decade, as a practice it is as old as agriculture
- Definitions of agroforestry have evolved during the first four decades from plot- to landscape- and policy-level concepts
- Agroforestry can be understood at these three scales as interactions, interfaces and synergy between agricultural and forestry components
- Agroforestry has its roots in farmer-focused learning loops supported by formal science

1.1 Introduction

> *"The existence of large numbers of people in the fragile ecosystems of the developing world, and the fact that these ecosystems occupy the greater proportion of the land of the developing economies suggest that means must be devised which will assist in increasing the productivity of these ecosystems while at the same time either rehabilitating them or arresting the process of degradation. Agroforestry is a system of land management which seems to be suitable for these ecologically brittle areas. It combines the protective characteristics of forestry with the productive attributes of both forestry and agriculture. It conserves and produces."*
>
> ____*(King 1978)*[1].

In the four decades of its existence[2], agroforestry as a concept has been understood and defined in multiple ways, often referring to a specific system scale of interest[3,4,5,6,7]. Its potential contribution to 'restoration' and 'conservation' alongside 'productivity' of land has been expressed in many ways, emphasizing soil conservation[8], land degradation[9], food security[10], land use for integrated natural resource management[11,12], or biodiversity conservation[13]. The range of studies include trees and their domestication[14], tree–soil–crop interactions at plot level[15], the interactions between land, labour, knowledge and risk at farm level[16], human livelihoods at landscape scale[7], dynamics of tree-cover change in space and time[17], social-ecological systems at landscape scale[12], the multiple value chains that start with tree, crop and livestock production in landscapes[18], and the policy domains[19] of forestry and agriculture in the context of sustainable development goals[20], global change and multi-species agroecosystems21, the role of trees in agro-ecology[22], responsible trade in globalizing markets[23] and global climate change[24]. The inclusion of all these aspects under a single term may indicate a need for greater clarity on the different system scales involved and their connections. Figure 1.1 provides a four-level typology of what can be seen as nested paradigms: mutually compatible but distinct in concepts, methods and implications for practice and policy. The various definitions that have over time been given for agroforestry reflect these concepts[25,26].

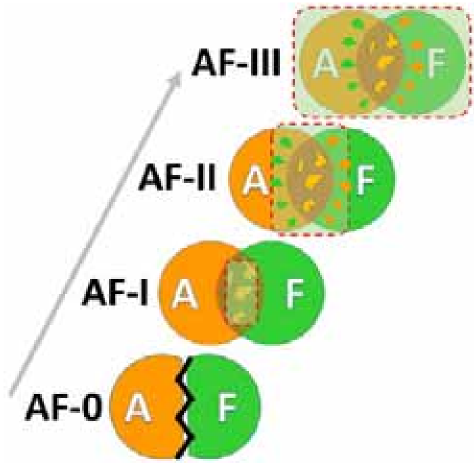

Figure 1.1 Evolution of what agroforestry is understood to be in relation to agriculture (A) and forestry (F): exclusion, by definition, of any interface (AF0), a collective name for specific practices involving farmers and trees (AF1), multifunctional landscapes (AF2) and a domain for coherent policies for all land uses (AF3)

We will describe the way these concepts evolved in this introduction to a book that in three sections takes stock of ***thematic aspects*** (focussed on understanding components, systems and their processes of change and feedback), ***change in context*** (focussed on 'theory of place' or the ways that contextual factors shape current efforts in 'land restoration') and on policies as part of ***theories of induced change***. The latter summarize experience and evidence of the way constraints at the level of knowledge, understanding, motivation, regulation and investment can be overcome (in their specific contexts) to let the full spectrum of agroforestry solutions contribute to rural livelihoods, to sustainable multifunctional landscapes and to attainment of the Sustainable Development Goals[27] at (inter-) national scales.

1.2 Definitions

Before the term 'agroforestry' emerged, agriculture and forestry had been on very different institutional pathways even though 'farmers' and 'forests' interacted in the real world in multiple ways for as long as agriculture existed (ten thousand years or so)[28]. From a farmer's perspective, forests were both a resource (source of firewood, utility and construction timber, hunting, fishing and grazing opportunity, protecting water quality, regenerating soil fertility in swidden/fallow rotations[29]) and a threat (wild animals, robbers and, in some environments, fire). 'Forest' as a word and as a concept originated in exclusion, in boundaries and in claims by sovereigns to reserve access to part of a landscape's resources. Use of forests for hunting preceded the relevance of forests for shipbuilding and navies[30]. Management of the regeneration of forests gradually led to plantation forestry controlled by forest authorities who inherited an ambivalent relationship with farmers, perceived as the major threat to forests. Schools for training professional foresters to work as resource managers on behalf of those in power were set up separate from schools of agriculture, training professionals to support commercialization and intensification of agriculture through business development, extension and research. Where agricultural and forestry training became united under a common umbrella, this difference in culture, science and relationship with rural communities persisted. As a formal concept, definitions of agriculture tended not to exclude trees and farmer-managed forests or plantations, but 'forest' definitions tried a combination of criteria based on tree cover and control by forest authorities to set apart some of the area. Statistics and spatial databases related to this distinction between agriculture and forestry were (and still are) maintained at national levels and compiled internationally by the Food and Agriculture Organization of the United Nations (FAO), with challenges to consistency and comparability that became problematic where international policy instruments emerged[31].

At the start of 'agroforestry' as a concept in the late 1970s, critique of the focus of the 'green revolution' on intensified monocultural forms of agriculture added to the recognized failure of forest authorities to interact with farmers. Existing combinations of trees, crops and livestock on farms could benefit from a more systems-oriented understanding under a new umbrella term while social contracts between forest authorities and farmers that had emerged in the plantation establishment as 'taungya' in Myanmar or 'tumpangsari' in Indonesia offered hope for widespread use in restoring deforested and degraded lands. In the first decade of agroforestry, definitions emphasized that it was a 'collective name for…', with specifications of the components and the 'deliberate' management of the combinations. The degree of 'deliberateness' was not easily assessed, however, challenging answers to simple questions on how much agroforestry existed where. The first agenda for agroforestry, indeed, was to prove that **agroforestry exists** and that the many practices and land-use systems described under the umbrella term had properties in common as well as a functional typology and terminology to differentiate them[32,33].

The definition of agroforestry (Box 1.1) that evolved in the first decade[34] is still the most widely quoted[35,36].

Box 1.1 AF1 DEFINITION[22]

Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos etc) are **deliberately** used on the same land-management unit as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In agroforestry systems, there are both ecological and economic interactions between the different components.

When the 'honeymoon' period of discovery of the many forms of agroforestry was over, a more critical phase emerged in which research became a relevant complement to what was established as an information-sharing body in a first incarnation as the International Council for Research in Agroforestry (ICRAF). The close interactions between trees and crops that involved competition as well as opportunities for complementarity became a focus of biophysical research[37,38], with associated economic evaluation of trade-offs and risk analysis[39,40,41]. This resulted in hypotheses about the functioning of tree-crop combinations such as 'Benefits of growing trees with crops will occur only when the trees are able to acquire resources of water, light and nutrients that the crops would not otherwise acquire'[42]. Active involvement in genetic selection and improvement of trees with desirable properties became one of the emphases of agroforestry research[43] although the diversity of trees and circumstances made it hard to emulate the successes achieved with research into the major food crops or industrial timber plantations. A balance was sought between compiling information on any tree of potential relevance anywhere[44] and specific efforts in 'domestication' of species of particular value, with science-based support for farmer-driven efforts[45]. Deliberate introduction of alien species became known for its risk of invasiveness[46].

Expectations on benefits of agroforestry practices involving close tree-soil-crop interactions at plot scale were tempered, despite evidence for many of the hypotheses on positive functions of trees. Meanwhile, the landscape and livelihood scale gradually emerged, in the early 1990's, as a relevant scale for understanding agroforestry, in the AF2 concept. A new definition, proposed by Leakey[47] emphasized the benefits that can be achieved, but did not make the term operational in a world where segregated agriculture and forestry concept remained dominant. He proposed a new definition (Box 1.2).

Box 1.2 AF2 DEFINITION[35]

Agroforestry is a dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in agricultural landscapes, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels.

The lack of recognition of the active interface of agriculture and forestry became the basis for the AF3 focus, in the late 2000s–early 2010s, on harmonization of regulations and incentives in order to achieve the higher-level Sustainable Development Goals. Rather than defining 'agroforestry' as a separate land-use category that had complex borders with 'pure agriculture' and 'pure forestry', the central idea became removing bottlenecks to change, which were the result of the artificial segregation of policy domains. The fuzzy boundary between 'agriculture' and 'forestry' reflects a continuum that cannot be satisfactorily sliced into two (or three) parts but needs to be understood and managed as a continuum of functions. Recent analyses of global tree cover on farms provide a new tool to quantify agroforestry, with a key finding that more than 40% of agricultural land has at least 10% tree cover[48]. Ten percent is the lower limit of tree cover that countries can, according to international agreements, use in their definition of 'forest', so the overlap of the two sectors is much larger than what is commonly recognized. In the AF3 paradigm, the definition of 'agroforestry' can be simple (Box 1.3) and refer to the roots of the word. In doing so, it inherits all the complexity of 'agriculture' and 'forestry', without having to spell them out.

Box 1.3 AF3 DEFINITION[14]

Agroforestry, a combination of agriculture and forestry, is land use that combines aspects of both, including the agricultural use of trees.

The three definitions have direct consequences for answers to the simple questions, 'How much agroforestry is there in the world?' and 'Is it increasing or decreasing?'. To earn a place at international negotiation tables, the simplest definition (1.3), which shows the largest relevance, may be preferable[49]. To motivate programs to promote agroforestry, the aspirational aspects of the second definition can open minds and doors. Empirical work on comparing and improving 'agroforestry practices' will likely stay within the first definition (1.1).

1.3. Researchable hypotheses, performance metrics and methods

In the first decade of research, the 'Diagnose and Design' framework[50,51] was formulated in support of regional development planning (Fig. 1.2). However, in the practice of its application it seemed to have standard answers rather than an 'evidence-based' portfolio of potential solutions on offer. It was short-lived as a method, but the idea of 'learning loops' came back in multiple forms[52].

The gradual development of 'agroforestry' as a concept with the need for operational definitions that allowed agroforestry to be distinguished from non-agroforestry interacted with efforts to involve the full spectrum of scientific disciplines (biophysical, socio-economic, integrative geographical, integrative development studies, legal and policy-oriented) in a wider and wider set of questions (Figure 1.3). The early formulation of 'hypotheses' on resource use in agroforestry did not distinguish between contexts and targeted general statements that were presumably valid for

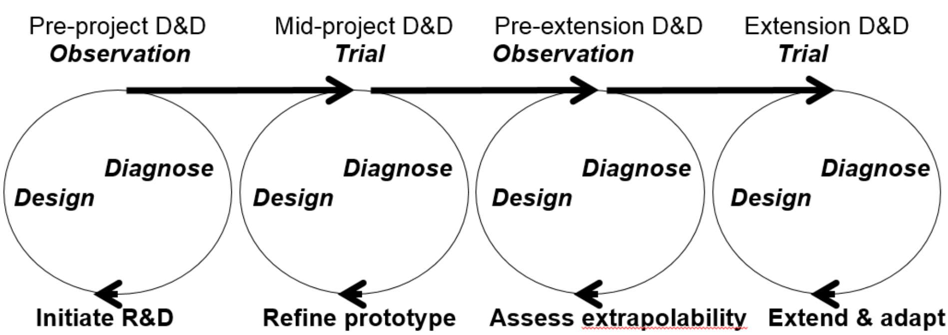

Figure 1.2 Representation in 1982 of multi-phase "diagnose and design" (D&D) learning loops and project cycles[38]

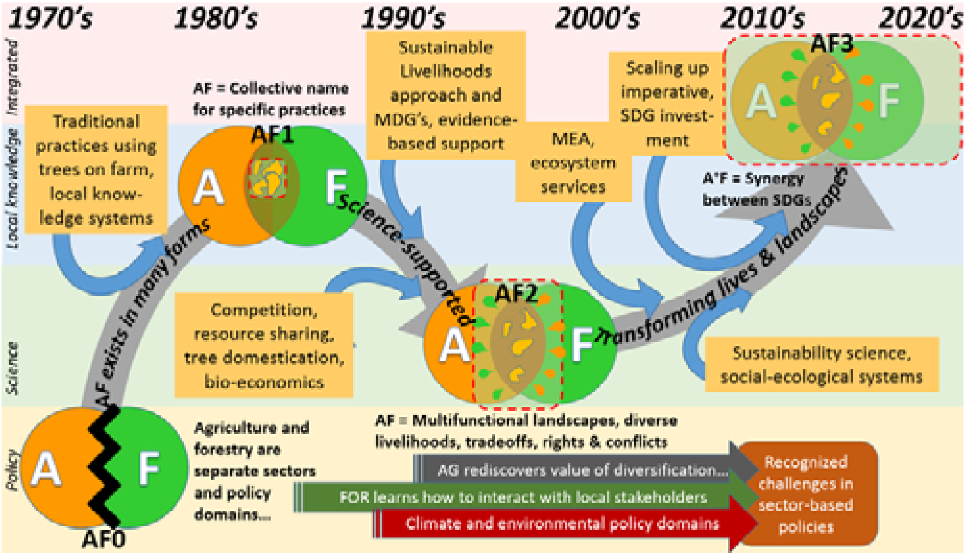

Figure 1.3 Summary of the evolution of agroforestry concepts and definitions over the last 40 years (MDG = Millennium Development Goals[6]; MEA = Millennium Ecosystem Assessment; SDG = Sustainable Development Goals)

all forms of agroforestry. Examples of validity could be found for each hypothesis in specific locations but not as generic truths[53,54].

Overall, research methods were derived from this wide range of disciplinary traditions, but the temporal and spatial scales of trees and landscape-wide interactions called for adjustments. The initial studies largely described existing land-use practices but in the interpretation the basic assumption of 'chronosequences'—that all land had the same initial properties and that changes were due to land use—became increasingly challenged. Soil science became one of the fundaments of agroforestry research[55].

The early use of replicated field trials was built on agronomic research traditions but ran into problems with the lateral expansion of tree roots that defied the treatments imposed and complicated the analysis. Use of larger plots and active root trenching were seen as answers but increased the cost and created a need to bring excluded interactions back into consideration of what happens on small farm plots[56]. Explicit attention to 'lateral flows' allowed empirical scale transitions by specifying what happens to a variable expressed per unit area when the scale of observation changes[57,58].

Many of the methods for characterization of tree diversity[59] and landscape functions[60,] built on established ecological rather than agronomic research methods. Agroforestry productivity estimates should refer to the whole plot, including the border areas, and not some subjectively selected central area that supposedly represents unit area productivity[61]. It became clear that uncontrolled crop, tree and management heterogeneity limited extrapolation of early on-farm research results to other farmers' fields while replicated case studies of 'best-bet' technologies (traditional or experimental) on different farms were preferable to the use of formal experimental designs.

Although landscape-scale planning of agroforestry in Kenya had been initiated in the 1980s from a landscape architecture 'research through designing' perspective[62,63], the interdisciplinary study of land-use change—its actors, drivers, consequences and feedback options—only emerged slowly in the agroforestry world[64], requiring the AF3 conceptualization to take shape alongside efforts to engage at policy level. Methods for co-location of research across disciplines in a pantropical comparison led to the Alternatives to Slash and Burn program of research on active tropical forest margins[65,66]. The focus on multi-scale, policy-relevant issues made this into a prime example of 'boundary work'[67]. Key to this type of boundary work was the recognition that science was only one of several knowledge systems and that clarifying contrasts and overlaps between knowledge systems could contribute to negotiated solutions in natural resource management conflicts involving the interface of agriculture and forestry[68].

System research traditions brought to agroforestry a shift from 'components' and 'cause–effect' relations to one of feedbacks, buffering and filtering[69]. The way 'process-based models' and 'empirical evidence' informed each other's progress in agroforestry was constrained by the disciplinary traditions from which agroforestry researchers continued to be recruited[70].

Performance metrics for agroforestry have evolved over time. Table 1.1 provides some examples of metrics for each of the three AF paradigms (scales of evaluation). Further details of these will be discussed in subsequent chapters of this book.

Silvo-pastoral system with native trees - Pacobamba, Apurimac-Peru. Photo: University of Bern, Switzerland/Sarah-Lan Mathez-Stiefel

Table 1.1 Performance metrics for agroforestry in the contexts of the three AF paradigms

AF1 (plot and farm level)[42,43,44]
Efficiency in productive use of land: Land Equivalent Ratio (LER) or the sum of relative yields of all components (with unsatisfied demand) compared to a 'current practice' monocultural production mode (LER values below 1 indicate that specialized (segregated) land use is more efficient than integrated ones)
Efficiency in use of labour: wage rate at which a Net Present Value calculation for total input and output accounting of a land-use system yields zero (wage rates below what is considered to be 'minimum wage' indicate a drive out of agriculture)
Efficiency in use of capital: Net Present Value (discounted flow of financial equivalents of all inputs and outputs of a land-use system; dependent on discount rate used) (relevant for capital investment and creditworthiness)
Flexibility and risk management: maintenance of multiple options in the face of variation in weather, prices, labour availability, pests and diseases (percent of the years that performance is satisfactory)
Resource conservation: avoidance of degradation of the resource base beyond the natural recovery capacity
AF2 (landscape and livelihoods' level)[56,71,72]
Landscapes in context of the Sustainable Development Goals: Multifunctionality Land Equivalent Ratio, sum of relative contributions to all Goals (relative to current shortfalls for each goal) compared to land uses specialized in a specific function
Above- and belowground terrestrial carbon stocks and net greenhouse-gas emissions
Water flow buffering metrics, such as Flow Persistence, and water quality of streams and lakes
Procedural and distributive equity (over gender, age, social and wealth strata) of landscape-level resources
Nutritional diversity: fraction of population (or specifically vulnerable groups) with access (physical, economic) to all key food groups, and relevance of all landscape elements in providing these
AF3 (policy level)[40,73,74]
Perception of agriculture as threat to forests and of forestry rules as threat to on-farm production of 'forest' resources
Coinvestment and cooperation between traditional agriculture and forestry/conservation agents in enhancing multifunctionality
Public recognition of 'trees outside forests' as providers of regulatory and productive functions
Footprints: area equivalent of all consumption associated with a given lifestyle at current production efficiencies
Carbon footprint: sum of attributable emissions per unit product or per capita (given lifestyles)

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Peter A Huxley

Founding father of agroforestry research (1931-2019)

INTERMEZZO 1

In (one of) his first publications after starting the research effort at ICRAF, Peter Huxley (1980) wrote: "Is there really a place for yet another research discipline? I believe there is, on two main counts. The first, and more pragmatic is that any new amalgam of research ideas needs to be positively encouraged and identified as such, whether it springs from entirely original concepts and practices or not. This is especially so when the component research disciplines, in this case of agriculture and forestry, have established themselves almost as separate entities. The second is that a positive thrust towards the multiple use of land through agroforestry techniques generates a definite need to appraise and re-assemble our research tactics, so as to take into account the increased complexities in space and time which have to be dealt with in such systems. We might add, also, that we have to enquire whether our methods of evaluating the outputs of agroforestry systems, in terms of the multiple products and benefits which can accrue, are up to the job."

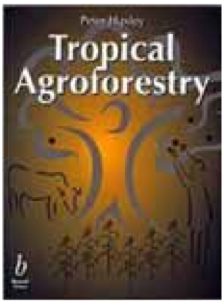
ICRAF University of Nairobi

Proceeding of the
Kenya National Seminar
on Agroforestry

12-22 November 1980

"Very few existing agroforestry systems have been studied critically and so far, many still await even broad description. Most agroforestry systems have arisen through the enterprise of indigenous rural communities who have, themselves, evolved them. Whether it is a home garden in Indonesia, a multi-storeyed mixture of trees and agricultural crops in Central America, or a silvo-pastoral system of fodder shrubs and grasses in the Sahel, suggestions for changing the inputs in terms of spatial arrangements, the temporal sequences of crops, or the very plant components themselves are unlikely, in many cases, to be used on measurement data because we have so few to work with."

Peter Huxley came to ICRAF with twenty years of research experience in Uganda and Kenya, with a strong interest in agriculture, climate, tree phenology and coffee, but also ideas about agricultural education and the gap between agriculture and forestry in terms of educational traditions.



In his Tropical Agroforestry book of 1999 Peter handed over the baton to next generations of agroforestry researchers with "... the first book to provide a comprehensive, analytical account of the principles as well as the practical applications of agroforestry. The focus is on understanding how agroforestry systems function whilst taking into account the conflicts and compromises that arise because of the farmers' requirements and the biological potentials and restraints of growing woody plants with crops."

"We should always remember that *people* are the key elements in agroforestry. Being inclined towards biology I can only refer to some of the socio-economic aspects in this book (and without claiming much authority)".


Diversity of food trees support food security

Early stage of agroforestry owned by a farmer in Buol, Central Sulawesi, Indonesia who planted maize, nutmeg and cocoa.

Photo: World Agroforestry/Dienda CP Hendrawan

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CHAPTER TWO

Tree diversity as basis of agroforestry

Meine van Noordwijk, Subekti Rahayu, Aster Gebrekirstos, Roeland Kindt, Hesti L Tata, Alice Muchugi, Jenny C Ordonnez, Jianchu Xu

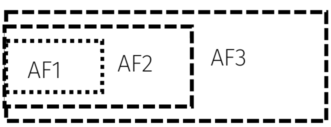
Highlights

- Of the more than 60,000 known tree species only 1% is represented in specific agroforestry databases
- Trees become part of agroforestry practices by three routes: selective retention, as volunteers and by deliberate planting (or direct seeding)
- On-farm tree diversity profiles differ between use categories and AF practices, with 1-10, 10-100 or 100-1,000 tree species depending on context
- Tree diversity transitions imply a loss of retained and volunteer trees and increase in actively managed ones
- Domesticating forest aligns with domesticating trees, with winners and losers in both

2.1 Introduction

2.1.1 Trees and three agroforestry concepts

Trees and forest relate to each other like eggs and chicken, and it is not possible to say which came first. Trees wouldn't grow as tall as they do without forest neighbours, and forests without trees exist only on paper and in a policy sense. From an agricultural perspective the trees are the most distinctive aspect of agroforestry, and similarity with forests is a secondary concept, however (Box 2.1).



In reviewing four decades of agroforestry research Chapter 1 described three 'nested' agroforestry concepts, with AF1 focused on 'trees on farm' at field and farm level, the technologies used and value chains supported, AF2 focussed on the agriculture/forest interface at landscape and livelihoods scale, and AF3 at the governance and policy aspects of the way agriculture plus forestry interact as continuum with the full spectrum of sustainable development goals. There is a logical sequence[1] of description and stock taking ('Theory of Place'), understanding of transitions, their drivers and consequences ('Theory of Change') and transformations and leverage on drivers ('Theory of Induced Change'). This applies at each of the three AF concepts, but effectiveness of ToIC's at AF1 level may well depend on relationships included in the AF2 and AF3 concepts[2].

Box 2.1 Seeing both the trees and the agroforest

In a meeting on plant research in agroforestry in 1981, the concept of 'agroforests' with high architectural and functional similarity to natural forests in the humid tropics emerged[3,4]. It sparked empirical studies. Initially especially in Indonesia[5,6], discussions on tree architectural models suitable for agroforestry[7] and the 'ecological analogue' idea that similarity in structure supports equivalence in function[8,9]. In parallel the concept of agroforests as 'intermediate intensity' agroecosystems[10] became the basis for a segregation versus integration discussion[11] that saw similarities between debates at tree level (maintaining 'multipurpose trees' or supporting 'tree improvement' for specific functions[12]), and at (agro)forest level (maintaining multifunctionality, or specializing and intensifying agriculture segregated from nature). The equations derived for this analysis[13] were later rediscovered as basis for the land sharing versus land sparing discussion[14], that reframed the issue for broader appeal.

Plant architectural analysis, 3D-representation and models[15] were focussed on the self-similarity in developing pattern as explanation for the resulting woody branching structure of trees. After developing an impressive terminology of 'architecture types'[16] , the specification of tree growth model became so detailed and complex[17], however, that to add an extra tree species to the library required an additional 4-year PhD project. Other scientists focussed on less-architectural 'plant functional attributes'[18] and more simplified fractal branching models for the resulting woody structures, above or belowground[19].

The direct link between trees (and tree improvement, see chapter 3) and ecological understanding of agroforests became weaker in subsequent research, and the 'tree domestication' work (see Chapter 3; mostly developed as an AF1 concept) became separated from the 'forest domestication' discourse[20], that mostly focussed at the landscape/livelihoods[21] level of AF2, and the policy level of AF3 concept. A recent study for the Amazon[22], however, synthesized literature about how indigenous and traditional Amazonian peoples still manage forest resources to promote useful plant species that are mainly used as food resources in 'agroforests', and how structure and composition of forests on and near archaeological sites along four major Amazonian rivers reflect management practices such as selective retention of useful plants, attraction of non-human animal tree seed dispersers, transportation of useful plants, selection of phenotypes, fire management and soil improvement. Long-term persistence of ancient cultural practices implies that we indeed need to see both the trees and the diverse agroforest patches rich in edible perennial plants to understand either and build on this heritage for food security in Amazonia.

2.1.2 Stock taking on trees and tree diversity

Trees are the defining element of agroforestry, from an agricultural perspective. They differ from crops and livestock in important ways, and it is relevant to understand their 'temperament' or 'character' as living organisms, just as it pays off to know crops, livestock and farmers' minds if one wants to understand agriculture. Trees may be the defining element of agroforestry, but they are neither a taxonomic category, nor sharply defined[23]. Woody perennials can take the tree and shrub as life form[24], but can also be grasses, palms or ferns.

The number of tree species currently known to science[a] is 60,065 (20% of all angiosperm and gymnosperm plant species)[25], with Brazil, Colombia and Indonesia having the most tree species and nearly 58% of all tree species single-country endemics. Nearly half the tree species are found in just 10 families, with *Leguminosae*, *Rubiaceae*, and *Myrtaceae* as richest families (5405, 4827, 4330 species, respectively) and *Syzygium*, *Eugenia* and *Eucalyptus* as richest genera (1069, 884 and 747 species, respectively). Only 1% of this GlobalTreeSearch[26] diversity is currently included in the agroforestree database[27].

The 600 trees included, however, from a major share of the worlds' agrobiodiversity. Over the past 50 years national food supplies worldwide have become more similar in composition, with an increasing role for globally important cereal and oil crops, and a decline of other cereal, oil, and starchy root species[28], many of which are traditionally associated with agroforestry and more shade-tolerant than the open-field crops that replaced them. Of the 150 or so species that make up most of our plant-based food, a mere three crops (rice, wheat and maize) supply more than 50% of the world's plant-derived calories, and only 12 crop and five animal species provide 75% of the world's food[29]. Fruits and vegetables consumption are far below recommended levels to avoid micronutrient deficiency in many parts of the world, in East Africa in particular[30]. Yet, due to limited storage and processing, tree diversity is essential to guarantee year-round availability of fruits that are 'in season'[31].

Agroforestry includes non-trees, especially shade-tolerant understory species such as gingers or cardamom, but also light-demanding crops in specific spaces or temporal phases. This chapter starts with diversity found within the tree category, forming a background on the 'tree improvement' or 'tree domestication'[32] focus in chapter 3; it then considers diversity of agroforestry trees at plot- and landscape scale with implications for tree-soil-crop interactions (discussed in subsequent chapters), functions and risk at farm enterprise level. It then uses understanding of tree diversity transitions in agroforestry (as Theory of Change) as basis for the management of agroforestree diversity (as Theory of Induced Change).

2.2 Trees: functional aspects of being a woody perennial

The occurrence of trees alongside non-trees in many plant families suggests that trees as a life form have advantages, as well as disadvantages, depending on context, and that the longevity and woody stem traits could be readily switched on and off in plant evolution. Trees live longer than most other plants, and this implies that adverse conditions (such as droughts, cold spells, fire, floods) must be bridged, without the option annuals have to avoid them in well-protected propagules. Survival contributes to reproductive fitness, and temporary storage of growth resources is common in trees and their reproductive success is measured at decade rather than annual scale for long-lived species. While avoiding grazing by common herbivores due to height (once past their early growth), they are fully exposed to insects and disease-causing pathogens. To counter these threats, the long-lived trees have devised structural and physiological mechanisms such as spines and have chemical defence (secondary metabolites) that support leaf longevity and fruit production. This is more

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[a] Including as-yet-undescribed species other sources estimate a total of around 80,000 or even 100,000 tree species

common in perennials (and biennials) than in annuals, as is evident from lists of plants with medicinal properties, based on the secondary metabolites that the plant formed to avoid grazing. Coevolution of hosts and pathogens has been compared to biological warfare, reaching a fragile, site-specific balance.

Among the 'woody perennials' the 'grasses', 'palms' or 'ferns' differ from the other, dicotyledonous and conifer trees in the absence of aboveground branching and, related to that, secondary stem diameter increments; their real long-term surviving component is the belowground 'clump'. Palms a have a specific 'modular' pattern of growth, in which every leaf contributes a small increment to stem (and thus tree) height, and a single bud that can become a flower bunch after a specified period of time. In some of the palms (incl. coconut and oil palm) flower buds develop at a given age of the associated leaf, in others (incl. sugar palm and sago) starch accumulates in the stem and flowering starts much later, signaling the end of the life cycle of the stem (with other shoots of the clump taking over). In this context a relevant distinction is between plants that are 'monocarpic' (flowering once; annuals, biennials[b] and some perennials) and those that are 'polycarpic'.

Woody stem

Leaving the monocarpic and non-branching woody perennials such as bamboo aside, most trees are characterized by their woody stem that keeps growing over time, as branches develop, mature, break off and their scars become covered in the 'nodes' in wood anatomy (Box 2.2). The relative size and direction of branches of trees differs between species (such that many trees can be identified in a leaf-less season from a distance by their branching pattern). Yet, this variation is bounded by narrow rules that can be understood as a combination of tree mechanics (wood strength, gravity and wind exposure), and the 'pipe-stem' theory. The latter is based on the simple logic that the transport function of woody stems is determined by the leaf area and its water needs for transpiration. Because of this, the number (and total cross-sectional area) of water-transport vessels at any point in a branched structure corresponds to the leaf area it supports. From here it is a small step to 'fractal branching' and the prediction of allometric equations that relate total tree biomass to stem diameter[33,34]. Trees growing in half-open circumstances, e.g. agroforestry, have a different allometry from those in closed stands[35].

Box 2.2 The structure and anatomy of woody stems, ring width and stable isotopes

Nearly all environments in which woody plants grow have at least some seasonal variation in circumstances, although the variation may differ from the strong yearly pattern of temperate and boreal zones. Wood growth is normally associated with this seasonal variation, which results in the formation of growth rings that are visible due to specific anatomical features (Fig 2.1.A). Other anatomical features that result from seasonal variation are vessel diameter, length, and frequency (Fig 2.1.B), all of which are features regarded as important phenotypic plastic traits that enable plants deal with changing environmental conditions[36].

[b] As an example of the policy relevance of botanical distinctions: in China's Sloping Land Conversion Program (See chapter 11) annual crops were not allowed once land was converted to trees, but biennial medicinal plants were tolerated, leading to a specific form of agroforestry

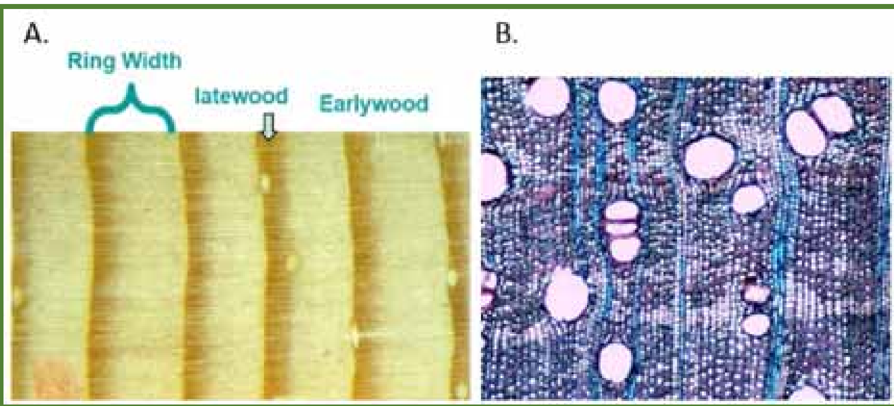


Figure 2.1 A. Illustration of earlywood and latewood, differing in colour on a cross section due to differences in vessel size and wood density; B. Vessel characteristics can be further distinguished and measured on a transverse section, such as this one of *Triplochiton scleroxylon* (African Whitewood)

Particularly, understanding density variation as a function of radial growth will facilitate greater knowledge about how to accurately estimate carbon sequestration, which could be useful for environmental mitigation strategies. Annual wood density is directly related to rates of carbon assimilation (photosynthetic rate), and inversely related to stomatal conductance[37]. Wood density within a species tends to vary within between early and late wood in a yearly (or half-yearly cycle in bimodal rainfall climates), and sites. Therefore, the inclusion of temporal and spatial variability of wood density improves substantially our knowledge to estimate carbon sequestration over time. Besides, the anatomy of xylem cells (vessels), late and early wood variations are also important variables to reconstruct past tree responses to environment because of its high intra-annual resolution and its direct link to important functional and physiological processes[36], and thereby to reconstruct past climatic conditions. Quantification of vessel traits and tracheids will also be essential for linking wood anatomy with dendrochronology.

The analysis of stable carbon and oxygen isotopes adds value to our understanding of past responses to climate, and how trees can tune their water–carbon balance. During carbon sequestration and water uptake by roots and subsequent wood formation processes, heavier isotopes may be discriminated against the lighter ones in response to a prevailing environmental condition and thus may imprint the environmental signal in tree rings[38]. For instance, variations in stable carbon isotopes ($\delta^{13}C$) in tree rings provide deeper insight into the occurrence of water stress and related changes of intrinsic water-use efficiency (iWUE). Intrinsic water use efficiency derived from tree-ring stable carbon isotope ratios ($\delta^{13}C$) has already been used as a potential proxy for past physiological responses of tropical trees to environmental changes[37]. By integrating anatomical data, ring width, and stable isotopes it is possible to address ecological aspects of plant hydraulic traits, study the long-term responses of trees to environmental changes from wood cell to the landscape, and from multi-decadal to centennial scales.

Beyond the site-specific variation and temporal patterns in wood density revealed by wood anatomical analysis (Box 2.2), an important part of tree 'temperament' at species level is reflected in its wood density. Fast-growing pioneer trees that try to get above their neighbours to capture light quickly tend to invest little in woody tissues – with a high branch turnover and sensitivity to wind as a consequence. Slow-growing trees with dense wood can ultimately become emergent above the canopy of other trees, but only in relatively stable environments.

Wood density[39] correlates with numerous morphological, mechanical, physiological, and ecological properties[40]. Wood density is relevant for allometric biomass equations[41,42] for trees; databases have been developed to allow tree diameter data to be converted to biomass and carbon stock estimates. A nested analysis of variance showed that 74% of the species-level wood density variation in a set of 2456 neotropical trees was explained at the genus level, 34% at the Angiosperm Phylogeny Group (APG) family level, and 19% at the APG order level[43]. Across available data, wood density correlates with growth rate[44], drought tolerance[45] and survival of fire[46]. The frequency with which trees of low, medium and high wood density coexist can provide a powerful way to compare agroforestry and natural vegetation (Figure 2.2).

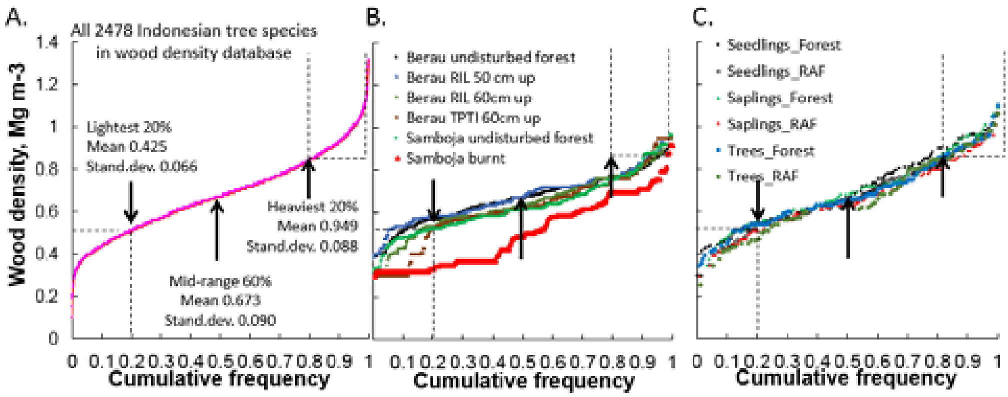


Figure 2.2 A. Wood density frequency distribution of Indonesian forest species; B. Examples for various types of forest management and post-burn forest recovery in E. Kalimantan; C. Example of wood density profiles of Indonesian rubber agroforestry (RAF) plots and remaining forests in Jambi, for seedling, sapling and pole/tree stages[47]

Wood density is important for the potential use of wood, as it relates to durability after the tree has been cut, as well as while it grows. Strength, however, is partly independent of wood density and an important characteristic for use in construction. Recent research on trees in peat swamps (compare paludiculture discussion in Chapter 14) has shown that trees with low wood density have effective gas exchange between root environment and atmosphere via their stems, leading to methane emissions[48], but likely also keeping roots supplied with the oxygen they need. For 'dendrochronological' research, woody stems are a history book, as it allows reconstruction of the conditions during the whole lifetime of the tree. When beyond growth ring diameters stable isotope signatures (especially carbon and oxygen)[49,50] long term fluctuations of rainfall can be interpreted, including for spatial correlates within 'precipitationsheds' (compare Chapter 17)[51].

Leaves and phenology

Tree leaves vary in shape and size, with large leaves of pioneer trees in humid environments with little wind grading into compound leaves that can regulate their degree of exposure to sunlight and (dry) air. An elaborate set of descriptors of leaf characteristics has been developed as part of the Plant Functional Type literature[52]. Diversity of plant functional types, which can be assessed without detailed taxonomic expertise is a reasonable proxy for taxonomic diversity, but in rainforests the latter exceeds the first by a factor two or more.

Tree leaves differ in longevity, with physical and chemical protection more pronounced in environments where leaves can function for a long time. In environments of low nutrient availability plants (including trees) tend to 'hoard' the nutrients they have taken up, hold on to their leaves and remobilize nutrients from leaves before they fall as litter. This contributes to slow litter decomposition (and ultimately peat formation in wet environments) and reinforces low nutrient availability. In contrast, where nutrient supply is more abundant litter turnover rates are higher and plants can rely on an external rather than internal way of nutrient cycling.

In seasonal environments most trees drop their leaves in dry (or cold, e.g. on mountains) seasons and flush young leaves after the rains have started. As young leaves tend to be attractive to grazers and vulnerable to insect pests and diseases, plants with sufficient access to deep soil water reserves tend to get a flush of young leaves before the actual start of the rainy season. In doing so, they can make use of the higher radiation intensity in non-clouded skies and avoid attackers. One tree that has developed such 'reverse phenology', at least in some environments, has become widely used in parkland agroforestry systems[53] (see also chapter 12) and has become a favourite role model for agroforestry that tries to combine benefits of trees with modest shading during the growing season[54]. Although early agroforestry researchers emphasized the lack of systematic data on phenology of the wide array of possible agroforestry trees[55], there still is little systematic information. It has been noted that trees in Sahelian parkland agroforestry flower more frequently than those in fallow or forest vegetation[56].

Roots

The logic of 'fractal branching' and 'pipe-stem theory' (Fig. 2.3) applies[57,58] to woody roots as much as it does aboveground, with the role of 'mechanical stress' restricted to the 'proximal root', close to the main stem. Belowground tree architecture is still largely the subject of speculation, rather than direct observation, with many 'rules of thumb' that relate expected rooting depth to tree height and lateral spread to crown diameter not valid beyond the species for which the ideas first were formed[59]. Like most plant characteristics, rooting patterns depend on both genotype and environment. The 'functional equilibrium' concept that plants synchronize below- and aboveground growth to balance water, nutrient and light capture[60] is still a good starting point to understand adaptive responses to environmental change[61] and aboveground pruning and management[62]. This includes the carbon strategy involved in the choice between keeping fine roots alive during a dry period or regrowing the quickly after the soil rewets as basis of fine root turnover[63]. Spatially and temporally dynamic adaptive fine root investment needs to be reconciled with the longer-term investment in woody transport roots[64]. In mixed vegetation, and agroforestry in particular, two complementary concepts coexist on nutrient uptake: the 'nutrient pump' (especially on weathering soils) and the 'safety-net', especially for mobile nutrients[65]. Deep roots are not only important when the tree is alive: old tree root channels may dominate soil physical conditions long after the trees have disappeared[66]. Direct measurement of water transport in roots[67] has increased the understanding and appreciation of 'hydraulic equilibration', that can under specific circumstances be a key part of 'facilitation' between trees and intercrops[68,69]. No tree can grow by itself. All depend on biota in the rhizosphere, if only to deal with potential invaders and 'rhizovores' (root-eating organisms). That poses interesting challenges for plants in how to recognize the welcome invasion of mycorrhizal fungi[70] and nitrogen-fixing bacteria (Rhizobium, Frankia)[71,72] in specific plant families.

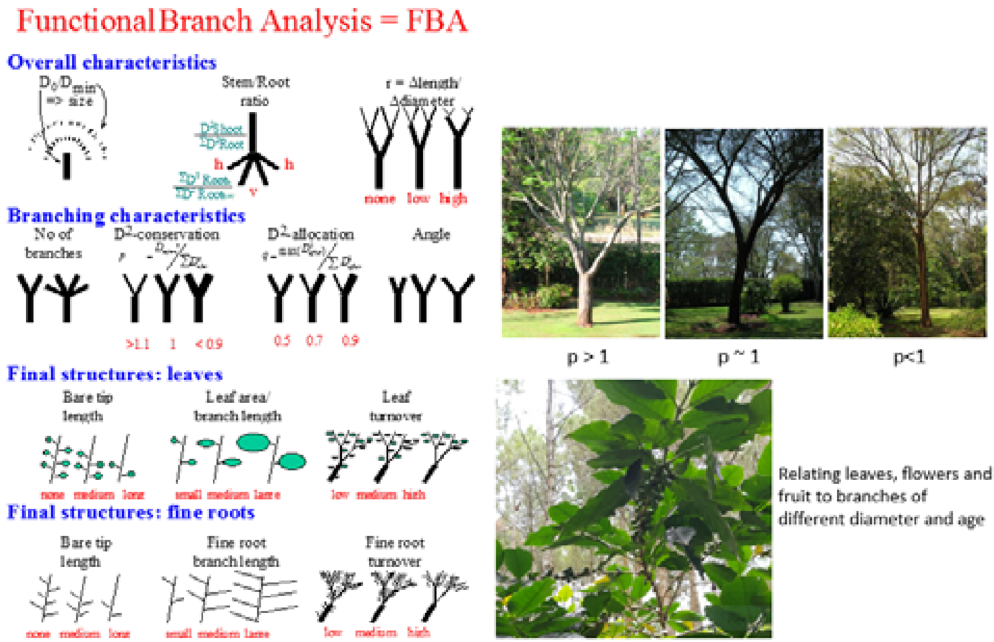


Figure 2.3 Functional branch analysis data collection as basis for fractal branching models

Flowers, pollination and dispersal

Phenology was mentioned as key aspect of the functioning of the leaf canopy, but it is also important for flowering and fruit production. Beyond the issues of avoiding specialist herbivores, trees need to coordinate (in a co-evolutionary sense) flowering and fruit ripening to the expected presence of pollinators and fruit/seed dispersal agents. Pollination strategies and associated flower (or inflorescence) morphology (Fig. 2.4) varies with environment (wind pollinators are most common in pioneer trees and harsh environments), climate and typical tree density. The low density at which the major part of rainforest trees occurs (often less than one individual per ha, linked to the high tree diversity of these habitats) helps in avoiding specialist feeders, but makes pollination a challenge. Larger-sized pollinators (birds, bats) with larger home ranges are attractive alternatives to insects for these reasons, and bat pollination is common in trees, but not possible in other life forms that lack the height and required free space around the flowers.

Fruit and seed dispersal can also be either abiotic (wind, water) or biotic (flying: birds or flying foxes; or walking: mammals), with the laxative properties of many tree fruits a functional part of inducing a suitable environment for tree seed germination.

Figure 2.4 Examples of the way pollination and fruit/seed dispersal can be inferred from flower and fruit morphology, across taxonomic databases

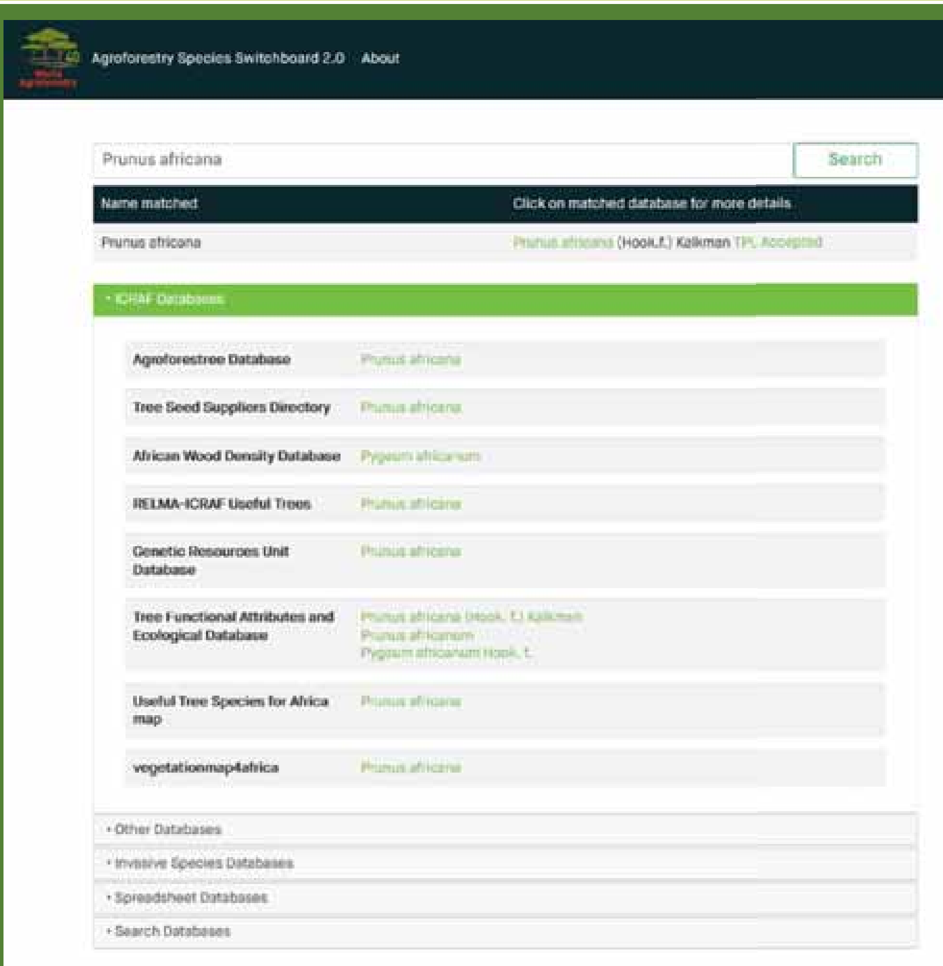
A consequence of the perennial strategy of trees is that they don't have to flower and fruit every year to have the required level of reproductive success. This aspect of the lifestyle is a challenge for the management and cashflow of agricultural production systems[73], and an argument for maintaining diverse tree portfolios rather than specialization. In some tree families (incl. *Dipterocarpaceae*) trees tend to flower with intervals of 5-10 years in a phenomenon called masting[74]. This is interpreted as a strategy to make life as difficult as possible for any organism specialized on seed predation – but it has consequences for the pollination strategy as well, as specialist pollinators cannot handle the uncertainty of resources on which they depend.

Irregular fruiting is a problem for human reliance on fruit trees, as for most the peak of production exceeds capacities of local markets to absorb fruits (in the absence of processing and conservation technology), while in in-between seasons and years other sources of nutrition and income are needed[75]. On one hand this is a key argument for retaining high diversity for portfolio risk reduction effects, on the other, one of the first issues to be addressed in 'tree domestication' (see Chapter 3) is to find management practices and genetic selections that lead to more regular and predictable fruit production.

Tree databases

Our brief overview of tree biology may have created interest in a more systematic compilation of 'functional traits' of trees that have potential use in agroforestry or are found as 'volunteer' parts of managed forests and forest landscapes. Indeed, compilation of data on trees has been an important part of agroforestry research in its first four decades. Current progress is described in Box 2.3. Several tree databases have now been connected by a 'switchboard' that avoids the taxonomic confusion that tends to plague any such comparison[76].

Box 2.3 Tree databases and plant functional traits



A completely revised version of the Agroforestry Species Switchboard was launched in May 2019[77]. The *Switchboard* currently documents the presence of 172,395 plant species across 36 web-based information sources for a total of 307,404 hyperlinks. Rather than limiting database links to tree species, all plant species documented in a particular database are listed via their current names inferred from *The Plant List*.

Only four databases have information for at least 10 percent of species listed in *GlobalTreeSearch*: the Tree Functional Attributes and Ecological Database, Useful Tropical Plants, the Global Wood Density Database and the Try Database. In many cases, the only trait that is available is wood density. Overlaps in species assemblages are generally higher for the AgroforesTree Database and the various databases listed. However, the small overlap with the European EUFORGEN database and smaller number of documented species compared to global databases such the GRIN World Economic Plants show a bias in the AFD towards tropical areas. Percentages above 50% for two invasive species databases highlight the need to check biosecurity risks when introducing typical agroforestry species into new areas.

Table 2.1 Number of species documented in databases listed in the *Switchboard* (in order of the website from where also details can be obtained for each database). GTS and AFD show the percentage of species shared with the *GlobalTreeSearch* and *Agroforestree* databases, respectively. Colours show 0-1-10-100% ranges.

Database	Species	GTS	AFD
AgroforesTree Database	616	0.9	100.0
Tree Seed Suppliers Directory	2836	3.5	60.1
African Wood Density Database	794	1.2	26.6
RELMA-ICRAF Useful Trees	661	1.0	42.7
Genetic Resources Unit Database	296	0.4	30.0
Tree Functional Attributes and Ecological Database	9606	12.9	95.6
Useful Tree Species for Africa map	436	0.6	24.7
vegetationmap4africa	1012	1.2	30.0
African Orphan Crops Consortium	97	0.1	7.1
Árboles de Centroamérica	198	0.3	9.6
Ecocrop	2338	1.7	67.9
Especies para restauración	315	0.5	11.0
EUFORGEN	105	0.2	0.8
Feedipedia	619	0.3	19.6
GRIN World Economic Plants	11438	5.6	75.3
MAPFORGEN	100	0.2	4.7
New World Fruits Database	1133	1.3	7.6
NewCROP Database	854	0.5	25.6
OPTIONs Pesticidal Plants Database	12	0.0	1.0
Pacific Island Agroforestry species	74	0.1	5.8
PROTA4U	9918	9.3	48.9
Seed Leaflets (University of Copenhagen)	172	0.3	19.3
Selection of Forages for the Tropics	172	0.0	2.8
The Tropitree Database	24	0.0	3.9
The Wood Database	311	0.5	9.7
USDA Food Composition Databases	260	0.1	8.0
Useful Tropical Plants	11575	12.6	89.1
CABI Invasive Species Compendium	9186	3.7	58.9
Global Invasive Species Database	468	0.2	8.8
Global Register of Introduced and Invasive Species	9727	2.9	54.9
eHALOPH	1374	0.4	7.0
Extrafloral nectaries	3252	2.3	15.9
Global Species Matrix	660	0.6	26.1
Global Wood Density Database	7591	11.7	69.6
GlobalTreeSearch	59649	100.0	90.1
Try Database	137308	51.0	96.8

Table 2.2 The top-40 species that were listed in a minimum of 19 databases.
* Indicates species listed for the African Orphan Crops Consortium

Species	DB	Species	DB
Albizia saman	28	*Artocarpus heterophyllus* *	20
Anacardium occidentale *	24	*Casuarina equisetifolia*	20
Ceiba pentandra	24	*Dalbergia sissoo*	20
Prosopis juliflora	24	*Hymenaea courbaril*	20
Cocos nucifera *	23	*Mangifera indica* *	20
Faidherbia albida *	23	*Psidium guajava* *	20
Gliricidia sepium	23	*Sesbania sesban*	20
Albizia lebbeck	22	*Acacia mangium*	19
Cedrela odorata	22	*Acacia melanoxylon*	19
Olea europaea	22	*Adenanthera pavonina*	19
Persea americana *	22	*Artocarpus altilis* *	19
Tamarindus indica *	22	*Azadirachta indica*	19
Ziziphus jujuba *	22	*Diospyros mespiliformis*	19
Acacia mearnsii	21	*Elaeis guineensis* *	19
Adansonia digitata *	21	*Eucalyptus camaldulensis*	19
Balanites aegyptiaca	21	*Flacourtia indica*	19
Enterolobium cyclocarpum	21	*Melia azedarach*	19
Jatropha curcas	21	*Prosopis chilensis*	19
Leucaena leucocephala	21	*Sclerocarya birrea* *	19
Moringa oleifera *	21	*Vitellaria paradoxa* *	19

Checking the number of databases where a particular species was mentioned results in top-40 ranking. Several of these species have identified as regional priority species by ICRAF's Genetic Resources collection expeditions, field genebank establishments and 15 were listed as priorities for the African Orphan Crops Consortium.

2.3 Tree diversity in agroforests and on farm

Diversity can be understood, managed and measured, analysed in multiple ways in the context of complex agroecosystems[78,79]. Beyond quantification of what trees are found where[80], analysis can include classification by 1) origin (Fig. 2.5) and seed dispersal (Fig. 2.6) of the species making up the local ensemble, 2) resulting below- and aboveground structure and phenology with consequences for microclimate, light capture, water and nutrient cycling, 3) as basis for pest and disease interactions, or 4) as providers of the range of goods and services that are desirable from a human perspective (Fig. 2.7). An important further dimension of diversity for agroforestry is the representation of trees in local knowledge and the degree of specificity of ethnobotanical knowledge, linked to culture, language and ethnicity[81].

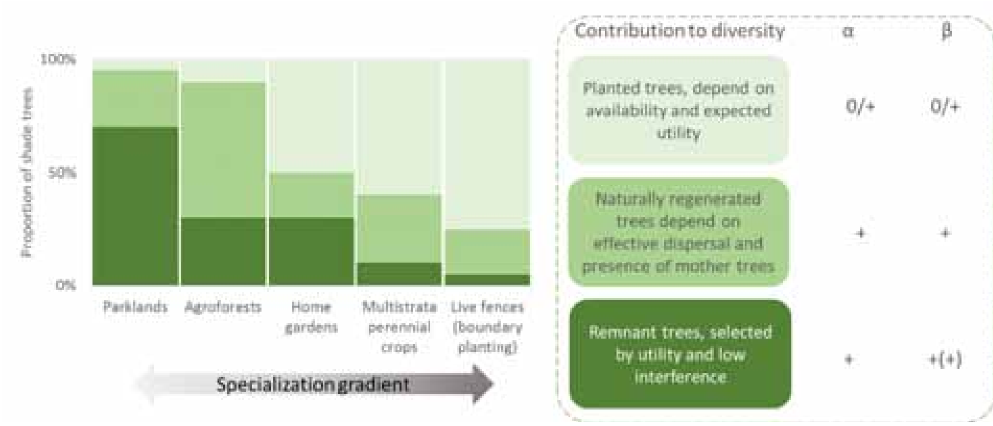


Figure 2.5 Tentative classification of trees by origin as remnant, volunteer or planted trees in various agroforestry systems[82]

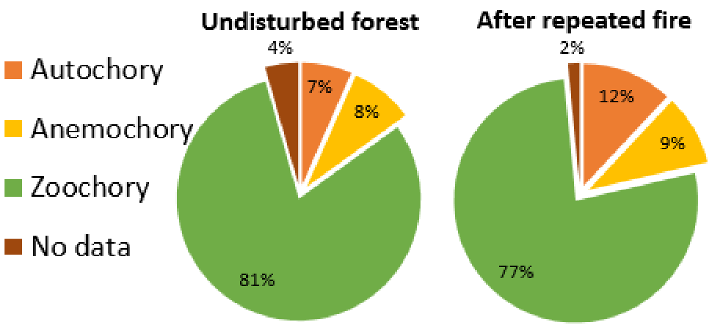


Figure 2.6 Example of the shifts in dispersal modes of trees between original forest plots and the same plots twenty-eight years after start of repeated forests fires in East Kalimantan (Indonesia), while 191 species naturally regenerated[83]

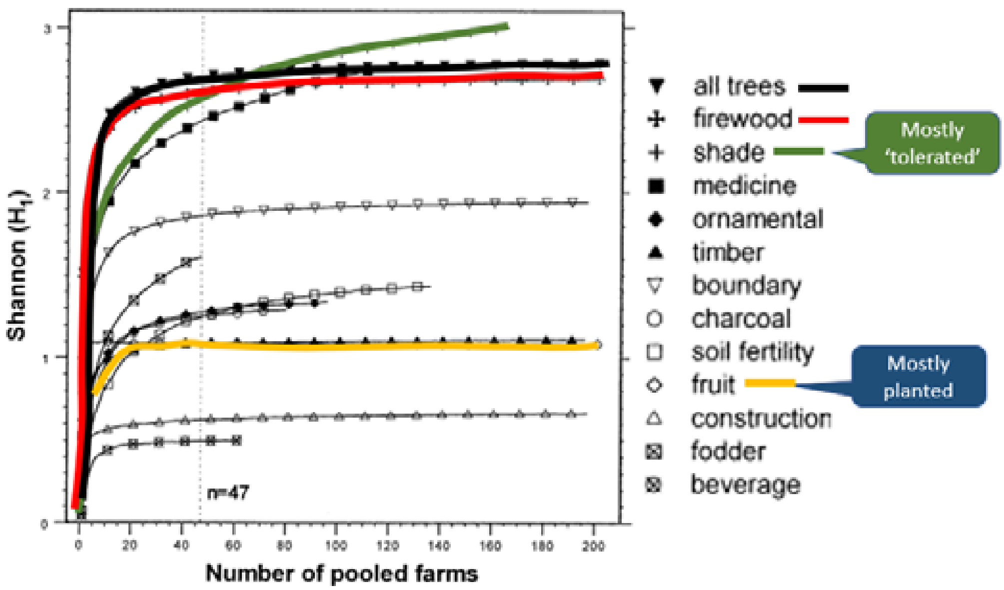


Figure 2.7 On-farm tree diversity in western Kenya in various use groups[84,85]

Similar studies have now been done in a wide range of settings, with results for total tree diversity ranging from around 10 to close to 1000 species per study. About 110 tree species were encountered[86], including 100 indigenous species, in tree diversity surveys in 16 villages in Burkina Faso, Mali, Niger and Senegal, totalling 300 quadrats randomly sampled from the main land use categories of parklands of village fields (VF), bush fields (BF), sylvopastoral zone (SP) and forest reserves (FR). A total of 127 species with acknowledged local use value in homegardens plus coffee agroforestry systems in Southwestern Ethiopia[87].

A total of 190 tree species (≥5 cm dbh) in a study of 180 coffee agroforestry on the slopes of Mount Kenya[88]. A total of 424 woody plant species, 306 indigenous, were encountered on 265 farm plots (each 0.5 ha) in 18 different agro-ecological zones around Mount Kenya, Kenya[89], with a mean of 17 species per plot; Eight of the ten most frequent species were exotic.

Hundreds of native tree species are currently found in extensive agroforestry ecosystems in the Peruvian Amazon[90], forming an important reservoir of biodiversity. A total of 930 tree species was documented in a study[91] in Jambi (Sumatra, Indonesia) that involved 77 transects in rubber agroforest (RAF; total sampled area 2.4 ha) and 31 transects in secondary forest (total sampled area 0.9 ha) during the period 2002-2005; 405 tree species were encountered in both forest and RAF, 284 species only in forest and 241 only in RAF plots. Nearly all species in the latter still belonged to the local tree flora (with *Hevea brasiliensis* naturalized and also found in the forest plots). Some differences in dispersal profile were noted: RAF-only species were 14.9% large-seeded (autochorous) and 64.3% long-distance zoochorous, versus 4.6% and 71.1% in these categories in the forest-only data, respectively, smaller differences in other categories and intermediate results for the species found in both. The RAF plots had less trees per ha than the forest (as a result of farmer management efforts to promote rubber), but equal densities and diversities in the seedling and sapling stages. Beyond the high tree richness found, a striking feature of these data is that many tree species were found only once, and the sampling intensity was insufficient to even approximate the total richness.

The contrasts between agroforestry contexts in tree diversity also suggest differential response to the 'strong prioritization' concept[92,93] of focussing scarce resource on the 'tree improvement' programs with the highest chance of success. The higher the tree diversity, the less attractive such formalized prioritization appeared to be – with a shift in paradigm to farmer-led domestication of species with a focus on generic, replicable principles, rather than the production of 'superior germplasm (see discussion in final section of this chapter).

2.4 Consequences of tree diversity

2.4.1 Knowledge and cultural diversity

A recent study[84] of palms in 57 Neotropical indigenous communities documented local utility of 120 palm species. Communities knew on average 17.8 ± 8.4 (mean ± SD) species, with on average two specific uses per species. The study concluded that the local knowledge is as fragile as the biological aspects of tree diversity.

An exploration of 'explanatory' local knowledge of farmers with several generations of experience in managing 'complex agroforests' in Indonesia, led to a surprising conclusion: farmers manage these systems with simple concepts on light, space and opportunistic responses (allow anything that doesn't disturb trees or patches with valuable components). Not aimed at maximizing output per ha but creating acceptable-to-good returns to labour (when compared with intensified, monoculture management), with high flexibility of response when rubber prices are down[94]. The explanatory information appeared to be simpler than that used to manage simpler forms of agroforestry elsewhere. Yet, the ethnobotanical knowledge was rich for species of direct value, while broad categories and local names are used for example for medium-quality timber trees.

Gender and religion were found to influence appreciation of sugar palm in North Sumatra (Indonesia)[95]. The centre of origin and history of human dispersal and migration helps to understand, and can sometimes be reconstructed from, intraspecific variation in and around a tree's centre of origin[96].

2.4.2 Portfolio risk reduction

One of the main advantages of tree diversity within each type of tree utility, is a reduction of risk. Risk can derive from abiotic factors (e.g. climate variability), market prices, but especially biotic relations. Specific studies on this in agroforests are lacking, but other forest-related evidence supports the hypothesis[97].

The agroforest diversity dynamics are mostly aligned in what ecologists recognize as dominant patterns in natural forest. Many tropical forests contain hundreds of tree species; some contain well over 1000. Several explanations have been discussed since decades in ecological research, without a single simple or agreed-upon answer emerging[98,99]. Empirically, the number of woody species in tropical forests tends to increase with precipitation, forest stature, soil fertility, rate of canopy turnover and time since catastrophic disturbance, and decrease with seasonality, latitude, altitude, and tree stem diameters[100]. The high tree diversity in the most productive environment can be understood from the increased importance of biotic, rather than abiotic, factors driving niche differentiation. Insects and fungi may be the primary cause of density-dependent plant mortality that favour diversity to emerge. The diversity-productivity relationship has since long been debated for the direction of causality. At the level of tree gaps as 'regeneration niche', strong recruitment (dispersal) limitations appear to control tree diversity[101].

Despite the impressive tree diversity data cited above (and similar results elsewhere)[102], it is not clear how much the agroforests contribute to long-term conservation of forest genetic resources. Tree species diversity in farmland can be high but may be transitory and dependent on the type of tree utility[103].

2.4.3 Exotic trees

There is a long-standing debate on 'Exotic' vs 'Indigenous' trees that has led to different perspectives and interpretations. First point to note is that the specific set of exotic trees that is most likely to be used is fast-growing and productive in the new environment while the ‘indigenous’ trees cover a wide spectrum of characteristics. Productivity in the new environment can be higher than that in the centre of origin where benefits of a temporary (unknown number of generations) escape from pests, diseases exceed costs caused by the loss of symbionts and pest control agents.

Several tree introductions to support ‘restoration’ have turned into ecological disasters of ‘invasive’ species replacing local ones that at least ecologically have higher value. The properties that appear to make an exotic tree attractive for introduction (growth rate, ease of reproduction), are now seen as primary risks for invasiveness. In selection of improved cultivars/varieties there rarely is explicit selection against invasiveness.

Part of the push for ‘exotics’ is an unintended consequence of efforts to protect local species from ‘illegal logging’ and exploitation. It is easier to show exotic trees are planted and grown on farm, than it is for local tree species, while valid conservation concerns apply only to the latter. This causes an ‘exotics paradox’ in policies towards on farm trees and their use.

2.5 Managing and governing tree diversity transitions in AF

The concept of a forest (or tree cover) transition has proved to be useful in both ‘theory of place’ and ‘theory of change’ type discussions[104]. However, the return of tree cover after the inflection point may be of different diversity characteristics than the tree cover that was lost in the left-hand side of the graph. Recognizing a ‘tree diversity transition’ curve (Fig. 2.8) may help understand the existence of four ‘tipping points’.

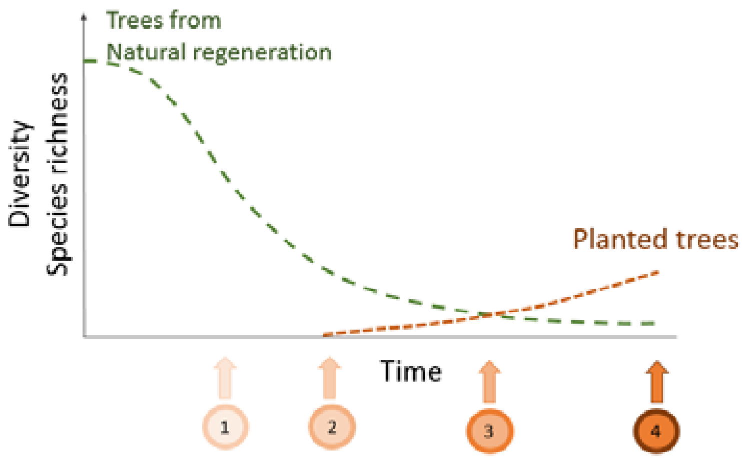


Figure 2.8 Schematic representation[84] of the ‘tree diversity transitions’ that may underpin ‘forest transitions’ in terms of tree cover, with four ‘tipping points’ discussed in the text

These tipping points are:

1. Seedling and sapling diversity decline as landscape-level recruitment has been affected and/or seedbanks are depleted, after the surrounding landscape lost its ‘forest’ status.
2. Start of tree planting, complementing managed natural regeneration and addressing local priorities[105,106]. A specific concern here can be the lack (or loss) of the required

symbionts for planted trees, such as mycorrhizal fungi. This has been suggested as bottleneck for obligatory ectomycorrhizal *Dipterocarpaceae* species, for example, but field tests with *Shorea* enrichment planting in rubber agroforests in Sumatra did not show a necessity for nursery-stage inoculation[107].

3. Start of dominance of planted tree diversity over remnant and volunteer tree species, with attention shifting to germplasm collection[108], tree seed sourcing[109] and delivery mechanisms[110], quality of planting material[111], and efforts to maintain intraspecific genetic diversity[112,113,114]. Active exchange of tree germplasm is governed by several international conventions, national laws and regulations, and centre-level policies (Box 2.4).
4. Returning of the land unit to a 'forest', 'tree plantation' or 'agroforest' status, depending on locally used definition, and with consequences in the local policy context (see Chapter 8).

Box 2.4 Policies and Guidelines[115] on Genetic Resources Utilization[116]

Several international conventions, agreements and guidelines govern the use of genetic resources and the related issues of biotechnology and intellectual property rights. Research centres under the Consultative Group on International Agricultural Research (CGIAR) adhere to these international instruments and each centre develops various policy, guidelines and position statements to guide and validate their decisions regarding genetic resources. Some of the key instruments related to use and exchange of plant germplasm include:

- International Treaty on Plant Genetic Resources for Food and Agriculture **(the Treaty):** The objectives of this Treaty are the conservation and sustainable use of plant genetic resources for food and agriculture and the fair and equitable sharing of the benefits arising out of their use as expounded in the Nagoya Protocol on Access Benefit Sharing. Under the Article 15 of the Treaty, the International Agricultural Centres are guided on the conservation and exchange of germplasm held 'in trust' for international community. Such material is exchanged via the Standards Material Transfer Agreement, an agreement between the germplasm provider and recipient, developed to ensure that the provisions of the Treaty regarding the transfer of germplasm are enforceable.
- International Plant Protection Convention (IPPC) is a multilateral treaty aims to secure coordinated, effective action to prevent and control the introduction and spread of pests of plants and plant products. Under the IPPC, internationally agreed phytosanitary measures have been developed that are enforced by the National Plant Protection Organizations (NPPO). The NPPOs issue plant import permits that allow plant material entry into their countries and issue phytosanitary certificate as guarantee of cleanliness of the plant material going out of their countries. The NPPOs also list the potential invasive species and regulate their entry into the country.
- The UPOV system of Plant Variety Protection (PVP) provides and promotes an effective system of plant variety protection, with the aim of encouraging the development of new varieties of plants, for the benefit of society.

ICRAF has policies and guidelines that ensure compliance with the various international legislations relating in use of tree germplasm such as the Tree Genetic Resources Policy and the Invasive Alien Species Policy. ICRAF researchers acquire authorisation of the various host countries' NPPOs in the acquisition of agroforestry tree germplasm for research.

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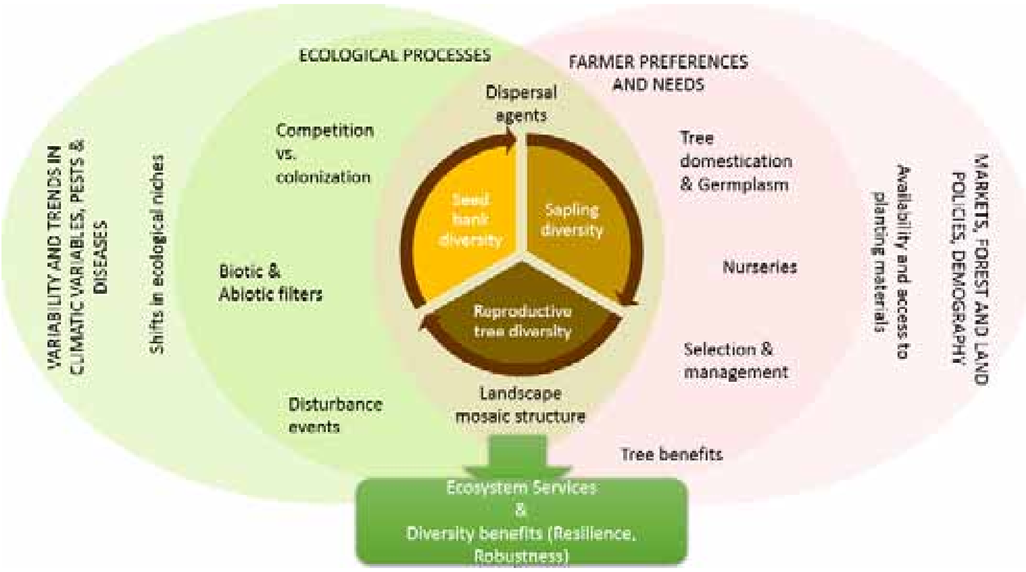

Figure 2.9 Synthesis of the ideas presented in this chapter, relating a tree life cycle perspective on natural plus anthropogenic dispersal to goods and services derived, with consequences for options to both conserve biodiversity and provide local benefits[84]

2.6 Domesticating both the tree and the agroforest

Trees and tree diversity as biological aspect of agroforestry is clearly interwoven with farmer preferences, options and opinions (Fig. 2.9), even more so than is understood for annual crops and livestock. One consequence is that the 'domestication' paradigm for trees is more complex. Box 2.1 discussed the challenge of seeing both the trees and (agro)forest. The same is true for 'domestication', where human control over biology and genetics of trees, interacts with human control over land on which to plant and grow trees[117], and the value chains that start with tree products (Fig. 2.10).

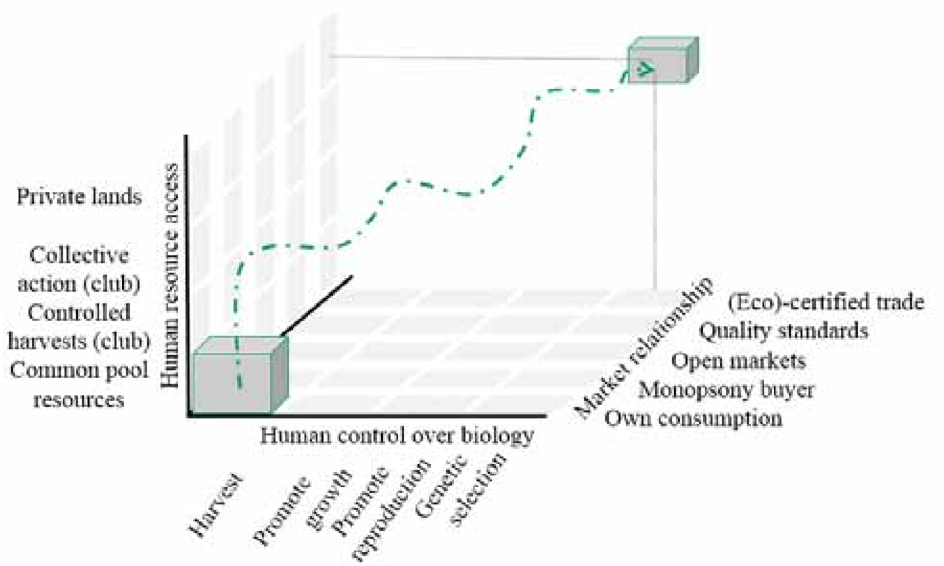

Figure 2.10 Correspondence between changes in three dimensions (human resource access, human control over biology, and market relationships) between a 'harvest of common pool resources for local consumption' and eco-certified global trade in products harvested on private lands from genetically selected' trees; the second axis has so far been the primary axis of 'tree domestication'

The general lessons for domestication of indigenous agroforestry fruit tree species learnt from 25 years of research and development efforts on peach palm[118]: 1) identify market demands, whether subsistence or market-oriented; 2) identify clients and consumers, and their perceptions of the product; 3) work on food and nutritional security aspects of the species and let entrepreneurs be attracted, rather than vice versa; 4) take up species improvement in a moderately sized effort, using a participatory approach tightly focused on clients' demands; and 5) reappraise the priorities from time to time.

Domestication of non-timber forest products such as Eaglewood can be expected to have winners and losers[119]. Domestication of other parts of the forest than trees may have faster returns and better prospects for local income enhancement[120]. Current domestication for specific environments such as tropical peats[121,122] may be driven by environmental considerations (reduced need for drainage) but challenged in its market dimension.

The shift from a laboratory-based to farmer-participatory approach[123,124] to tree domestication has built in the feedback loops to keep the complexity of Fig. 2.10 in the purview of adaptive project management (if the donors understand and accept changes that arise). Chapter 3 will discuss this issue in more depth.

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Tree domestication

The indigenous fruit ‘safou’ has been targeted for participatory domestication in Cameroon.

Photo: World Agroforestry/Charlie Pye-Smith

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CHAPTER THREE

Enhancing agroforestry systems through tree domestication

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Highlights

- Tree domestication can improve agroforestry functions: farmers' incomes, food and nutritional security, and wider product and service delivery
- Tree domestication can be approached in context specific centralised and decentralised ways
- Participatory domestication has had success in enhancing adoption and agroforestry development
- 'Mainstreaming' tree domestication requires appropriate links with 'demand' and market structures

3.1 Introduction

The domestication of trees is essential to enhance the products and services provided by agroforestry systems[1]. A range of domestication methods has been developed over recent decades. These methods are context specific and include a participatory domestication approach involving scientists and farmers working in close collaboration. This approach has had positive impacts on incomes, diets and in rural business development. However, to be more widely successful, agroforestry tree domestication still requires greater attention to scaling-up approaches, working with a wide range of partners in different partnership models. Future domestication work will also require more specific consideration of a wider range of traits related to ecosystem services' provision, with the appropriate mobilisation of genetic diversity.

Enhancing product and service provision from trees to improve livelihoods, increase productivity, combat malnutrition and adapt to anthropogenic climate change[2,3] involves their domestication — the genetic changes involved in bringing a plant into cultivation and in its continued development as a planted resource, through both unconscious and deliberate selection and breeding — to adapt them to meet human needs. The process of domestication began over 10,000 years ago for annual crops[4], and a few millennia ago for selected food trees[5,6,7,8], but the vast majority of the Earth's > 80,000 tree species are still essentially wild or only incipient domesticates[9].

This chapter outlines approaches for tree domestication and the benefits realised, as well as some of the dangers involved, and concludes by exploring requirements for future work. In particular, it will explore the domestication of food trees to address the problems of food and nutritional security in Sub-Saharan Africa[10]. Many of the world's nations with the highest burden of child under-nutrition are found in the region and, in particular, the consumption of fruit and healthier (non-starchy) leafy vegetables is overall well below global averages[11]. Conversely, a wide range of trees producing foods rich in micronutrients, fibre and protein is located in the region, which could support enhanced, biodiversity-based food solutions[12].

3.2 Methods of tree domestication

Appropriate domestication methods vary by tree biology, the planting environment, tree use and user, the value of the product and/or service provided, the available research and implementation partners, landscape configurations and the level of infrastructure development[13]. Two basic approaches have, however, been described (Figure 3.1). The first is a centralised approach involving field trials, controlled crosses and, in some cases, biotechnological methods to carry out genetic improvement[14,15] while the second makes use of more decentralised community-driven strategies[16]. The first approach is relatively straightforward to coordinate, has been applied to a few dozen timber and fruit trees often grown in plantations as well as on smallholdings[12], and has been boosted recently by advances in technology that have greatly reduced the costs of characterising and manipulating tree genomes. These advanced methods are being used increasingly to characterise 'orphan' (less researched, under-invested) trees as well as major plantation tree species, through initiatives such as the African Orphan Crops Consortium[17]. The challenge, though, is to link these advanced approaches effectively with downstream application: the results of centralised characterisation and breeding efforts often do not filter down to small-scale farmers, who face high transaction costs in obtaining external farm inputs such as tree planting material and the information needed for specific cultivars' management [18,19]. Bridges to farmers can be generated by working with them in priority setting, germplasm evaluation and in planting material multiplication[20]. A 'low input breeding' approach, involving integrated conservation, breeding and delivery, has been designed to overcome some of the challenges involved in linking genetic improvement and germplasm multiplication to smallholders' production[21].

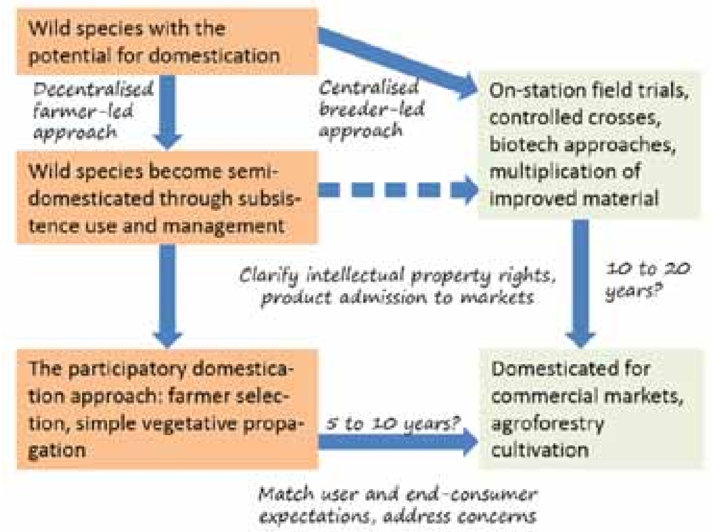

Figure 3.1 Examples of two routes to tree domestication

In recent decades, the second major approach to effectively mobilise genetic diversity has focused on decentralised, holistic tree domestication. One method, referred to as participatory domestication, has been developed in close collaboration between scientists and farmers. It involves combining scientific advances in genetic selection, propagation, processing etc with local communities' experience in tree management and has been used in Africa, particularly, to bring indigenous fruits and nuts into wider cultivation[22]. The initial focus of this approach is on satisfying immediate household needs for tree foods and other tree products, with expansion then occurring through farmers producing planting material for sale to other growers, and by tree product commercialisation[23,24]. The approach provides the conceptual 'building blocks' for domesticating a whole range of trees chosen by farmers themselves, based on family and market requirements and other considerations. Since it provides for a focus on multiple species, it buffers production and market risks that may result from the domestication of a single tree species[25]. The implementation of the approach is supported by rural resource centres that are managed by local communities. These train farmers in how to propagate and manage trees, hold stocks of plants for vegetative propagation, provide product-processing facilities and business training, and act as venues for farmers to meet and form associations that allow them to market their products and obtain farm services more effectively (Figure 3.2).

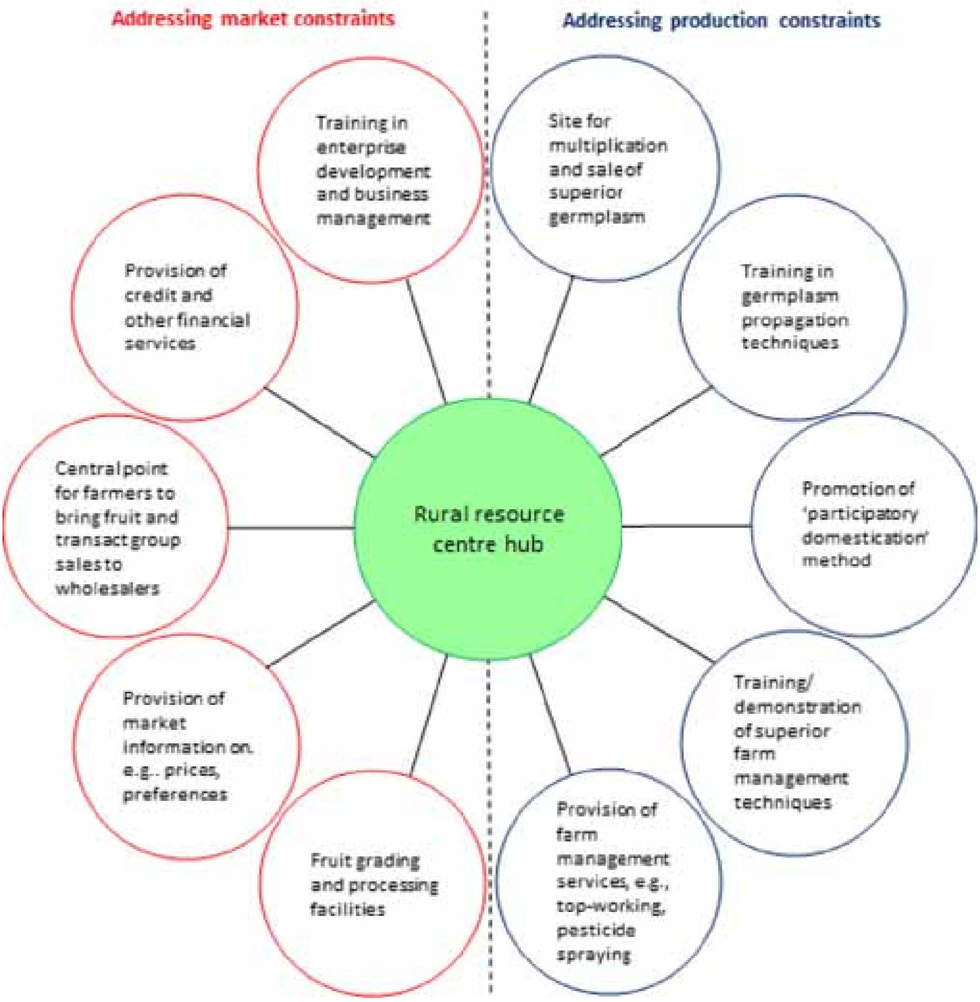

Figure 3.2 Market and production functions of rural resource centres[26]

3.3 Positive impacts of tree domestication

A crucial component of bringing new trees into cultivation is to increase their productivity and their ability to provide environmental services. This allows them to compete effectively with other crops and plants when farmers decide what they will plant on their land so that they can become properly established on farms to support production, lead to higher agrobiodiversity and contribute to resilience[27]. Fortunately, the large size of the gene pools of many tree species means that significant genetic gains can be obtained quite easily through selection and breeding. The case of indigenous tree fruits is informative[28], with > 2-fold variation common in nutrient content (for example, in marula[29]) and > 4-fold variation in yield (for example, in allanblackia[30]) across trees. Some of the variation observed in such cases is due to the environmental heterogeneity of the tree sample locations included in the comparisons but common garden field trials indicate an important proportion of variation has a genetic basis. Lower but still important genetic variation is also observed in other important food traits[31]. Large gains in timber[32] and tree fodder[33] yield and quality are also possible through straightforward selection and/or breeding. In the case of high value vegetatively-propagated trees, the use of simple cloning methods that have been adopted by farmers can result in gains in multiple traits simultaneously, addressing markets' particular preference combinations[34]. In addition, with vegetative propagation, the time between planting and crop maturity can be reduced for fruit trees compared to plantings from seed, decreasing the time gap between farmers' investments and their returns, which is important for adoption[16,35].

In the humid forest margins of Central Africa, where indigenous fruits and nuts are highly valued[36,37,38], the adoption of the participatory domestication approach has resulted in significant improvements in incomes, in diets and in rural business development, improving the overall well-being of the involved communities[24,25]. A multifaceted approach by which agroforestry can be mainstreamed to support food and nutritional security, and provide other products and services, involves the following steps: first, provide support for soil-fertility replenishment technologies to improve overall farm productivity and increase staple crop self-reliance; second, undertake participatory tree domestication of more nutritious fruit and nut trees (and of other trees providing high-value products); and, third, encourage entrepreneurship and value-addition to increase returns from the sale of tree products and tree planting materials[39]. Work on the allanblackia tree (a range of species in the *Allanblackia* genus), found wild in the humid forests of Africa, provides a model for the involvement of private-public partnerships in sustainable business development[28,40]. The seeds of allanblackia yield edible oil with significant potential in the global food market and wild harvesting, cultivation and market development are being promoted in parallel through a wide consortium of partners[41].

3.4 Potential negative impacts of tree domestication

Since domestication processes result in shifts and/or losses in underlying genetic diversity in tree populations, this can have implications for the sustainability of their cultivation. The impacts on genetic diversity depend on the domestication method. Cloning, for example, may lead to significant diversity bottlenecks, potentially mimicking commercial monocultural tree plantations that may be more vulnerable to pests and diseases[42] and other environmental catastrophes[13]. Risks are, however, reduced in participatory domestication when different villages each clone their local superior tree types for planting because a range of types are maintained in the wider landscape. To be avoided, though, are production systems where a new tree crop takes over the farming landscape to the detriment of other crops, to biodiversity more generally, and to the provision of a wide range of environmental services, as has for example been observed widely in palm-oil production systems[43,44] and, in some locations, in cocoa production[45]. This reinforces the need to seek the domestication of multiple trees and not to focus only on single species. As multi-functional, multi-species agroforestry systems are often favoured by small-scale farmers[25], this reduces overall production risks associated with losses of genetic diversity in any one tree species planted for a particular use. Another cautionary issue to be aware of during tree domestication is any possible negative relationship between mutually desirable product traits, such as fruits' yields and nutritional qualities.

Although tree domestication to promote tree cultivation is seen as a strategy for protecting forest resources by taking pressure off the natural resource base, this link should not be taken for granted. Indeed, tree planting may result in less priority being placed on the sustainable management of natural stands (which begin to be seen only as 'stopgap' supplies[46]), may stimulate the development of markets and infrastructure that unintentionally 'capture' wild resources as well as serving the harvest of planted stands[47] and may, if profitable, trigger forest and woodland clearance for further cultivation. Avoiding such impacts means placing tree domestication activities within wider landscape governance and management, ensuring appropriate policies and practices addressing a wide range of social and economic factors are in place to minimise unintended consequences[48]. Detailed research to establish when and where positive results for the conservation of forest resources can be realised through tree cultivation is required. This research should involve case study trees such as pygeum and allanblackia (Box 3.1). Market demands for product traceability, sustainability and uniformity may be factors that promote beneficial links between cultivation and forest conservation[49].

Collectors sorting allanblackia seed. Photo: World Agroforestry/Charlie Pye-Smith

Box 3.1 Can domestication and cultivation of trees in agroforestry systems preserve them in natural forests?

Two interesting case studies where exploration of links between domestication, cultivation and in situ conservation is merited[50] are the African trees, pygeum (*Prunus africana*) and allanblackia (*Allanblackia* species), both of which are currently being planted by African farmers.

Pygeum

An extract from the bark of pygeum, a tree found in montane forests across Africa, is used worldwide to treat benign prostatic hyperplasia. Historical wide-scale harvest from natural stands in Cameroon and Madagascar resulted in the species being listed in 1995 under Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). Over the last two decades or so, cultivation has been promoted to provide an alternative source of bark with a view to improving local peoples' livelihoods, with thousands of smallholders planting the tree in Cameroon, although this bark is not yet widely harvested for sale. Research is required to determine to what degree, within a CITES framework, bark from cultivated stands is able to substitute in the market for that from natural populations, and how this can best be done. If a switch from wild to farm harvesting does occur, what impact will this have on the livelihoods of the collectors of wild bark, who are often among the poorest people in communities and do not have access to land to plant trees? And what would be the effect of collection from farms on the attitudes of farmers and wild harvesters to forest management?

Allanblackia

The edible oil from allanblackia seed has significant global market potential in spreads and other food products. Within the last fifteen years, wild harvest for export has begun from humid African forests, and cultivation with a view to improve smallholders' incomes has commenced. Unlike many other non-timber forest products, cultivation has begun at the same time as market development, which may help to reduce wild over-exploitation and the associated negative impacts on biodiversity, but this premise needs to be tested. Large productivity gains appear to be possible under cultivation and this may afford greater protection for allanblackia in the wild but may also encourage wider cutting of forest for allanblackia planting. Will early cultivation be effective in taking pressure off natural stands by directing market demand for seed oil to planted sources? And how committed are commercial, research and conservation organisations to resolve the practical and reputational challenges involved in developing a sustainable business? If the development of the allanblackia business model fails due to a lack of profitability or environmental concerns, what will be the impact on the attitude of local communities to the use and management of indigenous trees and natural forest, more widely?

3.5 Trends in domestication research and future action to support impact

A review published in 2012[50] of > 400 papers on agroforestry tree domestication assessed the progress that had been made from 2002 to 2011 compared to the decade before. Between 1992 and 2001, there was a focus on assessing tree species' potential and the development of propagation techniques, with a strong geographic emphasis on work in Africa. Between 2002 and 2011, more emphasis was placed on new techniques for assessing variation, on product commercialisation, and on adoption and impact issues, and efforts were spread more globally. For the decade 2012 to 2021, the authors suggest that one of the major challenges worldwide would be to scale up successful agroforestry tree domestication approaches (such as happened with the participatory domestication method in Central Africa), in parallel with better market engagement.

As of 2019, further research progress has been made but the scaling challenge still holds in many geographic regions, with particular attention still needed to strengthen weak extension services that are a major bottleneck in practice adoption. In addition, the scale of the effort required to diversify agricultural production systems to make them both more sustainable and more productive has in recent years increasingly been recognised as a key challenge for the 21st century. To help address these challenges, since 2017 one of the flagships of the CGIAR's Research Program on Forests, Trees and Agroforestry has been specifically on tree genetic resources (TGR); this combines impact-oriented conservation, domestication and planting-material delivery research[51]. Tree conservation is also included in the current CGIAR Genebank Platform[52]. An enhanced focus on TGR is also supported by greater recent policy attention on these resources[53], renewed calls for healthy diets where trees provide nutrient-rich foods[54], and increased investment in forest restoration where the matching of tree planting material to environment is crucial[55]. Clearly, supply- and demand-led approaches to scaling are inextricably linked, as it is demand that will ultimately be the primary effector in mainstreaming production changes. In the case of market development, the role of consumer education in enhancing awareness of the benefits of eating healthy tree foods is recognised[56] and this can reinforce demographics shifts that already provide positive support for healthier diets[57]. Experience in domestication methods, including the decentralised participatory approach, shows that these interventions are most successful when part of a suite of measures that encourage the general upgrading of farm practices; one crucial measure of which is support for soil-fertility replenishment[39]. In addition, any measures that reduce farmers' costs of production — including in knowledge acquisition and in farm practices — are important; focusing on the underlying building blocks of domestication practices is an adaptive and cost-effective approach that deals with the context specificity of farmers' circumstances (comparable with wider agroecological practice adoption[58]). For farmers to innovate in planting trees that are new to them, a proper explanation of risks and benefits is also required, including not only for incomes but in terms of human and environmental health; advanced methods exist for risk-return modelling of decision-making processes, and these should be applied[59].

In terms of traits, in the light of globally homogenising agriculture and global diets[60,61], more of a focus on the genetics of interactions that support the effective co-production of tree foods, other tree products and other components (for example, annual crops, livestock, fish) in agricultural systems is needed[62]. Interaction traits that determine resource-use complementarity or conflict between crops and trees that can be targeted in tree domestication include tree architecture (for example, root angle and depth, stem/bole branching and height, the arrangement of leaves and fruits); mycorrhizal associations (for example, for nitrogen fixation); and phenology (of tree growth, leaf production, flowering, seed/fruit maturity etc). New methods of breeding that explicitly consider these interactions are required[63]. If these are adopted, it is possible to 'force' more optimal positive relationships between plant components in mixed agricultural systems than are represented by the complementary relationships between species found in natural ecosystems, due to different balancing of trade-offs[64].

More attention is also required to other genetically-controlled traits of trees that support the provision of suitable habitat for crop pollinators and beneficial crop pest predators[62], and which enhance carbon capture. The genetics of carbon capture, important for mitigating climate change (controlled, for example, by growth rate, wood density and wood composition), were found to be considered only rarely by tree-planting practitioners in a recent analysis[65] even though major capture gains could be achieved by choosing the right sources of tree planting material, at both inter- and intra-specific levels[32,66].

A third important area where improvements are required relates to the labour costs of tree production. Since these costs depend on tree form and phenology that are under genetic control, selection can be undertaken, for example, to spread tree fruit production to periods of the agricultural calendar when farmers are less busy tending annual crops. The same approach can be used to target tree food availability to hunger seasons (the times when annual crops have been consumed and communities are most nutritionally vulnerable[56]).

Cultivated lands with native *Schinus molle* tree in the centre and exotic plantations of *Eucalyptus* trees in the background - Taparcarí, Coc. Photo: University of Bern, Switzerland/Sarah-Lan Mathez-Stiefel

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Bjorn Lundgren

INTERMEZZO 2

Recollections from ICRAF's second Director General (1981-1991)

"The ICRAF that I came to in September 1981 was a small organization – a total of around 15 people, all categories, of which only five internationally recruited scientists, sitting in offices in downtown Nairobi and with a budget of less than USD 800,000, derived from only four donors. The first task was to develop a strategy and plan for ICRAF's medium-term future. This had three major components:

1) to collate, analyse and make available information on agroforestry technologies and systems, and identify their potentials to improve farming systems;

2) laying the foundation for the science of agroforestry, realising that it required interdisciplinary approaches in view of the often complex economic and ecological interactions between woody, herbaceous and animal components; and,

3) build the institution of ICRAF into a powerful and recognised international entity.

By the mid-1980s we had come a long way in achieving these goals. A global inventory of agroforestry systems and technologies was underway; the Field Station in Machakos was fully operational and used for research methods development (and demonstration); a well-functioning library, multi-purpose trees (MPT) database and information services were in place; and, not least, a truly multidisciplinary team of scientists/experts had been built up. Apart from the obvious agronomists, foresters, horticulturists, livestock experts and soil scientists, there also were social scientists, economists, meteorologist and information experts. The pivotal role in these years of the interdisciplinary Diagnostic & Design (D&D) methodology for ICRAFs' development and work cannot be over-estimated.

In the second half of the 1980s, much of ICRAF's efforts went into the development and launching of the four Agroforestry Research Networks for Africa (AFRENA) programmes. Based on extensive applications of the D&D methodology as a basis for identifying potential agroforestry technologies and systems that could improve the economy and sustainability of forming systems in four key agro-ecological zones of Africa, the AFRENA programmes were truly collaborative and participatory undertakings. They involved a large number of national agriculture and forestry research institutions, farmers groups, NGOs, and, even, some international centres (e.g. ICRISATs Sahelian Centre and IITA's station in Cameroon). Work was done both on stations and on-farm, and several promising results were obtained, which later came into fruition.

By September 1991, when I left ICRAF and Pedro took over as DG, ICRAF was, even by CGIAR-standards (ICRAF had joined the CG-system three months before), a medium-sized international research institution. There were c. 300 staff members, of which 80 professionals of different categories, a beautiful and very well-functioning HQ at Gigiri in Nairobi (where it still is), staff working in Kenya and 10 other African countries, and a budget of close to USD 12 million, derived from c. 20 different donors.

Taking soil samples for carbon measurement

Bulk density soil sampling as a step to estimate soil carbon stock, Central Kalimantan, Indonesia

Photo: World Agroforestry/Ni'matul Khasanah

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CHAPTER FOUR

Soil science as part of agroforestry[a]

Meine van Noordwijk, Edmundo Barrios, Keith Shepherd, Jules Bayala, Ingrid Öborn

Highlights

- New answers to land degradation problems have been an agroforestry focus for four decades
- Plot-level experimentation following agronomic traditions proved to be a challenge due to lateral interactions
- Testing hypotheses at process level and analysing tree–soil–crop interactions led to synthetic simulation models
- Policy attention to soil-nutrient replenishment in Africa and alternatives to slash-and-burn in humid tropics required more than technical analysis

4.1 Introduction

World Agroforestry (ICRAF) has as its mandate all agricultural land use that involves trees, beyond what is considered to be forest. The latter distinction is rather fluid, both temporally and institutionally, as the example of long-rotation shifting cultivation may show. Agroforestry itself ranges from croplands with a few trees added through to systems where tree crops (considered to be agricultural, such as coffee, cacao or rubber) provide a perennial vegetation layer, augmented with upper canopy layer trees utilized to modify microclimate, yielding economically valuable products. The consequences for soil conditions and functions vary along this range.

Agroforestry research has from its start operated on the active and often contested interface of the need to increase agricultural production, overall and per unit area, and the need to find more sustainable ways of managing natural resources. Agroforestry is typically associated with 'integrated' rather than 'segregated' solutions to meet the dual imperative, with specific attention to the understanding and management of trade-offs at the scales of farmers, the landscape, (sub-) national governments and the global policy arena. Soils have a key function

[a] A more extensive version[a] is available as ICRAF Working Paper 200

to both issues of land productivity and environmental effects, and soil research of one type or another has been part of nearly all research activities of ICRAF from its start.

Classifying the research output of ICRAF on the basis of citations to publications grouped by topic (Figure 4.1) shows six identifiable waves. Virtually all literature on agroforestry systems and improvement or 'tree–soil–crop interactions' that had been cited by 2013 had been published before 2000; by contrast, publications on agroforestry and environmental services and climate-change mitigation and adaptation started in the mid-1990s and flourished after 2000. Intermediate time patterns (steady progression in time) are found for agroforestry systems in social, policy and economic contexts, and for tree domestication.

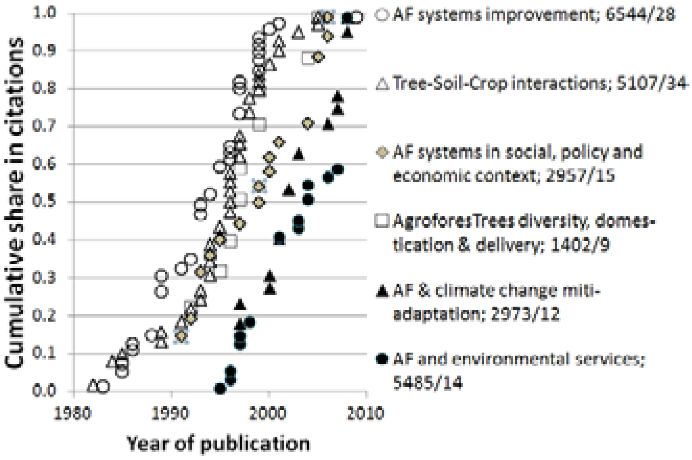

Figure 4.1 Citations to ICRAF publications classified by topic and year of publication (total / number of papers with more than 100 citations); based on Scholar Google (May 2013)

Note: AF = agroforestry

This chapter reviews progress in agroforestry soil science in the past two decades under seven headings and provides key references for each that point to more detailed reviews and syntheses.

1. Big-issues agenda with attention to local knowledge: soil depletion, land degradation, global climate change and loss of biodiversity

One of the first documents produced when ICRAF was being formed described the issues of land degradation in the tropics and the urgency of finding solutions for intensification that combine technical, ecological, social and economic aspects. This topic remained important in the first ten years of ICRAF[1] and forms a red thread through thirty-five years of institutional history. Partial successes have not yet combined to the breakthroughs needed at global scale because the issue interacts with international terms of trade, value chains for inputs and outputs in the local, national and international economies, and the dynamic rural–urban interface and its consequences for management of food prices. Arguments for public investment in soil-fertility replenishment in Africa received attention[2] but they were not backed by economic policy analysis, while the technical aspects of supporting phosphorus levels so that tree and grain legumes through biological nitrogen fixation could do the job of adding nitrogen to the soil were not convincing at farmer level[3,4]. Some success was made with fertilizer trees in fallow rotations but national subsidies for N-fertilizer to support grain crops won the day when food shortages became urgent again in southern Africa. Saving

Africa's soils still requires a combination of policy with science and technology for improved soil management that is not yet on the agenda in Africa[5]. The call for new initiatives to save Africa's soils remains urgent[6].

The 1992 Rio conference where the primary global environmental conventions were shaped marked the start of a new interest in how local, national and international actors interacted in the process of tropical forest conversion and how changes in land-use practice could be part of a package that obtained equal local benefits but substantially reduced global impacts on climate and biodiversity[7].The Alternatives to Slash and Burn (ASB) program was initiated to identify and support sustainable land-use intensification in the tropical forest margins, alongside protection of remaining forests. While declining soil fertility under reduced fallow lengths is one of the classical storylines that can be quantified in simple models[8], the focus of ASB was not on traditional shifting cultivation for subsistence livelihoods[9] but on its modern market-related versions. Almost from the start, researchers recognized that slash-and-burn as a method of land clearing was used by large-scale operators as a cheap way of establishing plantations, as a starting point for low-intensity grazing and as part of traditional shifting cultivation and crop–fallow rotations. The research program described patterns of land use in their social, economic and environmental contexts and then focused on a comparison of consequences of various land-use alternatives for an array of criteria. Soil-related constraints were found to be part of a much broader set of ecological, economic and social determinants of land-use patterns[10,11]. This led to analysis of trade-offs and interest in the way drivers of business-as-usual change can be leveraged to nudge systems into a more desirable direction[12].

An important part of the ASB research agenda along the forest transition curve was the rehabilitation of abandoned land, as an alternative to further deforestation. There was major confusion on whether such land areas were 'degraded' or abandoned for other reasons, for example, related to tenure issues and continued forest institutional regimes that prohibited other land uses[13]. The extent and dynamics of *Imperata* grasslands in Southeast Asia were reviewed[14], with specific attention to soil conditions. The latter were found to not be a real constraint to subsequent intensification[15,16].

Agricultural systems can greatly benefit from integrative approaches that combine formal and informal knowledge to address current sustainability problems associated with global change[17,18]. There is increasing recognition of the potential value of knowledge held by land managers who have been closely interacting with their environment for a long time to contribute important insights about the sustainable management of natural resources[19]. Increased concern about soil management as a key determinant of sustainability in agricultural landscapes has driven the demand for early warning indicators to monitor changes in soil health, and their impact in the provision of ecosystem services, as affected by land-use change and agricultural intensification[20,21]. A participatory methodology has been published recently, following several years of South–South collaboration, to guide the mobilization and integration of local and scientific knowledge on indicators of soil quality and soil fertility management[22]. It was designed to facilitate bottom–up approaches that integrate local knowledge into soil management decision-making processes and strengthen the relevance, credibility and legitimacy dimensions required for the adoption of best management practices. This methodological guide describes how to apply participatory tools in identifying, classifying and prioritizing local indicators of soil health knowledge so that they can complement technical indicators and later build farming communities' consensus about how to best address soil-health constraints following agroecological management principles and integrated soil-fertility management options. The development of a 'hybrid' knowledge base, combining local and scientific knowledge, reflects an effort to understand the complexity of land management decision making to promote and protect multifunctional land uses[23,24,25]. This is part of a continuing effort to develop land quality monitoring systems that strengthen local environmental and agricultural institutions and communities with tools that support local decision-making in natural resource management and promote sustainable land use in agricultural landscapes[26].

Corn-based agricultural development policy has led to land degradation in certain area in Gorontalo, Sulawesi. Photo: World Agroforestry/Ni'matul Khasanah

2. Agroforestry as a way to manage C, N, P capitals and beyond

In its first decade, ICRAF science dealt with an inventory of the diversity of agroforestry systems of the world and their primary reasons for existence. Soil and land-health management, interpreted as a combination of erosion control and maintenance of soil fertility[27], was identified as one of the strongest rationales for combining trees, crops and livestock on sloping lands. Soil-fertility improvement and better nutrient use-efficiency when introducing and managing trees (serving as nutrient pumps and safety nets) in agroecosystems were the focus of research aiming at optimizing agroforestry systems[28]. From the crop's perspective, however, most trees in most circumstances have a direct negative effect based on competitive resource capture, and the longer-term benefits of inclusion of trees will only weigh up to the negatives in well-defined circumstances[29,30]. Those circumstances potentially include, beyond sloping land, the seriously nutrient-depleted landscapes of Africa on geologically old soils[31,32,33].

In the 1980s, major hope became vested in alley cropping or hedgerow intercropping. Inspired by farmer-developed technology on sloping land in Flores, Indonesia, it was popularized in Africa by an Indonesian soil scientist working at the International Institute of

Tropical Agriculture in Nigeria. There are many versions of the history of the hope–hype–crash dynamics of public expectations of what this technology could deliver and how lessons could be learned from the experience[34]. It was to be largely repeated, however, in the improved fallow and fertilizer tree story that replaced it as a 'silver bullet' solution. While not ultimately leading to widespread success, the research done on hedgerow intercropping and improved fallows helped identify underlying principles on the technical, social and economic sides[35,36,37,38,39]. The search for locally appropriate agroforestry solutions continued.

Many studies have shown that soil organic matter (SOM) content of soil under trees is higher than in soils outside tree influence[40]. The attribution of this pattern to aboveground litter fall and belowground root turnover depends on local context[41]. However, crop yields do not correlate with total SOM, first of all due to the associated competition for light, water and nutrients but also because nutrient release from SOM is largely dependent on the fraction of SOM that is biologically active[42]. Aware of the competitive effects in simultaneous systems, research effort shifted to rotational crop–fallow systems as these are easier to understand and still part of farmers' reality. Efforts to identify biologically active fractions of SOM have shown that the amount of N in organic matter that is not physically protected and associated with soil particles, that is, light fraction N that floats on water or solutions[43] of densities below 1.1 g cm^{-3}, can be used as a sensitive measure of differences in SOM among cropping systems[44] as it correlates with whole soil N mineralization[45]. Planted tree fallows significantly modified light fraction SOM when compared to a continuous unfertilized maize control; total SOM, however, was not affected[46]. Furthermore, while the amount of N in the light fraction correlated with maize yield, the quantity of light fraction SOM did not, thus, highlighting the importance of organic input quality in soil N availability[47]. Key attributes of trees with the highest potential to increase soil N availability include the ability to fix nitrogen and litter with low (lignin + polyphenol)/nitrogen ratio that results in fast decomposition rates[48]. Additionally, planted tree fallow studies in which SOM fractionation and sequential P fractionation were conducted on the same soil samples showed that the amount of P in the light fraction could serve as sensitive indicators of the 'readily available' soil-P pool[49]. Planted tree fallows, therefore, have been successfully used to regenerate degraded soils in Africa and Latin America in areas where population pressure on land is reduced[50,51].

With trees as the primary point of differentiation between agroforestry and agriculture and range management, the specific aspects of perennialism imply a different sampling in space and time of soil functions[52,53]. Trees tend to be deeper rooted (with many notable exceptions[54]) and sample a much larger horizontal area, challenging traditional plot-based research despite all efforts at trenching-off plots. The net effect (positive or negative) for a farmer of inclusion of trees in an agricultural system depends on A) total resource capture (TotCapt), B) harvest index of resources captured (HarvIndex), C) losses to other environmental compartments of resources not harvested (Loss), D) economic value of the resources harvested (Value) and costs of losses to the environment (Cost), E) the expenditure of labour and other inputs at going price (Price) and F) possible changes in land value (ΔLandValue):

$$NetBenefit = TotCapt * HarvIndex * Value - Loss * Cost - Inputs * Price + \Delta LandValue$$

Research has tried to dissect this by relating A to tree architecture, phenology and growth rate, potentially independent of B and D, which are the focus of tree domestication and tree improvement efforts, alongside value-chain economics. Aspect E, the labour requirements of keeping the competitive aspects of trees under control while benefitting from the positive contributions to local nutrient cycles, proved to be a major challenge for the once-popular hedgerow intercropping systems. Meanwhile, aspect C has gained importance with current refocus on greenhouse-gas emissions, alongside erosion and leaching losses of soil particles and solutes. Aspect F may still be under-researched.

After a period of intensive research at process level on total resource capture, the conditions where 'over-yielding' of mixtures involving trees are fairly well established, while the effects of trees on losses by erosion and greenhouse-gas emissions have been quantified for a range of situations[55]. The interactions between trees and soil biota have been well explored in terms of mycorrhiza and earthworms (as reviewed later in this chapter) but a large part of the soil biological spectrum is open for further discovery. Science-based perspectives on bio-economic modelling can be compared with farmers' preferences and knowledge in the joint design of new management systems.

With depletion of agricultural soils due to nutrient export beyond the replenishment by fertilizer identified as a key challenge of farming[56], especially in Africa[57,58], considerable effort has been directed to the use of trees as 1) sources of biologically fixed nitrogen[59,60], 2) recyclers and safety-nets of nutrients from deeper layers[61], and 3) converters of less-processed nutrient sources, such as rock phosphate. However, farm-level nutrient budgets[62,63] caution that agroforestry can result in large nutrient extractions in product removals while pointing to opportunities for nutrient imports through livestock feed. The potential for tree fallows to re-capture leached nitrate held in the subsoil on anion exchange surfaces was demonstrated[64,65,66] and also the ability to reallocate some of the soil P into more labile P-pools[67]. While a number of technical solutions have emerged that are still worth further testing[68], no silver bullets have emerged that could revolutionize farming under the constraints of high nutrient exports and low economic feasibility of input use. As an alternative direction, the shift to tree crops with high economic value per unit harvested product has proven to be more successful.

Complementing the process and modelling approaches, new efforts are currently being made to efficiently describe the spatial variation in soil properties in the hope that this can lead to better targeting of sustainable land management practices while allowing for monitoring at real scale how soil properties change in response to land use[69]. A major challenge for any quantification of 'impact' is the counterfactual: what conditions could be expected without the intervention that is evaluated for impact? Any comparison of current soil conditions under two land-use systems must account for possible *a priori* differences between the locations where the two systems developed. This requires understanding of the existing variation in the landscape, local knowledge of conditions, preferences for specific parts of the landscape for specific land uses and ability to implement preferences[70]. There are some examples of tightly controlled designs for assessing changes in soil conditions in landscapes for forest transitions [71] and exclosures[72].

3. From process hypotheses and plot-level experiments to synthetic tree–soil–crop interaction models and management of filter functions

Research on tree–soil–crop interactions in agroforestry have focused on growth resources sharing between trees and crops mediated by soil with the hypothesis of trees creating favourable microclimatic and soil modifications for the crops. The findings have shown that trees on farms provide services to agriculture by contributing to 1) extended growing season by keeping the landscape covered with vegetation, 2) regulating water flows to the benefit of crops and groundwater recharge, and 3) soil regeneration, carbon sequestration and nutrient cycling[73]. However, the potential benefits depend on complex spatial and temporal interactions between the biological, physical, hydrological and climatic components of the system[74,75]. Such interactions change with time as trees grow larger together with the processes that affect the soil, which are governed by the root systems to a large extent[76,77], and also by the tree phenology[78,79,80]. Finally, management practices also affect these interactions, such as the tree density and vegetation cover, the use of fires to clear land[81,82,83], pruning of tree crowns or roots[84,85,86], and the maintenance of pruned biomass, crop residues and litter as mulch[87,88,89,90,91].

While tree species vary in rooting architecture and root biomass, tree roots can extend to deeper soil layers compared to those occupied by crop roots. They may, therefore, take water from the groundwater even though there is evidence of trees taking water from the top soil layers as well, depending on the species and its root systems[92]. Nevertheless, it is worthwhile to mention that there is no direct relationship between tree water extraction and fine root density because decreasing water potential also plays a role[93]. The effects of the increase of CO_2 and temperature as a result of climate change on changes to soil carbon storage were reported to be contradictory, calling for more investigation to separate the effect of increased C and that of possible changes in roots and rhizospheres[94]. In mixed agroforestry systems, the use of isotopes has helped to disentangle the contributions of the components and revealed larger contribution of the C3 plants (trees) to soil carbon in comparison with annuals[95,96,97]. As tree roots can grow deeply, they can also lift water and, with it, nutrients that leached below the reach of crops. They can act as a ‘safety net’ to capture nutrients leached from the topsoil and redistribute them to the soil surface[98,99]. Such a mechanism has been reported to improve N use-efficiency[100]. In addition, estimates of water volume lifted/redistributed can represent up to 30% of daily evapotranspiration[101,102]. According to the authors, this has a number of eco-physiological implications, for example, maintaining fine root viability and resistance to drought while affecting some of the soil processes, such as increasing soil water and soil biota activity.

Some synthetic analyses of published data using meta-analysis have also helped understand in which circumstances soil improvement translates into better crop production[103,104]. Another review and meta-analysis[105] showed that spatial heterogeneity in savannah vegetation was a result of termite mounds being fertility spots in the landscape, enriched with clay, carbon, nitrogen, calcium, magnesium and potassium.

Field investigations have helped generate a wealth of information on processes in isolation but have failed to reveal which one was the most prominent. A solution to this problem has been the development of a modelling phase which tried to synthesize the generated information to reveal the most limiting factors and processes for the production of associated crops. For instance, simulations using Water, Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS)[106] revealed that the decrease in *Zea mays* growth near *Grevillea robusta* water was due to lower soil-water content that resulted in a decreased P diffusion[107].

Similarly, water was found to be the most limiting nutrient under *Vitellaria paradoxa* while it was P under *Parkia biglobosa*[108]. For planning adaptation, WaNuLCAS was also used[109] to evaluate the effects of different management options (tree density, tree pruning, mulching and root pruning) on *Sorghum bicolor* production under future climate scenarios. There are a number of other models (APSIM, HiSafe, HyPAR, SCUAF etc) but they all have their limitations that are inherent to models, such as over-simplification, or our poor understanding of the processes involved in tree–soil–crop interactions, or to both[110]. If combining field investigations and modelling has helped to generate some scientific advances, there are still some methodological challenges in determining the 'parkland effect' (effect of a group of trees on biodiversity, microclimate etc), the trade-offs and synergies between and among goods and services, and how to boost the provisioning of ecosystems services[111].

Empirical research on agroforestry was initially largely built on the agronomic traditions of replicated field trials with plots in which a border zone was excluded from yield measurements to minimize lateral interactions between plots. Root research on trees, however, revealed that for many trees the lateral expansion can be multiples of the canopy height[112] and much of the experimental evidence needed to be interpreted with caution. It is possible that 'control' plots were effectively mined by tree roots from neighbouring plots, the performance on such plots enhanced by external nutrient capture, and hence the contrast between plots with and without trees magnified. Digging (deep) trenches around plots brings only temporary relief, as tree root systems can within a year occupy the space. A well-designed, replicated field trial[113] on various types of hedgerows as erosion control strategies showed that the underlying variability of the hill slope with respect to infiltration capacity had a major effect on what was measured as overland flow at plot level and the effectiveness of hedgerows as filters depended on the position of measurement. Much of the subsequent research relied on understanding spatial variability in the field rather than on controlled experiments. Despite substantial effort to spatially parameterize the Universal Soil Loss Equation (USLE) for a landscape in Kenya[114], the model correctly classified only 38% of sites into three degradation classes and the model sensitivity for delineating regions of severe degradation was only 28%. Local calibration with ground data could increase the correctly classified sites to 54% but without expectation that a modified model would be valid elsewhere. Similarly, there was little spatial agreement between predictions of different models (including modified USLE approaches) for a coffee-dominated landscape in Lampung, Indonesia[115]; there, in-field erosion was found not to be the major determinant of river sediment transport. Overland sediment flows were partially filtered while paths used for motorcycles, roads and shallow landslides contributed sediment directly to the river. Sediment and soil transport issues appeared to have different determinants at every scale between a soil pedon, a plot, a hill slope, a small and a large catchment. The fractal dimension that characterizes net sediment transport with a length scale to the power 1.5–1.6 was found[116,117] to have a parallel in the social organization of watershed management institutions[118]. There has been little accompanying work on the economic costs of soil erosion and benefits of agroforestry. Estimated ecological–economic costs of soil erosion in Kenya using emergy analysis at the national level were found to be equivalent to the value of agricultural exports or electricity production[119].

A further step in the scientific understanding of agroforestry came when lateral resource capture was seen not only as a challenge to research aimed at defining technology for 'homogenous' conditions but as an important aspect of real-world agroforestry, especially in the mixed stands typical of smallholdings, where edge planting of 'aggressive' trees may imply that half of the nutrients are scavenged off farm. This perspective on lateral resource capture aligned with the analysis of hedgerows of trees and naturally vegetated strips on sloping land. Rather than defining a uniform technology, science helped articulate a perspective on a range of niches in a diverse farming environment, with variation in tree properties that can be understood in, and used in fine-tuning of, farmers' decisions to plant, prune, manage, harvest and/or remove[120].

4. Trees and other soil biota: old tree root channels, earthworms, mycorrhiza, rhizobia and nematodes

Trees live above as well as belowground. Soil structure is a key determinant of root development and root function, as well as for other soil biota. Soil compaction as a consequence of agricultural use and/or overgrazing is both a symptom of soil (mis-)management as well as a cause of declining primary productivity. The importance of this, however, varies with the rainfall regime and climate zone. Macroporosity of soils, the class of pores most easily compacted, is essential for saturated hydraulic conductivity and the ability of soils to handle intense rain without overland flow and ensuing erosion. Macroporosity in the field is linked to texture (cracking clay soils), decayed tree root channels[121], the impact of deeply burrowing earthworms[122] and possibly other soil biota. Measurement of infiltration in the field typically shows log-normal distributions, with a small fraction of points having one or two orders of magnitude of higher infiltration rates. The question of how such infiltration hot-spots at field scale operate during extreme rain events cannot be easily assessed from current measurement techniques because much depends on their subsoil connectivity to landscape-level drainage systems. Agroforestry can influence the continuous formation of macroporosity through the provision of leaf-litter-feeding earthworms and, at another time scale, the formation of decaying tree root channels. At the level of mesoporosity, the tendency of soils to form aggregates is strongly influenced by soil-ingesting soil biota[123] and by fungal hyphae associated with mycorrhiza[124]. Attribution of biological activity associated with soil structure modification is not a trivial exercise but a methodological approach using Near Infrared Spectrometry (NIR) allowed the separation of soil aggregates produced by soil invertebrates and roots living in the same soil[125].

Vertical and horizontal water transport through and over the surface of soils is, however, a 'communicating vessels' problem with strong trade-offs. If water flows over the surface it may cause erosion but it reduces the problem of leaching, and vice versa. A more detailed examination of by-pass flow, however, made clear that macroporosity can drain excess water without much effect on solute transport in mesopores, especially where the latter benefit from physico-chemical ion adsorption acting as an additional safety net[126]. Later versions of the WaNuLCAS model[127] have included such processes and allow the dynamics of soil structure, bypass flow and root-based safety nets for leaching nutrients to be quantified.

In Burkina Faso, with yearly rainfall ranging 570–1180 mm, groundwater recharge was simulated to be the equivalent of 2–14% of the total gross water input. A combination of the measurement and modelling of drainage and transpiration in agroforestry parkland revealed that intermediate density of trees (5–25 trees ha^{-1} based on the assumption that 100–0% of transpired water came from below 1.5 m depth) can maximize groundwater recharge while at higher stockings there was a trade-off between tree cover and available water[128].

The soil environment may well host and interact with the most complex biological community once we account for scale[129]. Soil biota (for example, microbes, invertebrates) mostly contained in the upper few decimetres of soil are extremely diverse and make important contributions to a wide range of ecosystem services that are essential to the sustainable function of natural and managed ecosystems[130,131]. New high-throughput DNA profiling techniques are supporting efforts to assess the global distribution of soil biota and the relationship of belowground biodiversity to above-ground biodiversity[132]. Soil biota directly influence soil fertility by mobilizing nutrients[133] and form soil structures[134], increasing water infiltration and soil C storage and decreasing soil erosion. Therefore, in order to understand the distribution and diversity of soil organisms and how they respond to disturbance, be it agricultural practices or climate change, it is necessary to monitor the soil and environmental quality that is required for sustaining land health in agricultural ecosystems[135]. Strategies for maintaining native biota of farm soils, such as mycorrhizal inoculum potential, are generally preferable to inoculation strategies[136,137]. Recent global studies show that preservation of plant biodiversity is crucial to maintain multiple ecosystem functions like nutrient cycling, plant productivity and carbon storage, and also to buffer the negative effects of climate change[138]. Slash-and-mulch agroforestry systems show greater abundance of soil macro-fauna than native forest, suggesting that maintenance of soil cover with organic materials of different qualities promotes favourable conditions for soil biological activity[139]. Comparison of adjacent agricultural plots with and without trees show that tree presence increases abundance of several groups of soil biota[140]. Further, greater soil biological activity occurs near trees but the effect is greater for some tree species than for others[141]. This is likely related to differences in plant functional traits[142]. Trees can be considered as 'hot spots' of biological activity and play a major role in maintaining and promoting soil biological activity responsible for many of the functions that underpin soil-mediated ecosystem services[143]. Farmers' perspectives and knowledge of soil biota together with scientific knowledge contributes to a better understanding of tree–soil biota interactions in time and space that allow design of diverse cropping systems that can sustain multiple functions required for the adequate provision of ecosystem services[144,145,146,147].

5. Soil-carbon dynamics and greenhouse-gas emissions from agroforestry systems

The ASB program was the first to establish a cross-continental network of sites with consistent measurement of above- and belowground carbon stocks of forests and forest-derived land uses in the humid tropics[148]. A review of the way soil carbon stock varies with soil type, elevation (temperature) and land cover introduced the concept of C-reference values and associated soil carbon deficits[149], taking natural forest soils with the same texture, mineralogy, pH and elevation as the basis for a pedotransfer function. The empirical relationships between texture and soil-carbon content were aligned with the assumptions and process descriptions of the Century model; attempts to measure the 'functional' fractions represented in the model remained partially unsuccessful, however[150]. Analysis of carbon dynamics in aggregate fractions[151] could not be directly linked to fully functional carbon-balance models.

Farmers in Na Thau village, Veitnam, take samples in their community forest for soil-carbon measurement. Photo: World Agroforestry/Duc Minh Nguyen

Carbon stocks are additive and allow area-based scaling, making it straightforward to scale from plot to landscape[152] once the scale-dependent patterns of spatial variation are known. The high spatial variability of soil carbon, coupled to costs of sampling and analysis and challenges in attributing differences to cause–effect chains, make it unlikely that soil carbon, when assessed with current standard methods, can become part of carbon projects[153]. More optimistic perspectives related to methodological improvements will be discussed below. A further challenge to such inclusion is the observation that a 'soil-carbon transition curve', with recovery following degradation, can be observed in response to agricultural intensification, and without specific soil-carbon interventions[154]. Rather than being a primary target for interventions and finance as part of climate-change mitigation, soil carbon should be of interest from the perspective of buffering of soil water and nutrient content, as part of farm resilience and climate-change adaptation[155].

The early measurements of nitrous oxide and methane emissions in relation to tropical land-use change suggested that such fluxes will generally be small relative to the greenhouse-gas effect of tropical forest conversion through changes in (mostly aboveground) carbon stocks. Specific for the use of N_2 fixing shrubs and trees in agroforestry, where N-rich mulch is left on the soil surface without incorporation into the soil, high emissions of nitrous oxide are possible and were measured in shaded coffee systems[156]. In terms of net greenhouse-gas effects, the jury is out to determine whether biological N_2 fixation by trees is friend or foe[157]; the likely answer is that it depends on how and where such trees are used.

6. Soil/land health surveillance

ICRAF's work on low-cost, rapid, soil characterization using diffuse reflectance spectroscopy began with the use of field spectroscopy in combination with Landsat imagery to trace sources of soil erosion in Lake Victoria[158]. This early work, using the visible-near-infrared (VNIR) wavelength range, also showed the potential for using soil reflectance to measure management-induced changes in soil quality in long-term trials[159]. This was later demonstrated at landscape scale in land-use change studies in Madagascar[160] and along a tropical forest–cropland chrono-sequence in Kenya[161]. A scheme for the use of spectral libraries as a tool for building risk-based approaches to soil evaluation was demonstrated for a diverse library of over 1000 topsoils from eastern and southern Africa, including development of spectral diagnostic tests for screening soils with respect to critical soil-fertility limits[162]. The global applicability of soil spectroscopy was further demonstrated using a global soil library based on archived samples at the US National Soil Survey Center using VNIR[163] and for available samples from the International Soil Reference and Information Centre global archives using mid-infrared spectroscopy[164].

Infrared spectroscopy uses a different set of principles than conventional soil-fertility tests, providing a single multiple-utility measure of soil-production potential and response to management[165,166]. With IR, soils can be characterised in a single 30-second measure that requires no chemicals, only light. The shapes of infrared spectra respond to the basic molecular structure of mineral and organic composition of soils and their interactions. It is the organic–mineral composition that determines soil functional properties, including a soil's ability to retain and supply different nutrients and water, nitrogen mineralisation capacity, soil charge characteristics, soil structural stability and ability to resist soil erosion, and amount of soil organic carbon in different pools and its protection. Although calibration to conventional soil tests has been used as an intermediate step, the ultimate concept behind the spectral approach is to calibrate soil and crop responses to management directly to infrared spectra and completely by-pass the need for conventional soil tests[167].

The ability to derive spectral indicators of soil fertility was demonstrated in several studies[168] that successfully calibrated soil-condition classes, based on ten commonly used agronomic indicators of soil fertility, to both soil reflectance measured in the laboratory and Landsat TM reflectance, which permitted mapping of the index. The spectral index also related to δ13C dynamics associated with historic land-use changes, similar to other studies that spectrally discriminated forest–cropland chronosequence classes[169]. A similar approach was successfully used for spectral prediction and mapping of soil-fertility classes in Mali[170], while a similar study[171] calibrated principal components of soil-fertility variables to spectra to assess the prevalence of soil-fertility constraints on farm fields in Kenya.

Several studies have shown strong relationships between observed or measured soil erosion in the field and laboratory-measured soil spectra. A study in Kenya's Nyando River Basin[172] was able to spectrally discriminate ground visual observations of three ordinal erosion classes with validation accuracies of 78%. A similar approach in Kenya's Saiwa River Basin[173] obtained validation accuracies of 72%, with additional validation of the erosion classes using soil ^{137}Cs concentration data. An erosion–deposition index was developed[174] as a tool to rapidly screen soils in the Nyando River Basin into eroded, intact or depositional soil classes based on a spectral distance index using sediment spectra as a reference library. The spectral index was validated using ^{137}Cs analysis and soil spectra were also used to interpolate ^{210}Pb concentration in sediment cores. The combined data allowed a sediment budget for the basin to be constructed as well as the historic time trends in soil erosion from 1900.

Soil spectroscopy was shown to be able to predict various soil-carbon fractions and their mineralization rates. Mid-infrared (MIR) spectroscopy was used to predict the concentration of organic-carbon fractions present in a diverse set of Australian and Kenyan soils[175]. The coefficient of determination of measured versus predicted data (r^2) ranged from 0.97 and 0.73 for total organic carbon, particulate organic carbon, and charcoal carbon. Soil spectra were also shown to predict carbon mineralization rates from different soil physical fractions in two contrasting soil types[176]. At the same sites, mid-infrared spectra were used to interpret functional groups to help elucidate biogeochemical mechanisms that determine the fate of carbon inputs in soils and organic matter stabilization by aggregates[177]. Removing the mineral soil spectra in Alfisols, obtained from heated soils, did not improve spectral calibrations of soil organic carbon, indicting the robustness of the spectral method[178].

Reflectance spectroscopy was shown to be useful for predicting organic resource quality for soil and livestock management based on nitrogen, lignin and soluble polyphenol concentrations[179,180]. Validation r^2 of >0.8 were obtained for prediction of in vitro dry matter digestibility (IVDMD) and C and N mineralization for a diverse range of crop and tree residues of varying quality[181,182,183]. NIR for determination of crude protein content in cowpea (*Vigna unguiculata*) leaves was also demonstrated[184].

Infrared spectroscopy can enable an evidence-based diagnostic surveillance approach to agricultural and environmental management in developing countries[185], based on the scientific principles used in public health surveillance. Infrared spectroscopy was proposed as a rapid screening tool for assigning samples to case or reference and allowing characterization of the health of systems at scale using population-based sampling. The diverse range of applications of infrared spectroscopy in agriculture and environment was reviewed.

In response to the need for objective, quantitative and cost-efficient methods for assessment of land health to justify, target and prioritize investments, the diagnostic surveillance principles were taken further to form a conceptual framework for wide-area soil and land-health surveillance[186,187]. Land health is defined as the capacity of land to sustain delivery of ecosystem services and is a prerequisite for wise ecosystem management and sustainable development. The soil spectroscopy methods were key to enabling this approach by providing a soil analytical tool that could be applied cost-effectively at scale. Land-health surveillance is hinged on systematic georeferenced field observations based on probability sampling (Land Degradation Surveillance Framework/LDSF)[188,189], so that inferences can be made back to the target area sampled. Georeferenced soil spectral estimates of soil properties are statistically modelled to remote sensing covariates so that the models can be applied back to every pixel on the satellite imagery to provide digital maps of soil properties. The report and accompanying atlas[190] illustrate the land-health surveillance concepts with a case study in the West African Sahel, presenting results on regional remote-sensing studies of historical changes in vegetation growth and rainfall patterns in the area, indicating land-degradation trends, and on field-level assessment of land degradation in Mali. This combination of principles and scientific and technical advances formed the basis for the Africa Soil Information Service (AfSIS).

ICRAF played a foundational role in the establishing AfSIS. The project has implemented the first ever probability sample of African land health and soils, based on a set of 60 100-km^2 sentinel sites, providing a baseline for future monitoring of soil-health changes (www.africasoils.net)[191]. Spectral measurements were performed on all samples, while conventional reference measurements were done on a 10% random subsample[192]. A centralized African soil spectral prediction service is being piloted based on Bayesian Additive Regression Trees. This will allow spectrometer users to submit batches of spectra online and obtain predictions of soil properties with uncertainties given for each sample. Samples that are spectral outliers or have large prediction error can be submitted to the ICRAF laboratory for characterization and adding to the calibration library. This service could drastically reduce the need for conventional soil testing.

Figure 4.2 Portable mid-infrared spectrometer being used for rapid characterization of soil samples

In support of this initiative, ICRAF established a globally unique, Soil-Plant Spectral Diagnostics Laboratory, which focuses on analysing soils using only light (infrared, x-ray, laser). The laboratory established Fourier Transform near- and mid-infrared spectroscopy as a foundation for calibration transfer across a network of spectrometers. The light-based technologies have been extended to: benchtop x-ray diffraction for mineralogical analysis; total x-ray fluorescence for total element analysis[193] in soils, plants and water; handheld x-ray fluorescence spectroscopy; and laser diffraction particle size analysis for dry and wet aggregate stability, for which standard operating procedures are available at: http://worldagroforestry.org/research/land-health/spectral-diagnostics-laboratory. The laboratory supports a soil spectroscopy network spanning 10 African countries, to which it provides scientific and technical backstopping, including on-site training. Extensive support has been provided towards the establishment of the Ethiopia Soil Information System (http://www.ata. gov.et/projects/ethiopian-soil-information-system-ethiosis/). To enable easier access to soil spectral calibration techniques, ICRAF has developed the soil.spec software package in R (http://cran.r-project.org/web/ packages/soil.spec/soil.spec.pdf) and now runs an international soil spectroscopy training course.

Land-health surveillance approaches supported by soil spectroscopy are being applied in a number of sustainable land management projects in 10 African countries and in the CGIAR pan-tropical sentinel sites initiative. These include applications such as mapping soil carbon in rangelands[194], monitoring and degradation prevalence and soil functional properties in Ethiopia[195], and studying patterns in soil faunal and microbial activity in landscapes[196]. Soil spectroscopy has also been used to characterize patterns of variability in soil fertility in smallholders' farming systems[197,198,199,200]. Current applications include a pilot on integrating monitoring of soil fertility on farms into the World Bank Living Standards Measurement Study and soil monitoring in an integrated monitoring system for ecosystem services in agricultural landscapes (www.vitalsigns.org). Soil spectroscopy is also now being used by two private soil-testing services in Kenya.

Systematic application of land-health surveillance has the potential to generate improved understanding and predictive ability of agricultural systems and natural resources at multiple scales and improve intervention decision planning and impact assessment. Technological advances will lead to reliable handheld and mobile phone-based spectrometers and put the technology in the hands of farmers. The CGIAR can play an important role in building up centralized, online spectral calibration and advisory services. Digital mapping techniques based on Bayesian spectral-spatial one-step modelling with prediction uncertainties generated are already in development. These scientific and technical advances are paving the way for a new paradigm of predictive agronomy and crop breeding whereby response trials are co-located with soil-spectral measurements and remote-sensing observations. This could greatly enhance our ability to predict and map uncertainty in responses to soil and crop management and perhaps by-pass conventional soil tests. While the biophysical understanding of soil management has received much attention, there is need for much more attention on demonstrating the economic value of soil ecosystem services and improved soil management practices, and to better integrate soil information into decision-making processes[201,202].

7. The challenge of demonstrating development impact through soil changes

While the balance that draws us towards direct solutions for urgent problems of poverty, food security and environmental destruction swings back periodically to the equally pressing needs of scientific rigor and generalizable public goods, ICRAF as a CGIAR research centre has a long history of trying to satisfy all and debating where the best position is along the curve. Rather than choosing one point, it is important that the balance can swing.

From a time when 'packaged technology' was seen as a generic answer to local development challenges of many farmers in many places, we have moved forward to a greater appreciation of diversity. Spatial variability and diversity have often been seen as a problem in that they do not allow simplistic perspectives on scaling up. As 'homogeneity' has often been used as a site-selection criterion for field experiments, because it increases the chance of 'statistically significant' treatment effects to be seen with practically feasible levels of replication, scientists reviewing experimental evidence have a biased view of the world[203]. Technologies that were carefully packaged by scientists are generally unpacked by farmers, who will adopt the parts they like and find new ways around the parts they don't[204,205,206,207]. Having learnt from this experience, science and extension bodies developed a more modest approach to presenting a basket of options, with attention to risk management and the question of how many eggs should be put into each basket[208].

Unfortunately, the funders of international agricultural research are fascinated by the numbers of farmers and the area of land that can be claimed to benefit from 'improved practices' and are linking funding decisions to a 'beauty contest' among alternative programs judged on claims to impact. A direction that offers that one 'can eat development cake' and have good science as well, is seen to be in 'research in development'[209], with a focus on fine-tuning the baskets of options to what might have a chance to be accepted, and an equal attention to what and how farmers choose and why they do so, with social and gender stratification replacing the abstract, 'standard farmer' perceived in the past. This gives an even greater weight to taking local knowledge seriously: not only does it point to empirical experience from which formal science can learn; it also suggests a language in which scientific findings can be communicated back, alongside the baskets of options. Science in that perspective can be useful by testing and validating simple decision trees at component level[210].

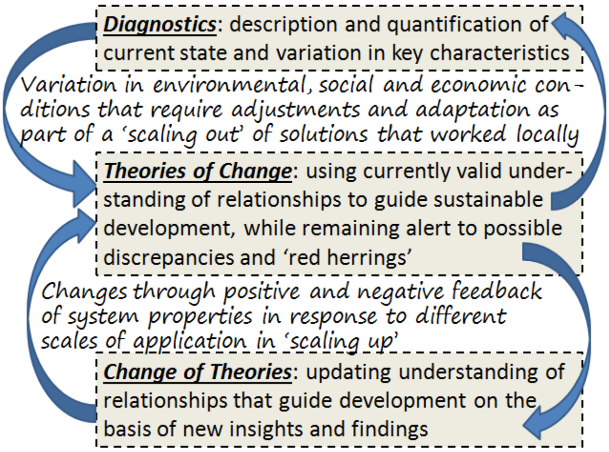

Figure 4.3 Key concepts of research in development, which require continued diagnostics as part of monitoring and evaluation and sentinel approaches, explicit theories of change that address both variation in circumstances encountered in 'scaling out' and changes in dynamic properties as a response of 'scaling up', and that may lead to change of theory

Change in soil properties tends to be slow compared to aboveground changes, and this 'slow variable' characteristic has consequences for impact studies. On one hand, it implies that changes in soil conditions, whether negative (depletion, degradation) or positive (restoration), once set in motion can be expected to have long lasting, negative or positive, effects that add to the importance of observed trends. On the other hand, slow change, combined with the high inherent spatial variability of soils, makes it difficult to obtain convincing evidence of any change at all. A simple spreadsheet model[211] (Figure 4.4) illustrates how a sampling of soil conditions found under different land-use systems can lead to strongly biased conclusions about 'effects of land use on the soil' if it does not account for the degree to which local variation of soil conditions informed land-use patterns in the first place.

Positive or negative changes in soil conditions in response to business-as-usual development, modified by specific development interventions, impact on many stakeholders. The most obvious ones are literally downstream, as the soil controls the switch between overland flow, with associated flashiness of rivers, and infiltration for slower 'interflow' in saturated soils and groundwater replenishment in other situations. The contrasting interests between 'water harvesting', where overland flow is to be stimulated and used, versus beneficiaries of infiltration has been noted before. The recent discourse on 'rainbow water' suggests that there are also 'downwind' stakeholders, whose interests may differ from those downstream[212].

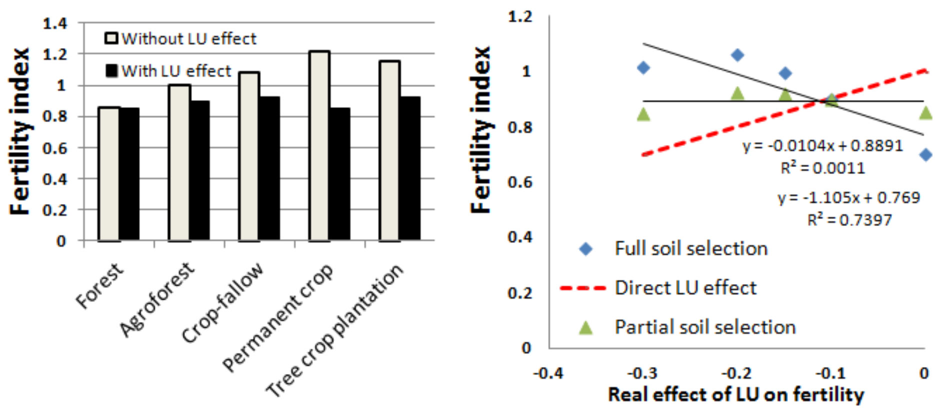

Figure 4.4 Illustration of the way land use (LU) effects soil properties, together with the preferential positioning of land uses in specific parts of a landscape, and influence survey results, with the possibility of apparent effects having opposite signs to real ones[213]

Further progress in soil science at the ICRAF will have to address the multiple agendas of global articulation of the ambitions for sustainable development, with growing evidence that forms of agroforestry can support many of the goals[214], national green economy ambitions with land uses that minimize damage or restore soils after phases of degradation[215], and farmer's preferences and choices. The complex involvement of multiple actors in what is perceived to be 'sustainable'[216] suggests that a close linking of technical and social expertise will remain important for impact-oriented fundamental soil science in agroforestry.

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A mosaiced agroforestry landscape

A mosaic of tree and crop species in an agroforestry landscape in Tosari, Pasuruan, East Java, Indonesia

Photo: World Agroforestry/Ni'matul Khasanah

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CHAPTER FIVE

Belowground resource sharing in mixed tree–crop systems: methods to better understand belowground interactions

Jules Bayala, Ingrid Öborn, Christian Dupraz

Highlights

- Research in agroforestry moved from a descriptive stock-taking phase to efforts to understand and quantify processes in the sharing of growth resources, above- and belowground
- Root distribution and structure are key to understanding of the interactions and processes involved
- Deployed methods range from basic but labour-intensive invasive approaches (coring, trenching, excavating and rhizotrons) to more sophisticated, expensive but non-invasive methods: X-ray Computed Tomography (CT), Gamma-ray Computed Tomography, Neutron Tomography, Magnetic Resonance Imaging (MRI) and Nuclear Magnetic Resonance (NMR)
- Despite the advances, root research in mixed crop-tree systems remains challenging because of the difficulty in finding the relevant spatial and temporal scales for real-world high heterogeneity soil conditions

5.1 Introduction

Cropping systems based on carefully designed species' mixtures over time (in terms of crop sequences) and/or space (within a farm or landscape) reveal many potential advantages under various conditions, both in temperate and tropical agriculture[1,2,3,4]. In general, annual crops are expected to be relatively shallow-rooted while perennial plants, including trees, can have roots extending deep below the crop root zone, giving a foundation to the safety-net hypothesis[5]. The safety-net hypothesis (intercepting mobile nutrients leaching from crop root zones) complements the nutrient-pump hypothesis (uptake of deep soil resources of relatively immobile nutrients)[6,7]. However, the actual situation of relative root distributions is more complex[8,9,10] and dynamic with seasonal shifts in the soil depth from which water and nutrients are taken up[11]. In some situations, trees and crops compete for nutrients and water in the same soil layer[12,13], even though the impact on crop performance and yield may vary according to rainfall[14] and nutrient availability[15,16,17]. Therefore, the potential benefits of trees in mixed systems depends on complex spatial and temporal interactions involving a large number of factors[18,19,20]. Strong positive effects (for example, through increased nutrient availability) can be offset by strong negative effects (for example, via shading), making optimization complex and context dependent[21].

The past decades of agroforestry research have revealed many interacting processes in the sharing of, and competition for, belowground resources, made progress in their quantification and established tools to study mixed tree–crop systems, as this chapter shows. However, the manner in which net effects depend on context still requires empirical verification of simulation models.

5.2 Complexity of the structure of agroforestry practices

Modern agriculture has been characterized by the promotion of sole crops in rotations or monocultures with the use of external inputs (germplasm, fertilizers, pesticides), which did not reach poor farmers living in the most vulnerable agro-ecologies, leading to deforestation when new areas of land were claimed for agriculture. This has resulted in reduced ecosystem services' delivery: 1) provisioning services (food, fuelwood, fibre, biochemical, and genetic resources); 2) regulating services (climate, disease control, water regulation and purification); and 3) supporting services (soil formation, nutrient cycling, primary production and provision of habitat). Such decline highlights the critical role of trees in farming systems, as attested by findings of a structured review of the roles of trees on farms for provisioning of ecosystem services in sub-Saharan Africa[22]. The majority of studies reviewed showed beneficial effects of trees on crops (58%), such as enhancing water and nutrient cycling, in particular in semi-arid areas. In 28% of the reviewed studies, no effects were found and, in 15%, crop yields were declining owing to tree–crop competition, for example, modification of the microclimate[23].

Traditional mixed farming systems are repositories of principles that can, if understood and correctly applied, make modern agricultural systems more productive and more resilient[24]. In other words, it is about getting the mixtures fitting well into the context such that trees acquire resources that crops would not otherwise use[25]. Studies of traditional systems that combine trees, crops and livestock on the same land unit have shown greater efficiency in using resources (water, nutrients and light)[4,26] than an exclusively annual-crop-based agriculture while they also are more resilient to climate change[24].

Such conclusions come from a long process that started by descriptive categorization of agroforestry systems and quantification of their benefits (production, effects on soils etc.). In contrast, experiments in which fast-growing, shallowly rooted trees were combined with cacao were found to make the cacao more vulnerable to dry years[27].

An on-station phase of research, where external variation could be partially controlled, helped to identify mechanisms of the tree–soil–crop interactions and critically test key hypotheses of safety-net functions[28,29,30] and the synchrony of nutrient supply by mineralization and crop demand[31]. However, findings of studies on interactions revealed that belowground niche differentiation did not hold everywhere as there were trade-offs between the beneficial effects of trees on soils and competition with crops for soil resources[32,33]. Indeed, many studies showed that root distribution of most of the tree species coincided with the upper soil layers occupied by annual crops[8,34,35] and that tree root systems may be highly opportunistic and reactive[36]. This property of accumulating maximum fine roots in the upper soil profile gives the plant an easy access to moisture and nutrients from the most fertile topsoil while the primary roots growing deeper help in extracting more moisture[37]. The fact that niche differentiation was found to not occur everywhere[38,39] triggered a range of studies on tree–crop root competition about ways to manage them through, for instance, root pruning[40,41] or crop competition[42]. Such efforts revealed that competition may induce changes in the phenology, activity and distribution of the roots of one of the competing species in such a way that competition is reduced or avoided[43;44,45;46].

5.3 Methods for research on belowground interaction at plot level

Research on belowground interactions emerged from the evolution of agroforestry science and the corresponding changes in research paradigms from descriptive studies to those on processes in growth resources sharing[47]. Thus, it was only during the 1990s that research on soils and root processes in agroforestry systems were emphasized[48,49]. Such research covered root distribution, water and nutrients content and uptake. Various categories of studies have been conducted, including observation of existing practices, field trials, station experiments and modelling[13,50]. This diversity of types of studies has also involved various experimental designs, including transects from one tree or shrub for scattered naturally regenerated trees (parklands, dehesa, farmer-managed natural regeneration) or from a line/row of trees for planted ones.

5.3.1 Root distribution

Because of the important role of roots in taking up water and nutrients for plant growth, they have attracted the attention of scientists both in studies of natural ecosystems and cultivated agro-ecosystems[51]. The studies started with very rudimentary methods, like core sampling and samples washed to extract roots, soil profiles to describe root distribution, excavating to study root system structure up to the recent use of imagery techniques. More broadly, methods have evolved from invasive field methods to non-invasive ones that are mostly restricted to laboratory conditions.

Invasive methods have helped describe root system architecture and distribution as an indication of the volume of soil explored and potential resource uptake. Basic methods for observing and quantifying tree and crop root biomass and length involve:

- Core soil sampling/monoliths and washing roots from soil[52] combining sieves or more automated root washers. Extracted roots are used to estimate a range of variables (weight, length, root length density, specific root length etc) manually or by scanning equipment and related software
- Trenching to use the wall profile for root distribution studies[53]
- Excavation around an individual tree to a certain depth and distance (up to the limits of the crown width) that allows observations of root architecture. This method is labour intensive

- Root pruning by trenches as a root management tool to limit competition for water and nutrients[38,54]
- Rhizotron technology allowing direct observations of fine root dynamics, including production, mortality, decomposition and turnover[55;56,57,58]. The forms vary from transparent tube to transparent plexiglas pane, or inflatable tubes[59]. However, the rhizotron approach has some limitations, including its inability to provide information regarding the chemical composition of fine roots and the rhizosphere, the difficulty of installing the tubes in stony soils, and soil disturbance caused by tube installation[60]. Inflatable rhizotrons avoid the gaps that tend to form between rigid structures and soil particles, improving visibility of roots and making turnover rates more realistic

Invasive methods can provide a range of information on roots interacting with soil profiles and companion plants but uptake functions are also controlled by root age and specific interactions in the rhizosphere[61,62,63,64] that require different methods. Non-invasive methods are meant to provide further insights into dynamic interactions because they cause no damage to the root systems. The use of 3D visualisation techniques to measure roots in soil started in the early 1990s and they include X-ray Computed Tomography (CT), Gamma-ray Computed Tomography, Neutron Tomography, Magnetic Resonance Imaging (MRI) and Nuclear Magnetic Resonance (NMR)[65,66]. A more detailed description of these techniques emphasized their continued development and limitations[60].

5.3.2 Soil water content and uptake

Sampling patterns for soil-water measurement vary according to the studied agroforestry practice: transect, random etc. Methods used can measure water content, water potential or its drainage. For water content, the oldest and most accurate method is gravimetry (weighing fresh and dried samples). More sophisticated and automated tools were developed but they all use surrogates as proxies for soil-moisture content[87]. Although changes in water content in the surface soil horizons are commonly measured gravimetrically, more sophisticated techniques allow rapid automated measurements. Time Domain Reflectometry (TDR)[67] is commercially available with substantial advances in its use to measure soil-water content and bulk soil electrical conductivity[68,69]. A variety of TDR probe configurations provides users with site- and media-specific options. Advances in TDR technology and other dielectric methods offer the promise not only of less expensive but also more accurate tools for electrical determination of water and solute contents[70] that can be used to measure soil-water content. Another technique for measuring surface soil-water content is the Surface Insertion Capacitance Probe (SCIP)[71]. Although this approach was initially manual, it has also undergone tremendous development and can be automated and remotely controlled using a wireless network[72]. Despite the fact readings may be sensitive to supply voltage, temperature and bulk soil electrical conductivity, SCIP sensors are low cost and can be deployed in wireless network, allowing coverage of large spatial areas[73,74].

At depths below 15 cm, soil water content has often been measured using neutron probes[75,76]. The neutron probe is one of the most appropriate approaches for soil-water balance studies because access tubes can be installed without disturbing the soil profile outside the tube, except in gravelly or stony soils, and the access tubes can be of indefinite length. This technique has some limitations for changes in water content at shorter periods than a week.

Water potential can be measured using tensiometers. However, tensiometers have the disadvantage that they only work for water potentials down to c. -80 kPa and so may be off-scale for much of the time in semi-arid or arid regions. Soil-water potential can also be measured using gypsum blocks[77], which function down to much lower water potentials (around -1500 kPa) but may exhibit hysteresis and must be properly calibrated to obtain accurate readings. The high maintenance requirements of gypsum blocks limit their research capability. Uncalibrated gypsum blocks were used to provide qualitative information regarding two-dimensional soil drying and wetting patterns in agroforestry systems during several rainy seasons in Kenya[78]. Various other approaches for monitoring soil-water content[79,80] include gamma-ray attenuation, capacitance probes, pressure plates, ground-penetrating radar and remote sensing of soil-surface properties.

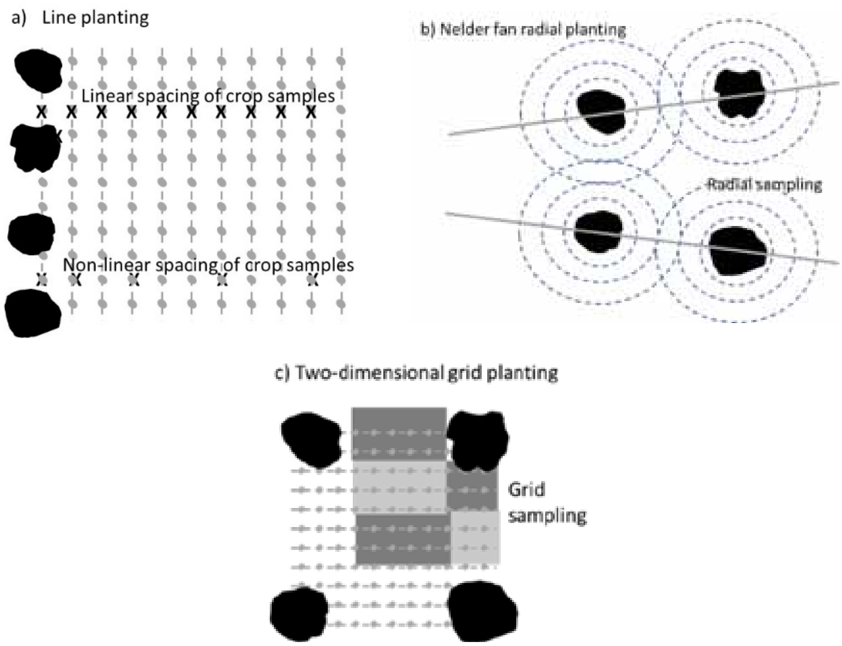

Figure 5.1 Examples of soil-water content sampling patterns used in mixed tree–crop systems
Note: Measurement points (x) can be arranged (a) perpendicular to the tree line, (b) at radial distances from individual trees and (c) in a two-dimensional grid[81]

Six approaches for determining drainage[82] are porous cups, porous plates, capillary wicks, pan lysimeters, resin boxes and lysimeters. The most basic approach is the use of lysimetry to capture drainage-water volumes using buried containers over various time periods. Several types of lysimeter have been employed, including pan lysimeters, equilibrium-tension lysimeters and wick lysimeters, each with their own advantages and disadvantages[83]. Recently developed passive-wick lysimeter using an inert wicking material, such as fibreglass or rock wool[83,84] can be linked to dataloggers to transmit drainage data to a remote host[85]. Collecting soil-pore water or drainage water will also allow for chemical analysis, for example, of pH, plant nutrients and other elements[86]. Drainage volumes can be estimated indirectly[87] and through modelling approaches[88,89].

Stable isotopes (D, ^{18}O, and ^{13}C) provide valuable non-invasive methods for determining of the soil layers of water uptake[90]. Soil and plant water potential[91] or ground-penetrating radar and plant ^{18}O ratio[92] to produce more accurate information.

5.3.3 Soil nutrients and uptake

Measurement designs for soil nutrients either in situ or by soil sampling are similar to those used for root distribution and soil-water content. Taking soil samples at various distances and depths, analysing them and comparing the situations with agroforestry practice without (control) has been the most common approach. Trees component of agroforestry practices are in general expected to directly contribute to carbon (photosynthesis and biomass recycling) and nitrogen (N_2 fixation and biomass recycling) and indirectly by taking up other nutrients from deep soil layers and recycle them in upper soil layers through the litter and root decay. Laboratory analyses have so far provided the most accurate data but there is on-going development of devices allowing in situ measurement of the concentrations of soil nutrients. Such devices still have a number of limitations. For laboratory approaches, wet chemistry is being combined with Near Infrared (NIR) methods[93,94,95], which allows analyses of thousands of samples and in very short periods of time. NIR methods still require a lot of improvement about the accuracy of the measurements.

For the uptake, again like water, stable isotopes (such as ^{15}N and ^{31}P) have been used for testing the safety-net hypothesis of niche differentiation between components of agroforestry practices ([28,96,97]). Other soil parameters measured in studies about the belowground interactions include soil texture, pH, bulk density, porosity, fauna abundance and diversity[13].

5.4 From plot to farm and landscape: modelling approaches for scaling

Models are a way of understanding the implications of processes we know sufficiently well to structure and parameterize the models[13]. These models are approaching the interactions from three different angles: separating positive and negative effects, establishing the resource balance, and modelling the resource capture[21].

5.4.1 Plot-level models of belowground tree–crop interactions

Plot-level models 'without roots' can be adequate to relate available resources to uptake at field scale at a monthly or annual timescale. However, models that use spatial details of root distribution are required for accounts of competitive or resource-constrained systems and can be classified in four classes[98,99]:

i) models that ignore root dynamics and use time-independent root distributions;
ii) models that incorporate simple root dynamics described by a generic distribution model independent of both aboveground processes and soil conditions;
iii) models that simulate root-system growth in response to conditions in the aboveground parts of the plant but without an interaction with soil environment; and

iv) models that simulate the growth of a root system that senses and reacts to local soil conditions as well as to the conditions in the aboveground part of the plant.

Most agronomical or forestry models at the plot scale include a one-dimensional root model and constrain the root distribution by a negative exponential decrease with distance (vertically and laterally) from the plant base[104]. A step forward was achieved with recent models that describe root systems in 2D or 3D, dynamically, and consider dynamic responses to local soil conditions. Two models designed for agroforestry systems include these features: 2D for WaNulCas[102] and 3D for Hi-sAFe ([100,103,101]). The Hi-sAFe model includes a continuum representation to simulate the growth of both fine and coarse root systems in 3D heterogeneous soil conditions and was designed with a 3D 'voxel automata' approach[36]. The Hi-sAFe root model is driven by the diffusion of fine roots across a soil compartmentalised in voxels, and linked by a coarse root system that is self-generated by the model. It provides a generic and flexible root model that can react to the soil heterogeneity that is always induced by the competing rooting systems of trees and crops[102].

5.4.2 Upscaling to farm and landscape levels

Almost all the studies of belowground interactions have been conducted at the plot level while key issues are at farm and landscape levels, bringing in more complexity. To address such complexity, several agroforestry models were developed (Table 5.1). However, they all show intrinsic limitations, including insufficient flexibility, restricted ability to simulate interactions, extensive parameterization needs, lack of model maintenance and with updating and investments needed[8,37,103]. Even though models that are maintained can now in their advanced versions describe root systems in 2D or 3D and dynamically consider changes in soil conditions[100,104,105], efforts are still needed to move from plot level to landscape scale.

Table 5.1 Different models used to study interactions in mixed tree–crop systems and their main characteristics

Model	Components	Unique features for below-ground modelling	Model source code
Historical			
SCUAF[106]	*N/A*	*Effect of trees on soil conservation and carbon*	**
ALMANAC[107]	Water, carbon, nitrogen	Supply, uptake, competition	**
COMP8[108]	Water, carbon, nitrogen	Supply, uptake, competition	**
CropSys[109]	Water, carbon, nitrogen	Supply, uptake, competition	**
GAPS[110]	Water, carbon, nitrogen	Supply, uptake, competition	**
WIMISA[111]	*Water, carbon, nitrogen*	*Supply, uptake, competition Windbreak Sahel*	**
HyCAS[112]	*Water, carbon, nitrogen*	*Supply, uptake, competition*	**
HyPAR[113]	*Water, carbon, nitrogen*	*Supply, uptake, competition*	**
Still actively maintained			
WOFOST[114]			https://www.wur.nl/en/Research-Results/Research-

Model	Components	Unique features for below-ground modelling	Model source code
			Institutes/Environmental-Research/Facilities-Products/Software-and-models/WOFOST.htm
WaNuLCAS[115]	*Light, Water, nitrogen, phosphorus, carbon*	*Dynamic tree and crop root systems*	http://www.worldagroforestry.org/output/wanulcas/download
APSIM[116,117]	Water, carbon, nitrogen, phosphorus	Crop rotations and land management	http://www.apsim.info/
Hi-sAFe[100,101,118]	*Light, water, nitrogen, 3D above-ground, 3D belowground*	*Dynamic and opportunistic tree and crop root systems*	https://www1.montpellier.inra.fr/wp-inra/hi-safe/en/
YIELD-SAFE[119,120]			http://www.isa.ulisboa.pt/cef/forchange/fctools/content/yield-safe-model
FARM-SAFE			https://www.agforward.eu/index.php/en/web-application-of-yield-safe-and-farm-safe-models.html
LUCIA[121] *Land Use Change Impact Assessment tool*	*Light, Water, nitrogen, phosphorus, carbon*		https://lucia.uni-hohenheim.de/en

NB: * Model still under active development, ** No longer active; N/A: Note Applicable; italic are agroforestry models. WOFOST and APSIM are not but their modular nature has allowed applications in agroforestry

Source: modified from 50

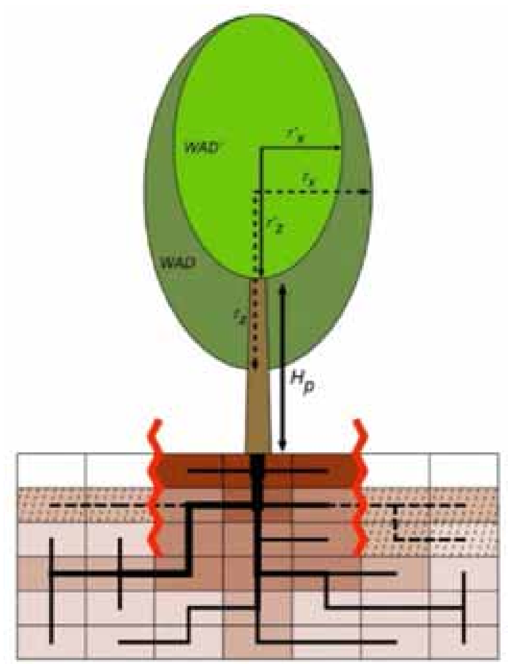

Figure 5.2 101 A simplified, 2D illustration of the branch and root pruning management interventions in sAFe-Tree

Coarse roots are represented by solid lines, with diameter proportional to line thickness. Fine root density is proportional to voxel shading, with darker colors indicating more fine roots. Branch pruning to a height Hp reduces vertical and horizontal crown radii by the same proportion. A reduction in WAD (and consequently LAD) can also be specified. Root pruning occurs along equidistant, parallel lines that straddle the tree (zigzag lines; into the page). Coarse roots that are cut by root pruning (dashed lines) are killed, along with all downstream coarse and fine roots (hatched voxels). It is possible for vertically growing coarse roots to avoid root pruning and maintain roots above the pruning depth, as shown on the left side of the illustrated scene. LAD: leaf area density within the crown; WAD: wood area density within the crown.

5.5 Way forward

Accuracy in the measurements of most parameters involved in belowground interactions is something to continue to pursue. The work on the belowground compartment remains tedious and expensive yet with still a large part of uncertainty in the measurements. Therefore, development of methods and tools to better describe processes in mixed cropping systems should continue. This includes scale of spatial sharing of belowground resources for which modelling has a lot to contribute once processes are well understood.

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Pedro Sanchez

INTERMEZZO 3

Recollections from ICRAF's third Director General (1991-2001)

"My first job as DG was to transform ICRAF from an advocacy council into a research centre of the CGIAR. Bjorn helped by leaving several positions vacant. I hired Roger Leakey a well-known forester as director of research to balance my expertise in the agro part of agroforestry. An effective management committee was formed with our own rules, composed of the deputy director general (Bruce Scott) and the directors of research, outreach (Ester Zulberti) finance and administration (Michael Klass) and I.

Friday seminars became well attended and followed by updates to the entire staff, lubricated by coffee and tea. While increasing our presence in Africa we expanded ICRAF to Asia and Latin America under the leadership of Dennis Garrity and Dale Bandy. Bruce

and I were pleasantly surprised when our fist medium-term plan was approved by TAC (the technical advisory committee of the CGIAR). Our board was very supportive and funding increased rapidly. ICRAF also added laboratories and support buildings to 'ICRAF house' at the Gigiri campus.

ICRAF took the leadership in establishing two "system-wide initiatives" the Alternative to Slash and Burn Agriculture (ASB) and the African Highlands Initiative. ASB became one of the most effective initiatives in the CGIAR. My leadership role as DG focused internally on science in agroforestry and externally on pushing the CGIAR towards action on climate change. When the Intercenter Working Group on Climate Change which I chaired proposed a research program at the last mid-term meeting in South Africa in 2001, the donors of the CGIAR rejected it, saying they didn't see the connection between agricultural research and climate change....

As to the way forward, ICRAF continues to navigate the almost continuous reorganizations of the CGIAR, and many consider the decade of the 1990´s, during my tenure, the golden years of the CG. The latest change of course is the impending merger of ICRAF and CIFOR, something I was able to deflect during my tenure as well as Dennis Garrity in the following 10 years, when both Centres played their own roles well and we benefitted from coordination at the BOT level. I am very impressed with the new directions Tony Simons has taken ICRAF as well as his fundraising ability. ICRAF is in very good hands with Tony and I wish him well in the upcoming merger so the science of agroforestry continues to flourish and novel applications get a chance."

Fruit trees plantation

Farming households growing selected fruit tree portfolios on their farms, to gain year-round supply of nutritious fruits to eat, for diverse diets and improved health. The fruit tree portfolio approach is designed to tackle the problem of micronutrient deficiencies, also known as 'hidden hunger'.

Photo: World Agroforestry

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CHAPTER SIX

Agroforestry options, issues and progress in pantropical contexts

Meine van Noordwijk, Robert J Zomer, Jianchu Xu, Jules Bayala, Sonya Dewi, Andrew Miccolis, Jonathan P Cornelius, Valentina Robiglio, Devashree Nayak, Javed Rizvi

Highlights

- Tree cover on agricultural land is strongly related to climate zone, with some regional variation
- Agroforestry allows for a gradual transition from subsistence to market-oriented land use
- Tropical commodity production is highly concentrated, with the top 1, top 3 and top 10 countries accounting for about one-third, two-thirds or 90%, respectively, of global production
- Agroforestry farmers face different and changing forest-policy and property-right regimes in countries and regions
- Progress in developing land-use policies supportive of agroforestry is uneven, with opportunities for inspiration and learning from frontrunner countries
- Upscaling agroforestry practices requires developing options tailored to varying, local, socio-ecological contexts and enabling environments

1.1 Introduction

There are many ways to classify and describe agroforestry practices based on the spatial and temporal arrangement of trees, the type of trees in relation to economic value, the non-tree components (crops, livestock, fish) or the balance between retained, spontaneous and planted trees (compare with Chapter 2). The simplest way that is compatible with existing global data sets may well be the classification of tree canopy cover on agricultural land[1,2] because it allows a direct comparison across regions and countries. In this chapter, we present data, experience and lessons from the six regions in which World Agroforestry is currently active. Together, they cover 66.8% of global agricultural land and 72.9% and 78.8% of such land with at least 10% and 30% tree cover, respectively. Across all regions, tree cover on agricultural land is positively related to rainfall (scaled by potential evapotranspiration in Figure 6.1).

Central America stands out as the region with the highest, relative, on-farm tree cover in any climatic zone, with relatively small differences between other regions, once climate is accounted for. From existing data, it appears that increases in soil carbon storage in agroforestry systems relative to open-field cropping (on average 19% for the 0–100 cm depth layer) are only partially related to aboveground carbon storage in trees across four different agroforestry practices (homegardens, alley cropping, windbreaks, silvopastoral systems), but do correlate with tree age[3].

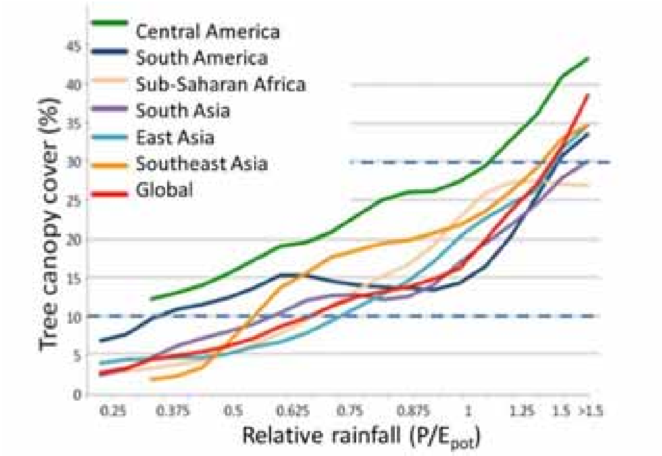

Figure 6.1 Relationship[1] between tree canopy cover in agricultural land and relative precipitation (P), scaled by potential evapotranspiration E_{pot}

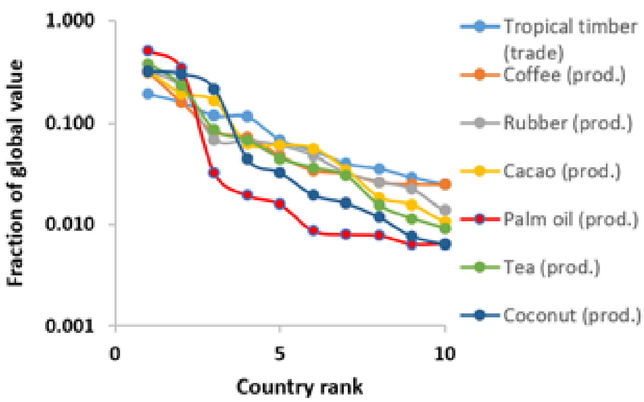

Figure 6.2 Frequency-rank relationship for tropical commodities

Source: FAO Stat data for 2014

Agroforestry is an important mode of production for some of the tropical commodities but has in others been replaced by monocultures. For these commodities, the top 1, top 3 and top 10 countries account for about 33%, 66% and 90% of global production, respectively.

However, there are some differences, with oil palm and coconut most concentrated, and coffee and tropical timber least geographically concentrated[a].

We will here give a brief characterization of the tree-cover data at country scale, the main development issues that agroforestry can contribute to, and the types of agroforestry research and development of the past four decades, with a focus on research performed by World Agroforestry and partners. Each of the six regions is 'represented' by single case studies in subsequent chapters (8–13), therefore, we will contextualize the examples here. As a generic group of settings with special consequences for agroforestry, Chapter 14 will focus on 'small islands' around the world.

6.2 Eastern and Southern Africa

The Eastern and Southern Africa region, covering 9.5% of global agricultural land, represents 6.7% and 2.5% of such land with at least 10% and 30% tree cover, respectively. This relatively low tree cover is linked to climate (most of the area has P/E_{pot} ratios below 0.62. See Figure 6.1), dominant food crops (maize, with little shade tolerance and little microclimatic benefit from shading as has been documented for other cereals[4]), and the classification of most 'rangelands' (extensive grazing in savanna landscapes with trees) as outside of 'agriculture'. Higher rainfall areas are found on the various mountain ranges, in what have locally been recognized as 'water tower' configurations[5]. Some of the earliest agroforestry descriptions of the diverse Chagga gardens[6] on the slopes of Mount Kilimanjaro are on such a water tower. As the climate at higher elevations is conducive to temperate vegetables and/or tea, these areas have attracted settlements in colonial and post-colonial periods. Within this region, Madagascar, Uganda, Burundi, Kenya, Ethiopia, Angola and South Sudan have the largest fractions of agricultural land with at least 10% tree cover.

East Africa is not a major player in tropical commodity trade but Kenya is the worlds' third-largest tea producer (9% of total) and Ethiopia the worlds' fifth-largest producer of coffee (5% of global production) while the region is the centre of origin of the main coffee species used and, thus, relevant for genetic diversity (including wild relatives). Research on the coffee agroforests of Ethiopia and some of the Eastern Arc mountains has considered the balance of local wellbeing and global value of conserving genetic diversity[7].

East Africa is the source area of the Nile, with current understanding of the atmospheric moisture transfer between the White Nile (originating in the Lake Victoria Basin) and the Blue Nile (in Ethiopia)[8] calling for a more integrated 'precipitationshed' approach[9,10] beyond current water-sharing agreements.

[a] Top producer: Highest for oil palm at 50.9% and lowest for tropical timber 19.2%; Top 3: highest for oil palm at 88.3%, coconut at 83.7%, tea at 70.3%, and lowest for tropical timber at 46.9%; Top 10: highest for coconut at 97.5%, oil palm at 95.5%, cocoa at 93.7% and tea at 91.9%, lowest for tropical timber at 83.4% and coffee at 81.5%

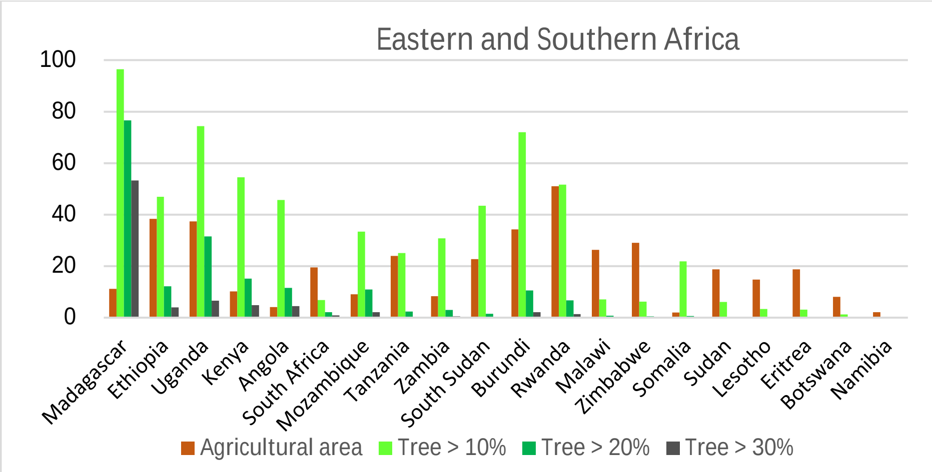

Figure 6.3. Agricultural land fraction and fractions of that with >10, >20 or >30% tree cover for countries in eastern and southern Africa

The Eastern and Southern Africa region has been afflicted by chronic poverty and food shortages, which are caused or exacerbated by a complex interplay between agroecological (declining soil fertility and crop yields, droughts, floods, environmental degradation), social (illiteracy, class and ethnic disparities), and politico-economic (unfavourable domestic policies, massive debt burdens, corruption, distorted international trade policies and skewed terms for development aid) factors.

While agriculture is the main source of livelihoods for approximately 80% of the rural population in the region, agricultural production is constrained by unaffordable inputs, especially fertilizers, lack of access to credit, and minimum involvement of smallholders in the market economy. Declining soil fertility is one of the root causes of low crop productivity and consequently of deforestation, with natural forests (of variable ages as 'fallow') being cleared for the expansion of farmland. In the wetter parts (the water towers), profitable understorey species, such as cardamom[11], lead to a gradual replacement of forest species. Owing to rapid population growth and inequitable land distribution, farmers now are forced to cultivate the same piece of land more frequently and, in some cases, continuously every year, thereby exhausting the soils. Given the small farm sizes (often under 1 hectare), many farm families cannot produce enough to feed themselves even during years of favourable rainfall. Most smallholders face food deficits during the periodic droughts affecting the region.

In this context, current agroforestry research is focussed on:

- Supplying farmers with high-quality germplasm for trees that provide fruit[12], energy[13] and fodder[14,15];
- Improving on-farm tree management[16,17];
- Disseminating science-based evidence and otherwise demonstrating the effectiveness of agroforestry systems at scale to encourage the uptake of these systems[18,19];
- Developing ecological services[20,21], particularly, water management services under agroforestry systems[22]; and

- Strengthening the capacities of government counterparts[23,24], research organizations and communities[25].

The landscape case study in Chapter 7, Shinyanga in Tanzania, represents the challenges in large areas where past development efforts in crop and livestock production did not include attention on trees or even saw them as the source of tsetse flies preventing livestock raising. Restoration and recovery of the landscape's potential to function in current and changing climates had to rely on a combination of institutional (reviving old natural management concepts), technical, social and economic interventions. The relevance and response to these options depends on context; any specific landscape example can provide inspiration but no 'blueprint'.

A farmer in Toben Gaa reducing vulnerability of smallholder farmer in western Kenya to the effects of climate change by improving their livelihood and environments. Photo credit: World Agroforestry/Joseph Gachoka.

6.3 West and Central Africa

The West and Central Africa region, covering 8.5% of global agricultural land, represents 6.1% and 8.5% of such land with at least 10% and 30% tree cover, respectively. Country-level data (Figure 6.4) show that 10 countries in the region have at least 30% tree cover on at least 80% of their agricultural land (mostly in the Congo Basin and humid West Africa); a small group (Ghana, Cameroon, Togo, Cape Verde) has intermediate tree cover; and the remaining countries, in the drier zones, have hardly any. More detailed data for this zone give a more nuanced perspective (increasing tree cover on farms while closed forest stands continue to lose out)[26] will be discussed in Chapter 8.

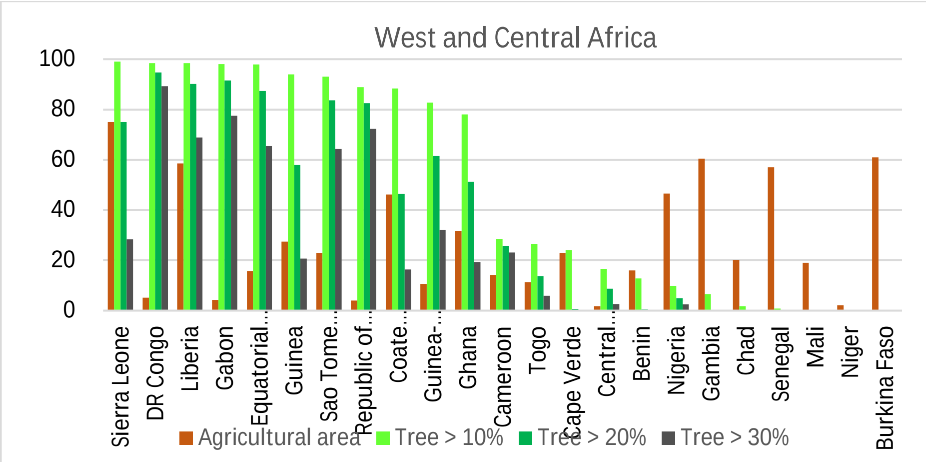

Figure 6.4 Agricultural land fraction and fractions of that with >10%, >20% or >30% tree cover for countries in western and central Africa

The West and Central African region covers approximately 1200 million hectares spanning 21 countries with a total population of more than 330 million people. It includes arid, semi-arid, sub-humid and humid ecological zones, with clearly differentiated types of agroforestry.

West and Central Africa features the worlds' primary production of cocoa (Ivory Coast in first place at 32%, Ghana second with 19%, Cameroon fifth with 6%, Nigeria sixth with 6%) and still plays some role in oil palm (Nigeria in fifth place at 2%) while it is the centre of origin of both oil palm and some of the coffee species used and, thus, relevant for genetic diversity (including wild relatives).

The Congo Basin contains the world's second-largest continuous area of rainforest and is home to more than 20 million people, most of whom depend on the use of natural resources for their livelihoods. In the humid tropics zone of Central Africa, early agroforestry research on improved fallows[27] has been transformed into interest in the direct value of trees for the local economy. Fruit tree domestication[28,29] became closely linked to processing and marketing of tree products[30,31,32,33], rural resource centres and marketing arrangements[34,35], jointly understanding adoption[36]. Technical efforts to develop new value chains for *Allanblackia*[37,38] still require a stronger economic embedding. Legal frameworks for tree management proved to be essential across the various zones and legal traditions[39,40] while what so far has been seen as 'community forest management' needs to connect agroforestry and local business development[41,42]. On the policy side, REDD+ and emerging climate policies also have a richer meaning when linked to agroforestry[43,44].

About 70% of the world's production is sourced from West and Central Africa. However, cocoa farming developed over time to the detriment of food crops and caused shortages of major food commodities not only in cocoa-farming households but also in food markets. A mapping of malnutrition in the major cocoa-producing areas of Côte d'Ivoire[45] and Ghana[46] revealed stunting rates varying respectively from 25% to 34% and from 25% to 38%. These high rates were linked to a very low dietary diversity, axed on consumption of energy-dense and nutrient-poor foods, such as fats and oils, white roots and tubers, excluding vitamin A-rich fruits or vegetables. While some positive relationship has been established between cocoa production and food security in cocoa-producing households, it is not clear how this happens. Also, cases of food insecurity are frequently reported by cocoa-farming families in West and Central Africa and the factors causing this are also not well known[47].

In general, food security is influenced by many structural factors like price fluctuation of commodities, low edible crop productivity, low level of incomes, lack of access to agricultural inputs and credit markets and, consequently, poor investment in the agricultural sector. Climate change also has direct effects on food security through abnormal changes in temperature, rainfall and extreme weather events[48]. Higher temperatures are affecting cocoa production, calling for more vigorous forms of agroforestry, associating trees for shade or other crops for diversification.

In the Sahel region, conventional approaches to reforestation have involved the use of expensive, environmentally destructive inputs and the propagation of exotic species, often with need for water that strains available resources. Owing to low survival rates of planted trees, farmer-managed natural regeneration (FMNR) has been developed over the three last decades as an alternative. FMNR can be combined with planting to broaden the portfolio of tree products and services. For planting, seedling production and propagation methods to shorten the juvenile phase and improve the quality of the products have been developed in a domestication effort[49,50]. Parkland agroforestry[51,52] and its role in supporting food production[53,54] has seen a revival after changes in forest policy (see Chapter 8). Clarifying tenure was essential to give efforts in dryland tree improvement[55,56] a chance of success. Tree products from the parklands contain vitamins and micro-nutrients that complement the starch-based (cereals) diet of the Sahel region. There are also sources of income and creation of jobs for women, who are the most active in processing tree products[57,58,59].

The main focus of the research in the region is on domesticating trees for high-quality germplasm to produce fruit and fodder, restoring cocoa orchards, managing tree–crop interactions to optimize parkland performance, developing tree-based land restoration, developing value chain and public–private partnerships, analysing regulations and supporting the development of conducive environments for the promotion of trees and agroforestry[60,61,62].

6.4 Southeast Asia

The Southeast Asia region, covering 7.9% of global agricultural land, represents 14.7% and 28.9% of such land with at least 10% and 30% tree cover, respectively. The region includes Indonesia with 6.3% and 13.8% of global agricultural land with >10 and >30%, respectively, as a champion of agroforestry. Myanmar and Cambodia have the lowest fraction of agricultural land with at least 10% tree cover but would still be in the high tree-cover frequency class if they were part of Africa or the rest of Asia.

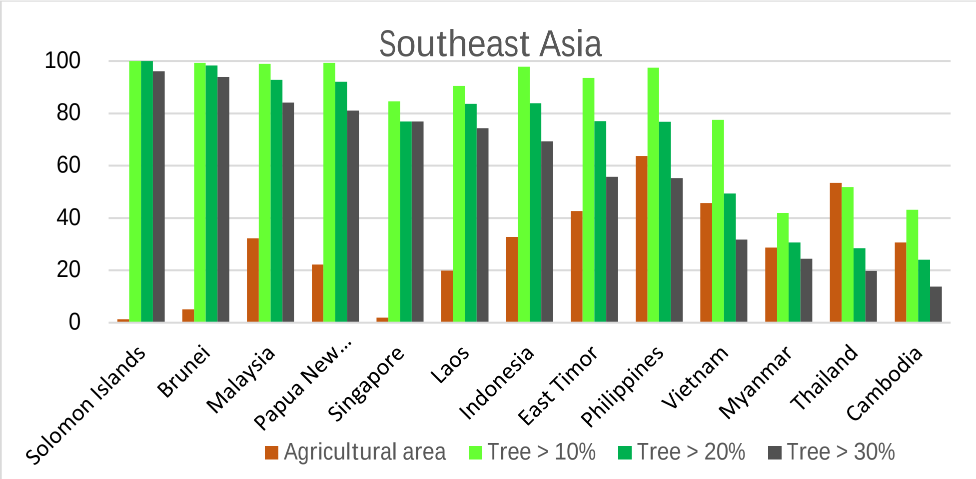

Figure 6.5 Agricultural land fraction and fractions of that with >10, >20 or >30% tree cover for countries in southeast Asia

Southeast Asia dominates tropical commodity production and trade in oil palm (Indonesia is in first place at 51% of global production in 2014, Malaysia is second at 34%, Thailand third at 3%, Papua New Guinea is sixth at 1%); rubber (Thailand in first place at 32%, Indonesia second at 22%, Viet Nam third at 7%, Malaysia sixth at 5%, Philippines seventh at 3%); and coconut (Philippines in first place at 32%, Indonesia second at 30%, Thailand fifth at 3%, Viet Nam sixth at 2% and Malaysia seventh at 2%); while being also relevant in coffee (Viet Nam in global second place at 16%, Indonesia fourth at 7%); cocoa (Indonesia globally third at 16%); and tea (Viet Nam sixth at 4%, Indonesia seventh at 3%).

Farmers tending a pepper garden in Southeast Sulawesi to improve rural livelihoods by raising on-farm productivity, encouraging better environmental management, and improving governance. The initial focus has been on South and Southeast Sulawesi, two provinces which suffer from high levels of poverty and still possess significant tracts of natural forest. So far, several thousand people have benefited from training sessions on marketing, establishing demonstration trials, participatory governance and development of land-use models. Photo: World Agroforestry/Yusuf Ahmad

The region has more than 200 million hectares of forested land, covering nearly half of its total land area. These forests contain some of the highest levels of biological diversity in the world. Indonesia's rainforests alone, while covering only 1% of the Earth's land area, contain 10% of the known plant species, 12% of mammal species (including endangered orangutans and critically endangered Sumatran tigers and rhinos) and 17% of bird species.

It is estimated that forest cover in the region is reduced by an average of almost 1.4 million hectares a year. The main drivers of this forest (and agroforest) loss are conversion to agriculture, with a continuing proliferation of monocultural rubber, oil palm[63], and pulp-and-paper plantations. As a result of land conversion and other factors, the region has lost almost 15% of its original forest cover over the past fifteen years, with some areas, including parts of Indonesia, projected to lose up to 98% of their forests by 2022.

Within this context, some agroforestry research has documented two pathways of 'swidden intensification': one focussed on crops that can grow with shorter or ultimately without fallows (but may still have trees between upland rice paddies[64]), another in which the fallow became agroforest and as such was prolonged[65,66]. Such agroforests[67,68] have been shown to reduce pressure on remaining forests[69]. They used to harbour as much tree diversity as secondary forests as long as the surrounding forest matrix and its 'seed rain' was intact (Chapter 2) but where the landscape crossed a 'diversity tipping point' they lost species, except those that were allowed to mature and reproduce in agroforests[70,71].

In response to the agricultural-intensification (or Borlaug) hypothesis, a deeper understanding has emerged of relative advantages for the combined targets of productivity and conservation in both segregated and integrated land-use arrangements[72]. Efforts to introduce more productive rubber clones into agroforest management practices proved to be remarkably complex[73].

Early work on quantifying the prevalence of *Imperata* grasslands in the region has shown that such symptoms of land degradation can be transient if tenure regimes allow smallholders to restore multifunctionality[24,74]. Smallholders' timber production has become an important component of agroforestry in the region[75,76,77].

Part of the regional fire incidents stem from land-right conflicts[78]; addressing such[79,80] conflicts at their roots goes a long way toward facilitating agroforestry-based, sustainable land use. In the case of tropical peatlands[81], however, the current range of tree species usable in 'paludiculture' is limited.

Two decades of research on incentive and reward systems that support environmental-service-friendly land uses has shown the relevance of co-investment[82,83] paradigms, rather than 'payments'.

Along with the high diversity of languages, ethnic identities and a complex historical pathway of political change, gender-based role differentiation varies within the region but is in many instances relevant for the ways agroforestry can contribute to transforming lives and landscapes[84]. The landscape case study of Chapter 9, Sumber Jaya in Indonesia, represents one of the main open-air social-ecological system laboratories where 'negotiation support' systems emerged in interactions between farmers, foresters, local government authorities and agroforestry researchers. In the Philippines, the Landcare[85,86] movement allowed forms of collective action and actively supported learning to emerge, partly in the specific post-land-reform era.

The region is rich in 'small islands', in which agroforestry has a specific meaning and contribution to make (Chapter 13). The region is, unfortunately, also a global leader in 'natural disasters' and the loss of ecological buffering that increases human impacts of extreme events (Chapter 14). In the region, climate resilience[87] has a specific meaning. Tropical deforestation and its various drivers at multiple scales have made the region a frontrunner in the climate-change policies aimed at reducing emissions from deforestation and forest degradation (REDD+), with some progress in clarifying the solutions an agroforestry approach can bring[88,89,90,91]. From a focus on 'opportunity costs', the agroforestry agenda has transformed into one of supporting 'green growth'[92,93]. Long-term impacts of agroforestry research in the region can be seen in the high-level policy support for agroforestry that the *ASEAN Guidelines for Agroforestry Development* (Chapter 18).

6.5 East and Central Asia

The East and Central Asia region, covering 11.5% of global agricultural land, represents 8.5% and 5.3% of such land with at least 10% and 30% tree cover, respectively. It includes China with 8% and 5.1% of global agricultural land with >10 and >30%, respectively. Tree cover on agricultural land is generally low in East and very low in Central Asia. The size of China, however, masks the considerable variation in tree cover and agroforestry[94] within the country, which is highest in the wettest southern part, especially in Yunnan Province, where it coincides with high ethnic diversity and strong agroforestry traditions. Agroforestry in China includes the well-studied *Paulownia* and wheat systems in the north[95] and sacred forests[96].

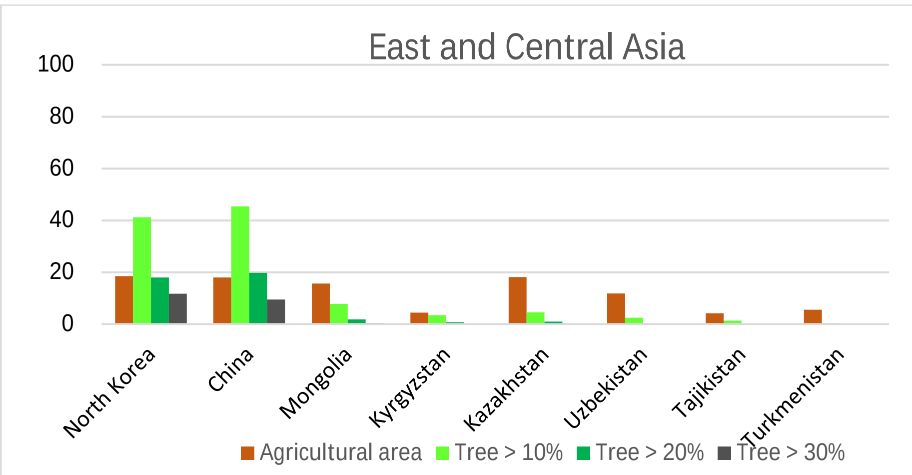

Figure 6.6 Agricultural land fraction and fractions of that with >10%, >20% or >30% tree cover for countries in East and Central Asia

East and Central Asia plays a modest role in tropical commodity production but China is the worlds' fifth-largest rubber producer (6% of global total), world's largest tea producer (38%) and is the centre of origin of tea (*Camellia sinensis*). Rubber expansion in the mountainous parts of Yunnan is causing problems[97] although a recent study of hydrological impacts showed that it matters what land cover rubber replaces and where in the landscape the conversion occurs[98]. Water flows from the higher mountains (including the cascading effects of a warming Himalaya[99]) are a major concern for land-cover management in Yunnan[100].

Since 1998, following the devastating impact of floods caused or exacerbated by deforestation, China has implemented a massive initiative to restore and conserve forests. The landscape case study of Chapter 10 represents the challenges and opportunities created at local level by the top–down Sloping Land Conversion Program, also known as 'grain to green'. China was one of the first countries in Asia to report an increase in forest cover, after decades of decline[101]. Such 'forest transition', however, masks qualitative changes in the type of tree cover that is included in 'forest' statistics. Government statistics indicate that China's programs have achieved significant success, with gains of 434,000 km^2 of forested land from 2000 to 2010. However, these figures hide the fact that the term 'forested land' is loosely defined, including both low-density monocultural plantations and areas of dense, high tree cover[102]. A large proportion of land classified as 'forested land' includes scattered, immature or stunted plantations often consisting of a single species or even single clones, which are unlikely to provide the same benefits as large areas of dense and tall forest[103]. If only land with tall, relatively dense tree cover is included[104] then the expansion of China's forests is much less impressive than that claimed by official statistics, increasing by only 33,000 km^2.

A remarkable agroforestry success has been reported from the Democratic People's Republic of Korea[105,106], where new ways of local food production alongside reforestation of sloping land emerged as an opportunity for local initiative in an otherwise strongly regulated landscape.

6.6 South Asia

The South Asia region, covering 9.3 % of global agricultural, represents 5.2% and 1.8% of such land with at least 10% and 30% tree cover, respectively (Figure 6.7). Relatively high tree cover is found in Bhutan, Sri Lanka, Nepal and Bangladesh. South Asia plays a modest role in tropical commodity production but India is the world's second-largest tea producer (24% of global total), third-largest coconut producer (22%), fourth-largest rubber producer (7%) and sixth-largest coffee producer (3%). Sri Lanka is the world's fourth-largest tea (7%) and fourth-largest (4%) coconut producer.

The eight countries of South Asia occupy no more than 4.5 million km^2 but are home to more than 1.6 billion people, more than a fifth of the global population, making South Asia one of the most densely populated regions. This population is growing at the alarming rate of 1.5–1.8% annually. Agriculture accounts for a quarter of the region's GDP and half of all jobs as well as providing industrial raw material for domestic consumption and export. In India, agriculture contributes just 15% to GDP but supports the livelihoods of over half of the population. Thus, the health and resilience of the region's ecosystems is vital for the region's social and economic well-being.

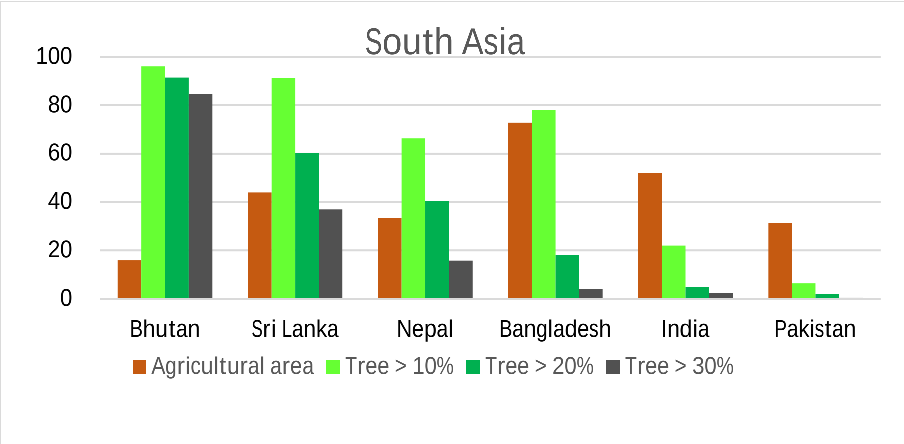

Figure 6.7 Agricultural land fraction and fractions of that with >10, >20 or >30% tree cover for countries in South Asia

The region includes four major agroecological environments:

- The mountainous regions of Afghanistan, Bangladesh, Bhutan, northeast India and Nepal
- The Indo-Gangetic Plains of Bangladesh, India, Nepal and Pakistan
- The humid coastal areas of Bangladesh, India, Maldives and Sri Lanka
- The semi-arid lands of India, Pakistan and Sri Lanka

The landscape case study of Chapter 11, Bundelkhand Jaya in India, represents the semi-arid lands where seasonal water shortages can, in part, be tackled by restoration of traditional water harvesting and retention techniques ('haveli'). The watershed rehabilitation program in the dry landscape around Jhansi (India) as initiated in 2012 in the Parasai-Sindh watershed inhabited by 3000 people in three villages covering 1246 ha. Co-investment of public funds with support of local community, scientific expertise and Government machinery in such a critical ecosystem had a substantial social welfare multipliers[107]. The program restored the traditional water reservoir structures, 'haveli' for recharging the groundwater, slowing the streamflow in check dams, thereby making water available for second growing season plus a year-round domestic water supply. For success of such endeavours, clear responsibilities and common understanding for resource management at landscape scale are key. For landscape management, the land-use rights in the area which is to be utilized for rainwater reservoir structure need proper care and handling, so that all stakeholders are engaged and see benefits of participation. With a water reservoir upstream, the downstream reservoirs benefit from less sediment deposition, but also face lower annual water yields. The community gained from the water availability as they could take two crops annually, and shift to the use of perennials, including fruit trees such as guava, citrus, and pomegranate as well as timber species. The landscape serves as an excellent opportunity to assess the working of National Agroforestry Policy of India, as the policy could serve as a basis to assign water use rights to trees in the restored sub catchment areas of such landscapes.

Since early 1990s, the Forest Survey of India (FSI) has been estimating the number of stems along with wood volume of Trees Outside Forest (TOF) at state and national level. FSI is reporting the information on National level estimates of growing stocks, both inside and outside the forest area in the biennial reports, India State of Forest Report (ISFR) since 2003. Although the agroforestry systems constitute an important component of TOF, information on available tree resources in agroforestry system has not been separately reported until 2013. The ISFR 2013,[108] reported 11.2 million ha area as total tree green cover under agroforestry system in the country, which is 3.39 per cent of the country's geographical area of 328.7 M ha. For this agroforestry estimation, only rural TOF inventory has been taken into consideration by FSI. The Central Agroforestry Research Institute (CAFRI), under the umbrella of Indian Council for Agricultural Research (ICAR) has mapped 16.6 million ha under agroforestry area in 2018[109], through GIS mapping that covered 208 M ha geographical area of the country. In the recent ISFR 2017[110], the growing stock of wood in the country is estimated to be 5 822 million m^3, which comprises of 1 604 million m^3 outside recorded forest (TOF). The annual production of timber from TOF for the year 2017, has been estimated to be 74.51 million m^3, an increase of 5.47 million m^3 as compared to updated estimates of ISFR 2011. Successful agroforestry practices, better conservation of forests, improvement of scrub areas to forest areas, increase in mangrove cover, conservation and protection activities have led to increase in the forest and tree cover by 8,021 km^2 as compared to assessment of 2015 (ISFR 2017). Moreover, by using agroforestry technologies developed by the research institutions, forest departments, non-governmental organizations (NGOs), National Wasteland Development Board (NWDB), and other developmental agencies in India have rehabilitated more than 1 million ha of salt-affected soils, particularly the village level community lands, areas along road side, canals, and railway tracts[111].

Throughout Asia home-gardens are a tradition[112,113], and though small in extent at individual level, collectively they occupy substantial area, as much as 36% of the arable land in Matara District of Sri Lanka, for example. Tropical homegardens cover about 8 million hectares in south and southeast Asia[114]. The homestead agroforestry in Bangladesh, Kandy homegardens in Sri Lanka, Kerala homegardens in India, and alnus-cardamom systems in Nepal and north eastern India are some of the examples of the classical homegardens. The main factors affecting the appearance, function, structure and composition of home gardens are environmental conditions, geographic location, socioeconomic and house hold needs, cash income opportunities and the cultural specificity.

In Bangladesh, majority of the agroforestry area is dominated by homestead agroforestry, which is the integrated production of crops, trees, and/or livestock in the household's residence and its surrounding areas. It contributes about 70% fruit, 40% vegetable, 70% timber, and 90% firewood and bamboo requirement of the country[115]. Homestead agroforestry or home gardens combines all farming components and forms a highly intensive and multi-strata integrated production system depending on household needs, preferences and knowledge.

In Sri Lanka, home gardens are one of the oldest and major land use forms[116,117] that covered 858,100 ha in 1995, representing 13.1 per cent of the total land area of the country[118,119,120]. They are an integral part of the landscape and culture for centuries in the country. There are 196 fruit species recorded in Sri Lanka, and more than half of these species are recorded from

17 per cent of the home garden area of Kandy and adjacent districts, such as Badulla, Kegalle, Kurunegala, Matale, Nuwara Eliya and Rathnapura, which are defined and popularly known as Kandyan home gardens or Kandyan forest gardens[121]. This land use system that maintains, enhances and conserve the diverse crop genetic diversity, over time and space, and hence they can be regarded as a good practice for maintaining diversity[122]. Year-round production of a wide range of products required by householders, new business ventures through value addition, provision of many ecosystem services and easing pressure on natural forests have been identified as key elements of these Homegardens (or agroforests).

The Government of India formulated the National Agroforestry Policy[123] in 2014, to address the vulnerability in agriculture caused by climate change[124]. The policy recommends for setting up of a Mission or Board to address development of agroforestry sector in an organised manner. The Sub Mission on Agroforestry was formulated in 2016-17 under the National Mission for Sustainable Agriculture (NMSA) with a capital outlay of USD 450 million for 4 years (2016-17 to 2019-20)[125]. The policy has been an effective instrument in providing an overarching positive trend, an official home of agroforestry at the Ministry of Agriculture, and a negotiation platform for agroforestry produce in the country. The policy has been effective in relaxing the tree felling and transit regulations, de-regularization of saw mills opening, and inclusion of agroforestry in many of the central government agricultural schemes. As of 2018, 21 states, out of a total 29 states, had de-notified at least 20 tree species from felling and transit regulations. Further, there is relaxation of ban on setting up of new saw mills, especially in places having less than 5% forest area.

Intercropping of Napier grass in coconut-based agroforestry system in Tumkur, Karnataka, India. Photo: World Agroforestry/SK Dalal

Some of the significant successes which can be attributed to effective implementation of the agroforestry policy in India are: Establishment of the Central Agroforestry Research Institute

(CAFRI) by ICAR through upgradation of its National Research Centre for Agroforestry (NRCAF); inclusion of agroforestry in the eligible activities for CSR funding, and initiation of a dialogue through Finance Commission of India that Federal Government provides more funding to state having more green cover. The Indian policy has also created ripple effect in the region and has inspired Nepal to work with ICRAF on its own agroforestry policy. The Ministry of Agriculture and Livestock Development & the Ministry of Forest and Environment with ICRAF have completed the development of the Nepal agroforestry policy which is now due for approval by the Cabinet of Ministers of Nepal.

6.7 Latin America

The Latin America region, covering 20% of global agricultural land, represents 31.6% and 30.8% of such land with at least 10% and 30% tree cover, respectively. Brazil alone has 18.3% and 11.4% of global agricultural land with >10 and >30% tree cover, respectively. In Central America and the Caribbean, nearly all agricultural land has at least 10% tree cover (Figure 6.8).

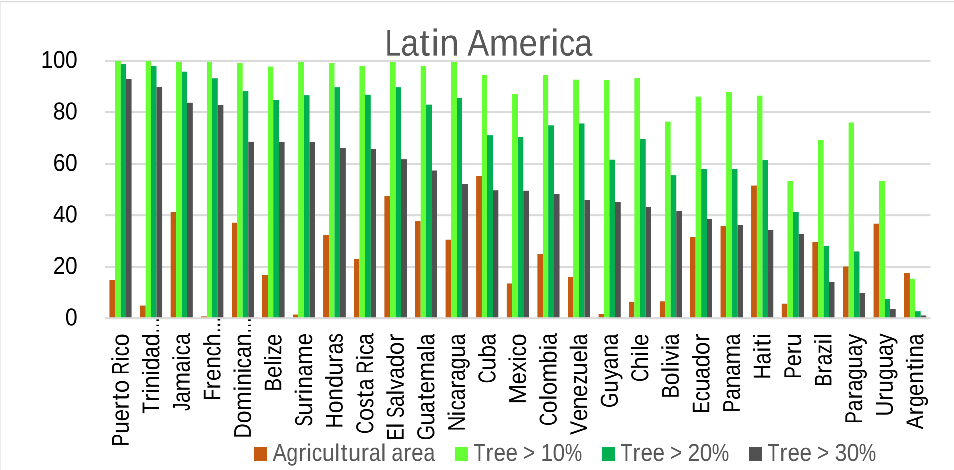

Figure 6.8 Agricultural land fraction and fractions of that with >10, >20 or >30% tree cover for countries in Central and South America

Latin American countries are major producers of several tree commodity crops: coffee (Brazil first in the world at 32%, Colombia third at 8%, Honduras seventh at 3%); cocoa (Brazil fourth at 6%, Ecuador seventh at 4%) avocado (Mexico first, Dominican Republic second, Peru third, Colombia fourth); and oil palm (Colombia fourth at 2%). The region is also the centre of origin of cocoa, avocado, rubber, cassava, and numerous globally cultivated agroforestry species (fruit, nut, timber and agroecological-service trees), thus, an important source of genetic diversity (including wild relatives).

Latin America is comprised of a wide range of ecoregions, including the Amazon rainforest and the Guyana shield; the Caatinga, the dry forests and shrublands of Northeast Brazil; the Mata Atlântica, or the Brazilian Atlantic Rainforest; the Cerrado, a vast woody savanna located to the south and east of the Amazon Basin; the Pantanal, a large wetland area forming the floodplain of the Rio Paraguay; the Chiquitano dry forests located in north-eastern Bolivia; and the Tropical Andes montane forests, Mesoamerica dry and tropical pine forests.

Agroforestry in Latin America began with the indigenous peoples that inhabited the region well before European conquest[126] and has since been taken up by other social actors, predominantly, family farmers and traditional communities of both indigenous and colonial origins. Common practices across ecoregions and social groups include tree fallows (improved or predominantly based on natural secondary succession processes) in slash-and-burn and swidden[127,128]; and trees and shrubs along boundaries, watercourses and contours in the Andes[129] and in the upper and low-lying floodplains; trees associated with both annual and permanent crops, including commodities such as cocoa[130] and coffee systems, silvopasture[131], and home gardens[132]. Use of both natural regeneration — particularly timber and shade species — stem coppicing, seed dispersal and planted trees is common as well as preservation of useful species[133] . The acronym SAF (from the Portuguese and Spanish words for 'agroforestry system') is widely used and usually means multi-storey systems. Agroforestry has assumed a prominent role in prevention, mitigation and reversal of land degradation as the region has taken on international initiatives (for example, the Bonn Challenge) to translate commitments into action (https://initiative20x20.org), and many national and sub-national governments have followed suit by establishing ambitious restoration targets.

In Brazil, successional or biodiverse agroforestry, usually combining short-cycle crops, fruits, fertilizer species and native trees, has become widely disseminated throughout its ecoregions. Research on agroforestry-based restoration has shown that such systems are the most suitable for reconciling environmental and social functions associated with restoration of conservation set-asides on all rural land (Permanent Preservation Areas and Legal Reserves)[134]. Key constraints to upscaling these relatively complex systems, which vary considerably according to local context, most commonly include access to knowledge (training and extension), labour, credit, markets, and germplasm[135] (Chapter 12).

World Agroforestry research in the region revolves around livelihoods, design and implementation of agroforestry practices tailored to local socio-ecological contexts in the framework of climate-change mitigation and adaptation, restoration and reforestation, biofuels and renewable energy, and tree functional diversity and its role in reducing vulnerability to climate change. Moreover, research has supported the development of restoration practices that further family farmers' productive objectives (Chapter 12) and has delved into cocoa[136,137], coffee[138] and oil-palm agroforestry[139], silvopastoral systems, and the contribution of local knowledge to smallholders' tree-based adaptation strategies. The Amazon, with its history of uncontrolled forest conversion and wealth of traditional communities, has long been the subject of research on agroforestry, its social and ecological benefits and key constraints to upscaling[140]. Farmer-based domestication of local timber species in the Peruvian Amazon has contributed to global understanding of how such processes work[141,142,143]. Cocoa-based agroforestry systems, oftentimes intercropped with native Amazon palms, fruits and timber species, are one example of an Amazon agroforestry option that can both improve livelihoods and produce deforestation-free commodities while restoring environmental functions. Restoration and conservation have become major themes of agroforestry policies and initiatives in the region.

In Brazil, the 2012 Forest Code laid out opportunities and incentives for farmers to perform mandatory restoration of privately-owned land using agroforestry systems, provided they maintained basic ecological functions (Chapter 12). A host of innovative rural credit and procurement policies favouring the adoption of agroforestry[144] may also serve as examples for other countries.

Similarly, in Peru, work on agroforestry concessions, a legal mechanism provided by the last forestry law of Peru approved in 2011, has shown promising results by mingling direct and indirect incentives. The scheme is considered crucial as it enables the granting of a 40-year, renewable lease to farmers who had encroached on public forestland, conditional to the commitment to conserve forest remnants, to maintain or establish sustainably managed agroforestry systems on 20% of the designated area, and to implement soil and water conservation measures. A recent study of the extent to which smallholders were participating in the scheme identified weaknesses in its current design and made recommendations for its improvement[145].

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Shinyanga landscape with abundant livestock

Abundant livestock feed after Ngitili restoration that provides fuelwood and building timber as well as livestock fodder

Photo: World Agroforestry/Lalisa A Duguma

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CHAPTER SEVEN

Shinyanga: blending old and new agroforestry to integrate development, climate change mitigation and adaptation in Tanzania[a]

Lalisa A Duguma, Peter A Minang, Anthony A Kimaro, Robert Otsyina, Mathew Mpanda

Highlights

- The Shinyanga landscape was severely degraded by past 'development' efforts, but still had recovery potential, ecologically and socially
- Challenges of the Shinyanga landscape were multiple and interconnected, they required a comprehensive approach to tackle them
- A menu of practices associated with the traditional Ngitili system of regulated grazing ensured the multifunctionality of the landscapes providing mitigation, adaptation, development and conservation benefits
- Among the factors for the success of the Ngitili expansion in Shinyanga were:
  1) multistakeholders' engagement and institutional collaborations to leverage resources, knowledge and improve overall efficiency of the actions,
  2) long-term investments by financing agencies and long-term commitment by actors,
  3) favorable and supportive national and local policy processes,
  4) use of local practices and knowledge in the implementation scheme.
  5) Ownership of the local community of the processes involved in the restoration efforts

7.1 Landscape level processes and their impact on the changing positions of Ngitili in Shinyanga region

The Shinyanga region, a wide semiarid zone receiving an annual rainfall of 600-800 mm, is located in the Northern part of Tanzania[1]. Almost two-thirds of the land in the region is used

[a] updated from ASB Policy Brief 40[a]

for agriculture and around 24% serves as grazing area. The vegetation of the area is characterized as extensive Acacia and Miombo woodlands that were estimated to cover around 15% of the region's land. The majority of the society residing in this area are agropastoralists (dominantly the Wasukuma people) with livestock rearing being among the major economic activity. The region hosts 20% of the livestock population of Tanzania and around 80% of the households in the area have 20 to 500 heads of cattle per household. The prominence of *Trypanosomiasis*, a livestock disease transmitted by tse tse fly contributed to clearing of the woodlands, a measure taken to control its spread (Box 7.2). This measure has changed the ecosystem abruptly and with time drought and desertification became eminent threats to the whole region.

Box 7.1 Blending old and new institutions to achieve restoration[2]

When President Julius Nyerere visited the Shinyanga Region in 1984 he was shocked by what he saw. Decades of deforestation and inappropriate land management had turned Shinyanga into the 'Desert of Tanzania.' The president immediately launched the Shinyanga Soil Conservation Programme, widely known by its Swahili acronym, HASHI. The HASHI project helped tens of thousands of smallholders to restore degraded land, and in doing so to significantly improve their incomes. One of the project's great achievements was to revive a traditional system of land management which increases the supply of livestock fodder for use during the dry season. When the project began, there were close to 600 ha of documented ngitili – enclosed fodder reserves – in the region according to local experts who were involved in the HASHI programme. The ngitili provides fuelwood and building timber as well as livestock fodder. Its rapid expansion has brought about a significant increase in biodiversity. Species that had disappeared decades ago are now returning to the landscape. The economic benefits have also been considerable. One study calculated the total monthly value of benefits derived from the ngitili to be US$14 per person – a significant sum in rural Tanzania. The HASHI project also encouraged farmers to adopt a range of other agroforestry technologies, including the planting of woodlots, fodder banks and fertilizer trees. These, too, have yielded considerable environmental and economic benefits.

HASHI was deeply rooted in the administrative structures of Tanzania's central and local governments, and this helps to explain why it has been such a success. Throughout the 20-year project, staff from the Forestry and Beekeeping Division in the Ministry of Natural Resources and Tourism worked closely with local government staff, researchers from World Agroforestry and the region's entire agropastoral communities. The project encouraged village governments and traditional institutions to work together to restore and manage ngitili. The experiences here, we believe, hold lessons that could be a basis for models to help transform lives and landscapes in many other areas in Tanzania and beyond which have suffered from serious environmental degradation.

"The Shinyanga Region in central Tanzania, formerly extensively forested with dense woodland and bushland species, came to be called 'The Desert of Tanzania'. Drought, overgrazing, political changes which destroyed Sukuma forest protection traditions, cash crop cultivation and the destruction of forests to wipe out the tsetse fly, reduced forest cover, increased soil erosion, and threatened people's livelihoods in the region. Indeed, most of the goods and services provided by trees and woodlands were lost. It took many more hours to collect fuelwood, the forage badly needed by the oxen was no longer available, and the wild fruits and medicinal plants became rare to find."[3]

Cattle grazing in degraded woodlands. Photo: World Agroforestry/Lalisa A Duguma

Box 7.2 Tse-tse fly control as start of land degradation in Shinyanga

The Tse-tse fly problem has been a major factor in the human ecology of sub-Saharan Africa, as its presence determined the border between ecological zones dominated by crops and livestock, slowing down the 'savanisation' of forests. Tanzania in the 1920's became the scene for one of the most drastic measures to deal with the tse-tse fly risk, by eliminating. To the extent possible, all woody growth from the landscapes in which tse-tse flies might hide.

In 1922 Swynnerton reported success in 'reclaiming' western Shinyanga by bush clearing. In 1929 a Department of Tsetse Research was formed that experimented with late grass burning (to more effectively control tree regrowth), fire exclusion, discriminative clearing, game destruction, the biological sterilization of the female tsetse flies, and studies on long-term fluctuations in tsetse numbers.

To the east of Shinyanga, a study of coexistence between traditional societies and wildlife in western Serengeti identified four ways in which customary institutions and practices can contribute to current conservation efforts: regulating the overexploitation of resources; complementing the current incentives aiming at diffusing prevailing conflicts between conservation authorities and communities; minimising the costs of law enforcement and; complementing the modern scientific knowledge in monitoring and responding to ecosystem processes and functions.

The 'villagization' programme (Ujamaa) implemented throughout Tanzania, also led to a serious shortage of wood for fuel and construction wood resulting in the overexploitation of the remnant forests and woodlands. Understanding the seriousness of the problem, the government began expanding a traditional fodder reserve management system (Ngitili)[4] together with other agroforestry interventions such as woodlots, boundary tree plantings, etc. This Ngitili based restoration programme (HASHI project (*Hifadhi Ardhi Shinyanga* - Shinyanga Soil Conservation Programme) commenced in the 1980's and has continued since then to cover around 370,000 ha as of 2004 across the 833 villages of the region[5]. Figure 7.1 illustrates the key milestones in the changes in Shinyanga region. In sum, the region has gone through a severe land use land cover change that has had an adverse effect on the ecosystem and the society.

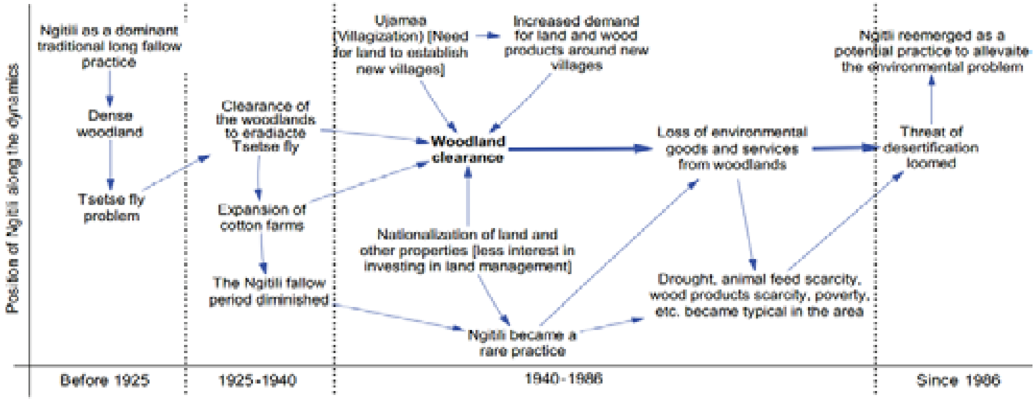

Figure 7.1 Temporal illustration of the position of Ngitili in Shinyanga region and the associated key landscape processes. Note: Recently the Shinyanga region was divided into a number of smaller regions. However, in this brief we refer to the old Shinyanga region when the HASHI project was active

7.2 Menu of land uses in Ngitili dominated landscapes and implications for development, adaptation and mitigation

Table 7.1 shows a synthesis of the role of menus of practices existing in Ngitili dominated landscapes for achieving development, adaptation and mitigation objectives, blending local ecological knowledge[6] with new policy objectives, technical and social-ecological understanding. Practices such as cotton farming, maize farming, cotton, sunflower farms and livestock rearing were among those having significant positive impacts for development and adaptation benefits though affecting mitigation efforts.

Table 7.1 Relative importance of landscape level practices for development, adaptation and mitigation objectives

Practice	Development objectives	Adaptation objectives	Mitigation objectives
Ngitili	++++	++++	+++++
Maize farming	+	-	-
Cotton farming	++	++	--
Mixed cotton and sunflower farming	++	+++	-
Livestock rearing	++++	+++	---

Practice	Development objectives	Adaptation objectives	Mitigation objectives
Agroforestry (e.g. fertilizer tree systems & woodlots[7,8])	+++	+++	++++
Beekeeping	+	+	+
Tree nursery	+	+	+++
Fodder banks	+	+	++

NB: + and – indicate promoting and demoting effects respectively on the objective being examined. The number of +s and –s show the extent of impact.

Ngitili and other agroforestry practices were among those with strong positive impacts for all the three objectives i.e. development, adaptation and mitigation (Table 7.1). Such integrated approaches that involved natural regeneration mechanisms and expansion of agroforestry practices have helped enhance the restoration of the ecosystem as a whole thereby, promoting the provision of ecosystem services. The agroforestry practices minimized the pressure on the remaining forest resources for energy and construction wood[9]. The communities were also able to generate income by raising tree seedlings that are to be planted in the agroforestry schemes.

Other practises that contributed to the climate smart nature of the Ngitili dominated landscapes include:

- Water harvesting in dams using Ngitili vegetation as a protective means/measure against surface runoff and siltation,
- Dry season livestock feed management and income from grazing contracts,
- Growing drought resistant crops like sorghum, cotton and sunflower,
- Use of wild fruits, insects, mushrooms, honey and herbal and tree-based medicines[10] to maintain a healthy society,
- Adoption of improved stoves and biogas for household energy demands with the support of Tanzania Traditional Energy Development and Environmental Organization,
- Rainwater harvesting from rooftops for the purpose of growing vegetables,
- REDD+ piloting to reduce GHG emissions[14].

Figure 7.2 shows linkages, interconnections and pathways of impact among the dominant practices identified in the Ngitili dominated landscapes and how they relate to adaptation and mitigation efforts besides providing other basic developmental and conservation objectives.

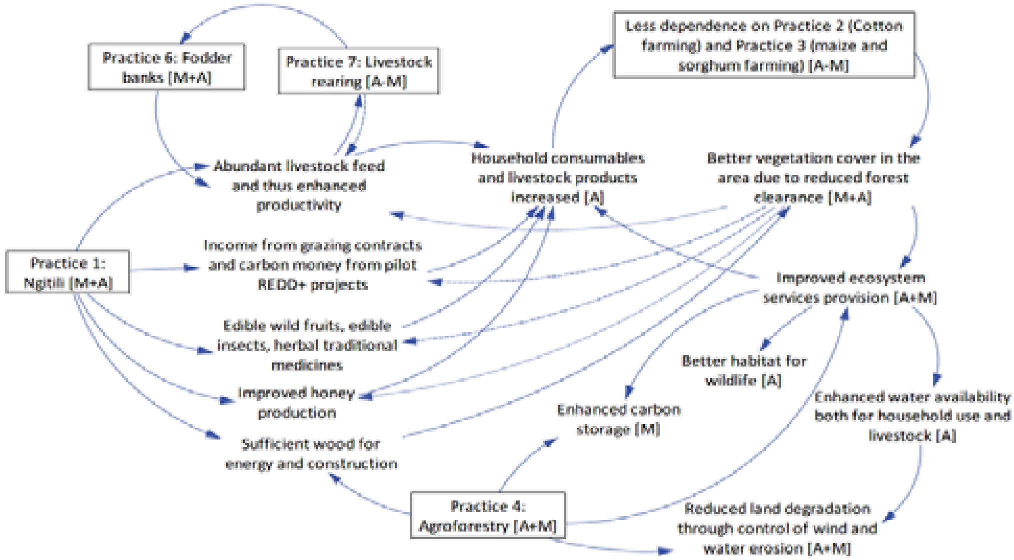

Figure 7.2 The interconnectedness of various practices in Ngitili dominated landscapes in relation to climate change adaptation and mitigation and development needs of the community. Practices are put in boxes. Broken arrows show indirect reverse positive impacts. A – Adaptation, M – Mitigation, A+M – Practices contributing positively to both adaptation and mitigation, A-M – A practice which by nature is an adaptation but negatively affecting mitigation

Restored degraded areas after long-term investments. Photo: World Agroforestry/Lalisa A Duguma

7.3 Multifunctionality of Ngitili dominated landscapes: set of indicators

Climate smart landscape refers to processes that entail strategic planning in which a set of sustainable intensification and sustainable land management practices are prioritized and supported through policy and investments to simultaneously address climate, environment and development objectives. Table 7.2 presents how Ngitili dominated landscapes are evolving into climate smart landscapes; using a set of functions and respective indicators that justify multifunctionality of the landscapes.

Table 7.2 Indicator sets eliciting the importance of the Ngitili system for development, climate change mitigation and adaptation and biodiversity conservation at a landscape level, summarized from an IUCN study[11]

Key functions	Specific indicators	Quantity/number
1. Consumables from/associated with Ngitili (Annual consumption per household)	Vegetables	78.9 kg
	Edible insects	10.9 kg
	Milk	533.7 litre
	Bush meat	14.00 kg
	Mushroom	30.3 kg
	Honey	33.4 litre
	Fruits	30.4 kg
2. Economic value of Ngitili (as of 2004)	Average value per person per year	168.57 USD
3. Carbon sequestration	Change in C stock 1986-2004	17 Mton C
	Carbon in all pools within Ngitili	47.1 t/ha
4. Biodiversity conservation after Ngitili restoration	Bird species re-emerged	22-65
	Mammal species re-emerged	Up to 10
	Plant species (trees, shrubs and climbers) recorded in the restored Ngitilis	152

7.4 Multi-stakeholder engagements and long-term commitments in restoring Ngitili in Shinyanga Landscapes: Actors, roles and responsibilities

The success of the Ngitili system is the result of a multistakeholder engagement process over a long period of time. The various stakeholders brought in various expertise, resources and motives to foster the recovery of the Shinyanga landscapes. The strong commitment by the local government, national government and international donors and actors is exemplary. For example the Norwegian Agency for Development Cooperation (NORAD) committed itself in supporting the HASHI Programme on a long-term basis and in establishing institutions and local capacities and infrastructures that continued functioning even beyond the programme. World Agroforestry (ICRAF) was among the key actors involved in the programme from the beginning through provision of technical support to NAFRAC (Natural Forest Resources and Agroforestry Management Centre) and through generation of appropriate agroforestry technologies that complement the Ngitili.

Those at the local and national levels were also engaged and committed in facilitating the Ngitili restoration and management. For example there are numerous local traditional and formal institutions with considerable roles in fostering the protection, development and use of the Ngitili landscapes. Table 7.3 highlights, the key stakeholders and their roles and responsibilities in the transformation of the Shinyanga region with the help of Ngitili. There was also a strong political support and will in restoring the Ngitili system dating back to the inception of the HASHI programme in 1984 by the then president of the country, Julius K. Nyerere.

Table 7.3 Synthesis of the main actors and their roles and responsibilities in Ngitili restoration and management in Shinyanga region

Type	Institution	Roles and responsibilities in Ngitili development or management
Local traditional institutions	Dagashida	Decision making, developing bylaws[12], organizing cultural events
	Sungusungu	Securing the communities and their properties, law enforcement
	Elder's council	Mediates between traditional and formal institutions Advices the formal institutions e.g. Hamlet leadership
	Basumba Batale	A group of middle-aged men whose responsibilities are arresting and bringing to charge wrong doers.
Local formal institutions	Village government	Establishes and institutes local by-laws without contradicting those of the traditional institutions Participate in conflict resolution when issues are not resolved at community level
	Hamlet leadership	The arm of the village government closest to the community and is actively engaged in Ngitili management usually by enforcing local and formal by laws
	Environment committee	A committee established by decree to give responsibility of protecting local environments to local communities.
	Village Ngitili committee	Responsible for day to day management of the Ngitili system Implements activities, monitors and reports the development of Ngitili, manages the benefits from Ngitili, maintains the cash flow (revenues and expenditures from the Ngitili) Determines use rights for grazing, fuelwood, construction, etc.
Regional, National and Global institutions	NAFRAC - *Natural Forest Resources and Agroforestry Management Centre*	Provided technical and infrastructural support to promote Ngitili
	TaTEDO - *Tanzania Traditional Energy*	Promoted energy efficient technologies to reduce GHG emissions.

Type	Institution	Roles and responsibilities in Ngitili development or management
	Development and Environmental Organization	
	DASS - *Development Associates Ltd*	Conducted carbon monitoring and accounting in Ngitili systems
	Sokoine University of Agriculture	Conducted research on various aspects of Ngitili and other land use
	NORAD - *Norwegian Agency for Development Cooperation*	Has been the main donor of the HASHI programme for promoting Ngitili in Shinyanga
	ICRAF	Assisted in developing and implementing agroforestry practices complementary to Ngitili, Strengthened local capacities

Currently the Ngitili land management system is being institutionalized in the government system as community-based forestry management under the pilot REDD+ being implemented in the region. The REDD+ project has made considerable progress in introducing community forest management practices into the Ngitili land management systems and organizing owners into formal learning groups to ensure sustainability of the system. A study[13] of the economic feasibility of sustainable smallholder bio-energy production in the eastern part of Shinyanga region found that rotational woodlots were the most profitable and provided the highest return to labour; they thus complement Ngitili in which rates of biomass production are modest.

7.5 The bigger picture: implications

Our retrospective analysis of the Ngitili system experience in Shinyanga region has given us the opportunity to learn how targeting land use practices that can simultaneously contribute to multiple objectives could help achieve climate smart landscapes. The lessons from this case in Tanzania also provide a good basis for some of the AFR100 landscape restoration targets. Though our analysis is preliminary, it demonstrates a number of lessons for climate smart landscapes:

a) It confirms that designs based on local knowledge and practices can contribute to the success in achieving climate smart multifunctional landscapes.

b) Policy processes and financial mechanisms at national level that support local level actions (including agroforestry)[14] are necessary to make climate smart landscapes a reality.

c) Land use planning that takes into account trade-off and synergies between climate change mitigation, adaptation to climate change, livelihoods, and biodiversity conservation is necessary to make landscape level actions effective and efficient.

d) d) Local ownership of restoration interventions is crucial as the community are have to be the one to continue working on the investments after projects leave the landscape.

e) e) Community preferences for restoration interventions and for restoration objectives should be an integral part of the intervention design to make restoration efforts successful.

Box 7.3 Policy recommendations

- More efficient and equitable policy instruments need to be developed to allow the integration of mitigation and adaptation through land use practices that enable simultaneous contributions to livelihoods, biodiversity conservation, etc.
- A co-investment mechanism which engages the private sector; and combinations of financial instruments such as REDD+ (Reducing emissions from deforestation and forest degradation) and payment for ecosystem services (PES) are necessary to sustain the current promising efforts.
- Land-use planning that links landscape level actions to national and subnational policies and strategies is the key to support integrated development and investment in resource management. Such plans should ensure the following:
  a) Define the thresholds of expansion to maintain the ecological balance in the landscapes where Ngitili systems are expanding very fast.
  b) Enable linking landscape level experiences and actions to the national processes such as the National Adaptation Plans of Action, and the National Strategy for Growth and Reduction of Poverty of Tanzania.

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Trees help to increase crop yields

In Niger, Faidherbia trees help to increase crop yields.

Photo: World Agroforestry

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CHAPTER EIGHT

Zinder: farmer-managed natural regeneration of Sahelian parklands in Niger

Dennis P Garrity and Jules Bayala

Highlights

- Farmer-managed natural regeneration (FMNR) of trees on croplands has spread to 7 m ha in Niger and now occupies about 21 m ha across the Sahelian countries. Sahelian croplands now have 16% tree cover on average, which can be further increased and intensified in many ways.
- The broader spread of FMNR will be enhanced by deeper forest policy reform to avoid disincentivizing farmers from growing trees on their farmlands, and by government and international support for adopting these agroecological practices
- FMNR scaling-up complements other agricultural improvements. It should be embedded into all rural projects in the region
- Further development of tree product markets will enhance the uptake of FMNR.

8.1 Introduction

There is little doubt that a remarkable 'regreening' has taken place in part of the Sahel in recent decades. After severe episodes of drought and famine in the 1970s and 80s, that caused massive crop and livestock losses, and human migration and mortality, a process of agroforestation on more than 5 million hectares of farmlands has 'regreened' the southern part of Niger[1]. This has had major positive consequences in improving crop and livestock productivity, and it has enhanced the resilience of these agricultural systems to drought and temperature extremes in the face of climate change. The practice of farmer-managed natural regeneration (FMNR; Box 9.1) of trees on farmlands is now accelerating across all of the Sahelian countries. Currently, trees occupy 16% of the total area of croplands in the semi-arid and subhumid zones of the Sahel[2], and 23% in the West Africa savannas. Nearly 100% of this tree cover is a result of the practice of FMNR by the millions of small-scale farmers of the region. The how and why of this regreening process has been an interaction of actors, policy changes, behavioural changes and practices[3]. This chapter examines current understanding of the drivers of change, the change itself and its implications for the future of agriculture in the drylands of the Sahelian region and beyond.

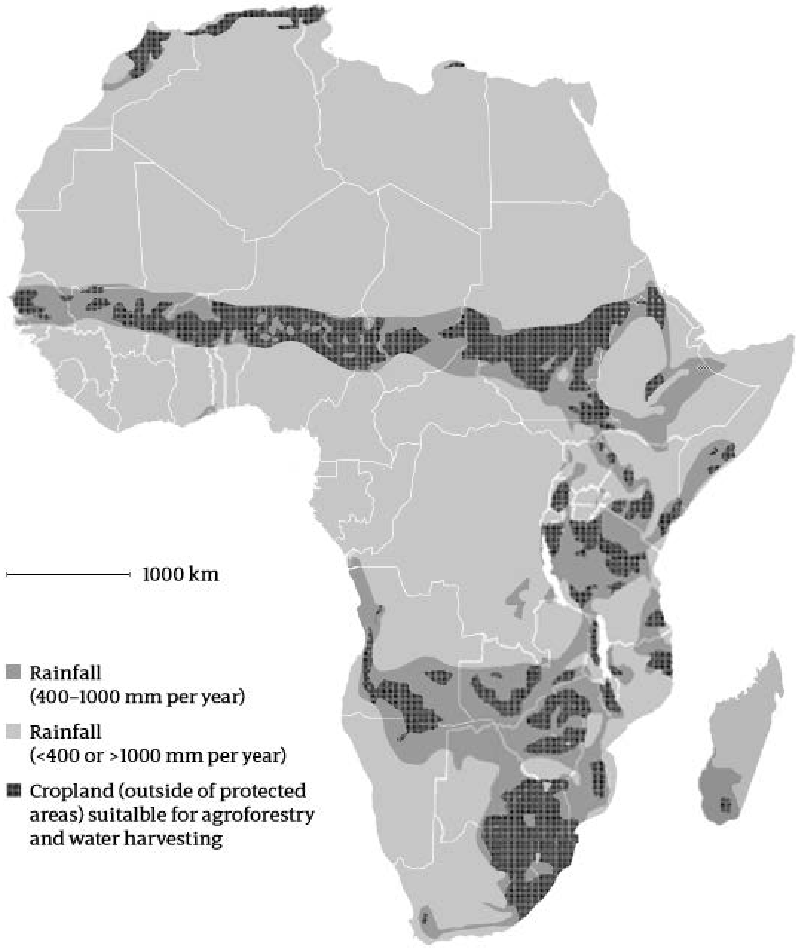

Figure 8.1 Map of dry semi-arid zone of Africa[4], with the star indicating the Zinder region in Niger

Box 8.1 What is farmer-managed natural regeneration?

Farmer-managed natural regeneration (FMNR) – *régénération naturelle assistée (RNA)* in French, *sassabin zamani* in Hausa – is a practice which involves identifying and protecting the wildlings of trees and shrubs that establish themselves on farmlands. It depends on the existence of living root systems and seeds. Shoots from roots grow more rapidly than saplings from seed because of better- and well-established root systems, and they make up the bulk of the protected woody matter on farms in southern Niger. Farmers will generally choose one to five of the strongest stems from stumps they wish to retain on their land, pruning away the remainder. These stems are managed to grow into full-canopy trees that are harvested to provide fodder, biofertilizer, fruits, medicine, firewood, and timber. The species favoured vary from place to place; as does the density of the trees in the crop fields. Some projects have advised farmers to keep at least 40 trees per hectare, but densities of over 150 trees per hectare are not unusual.

The context

Interest in the development of the African drylands has increased in recent years, but widespread concerns over 'desertification' of the region go back to at least the 1970's[5]. This has been driven mainly by recognition that they have been the target of considerable humanitarian aid over the last three decades, and they are currently the cause of great concern about rising insecurity and conflict. But comparatively little effort has been invested in their development to increase people's resilience and to address insecurity and dependency on aid. This reawakened interest has translated into support for livestock and crop-based development pathways, and efforts to foster resilient livelihoods revolving around agricultural commodities. Such efforts, however, will be of limited impact without attention to a broader systems approach that builds on the synergies that trees provide in these systems based on a crop-tree-livestock perspective.

Dryland peoples and their communities have acquired, through the millennia, considerable resilience to these conditions. This enables them to recover following droughts and other nature-induced shocks like floods and fires. However, the recent very-high rate of human population growth in the drylands, and the increasing frequency and intensity of droughts, are both seriously undermining the resilience of both the land and the people. In the agricultural domain, production of the most important dryland crops is already typically associated with dispersed trees in the farm fields. This form of land use is referred to as agroforestry parklands in the Sahelian context[6]. Variants of the parkland system are also common in the Eastern and Southern Africa drylands (or *Miombo*)[7].

When parkland trees are pollarded or die the full positive effect on soil fertility is revealed. Photo: World Agroforestry

Often, the trees in these systems directly provide an important product such as wood, gum, oil or fruit. In other cases, they provide an input into the production of other major products such, as foliage used as fodder for meat and milk production, tree nectar for honey, and tree leaves as biofertilizers for improved soil health and crop production. A considerable number of well-recognized species and products are associated with the African drylands. These include the baobab tree (*Adansonia digitata*), which provides nutritious fruits and leaves; the shea tree (*Vitellaria paradoxa*) that provides butter used in cooking, in chocolate and cosmetics; gum arabic (*Acacia senegalensis*) that provides a gum used in many food items; and the acacia tree *Faidherbia (Acacia) albida,* which enriches soils and provides valuable pods and foliage for fodder[8]. The environmental services derived from trees on farmlands provide another significant stream of benefits, such as soil and water conservation, and a more favourable microclimate for crops to withstand wind and heat and drought stress[9,10,11].

Farmer-managed natural regeneration (FMNR) on agricultural lands, and assisted natural regeneration (ANR) on community lands, provide the most cost-effective way of achieving a widespread increase in the number of valuable, adapted, and diverse trees. What these practices have in common is that in both cases, people (individual farmers or entire communities) actively influence the natural biological regeneration processes to achieve tree patterns that best suit their needs.

On agricultural lands, farmers identify naturally regenerating tree seedlings or sprouted rootstocks in their fields. They protect and manage them to provide various benefits (for direct products and for better crop and/or livestock production). On community lands, local groups may adopt the same practices, and they may also introduce grazing management systems at the community level that are designed to allow successful tree regeneration in the targeted areas. Under both systems, protecting and weeding around young trees, and thinning the trees as they grow, may be necessary to help them survive and flourish.

In recent years, FMNR has gained in popularity in many dryland areas in western, eastern and southern Africa. Because it requires very little or no cash investment, FMNR can expand rapidly through farmer-to-farmer and village-to-village diffusion. The case of Niger provides the most dramatic example of how quickly and how extensively the practice can spread[12]. But Niger is not unique. A recent study carried out in Niger, Mali, Burkina Faso and Senegal has found that almost all farmers are now actively regenerating trees on their farms[13].

The products and services derived from FMNR vary from location to location, depending on the tree species that are present in the area, and that are valued by farmers. Throughout the Sahel, more than 110 different woody species are being managed by farmers through natural regeneration[14]. These trees provide a high level of value to local people[13]. They contribute products for human consumption (more than $200 per household per year), and nutritious fodder for livestock during the late dry season, and they have positive effects on crop yields (accounting for roughly 15-25 percent of the variation in millet and sorghum yields).

A healthy parkland agroforestry system would include both mature trees that provide benefits today, along with some younger trees to replenish the system for the future[15,16]. However, demographic, economic, environmental and social developments during the past 40 years have put serious pressure on the traditional land-use systems of the Sahel. Modern Sahelian forest laws that banned the cutting of trees without a license, and the ways that they are locally enforced, discouraged farmers from engaging in optimum parkland management practices, and led to the degradation of the parklands to a varying extent across the region[12]. This was particularly the case in Niger.

What happened in Niger and how did it happen?

During the 1970s and 1980s, Nigerien farmers faced massive tree losses from drought, and human population pressures, resulting in widespread desertification of the agricultural landscape. After conventional reforestation projects had consistently failed, pilot projects were initiated during the mid-to-late 1980s, followed by larger development projects, that began to emphasize FMNR as a way to re-establish useful trees in the desertified agroecosystems of southern Niger[17].

Interest in FMNR was further stimulated in the 1990s when the successful experiences of several pilot projects were shared with government policymakers. This encouraged the government to relax the restrictive forestry regulations (Code Forestier) that had severely limited farmer management of their own trees. Farmers had previously been strongly discouraged in regenerating and managing trees on their own land because foresters claimed this was illegal. Farmers were threatened with imprisonment if they so much as pruned a tree. Foresters typically extorted cash from farmers after accusing them of 'breaking the law'.

But when these 'enforcement' practices were suppressed, FMNR landscapes began to spread rapidly. In 2004, the Government of Niger formally recognized the trend by revising the national forestry laws to eliminate the onerous restrictions on the freedom of farmers to manage the trees that they regenerated and managed on their own land.

Tree densities and tree cover in Niger have increase dramatically in recent decades[18]. Analysis of high-resolution images acquired during 2003 to 2008 shows that in the Maradi and Zinder Regions of Niger alone, about 4.8 million hectares of farmlands were regenerated by 2008 through FMNR[12]. An estimated 1.2 million households were engaged in managing these FMNR systems through their own independent efforts. Many villages now have 10–20 times more trees than 20 years ago and the agricultural landscapes of southern Niger have more than 200 million more trees than they did 30 years ago. Reij and colleagues[12] estimated that this transformation has resulted in an average of at least 500,000 additional tons of additional food produced per year which covers the requirements of 2.5 million people. More recent satellite image analysis has revealed that FMNR is being practiced on over 7 m ha in Niger[19].

The further scaling-up of farmer-managed natural regeneration has been spreading to other countries in the Sahel, inspired by the Niger experience. The US Geological Survey recently mapped 450,000 hectares of young, contiguous FMNR on the Seno Plains of eastern Mali[20]. This had evolved through a similar process as in Niger, and was accelerated during the past 15 years as the enforcement of forestry laws prohibiting FMNR was relaxed. FMNR is also now locally-prominent in northern Burkina Faso. Interestingly, some farmers there are managing FMNR in more standard row patterns, in order to avoid interference with ploughing operations[21].

In Senegal, the Serere people have sustained a dense cover of mature *Faidherbia albida* parklands on about 150,000 hectares of farmlands for at least the past few generations. But degradation of the tree and land resources prevailed in much of the rest of the country. The Government recently has revised its agricultural strategy to promote FMNR for land regeneration. This has led to over a dozen FMNR pilot projects that are providing the technical and institutional experience to enable the widespread renewal of regreening[22,23,24]. World

Vision's FMNR project in the Kaffrine region has enabled the adoption of 70,000 hectares of new FMNR.

What has happened since 1994 on Mali's Seno Plains illustrates the importance of forestry legislation. In 1991, Mali's president was toppled by a popular uprising. During that period many forest agents were thrown out of the villages and some were even killed. They had managed to make themselves very unpopular, for instance, by starting bushfires themselves, while later accusing the villagers that they had done so. Since this practice was against the law, the forest agents were subsequently able to impose unjustified fines on the people[25]. In 1994, a new forest law was adopted, which specifically mentioned on-farm trees and the farmers' rights to these trees, on the condition that the land was not left fallow for more than 10 years. This policy encourages farmers to reduce the number of years that they leave their land fallow and to protect on-farm trees. Due to the high and rapidly growing population densities on the Seno Plains, most farmers have to cultivate their land permanently, in any event.

A radio station in the small town of Bankass on the Seno Plains, which was funded by the NGO SahelEco, decided to broadcast the contents and implications of the new forest law. The reaction of villagers was "does this mean we can refuse access to those who cut our trees with a permit of the forestry service?" The answer was yes, and it was also broadcast by the radio station. From that day farmers refused access to woodcutters arbitrarily contracted by the Forestry Department to harvest farmers' own trees without compensation. Farmers now had the incentive to begin protecting their on-farm trees[25].

It took until 2011 before the scale of the new agroforestry systems on the Seno Plains was fully uncovered. Local staff estimated the scale to be on the order of 16,000 hectares. However, Gray Tappan of the US Geological Survey's EROS Data Center in South Dakota, used satellite images and mapped the area under medium and high-density agroforestry to be almost 500,000 ha. Until 2011, no one had the slightest idea of the scale of this re-greening process. Field visits have showed that 90 percent of the trees are less than 20 years old.

Projects in Niger have invested less than $100 million since 1985 in the promotion of re-greening by farmers. Part of the 5 million ha is the result of project intervention, but a substantial part is the result of farmers spontaneously adopting the practice because they have observed the benefits and do not wait for external support. One key activity was the organisation of farmer-to-farmer study visits. Letting farmers (men and women) who don't yet use the practice visit with those who have gained experience with it is one of the most effective ways of spreading the practice widely.

If an investment of less than US$100 million has led to 5 million hectares of new agroforestry parklands, then the average costs of adoption per hectare were less than 20 US $/ha. The annual labour costs per hectare for pruning and protection are also quite low. The International Fund for Agricultural Development recently calculated the costs of farmer-managed regreening in the Maradi Region. The costs amounted to 9000 CFA/ha, which is US$14 per hectare at current exchange levels (1 $ = 607 CFA)[26].

Reij and colleagues[12] conservatively estimated that the 5 million ha of new agroforestry parkland had increased average grain yields by 100 kg/ha. They postulated that the yield increases are higher in areas dominated by *Faidherbia albida*, but it may be less elsewhere. In this way, regreening by farmers was calculated to contribute an estimated annual increase in grain production of 500,000 tons. This is enough grain to feed 2,500,000 people.

Not all smallholder farmers practice agroforestry. In the Southern part of the Zinder Region, the agroforestry parklands are fairly contiguous, but in the Maradi Region one can find villages with and without agroforestry adjacent to each other. The reason behind this difference seems to be that internal conflicts in some villages have prevented them from engaging effectively in the protection and management of natural regeneration, which requires community efforts and organization, particularly in grazing management.

What are the consequences of the spread of FMNR?

Global temperatures are significantly increasing as a result of climate change. Average temperatures in the Sahel have increased by about one degree Celsius during the past 40 years[27]. Periods of extreme day-time temperatures are also more frequent and severe. Most annual crops experience a reduction in their yield potential as a result of higher temperatures due to two processes: they have higher respiration rates, which burns up more of their energy, making less available for grain filling; and they shorten of the crop maturity period (fewer days between flowering and maturity) which reduces the size and weight of the grain[28].

Trees in crop fields significantly reduce temperatures in the crop canopy and at the soil surface, thus reducing the crop exposure to high temperature shock, particularly at mid-day[9,11]. The aggregate effect across the growing season is to reduce the shock of a shortened crop maturity period, thus enabling the crop to photosynthesize longer during the daytime, and to increase the amount grain filling and the ultimate yield[29]. The sum of these effects is a more stable crop yield in drought years in fields with tree populations, than in fields without them. Surveys in Niger comparing the crop performance in drought years between villages and households with and without the practice of farmer-managed natural regeneration of trees, have also provided farm-level evidence of this[12]. The research data are consistent with farmer observations that higher tree populations reduce the drought effects on their crops.

Trees in crop fields directly and significantly ameliorate the severity of drought effects on annual crop performance by modifying the humidity. Crops in the vicinity of trees experience a more favourable microclimate, with significantly higher humidity in the crop canopy, causing a lower vapor pressure deficit. Trees also slightly lower solar radiation stress. They also dramatically increase the infiltration and storage of rainfall in the soil by reducing surface runoff[30]. The additional biomass that they provide increases soil organic matter, which enhances both soil moisture storage capacity and nutrient availability to the crops[31]. Moreover, there are circumstances under which some species of trees effectively transfer water from deeper depths, bringing it up to near the soil surface through their root systems, thus making such water available to nearby crops ("hydraulic lift")[32,33,34]. These phenomena reduce the rate of onset of crop water stress, enabling the crop to more successfully withstand periods of drought during the growing season.

A diverse portfolio of trees on the farm can enhance a household's ability to cope with stresses, because the fruits or edible leaves are available at different times during the year.

The leaves from several species of trees are used as vegetable protein throughout the year for human or livestock nutrition (e.g. baobab, moringa, and others).

Trees are assets that can be cut and sold for cash or exchanged for goods in times of need. In the Maradi and Zinder Regions of Niger, and where 1.2 million households now sustain medium-to-high densities of tree populations on their farms, tree branches are cut on a continuous cycle for household fuelwood supplies and for sale. Some of the mature trees are also cut down and sold in local wood markets for poles and construction materials. Export markets are now active in buying and shipping wood south to Nigeria. During prolonged drought periods, these tree assets may be gradually liquidated to supply the household with cash for food purchases. This process is an important source of coping capacity for households during prolonged drought[12].

In Niger, Faidherbia trees help to increase crop yields. Photo: World Agroforestry

Trees are important to the livelihoods of dryland households, and they can contribute in many ways to resilience. Income from wood and non-wood tree products can make a significant contribution to rural households' budgets and their food security. The services that trees provide for crop and livestock systems are in many cases even more important, and of higher value, than their direct products alone. Building resilience and improving livelihoods requires an integrated approach. Investment in scaling-up FMNR is now widely seen as an essential component of a basic set of technological options for supporting dryland livelihoods.

Trees of all types have some properties that are beneficial for soil conservation and fertility, chiefly through their root systems, which help to hold soils in place, the litter that falls as mulch, and the organic matter that the roots and litter provide to nourish micro and macro fauna in the soil[9]. Many farmers have known and appreciated these properties for generations[34]. At the same time, trees can compete with crops in terms of nutrients, water and light. So, farmers weigh the benefits and costs in associating trees with crops and they make decisions on the appropriate tree species, and the optimum densities of these trees to establish in their crop fields. Trees in crop fields may also compete with animal ploughing operations, by imposing additional time and costs. Cultivation with 'clean' fields is often the message that extension agents have conventionally conveyed to farmers[35], a message that needs to be actively disputed based on the positive evidence and experience that now exists in favour of sustaining a more productive tree-crop-livestock system.

Quite a number of tree species have been found to offer significant benefits to soils with relatively little competition with crops. *Faidherbia albida* (formerly *Acacia albida*) is popular in many parts of the Sahel and throughout eastern and southern Africa[36,37]. It fixes atmospheric nitrogen, has a deep rooting system, has a light, open canopy, and it drops its nitrogen-rich leaves onto the soils right as the rainy season begins, and remains dormant during the crop-growth period. This means that it throws minimum shade onto the crop. There are many other useful species for soils as well. These are often the same species that are beneficial as livestock fodder (such as many of the acacia species).

Studies on the effects of fertilizer trees on maize yields found that they often have significant positive effects[37,38,38]. The effects of FMNR on millet and sorghum yields, the major food crops in the Sahel, were found to be between 16% - 30% in Mali, Burkina Faso and Niger, controlling for other inputs and conditions[13]. The limited evidence suggests that while the fertilizer tree systems cannot completely shield crops from some yield losses in droughts, they provide higher yields than when trees are absent[39].

Tree vegetation cover in the drylands may also reduce wind speeds and dust loads. African drylands contribute over 50% of total global atmospheric dust circulation. They have dust concentrations considerably higher than any other region of the world[40]. High child mortality is associated with respiratory illnesses, especially in Africa; this has been partly attributed to exposure to dust[41,42].

How can FMNR be scaled up most effectively?

Empowerment of village communities

Individual farmers can protect and manage trees, but it is more effective if village communities organize themselves to do so, and develop enforceable by-laws for managing the trees. This is what was done by an IFAD-funded project in the Maradi Region, which supported the building of village institutions. Men and women farmers, but also representatives of the herders, are members of the management committee. The committee holds meetings with surrounding villages (inter-village organisation) to foster cooperation in tree protection. They have developed rules and set fines for the illegal cutting of trees. And these rules are enforced. The village of Dan Saga receives many national and international visitors, who come to learn from their experience in landscape management of their village-wide FMNR success. They feel empowered by this outside attention to their technical and institutional innovations.

Forest Policy Reform

The issue of forest regulations which create disincentives for farmers is one that is widespread in the developing world. These include the banning of felling or cutting of a number of species without obtaining a prior permit, at a fee. Violation of such regulations entails a hefty fine, and so farmers will often remove young trees from their land to avoid having to adhere to these rules in the future. Among such regulations, the adverse effects of the Sahelian forest codes have long been recognized[43]. There have been many policy dialogues in the region to try and move reforms forward. Although not initially backed by formal policy change, the recent regreening in Niger and Mali has been attributed to a significant extent by the relaxation of enforcement of such policies[12]. A recent analysis of the forest codes[44] led to recommendations for action[45,46].

There are several institutional-related factors that have been identified as limiting the potential for FMNR, such as fire setting, free grazing and rights and regulations over trees[47]. The use of fire and free grazing systems generate benefits to some local people - in terms of grass regeneration, clearing of debris, catching wild rodents for food, and in the case of free grazing, offering a cheap mechanism for feeding livestock. Thus, it is challenging to deploy institutional reforms that can accommodate the interests of FMNR with these other benefits. However, practices such as controlled fires, rotational grazing areas, and the promotion of livestock corridors are all options that have been successfully implemented in the drylands to facilitate the scaling-up of FMNR.

Market Development for Dryland Tree Products

The existence (or not) of markets for tree products is another factor that impacts on incentives to manage trees. The development of tree product markets will have a positive effect on encouraging tree-based systems in general. For FMNR in particular, market development may have different effects. In general, as tree product markets develop, there is more incentive to maintain trees on farms, as the case of shea in Burkina Faso has demonstrated. There may be further incentives that influence the selection of tree species to retain in the crop fields, based on market signals, but only if market signals -persist for a long enough period of time, since changes in tree species composition is a long-term evolutionary proposition in the drylands. Furthermore, in the semi-arid and dry sub-humid zones where tree planting opportunities are greater, certain types of market development may favour tree planting by farmers and, as a result, may also reduce farmer interest in FMNR.

Continental Recommendations

Recently, there has been a resurgence of interest by the Heads of State of the Sahelian countries in the creation of a Great Green Wall across the continent. At the 1st African Drylands Conference (Dakar, June 2011), scientists presented evidence underpinning the value of an approach based on a grass-roots, participatory engagement of the local rural populations to expand the farmer-to-farmer dissemination of FMNR region-wide. This was supported by the World Bank and the Global Environment Facility, which are now collaborating with each of the Sahelian countries to invest a pool of $1.8 billion dollars to implement land regeneration projects based on these community-based natural resource management systems and other restoration methods. The declaration of the 2nd African Drylands Week, convened by the African Union in August, 2014, urged that the drylands development community commit seriously to achieving the goal of enabling every farm family and every village across the drylands of Africa to be practicing Farmer-Managed Natural Regeneration and Assisted Natural Regeneration by the year 2025.

At a coarse scale, FMNR should be considered as a recommendation in all geographical regions, and particularly in the semi-arid and dry sub-humid drylands. FMNR will continue to support the largest number of established trees on farms in the drylands. Place and Binam[13] found that over 90% of trees on farms in the Sahelian countries were established by farmer-managed natural regeneration.

Within a particular dryland zone, there may be further nuances on recommendations for how to practice FMNR. For example, certain institutional arrangements, such as improved grazing management may be an important complementary action in some places, while not in others. The types of trees that will be desirable for farmers to retain, as well as the densities of trees, may also differ across locations. For example, where fertilizer use is extremely low, promoting the regeneration of trees which have known positive soil fertility properties will be more important.

Due to the continued expansion of agricultural land in the drylands, FMNR is all but assured to play an ever-important role in overall tree management. It can be considered a 'foundational practice' that is relevant for virtually all farming systems in the semi-arid and dry subhumid dryland zones. It has such a wide recommendation domain because establishment costs are very low. Regeneration has high success rate due to growth from rootstock, and it involves species that are well-adapted to each site environmentally and climatically. The practice can be integrated with the full range of traditional and improved crop and management systems. Other tree-based systems that involve the planting of trees can then be built around the basic FMNR practice, further enriching the species portfolio on the farm. Tony Rinaudo refers to this process as FMNR+.

By contrast, tree planting has more limited niches in the drylands. It is more suited to the semi-arid and sub-humid and humid zones, where rainfall is higher, where there is access to dry season water to be used in tree nurseries (e.g. proximity to low lying wetland areas). Tree planting is further induced where there are attractive commercial opportunities for specific tree species suitable to the drylands.

How to massively scale-up FMNR?

There is growing political support for massively scaling-up FMNR. The African Restoration Initiative (AFR100) of the African Union is now supporting a process of engaging many countries in Africa to restore 100 million hectares of degraded landscapes by 2030. This AFR100 initiative has an audacious level of ambition that can only be achieved if FMNR, led by farmers and their communities will be a dominant component of the effort. No other set of practices could possibly accomplish the job – given the enormous areas of land involved and the limited investment funds available.

Six Steps to Success

The World Resources Institute recently published a report[48] about how to scale up regreening successes. This report builds on and distils the regreening experiences observed in the West African Sahel that was discussed above. The scaling strategy has 6 steps, and some activities under each of the steps.

Step 1 Identify and analyse re-greening successes

There are many smaller and bigger re-greening successes in Africa's drylands. As the examples from Niger and Mali show, re-greening by farmers is often overlooked. Each country should make an effort to identify its re-greening successes, because these can be used as sources of inspiration and as training grounds for farmers who do not yet protect and manage their naturally regenerating trees. It is interesting to note here that farmer-managed natural regeneration occurs in the Sahel, but is also extensively practiced in Ethiopia, and under the higher rainfall sub-humid conditions and the different farming systems practiced in Malawi.

Step 2 Build a grassroots movement

In most countries, donor-funded projects are already promoting some forms of participatory natural resource management, but they are not always working together. The challenge is to get them around the table to create synergies and stronger political leverage in discussions with government about enabling policies and legislation.

Farmer-to-farmer study visits are a very effective way of scaling-up FMNR. In some regions, farmers (men and women) have gained so much experience with the practices that they have become the experts who train other farmers. If it is true that practice precedes policy, then it is important to inform government about the successes, and about the existing dynamics that can accelerate the process on-the-ground.

Step 3 Address policy and legal issues and improve the enabling conditions

Working at the grassroots level only is not sufficient to accelerate the scaling-up of FMNR. The role of national governments is to create forestry legislation and agricultural development policies that induce land users to invest in trees. Current forest legislation tends to show some weaknesses. One of these is that they often do not recognize farmers' right to own, manage and harvest the trees that are established on their land. For instance, in most Sahelian countries, farmers are allowed to exploit and also cut the trees that they have planted, but if they have protected and managed natural regeneration they may need a permit from the forestry service in order to manage or to prune or harvest the tree.

A major weakness that needs to be addressed is that Ministries of Environment tend to be interested in natural forests and in planting trees, but not in the protection and management of natural regeneration; whereas Ministries of Agriculture usually concentrate their extension efforts only on annual crops. However, as soon as funding for agroforestry projects becomes available, turf fights often emerge between both Ministries. The Ministries of Environment then claim that agroforestry is about trees, which is their domain, while the Ministries of Agriculture, which have much stronger extension services, usually have a much greater capacity to implement such projects, claiming that it is all about farming systems. The solution is the development of inter-sectoral platforms that combine the strengths of both Ministries in the accelerated scaling-up of agroforestry.

Step 4 Develop and implement an effective communications strategy

It is possible to reach out to tens of millions of smallholders by using rural and regional radio stations to spread the messages about regreening, and by linking mobile phones with radio and ICT to make the web more accessible to rural people. The process can be enhanced by inviting national and international journalists to visit re-greening successes. However, at this moment most regreening projects don't have a communication strategy, or if they have one, it is seriously underfunded. The challenge is to inform all land users in a country about what has been achieved, and about what they and their communities can do to participate. Land users themselves should be at the heart of FMNR communication strategies.

Step 5 Develop or strengthen FMNR tree product value chains

This is where the private sector has a major role to play. They can support the development of value chains around the agroforestry products from FMNR. This will put more cash into the pockets of smallholder farmers.

Step 6 Design research activities to fill gaps in knowledge about FMNR

We know enough to move into accelerated action on FMNR scaling-up, but at the same time it is important to fill some important gaps in our knowledge. For instance, too little is known, about the impact of landscape-level FMNR on surface and groundwater hydrology, or about the impact of re-greening on rainfall, on carbon sequestration in biomass and in soils, and on nutrition and food security.

What are the 'next generation' issues and how can they be addressed?

Tree-based systems provide regenerative or restoration effects that are realized at a landscape scale. They cover a wide range of practices that enrich the quality of the land resource, and they provide additional environmental benefits such as watershed protection and enhanced biodiversity. The natural regeneration of trees may be applied across the range of land use types, including farmlands, forests, woodlands, and rangelands. Restoration at scale has been achieved through the efforts of large numbers of rural residents,

Besides environmental conditions, other factors may limit the technical potential of FMNR. There are several other institutional related factors that have been identified as limiting the potential for FMNR, such as fire setting, free grazing, and the rights and regulations over trees. Place and Binam[13] found a large percentage of Sahelian farmers identifying unreasonable forest codes as still a limiting factor (44%), heavy-handedness on the part of forest officers (38%), uncontrolled cutting of trees by outsiders (31%), and animal damage (28%).

Although the scaling up of FMNR in the Sahel has been labelled as farmer-driven with little external support, a number of programs are now investing in the scaling-up of FMNR. These programs are spending resources on enhancing farmer awareness of the benefits of FMNR, building farmer tree management skills, organizing landscape management of grazing and fire, developing tree product markets, and identifying workable solutions to forest code regulations. The increased rural population, coupled with dwindling woodland, also suggests that woodland management is not an alternative to FMNR, but rather it is a highly complementary activity[49,50].

Policy recommendations for scaling up

FMNR has great potential to reduce vulnerability and increase resilience of households living in the dryland regions of sub-Saharan Africa. This potential is not always appreciated, however, so work remains to be done to change the mindsets of policy makers, development professionals, and even technical specialists such as researchers and extension agents. For many, mixing trees with crops is considered unconventional and to be avoided, yet a growing body of evidence suggests that successfully integrating trees into farming and livestock keeping activities can be extremely profitable, provided the appropriate species and management practices are used.

Key policy factors and proposed action for the mass scaling-up of FMNR are discussed below[25]. They cover aspects of production, value chain development and policies/institutions. Each of the factors is equally relevant whether trees are established through regeneration or through planting.

1. Changing attitudes/mindsets towards the integration of trees in agriculture

The benefits of trees have been well-appreciated by generations of farmers. However, there remain some obstacles towards the better integration of trees on farm, for which there is increasing need given the continued conversion of woodlands into agriculture in the drylands. First, there is renewed interest from agricultural programs to promote conventional crop agronomy --- good seeds, mineral fertilizer and having ‘clean’ fields using animal traction – where mixing trees with crops has not been typically recommended due to the perception that they compete with crops. This, of course, ignores the positive synergies that trees can have with crops and it also ignores the fact that some trees can provide products of higher unit area value than crops. Second, foresters in most countries continue to implement policies which have adverse incentives on farmers to grow trees on their land. The most common one is the protection of certain indigenous species meaning that they cannot be cut or sold without license and fines are issued for violations. This legacy of being ‘forest policemen’ instead of tree extensionists continues today.

The conventional mindset permeates the formulation of development programs by governments, and even some NGOs, who then neglect to include trees as part of agricultural development programs, or even discourage the practice. Therefore, this issue is mostly about changing attitudes among organizations that interface with farmers. There is as well the need to alter the mindsets of higher-level policy makers. Many see trees serving only environmental purposes and they fail to recognize the large income-generating roles that trees can play in sustainable agricultural intensification, increased crop production, and livelihood improvement.

Farmers themselves are generally very open and receptive to managing trees on their farms, as they all tend to use trees as part of their farming system. One key issue here relates to attitudes towards women’s rights to trees, which are not very progressive in many communities. If both women and men were able to influence tree management decisions, trees could play a more beneficial role on farms. Lastly, there are other resource users whose main objectives may come into conflict with those managing trees. These include herders and charcoal burners, whose actions regarding grazing/browsing, fire-setting and felling can conflict with successful tree regeneration and management.

Proposed actions include:

(1) Expand the documentation and dissemination of the benefits of FMNR, notably systems that are integrated with crops and livestock.

(2) Increase the documentation and dissemination of the costs associated with onerous forestry regulations.

(3) Intensify advocacy for and implementation of pilots of new approaches for agriculture and forestry that can be jointly monitored.

(4) Deepen the technical support to the designers of all agricultural development programs to be able to better include FMNR among their interventions.

2. Spreading awareness and knowledge of improved or new practices

While farmers have been managing trees for generations, in the drylands more than anywhere else, they are accustomed to the performance of native species which have locally regenerated without significant management. This means that most farmers are unaware of the potential improvement in the productivity of native trees that can be achieved under improved management. They need to be exposed to the different propagation techniques, improved tree germplasm, and using better management techniques for which growth and productivity can be significantly greater than what is observed in the typical landscape.

There are in addition, a range of management options available for soil fertility regeneration, fodders, fruits and timber in the semi-arid and dry sub-humid zones that relatively few farmers are aware of. Extensionists and development organizations (including farmer organizations) themselves are poorly trained in these new techniques, and building this technical capacity should be a focal emphasis of a scaling up program.

Proposed actions include:

(1) Expand the documentation of promising FMNR/agroforestry options and dissemination for awareness creation via many different media.

(2) Regionally, intensify the promotion of FMNR in large development initiatives, like the Great Green Wall of the Sahel.

(3) Broaden the technical training of agricultural and forestry extension agents and development staff to cover FMNR.

(4) Locally, promote FMNR through demonstrations on farmers' fields.

(5) Promote field visits for opinion leaders & farmer leaders to successful FMNR practices on farms.

3. Improving local landscape management – especially grazing management and fire control

In the drylands, a number of resource users apart from farmers have effects on the success of tree-based systems, both on farms and in the woodlands. These include herders, charcoal makers and mammal and rodent hunters. Trees and shrubs are essential sources of feed during the long period of time when there is no fresh pasture or crop stover. While browsing can often be a mutual benefit to the herder and tree owner, it is also recognized by many farmers as a key threat to natural regeneration.

Charcoal makers do negotiate the use of trees, but not all stakeholders are involved in the final decisions, and thus the resulting felling of trees may not be in the community's interest. Hunters use fire as an aid for catching rodents and small mammals with the externality of destroying some vegetation. These practices provide many benefits, and therefore will need to continue. But more progress can be made to protect mature or young trees temporarily from grazing through local enclosures, or to create more incentives for herders to manage livestock away from young fragile trees. This requires investments in dialogues on landscape management among different interest groups.

Proposed actions include:

(1) Expand support for landscape stakeholder meetings to diagnose problems and jointly identify solutions at the landscape level that can benefit communities and manage trade-offs,

(2) Disseminate successful landscape management experiences and models,

(3) Promote the creation or strengthening of local environmental management institutions to undertake improved landscape management programs, and

(4) Develop and enforce local bylaws that influence the behaviour of all land users for the common good.

4. Increasing tenure security

Devolution of ownership of woodlands is least-advanced in Africa compared to other continents. Moving forward on co-management models could enhance both the productivity and sustainability of woodlands in Africa. Tenure on farms is also not well clarified or secure for farmers in the drylands. Many of these lands have not been formally adjudicated either at the community or household levels. This not only creates uncertainty among communities and households, but it also creates conflicts between the state and communities. Dryland areas are often seen as unutilized or underutilized by outsiders, and thus prone to large-scale investments that take little cognizance of local rights and circumstances.

More settled dryland areas normally do offer secure tenure for long term investments, but even there, tree ownership and rights are less clear. This is because of the predominance of natural regeneration, the shifting of fields in and out of fallow, and the fact that some trees have been present for more than 100 years, and thus have entrenched use rights to them. Forest departments in most countries protect many indigenous species which means that they cannot be pruned, felled or marketed without license. These are always indigenous trees, which are among those that regenerate on farmers' fields. This discourages farmers from allowing the trees to grow. And where feasible, farmers will choose not to plant such trees but rather opt for exotic trees that are exempt from such regulations.

Proposed actions include:

(1) Identify tenure insecurities and support negotiations to alleviate them

(2) Support the piloting and eventual change towards smart forest policies that do not create disincentives for farmers to manage trees on their farms and also provide forest departments with new mandates and funding sources

5. Strengthening markets for tree products

Many trends within and outside Africa are favorable for the commercialization of tree products: the new generation of farmers who are much better connected with urban areas and with ICT than their forefathers; urbanization that raises demand for wood, fruits and other products; growing health concerns that increase markets for natural products like gum arabic, baobab, and moringa; more interest in sustainable sourcing of products, more value being now given to farm than forest harvesting of tree products.

At the same a number of obstacles remain in Africa for meeting such increased demand. These include: (1) poor market information systems for tree products, (2) poor rural infrastructure (and particularly in low populated areas such as drylands), (3) a growing but low level of collective action by farmers, (4) low numbers of farmers participating in outgrower schemes, (5) very little investment in basic tree product processing at scale (much done by individual farmers/collectors), and (6) little final finishing of products in-country (and continued imports of furniture and fruit juice ingredients, when raw products are available).

Proposed actions include:

(1) Fund the inclusion of key tree products in market information systems,

(2) Support the development of outgrower schemes between processors/buyers and farmers,

(3) Provide venture capital and support services (e.g. to gain information on preferences of consumers for processed products) for the tree product processing industry.

These policy recommendations are the most common ones needed for FMNR in dryland areas. But the priorities may vary across different geographical locations within a country as market connectivity and local institutions vary[51]. There will be need for much more diagnostic work to identify the most appropriate actions to take. There is no blueprint for promoting FMNR that applies in all dryland areas.

Investments in these areas do not need to be borne primarily by the public sector. Helping to strengthen markets for tree products through engagement with the private sector has been shown to attract and leverage additional finance and awareness generation for FMNR from the private sector in some countries.

The practice of FMNR is not confined to Niger, but it is ubiquitous across the region. In the next phase of supporting the further massive scaling up of FMNR we ought hone in on two things: Encouraging a more optimum age and species distribution of trees on farmlands where FMNR is already being practiced, and focusing our FMNR scaling-up efforts more intensively on those areas where tree cover is still unusually low compared to the average.

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Dwi and Anton

"We are afraid of being evicted again." ANTON

INTERMEZZO 4

ASB Voices N0. 8, 2002

Brothers Dwi and Anton have grown up in a family that values education highly. Their mother teaches pre-school, and their father is a clerk in the local high school. Even so, beginning from primary school, both of these recent secondary school graduates spent their free time helping their father Wahono on the family's 3-hectare coffee plot. That plot is situated on the steep volcanic slopes of Sumber Jaya, a sub-district of Lampung Province in southern Sumatra. Sumber Jaya lies in the foothills just to the east of a major national park and is part of Indonesia's main coffee-growing belt. Over the past 50 years, large areas of 'protected' natural forest on gazetted State Forest Land—including the 3 hectares managed by the brothers' family—have been converted into coffee gardens. Since graduation from secondary school, Dwi and Anton have taken the lead in managing the family's coffee. But their future on this plot is uncertain. The brothers' biggest worry is that the family will be forced from the land—again. In 1995, the Indonesian Government initiated a reforestation project in the State Forest zone, forcing small-scale farmers off the land by destroying their coffee gardens and planting timber trees in the hope of preventing the farmers' return. Some were forced at gunpoint to uproot the coffee themselves. In hopes of securing rights to the contested land in Sumber Jaya, several groups have formed recently to apply for stewardship contracts through the Community Forestry Programme (HKM) of the Government. Anton and Dwi's father is the leader of one group, which joined together in 2000. ASB researchers are working with several of these groups, local government and the Forestry Department to facilitate negotiation for HKM status. The overarching goal is to develop a process by which the Government can meet its environmental objectives to protect watersheds and park boundaries, while also enabling established settlers to make a living by managing their coffee systems in ways that are environmentally sound.

For example, under the HKM agreements, farmers' continued rights to existing plots are linked to preservation of the remaining natural forest nearby. In addition to the moratorium on clearing new land, farmers also agree to use agroforestry practices to enhance sustainability of coffee production on the land they already have cleared. For their part, Dwi and Anton have planted valuable trees such as durian, avocado, breadfruit and nutmeg within their coffee, thereby creating a more complex multi-strata system to control erosion and improve habitat. They also support a nearby community nursery as a source of additional planting material. Like their older brother, who is currently living in Java and studying accounting, both Dwi and Anton want to attend university. Anton, who just graduated from high school, hopes to study agriculture at Lampung University. Ultimately, he dreams of working for an agricultural company or the Civil Service. Coffee farming is a fallback option if these plans do not materialise. However, he prefers not to farm on State Forest Land for fear of being evicted again. Dwi plans to farm while waiting for his turn at university. In the meantime, he is hopeful that the group his father leads will succeed in securing HKM status for their land. Failing that, he also might leave their coffee field. He would prefer to cultivate annual crops on land nearer to the family's home in town, because it involves fewer restrictions and less risk of eviction.

Multi-stratum coffee agroforestry

Multi-stratum coffee agroforestry become a priority of cultivation on farmer own land in Sumberjaya, Lampung, Indonesia.

Photo: World Agroforestry/Arif Prasetyo

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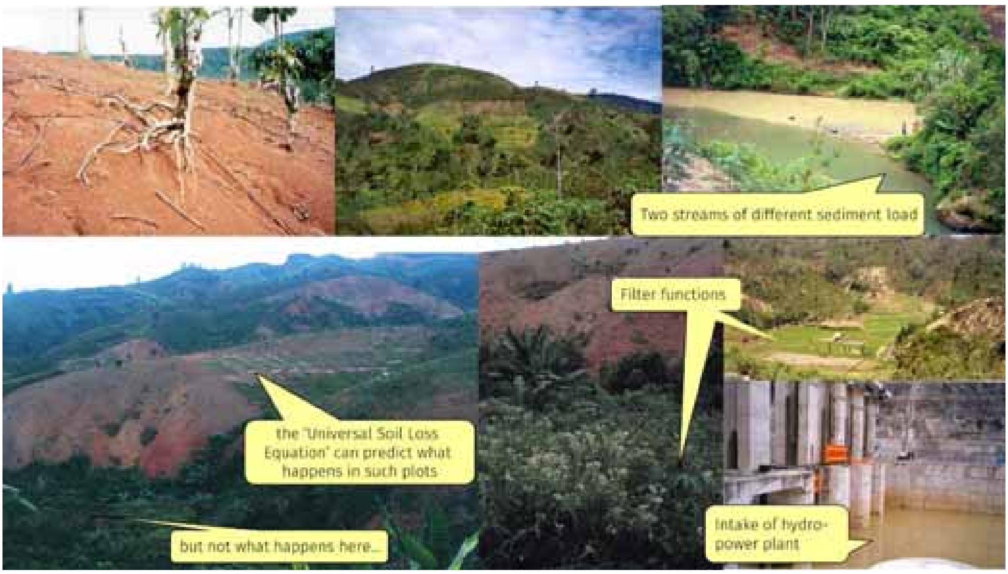
CHAPTER NINE

Sumberjaya from conflict to source of wealth

Meine van Noordwijk, Beria Leimona, Sacha Amaruzaman

Highlights

- A coffee-producing landscape in the mountains of Sumatra had become a hot spot of conflicts between forestry officials and farmers
- Engagement by research and development partners became known as Negotiation Support
- Innovative use of policy instruments in Indonesian forestry law did resolve the conflicts
- In a second phase attention shifted to voluntary, conditional rewards for and coinvestment in sediment reduction



Starting point: a pioneer coffee landscape with serious erosion and sediment loading, affecting a new hydropower plant. Photos: World Agroforestry

9.1 Introduction

Setting the scene: a 40,000 ha area, home to 100,000 people, with coffee (robusta) production as primary source of income, living in a huge old crater, with consequences for spatial variability of soil properties from various eruptions and lava flows. Adjacent to the Bukit Barisan mountain range that runs along the length of Sumatra island (Indonesia), the *Way Besai* river feeds one of Lampung's main rivers. Coffee farming expanded here from start of 20'th century, but a large influx from Java (government sponsored + spontaneous migrants) led to a densely populated landscape. The river became the catchment for a hydroelectrical power plant, developed in the early 1990's. This started the '***issue***' that dominated the landscape from that time: evictions of coffee farmers from a 'protection forest' part of the landscape, motivated by concerns over water quantity and sediment load. When ICRAF engaged in the late 1990's, evictions had made it a 'worst case' example of conflict. The 'action research' here became the basis for a 'Negotiations Support System' approach (NSS), where three interacting knowledge systems (local, public/policy and science/modellers ecological knowledge – LEK, PEK, MEK for short) were charted, landscape-level scenarios were explored, as well as reconciliation/ negotiation processes were supported to turn an ugly lose-lose setting into a win-win. The solutions that emerged varied by landscape zone: community-forest management (HKM) agreements for the watershed protection forest, and a number of PES experiments and ES auctions on the private/village lands by the RUPES (Rewarding Upland Poor for the Environmental Services they provide) program[1]. Now, nearly 20 years after the start of the engagement, the landscape has become a source of inspiration (aligned with the 'Source of Wealth' meaning of the name) for watershed management elsewhere in Indonesia[2].

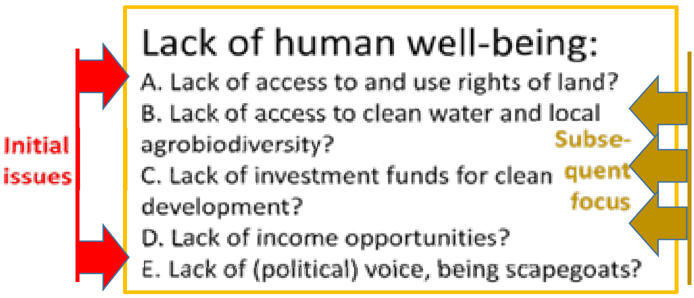


Figure 9.1 Five aspects of rural poverty[3] that were addressed successively in Sumberjaya in a agroforestry action research on agroforestry at landscape, farm and plot level

In the cooperation between ICRAF and a range of national and local partners centred on Sumberjaya (Lampung, Indonesia), three 'learning loops' can be distinguished. In the first the issue at stake was

i) Tenure security for coffee farms in the 'protective forest' zone (NSS)[4]. Once that was on its way to be resolved,
ii) Reducing sediment fluxes from the non-forest zone: voluntary & conditional ES contracts (RUPES)[5,6], and
iii) Increased income from ES-friendly coffee production systems.

Step 1: Negotiation support for resolving tenure conflict

Engagement in the first stage was part of a wider involvement that has been described as 'Negotiation Support System', consisting of two parts: an assessment aimed at bridging between three types of ***knowledge*** (local, policy-based and science-based) of functions, changes and options in the landscape, and an ***action***-oriented process of reconciliation after serious conflict, trust building and negotiated solutions.

After an initial (***exploratory***) assessment by researchers that much of the conflict (expelling coffee farmers from the landscape) was based on mythunderstanding of eco-hydrological relations in the area[7], while the recently approved national Forestry Law included articles that could be used to come to a negotiated set of use rights, we responded to an invitation by local stakeholders to engage and were able to get the funding (from various sources) needed to do so.

Subsequent ***informative*** assessments were aimed at a deep dive into local ecological knowledge systems, biophysical assessments of land use options, erosion and water flows (identifying major diversity in soils as key factor in the differential responses to land use change), and exploration of the rules and underlying concepts of existing public policy for the area, in its historical context (of alternating phases of attracting and repelling migrants).

In the first step, researchers listened to local perspectives and helped translate local concerns and solutions to the negotiation tables with government officials. Photos: Brawijaya University/Kurniatun Hairiah

As a next step, ***decisive*** assessments focussed on the modalities of 'conditional tenure' agreements, with specified restrictions on land use (shift from open to shaded coffee systems). With an initial validity of the agreements of 5 years, the evaluation criteria that could be used to judge their effects in a first phase and turn them into the (legally maximum) duration of 25 years (renewable) became the next point of analysis and negotiation support. While initially the groups that had best social capital connections with government officials and NGO's could benefit most[8], subsequent scaling up to all of the forest margin within the subcatchment, also included the ecologically higher priority communities.

Breakthrough in the conflict resolution when government officials sat down with villagers to discuss possible solutions for tenure security under 'community forestry' rules. Photo: World Agroforestry

Step 2: Rewards for, and coinvestment in sediment load reduction

Design became a prominent part of the second learning loop when attention shifted to the way the sediment load of the river, with its negative consequences for the hydropower company at the outlet of the *Way Besai* subcatchment, could be tackled on the privately owned lands below the 'forest margin' and collectively improved the conditions of the riparian by planting bamboo, constructing a sediment retention dam and strengthening the river banks. Innovative 'auctions' for contracts to (voluntarily) adopt additional soil conservation measures were designed and implemented at the private lands, with followup research on factors predisposing 'winners' of the contracts, as well as success in completing what had been agreed. At the scale of headwater subsubcatchments a 'Rivercare' contract was designed and followed up.

Step 3: Farmer groups engaged in better marketing

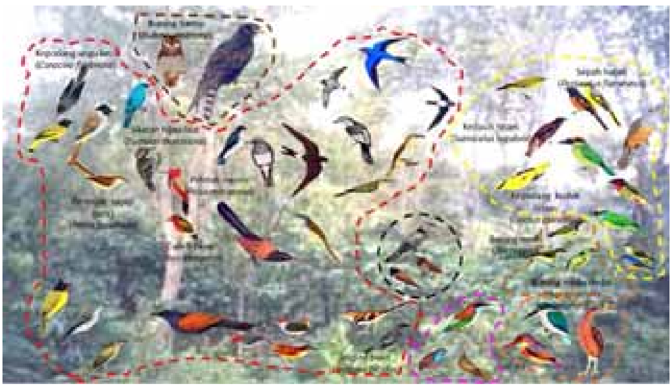
In the third 'learning loop' attention has shifted to options to increase income from environmentally friendly farms, with the initiative shifting to local groups (incl. those initiated around 'River Care') and limited support (mainly in establishing external contacts) by the World Agroforestry Centre team.

9.2 Values at stake

At the start of the learning loops, the conflict involved both instrumental values (land use as basis of local needs and income *versus* water yield as source of hydropower and sediment loads that reduced their efficiency) and relational ones (perception of 'forest' as sole provider of water security[9]). The 'instrumental' ones could be more easily quantified and challenged and coupled to spatial data[10] than the relational ones. Among the 'relational values' the terminology used for various types of forest and gardens were the tip of the iceberg of underlying value systems. Getting government recognition for some of the local concepts was key in the trust building process.

Before the first phase an expulsion threat to 'forest encroachers' had marginalized a large part of the villages and settlement, and brought them into conflict with provincial authorities (acting on behalf of national forest authorities)[11]. Once solutions to that conflict were at the negotiation table, it became clear that better-connected farmer groups got priority. But the success they had opened doors for others as well, so there was a 'trickle down' when the tenure contract model became widely implemented. From surveys we learned that the Gini coefficient of individual land claims within the community-based tenure contracts differed from that for other land holdings in the village, showing a trend towards greater equity[12]. Specific attention to gender was part of the knowledge/perceptions phase, but did not play a major role in the land tenure and ES contracts[13].

Coffee monoculture



Coffee agroforest

With secure tenure multistrata coffee systems, evolving into coffee agroforests were both economically and ecologically feasible and desirable

Throughout the involvement by researchers multiple metrics remained in focus. Some of these relate to 'land cover' (as the tenure contracts had specified the number of trees per ha that were to be planted/maintained), presence of soil conservation structures ('rorak'), others to water yield and sediment concentrations (the basis of 'river care' contracts) and the income streams that farmers could expect from various land use practices (in dependence of discount rates and perceptions of tenure security). For the hydropower company a financial assessment of the costs to their operations of current sediment loads of the river was made, to help them assert their 'willingness to pay' for voluntary sediment reduction in the landscape. Within the process as it unfolded there was no perceived need for integral assessments of economic value of the landscape as a whole – our assessments focussed on specific decisions that could be made.

Participation covered a range of meanings: in some parts researchers were allowed to participate in locally led activities, in others it was the reverse. Efforts were made to involve schools in biological water quality assessments[14,15] to broaden the basis for a more evidence-based discussion on environmental impacts of land use.

The Sumberjaya from its inception recognized and reconciled multiple cognitive models and worldviews, in its focus on three interacting knowledge systems[16]. In doing so it unpacked trade-offs and interlinks between values – finding common space for negotiated agreements by challenging dominant views that only 'forest' could provide the watershed services desired. For local people livelihoods and security of tenure (no fear of evictions) were key[17], for the hydropower company its number of operating days and net profit, for foresters a new way of dealing with people in the landscape etc. Once tenure security had been addressed farming techniques that combined farmer income and environmental protection could become the focus[18,19,20].

Table 9.1 Value concepts that appeared to dominate for the various stakeholders in the three 'learning loops'

I. Tenure security for coffee farms in the 'protective forest' zone (NSS)	II. Reducing sediment fluxes from the non-forest zone: voluntary & conditional ES contracts (RUPES)	III. Increased income from ES-friendly production systems
Farmers: tenure security; **Government**: compliance with law; **Hydropower company (PLTA)**: operating days; **Scientists**: evidence-based options; **NGO**: fairness	**Farmers**: returns to labour, farm sustainability, clean rivers; **PLTA**: reduced sediment loads for increased efficiency; **Scientists**: fairness/ efficiency balance	**Farmers**: income, reduced risk; **Coffee processors**: blame-free business; **Consumers**: guilt-free quality products; **Conservation agencies:** stop encroachment to national park

9.3 Boundary work

Where 'boundary work' in its initial description involves two main stakeholders 'science' and 'policy', from the start the Sumberjaya case was understood to involve three: 'local', 'policy' and 'science'. This meant three types of primary knowledge boundaries local-policy, local-science and science-policy, and overarching work in the triangle defined by the three boundaries[21]. An earlier analysis[22] of 'boundary work' in Sumberjaya and its Negotiation Support Systems[23] articulation was provided as example of the most complex case (multiple knowledge systems, multiple stakes). The case also enriched understanding of the 'issue attention cycle', with attention to the various 'boundary objects' that marked progress in respective learning curves for the key stakeholders[24]. In a Social-Ecological Systems perspective, the 'perceived' issues were unpacked, through a series of 'methods' that were subsequently formalized[25]. The issue first was at the 'Who' level (who is living, c.q. is

Table 9.2 Boundary objects that emerged in the three learning loops in Sumberjaya

A. Tenure security

Boundary objects	Trigger	Use	By whom
Water balance and effects of coffee gardens of different age[26,27]	Perception that coffee gardens are a threat to PLTA water supply	Debunking 'myth' about need for 'reforestation'	Used by farmers to challenge government officials during meetings
GenRiver as simple (parsimonious) model of river flow in response to land cover change[28]	Lack of existing models that logically respond to land cover change but don't require intensive parametrization	Hypothesis testing, consistency checks	Researchers, students
Flow persistence as metric of hydrological buffer functions[29,30]	Gap between farmer concepts of flow predictability and formal hydrological metrics	Characterization and scenario studies	Science-Farmer interface
Litter layer as key erosion control[31,32,33]	Need for simple 'soil health' criterion	Differentiating between acceptable and less-desirable LU	Science-Farmer interface
'Kebun lindung' as concept[34,35]	Need for term describing 'protective garden' aligned with 'protective forest'	As communication tool	Used by farmers to challenge government officials during meetings
Discount rate (linked to tenure security) as determinant of profitability of sun vs shade coffee[36]	Concern over continued attractiveness of 'sun coffee'	With lower discount rates shade coffee is economically attractive	At science-governance interface, addressing long-term sustain-ability issues
Draft HKM-contracts[37];	Untested legal oppor-tunity, waiting for its first implementation in 'protection forest'	Contracts were negotiated based on drafts	Government-farmer interface
HKM-evaluation criteria (from 5 to 25 year contracts)	Absence of clear criteria, threatening long term agreements	Becoming national standard	Government-farmer group interface

B. Reducing sediment fluxes (RUPES)

Boundary objects	Trigger	Use	By whom
Spatial sediment source data[38,39,40];	Uncertainty about where most of the sediment came from	Prioritizing areas for soil conservation auction and River Care	PLTA + RUPES team
PLTA-level cost/ benefit analysis;	Background to PLTA 'willingness to pay'	Discussions with PLTA staff	Scientist – PLTA interface
Private lands: auction design & implementation for erosion reduction[41,42,43];	Lack of ideas on how incentivized soil conservation on private lands could work	Pilot application in two communities	Lessons learned for similar auctions elsewhere in Asia
River Care experiment in collective action with conditional incentives[44]	Lack of ideas how collective action can be stimulated in the landscape	Direct PLTA involvement, scientists facilitating	Subsequent replication elsewhere in Sumatra by PLTA
National awards for the best practices of Public-Private-Partnership (PPP) to PLTA	PLTA was considered bringing innovations in implementing the PPP	Mainstreaming of the performance-based scheme within the internal policy of PLTA rather than a one-shot, ad-hoc action	National PLTA management board

C. Increased income

Boundary objects	Trigger	Use	By whom
Farm-level profitability analysis for diversified coffee farms	Need for increased on farm income	Assess tradeoffs between farm components	Farmer groups
District government's agricultural and livestock development programs	Need for diversification on farm income	Local government recognition to farmer groups as 'conservation champions' Longer-term incentive schemes	District government

allowed to live, here), followed by the 'What/How/Where' questions of land use practices. Meanwhile the 'So what?'/'who cares?' of landscape impacts on ecosystem services (esp. aspects of river flow) had to be clarified and serious myth-perceptions in the public/policy level ('no forest, no water') had to be challenged by data that were collected in a transparent manner. Where it showed results rather different from what the engineers/foresters had at first said, a new type of 'boundary work' arose. In first instance the main stakeholders were forest department, hydropower company, provincial government authorities and local villagers. Later on, the latter group was differentiated by location, ethnic background (and associated political connectivity), wealth and gender. Specific options and strategies differed among groups, with actual performance of the river and farms at the core of it.

9.4 Looking back at enabling and restricting factors

In looking back across the three phases a number of enabling and restricting factors can be identified:

Enabling:

- Remarkable individuals willing to take risk within their institutions,
- Involvement of international and national partners of undisputed reputation, plus locally rooted NGO's,
- Trust building between partners of different backgrounds,
- Semi-transparent 'wall' between the ecological (focused on understanding) and social (focused on negotiation) parts of the team (each with their 'safe space'), allowing sufficient information exchange, but allowing each to proceed at a speed that could lead to quality products.

Restricting:

- Individual team members being restricted by their less-engaged institutions,
- National-scale policy fear of 'precedent' effects; objections to the 'kebun lindung' concept as undermining forest policies,
- Non-existence of national policy that provides an enabling condition on what type of intermediary institution and how environmental funds deriving from performance-based schemes both from private and public sources are managed, distributed and managed. Thus, upscaling of this scheme becomes somehow limited.

A shared understanding of the hydrological relations between forest, coffee, the streams and the hydropower company was essential to give all stakeholders a deeper understanding of the respective 'stakes'. It showed opportunities for a win-win, avoiding the hard choice between hydropower production and farmer's livelihoods.

The analysis suggested that the PLTA and forestry departments' interests were not as strongly aligned as initially perceived. This strengthened those within the Ministry of Forestry in support of 'community forestry'. The process, however, revealed conflicts within the Ministry of Forestry between those fearing 'loss of control' and those in favour of 'community involvement'.

The shift from a 'worst case' of environmental conflict to a 'success story' of negotiated solutions within the framing of the Forestry Law was certainly noticed at the national scale, and helped in triggering efforts elsewhere (with various success rates; generally without the strong research involvement Sumberjaya had had). The current Government of Indonesia (with a Minister of Environment and Forestry who was intimately familiar with the Sumberjaya case from her previous role in the provincial development planning agency of Lampung) committed to a rapid scaling up of devolution of forest tenure rights – but has so far not been able to meet these expectations.

The ES auctions held and the collective action 'river care' experiment showed how a coinvestment in stewardship rather than 'commoditized ES' was the more relevant framework in this landscape. The PLTA could 'buy' increased community involvement in maintaining the watershed functions embedded with their trust that the local community will keep their commitment, rather than metrics of sediment reduction as the basis for sustaining the contractual agreements between both.

A number of impact studies have assessed the social dimensions of the changes that took place[45,46,47] in the Sumber Jaya landscape, and its wider impacts on tenure conflicts in Indonesia. The sustainability of the ES mechanisms remains a point of concern[48], as coinvestment partners are interested in an initial change, not in indefinite financial transfers. Further ecological analysis showed that in terms of terrestrial C stocks[49], plants[50] and birds[51] as biodiversity indicators and belowground biodiversity, the induced shift towards shaded coffee systems had co-benefits. In terms of N_2O emissions[52] the use of leguminous shade trees involved more complex tradeoffs. Overall, the landscape has shifted from a 'crisis' to 'manageable issues' stage in its development.

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Agricultural livelihood transitions

Farmers benefit from the transition from extensive agriculture to forest-oriented livelihoods.

Photo: Yunnan University/He Jun

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CHAPTER TEN

Justice notions in Payment for Environmental Services: insights from China's sloping land conversion programme

Jun He and Thomas Sikor

Highlights

- China's Sloping Land Conversion Programme (SLCP) is the world's largest payments for ecosystem services (PES) scheme.
- State policy on the SLCP contains provisions for distributive and procedural justice
- Villagers, local officials and state policy share the concern about distributive justice
- The shared distributive concern contributes to reforestation and rising incomes

10.1 Introduction

For over a decade, the Chinese government has implemented the Sloping Land Conversion Programme (SLCP), the world's largest payments for ecosystem services (PES) programme. It uses public payments to convert marginal cropland located in upper watersheds into forests, engaging millions of mountain-dwelling households in the process[1]. The SLCP has received significant criticism from researchers in China and abroad in term of its effectiveness, efficiency and fairness[2]. However, after some adjustments, the SLCP has also generated successful outcomes in terms of expanding tree cover and improved livelihoods. Based on an in-depth case study from the Yangliu watershed in Yunnan province[3], this chapter explores the underlying reasons for the SLCP's environmental and economic successes by analysing how different stakeholders frame their justice concerns in the SLCP. It suggests that the SLCP has been successful because, among other factors, its implicit model of justice has sufficiently overlapped with local officials' and villagers' notions of justice.

10.2 Innovating payments for ecosystem services in China

In 1998, a massive flood swept through the Yangtze Basin, attracting national attention to major environmental degradation in the upper watershed. Soon after, the Chinese government initiated the SLCP, which aims to increase forest cover and prevent soil erosion on sloping cropland by converting marginal agricultural land into forests. Primarily implemented in remote and poor mountainous regions, this programme also seeks to restructure rural economies and improve livelihoods by providing subsidies and off-farm working opportunities for farmers[4]. The goal is to gradually shift residents' focus to more environmentally and economically sustainable activities.

As the world's largest pioneering PES scheme, the SLCP has several innovative characteristics and is a turning point in Chinese forest policy, shifting away from mandatory to more incentive-based instruments. The programme uses public funds to compensate upstream farmers for losses of their farming livelihoods via a contract-based implementation between government and farmers. The policy aims to stimulate voluntary participation in a way that maximizes environmental benefit through afforestation in cropland, and it supports rural economic restructuring and livelihood development in mountainous regions through ecological restoration. To date, the SLCP has spread across 25 provinces. 26 840 778 households have participated and the state has invested nearly USD 23 billion, converting over 8 million hectares of cropland into forestland[5].

10.3 Innovating payments for ecosystem services in China

Yangliu is a small upper watershed in Baoshan Prefecture of Yunnan Province. It spans some 42 km^2 and has a population of 7 300 in five villages. Until ten years ago, its people were considered poor even by Chinese standards, because the average annual per-capita income did not exceed USD 100. The returns from farming the steep slopes were extremely low.

In 2003, the SLCP was launched in the watershed, as it met the key requirements: almost half of its land slopes 25 degrees or more, and the villagers in the watershed were classified as poor. The SLCP has been implemented twice in Pingzhang, although differently on each occasion. Implementation started between 2002 and 2003, involving 229 households and converting 49 ha of cropland into pear tree plantations (*Pyrus pyrifolia*). In 2005 it enlisted a further 106 households and 38 ha of walnut plantations (*Juglans sigillata*). Meanwhile, tree-planting had turned into a much broader trend as many other villagers in the watershed started to grow walnut trees, leading to a significant change in land use and local livelihoods.

Judging from land-use and land cover analysis, the SLCP has contributed significantly to recent forest cover increase (Figure 10.1). Agricultural land cover reduced from 48.99% to 37.72% of the total area between 2002 and 2011, while forest cover increased from 30.37% to 44.62%[6]. Tree planting has significantly reduced farming activities in the region. This has in turn reduced workloads and allowed for more off-farm job opportunities, which typically have higher economic returns in comparison to traditional farming. The afforestation efforts in this region improved also the provision of hydrological services.

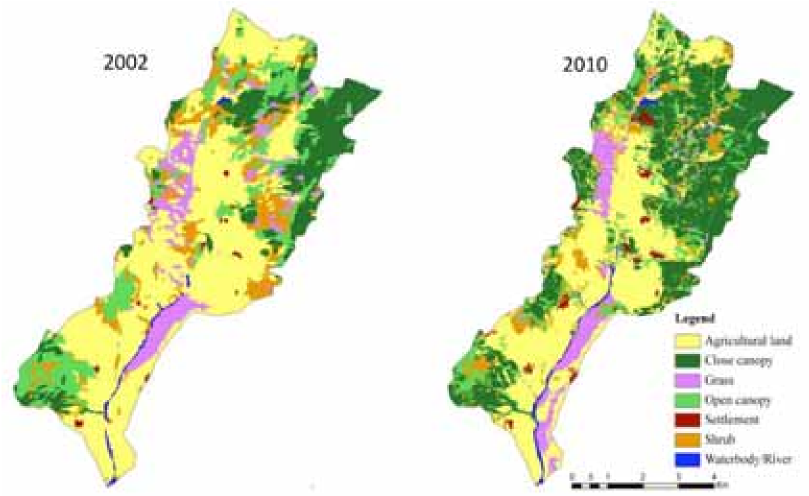

Figure 10.1 Land-use and cover change in Yangliu watershed 2002–2010

The SLCP has contributed to changes in land-use patterns and reduced the size of farmland, which provides opportunities to farmers seeking alternatives, and diversifies their income by combining on-farm and off-farm activities. The change in livelihood dynamics and farming systems corresponds to China's overall economic growth, which has significantly benefited local incomes.

According to village records from the region, there has been a 295% increase in local income between 2002 and 2010, which has taken the villages well above the national poverty line now[3]. The overall economic growth and reduced burden on farmers provides more opportunity for off-farm activities, which make up a significant part of local income, mostly in the form of younger household members migrating to urban centres. According to the village survey, 55.8% of the sampled households in Pingzhang have people involved in off-farm jobs, either outside the agricultural season or all year round. On average, 1.21 people in Pingzhang in the sampled households engaged in off-farm work for an average of 7.19 months a year.

The tree cover expansion and local economic development is not simply attributable to sufficient compensation and subsidy with free seedlings to encourage farmers' participation in tree plantation. Instead, we argue, compensations and subsidies worked, among others, because there is overlap of the different stakeholders' justice frameworks that led to local people's active engagement in the SLCP.

The SLCP has generated positive outcomes in Yangliu because it has matched the justice notions of all involved actors: central government designing the policy, local officials implementing it, and villagers reacting to the policy. The SLCP's success has not been simply a matter of paying farmers enough so they would convert. Instead, payments mattered to farmers because they considered them to constitute a fair deal with the government. Table 10.1 summarizes the three key actors' justice framings with regards to the SLCP.

Table 10.1 Actors' framing of justice

	Distributive justice	Procedural Justice
Policy	The policy states that farmers should be compensated from public funds for livelihood losses incurred through land conversion.	The policy notes that participation in the programme should be voluntary.
Local officials	Local officials have adopted the policy conception to compensate farmers for losses incurred from generating hydrological services downstream. In addition, local officials perceive SLCP as a programme allowing rural people a share of the benefits of China's economic growth.	
Farmers	For farmers, the programme is a means of transitioning their livelihoods from low-return on-farm work to new livelihoods, which raises living standards and participation in China's economic growth.	The farmers perceive it as just to participate in the programme on a voluntary basis. Some assert that farmers can play active roles in the implementation of the SLCP.

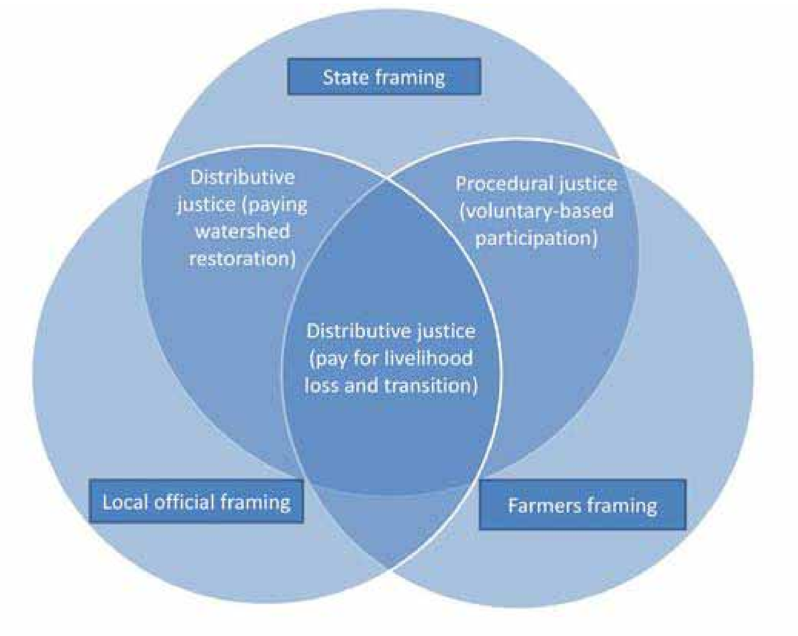

Figure 10.2 Overlaps in actors' justice concerns

Actors' notions of justice are not identical, yet they overlap to a sufficient degree (Figure 10.2). All three share the primary concern with distributive issues. The state considers it just to pay for livelihood losses incurred in the conversion of cropland to forest. Villagers think it just that the payments help them to make the livelihood transition from agriculture to livelihoods which combine on-farm and off-farm activities. Local officials adhere to both notions of justice. Due to this shared concern with distributive issues, the payments assumed critical importance and successfully motivated the desired outcomes.

Although some success has been achieved in Yangliu, there remains a mismatch of other justice dimensions among actors. These need to be considered in order to improve the programme's implementation. First, procedural justice in programme implementation has been largely ignored by local officials. Although central government and local farmers share the same perception for voluntary participation, local officials applied a merely semi-voluntary approach. They only consulted farmers about their willingness to participate, yet largely ignored giving them active roles in the implementation of the programme. This absence of procedural justice limits positive programme outcomes in both environmental and socio-economic terms.

Second, recognition in programme implementation has been ignored at both local and central levels. From the programme's design to its implementation, there has been little recognition of indigenous people's knowledge in watershed management and afforestation, despite the fact that the experiential knowledge of local people can significantly contribute to ecosystem management[7]. This ignorance from the state and local officials hinders improved watershed management.

10.5 Just watershed management in and beyond China

The SLCP provides lessons and experiences with the potential to improve the design and implementation of PES schemes for watershed management in China and around the globe. The SLCP policy contains a clear model of justice: farmers need to participate on a voluntary basis and should be compensated for losses incurred from moving away from crop cultivation to planting trees. It has generated positive outcomes in Yangliu because this model overlapped with farmers' and local officials' notions of justice.

To achieve just watershed management, it is important to understand how different stakeholders frame justice and injustice in terms of management and practice[3]. Watershed management will be successful where, among other factors, the underlying model of justice that is incorporated into policy interventions overlaps with local justice framings, as was the case in the Yangliu upper watershed. This significance of justice requires policymakers and local officials to understand local people's notions of justice and to consult them, particularly those who do usually not have a voice in the design and implementation of interventions for watershed management.

This photo illustrating the topography of the Yangliu watershed where the SCLP was implemented. Photo: Yunnan University/Jun He

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The groundwater restoration

Lively discussion between farmer and researchers, standing at the haveli dyke at the start of the second cropping season.

Photo: World Agroforestry/Meine van Noordwijk

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CHAPTER ELEVEN

Public co-investment in groundwater recharge in Bundelkhand, Uttar Pradesh, India

Ramesh Singh, Meine van Noordwijk, OP Chaturvedi, Kaushal K Garg, Inder Dev, Suhas P Wani, Javed Rizvi

Highlights

- Co-investment of public funds in a critical ecosystem (ES) can have substantial social welfare multipliers
- Explicit resource management at landscape scale based on common understanding is essential
- Land-use rights in the area used for rainwater harvesting need further attention
- 'Mainstreaming' tree domestication requires appropriate links with 'demand' and market structures

11.1 Introduction

The 880 mm of rainfall that the landscape around Jhansi (India) receives in an average year easily allows for one cropping season. In the long dry season, however, life becomes difficult in the rural areas and the wells used for irrigating a second crop rapidly dry up, so only a small part of the land can be cropped twice. Many people look for seasonal jobs in cities in this period, as even drinking water becomes hard to obtain, while the livestock roams around freely to feed on whatever biomass it can find. This practice of abandoning cattle is known as *annapratha* locally.

In the dry years from 2004 to 2007 and in 2014, 2015 and 2016, more than 80% of open wells dried up soon after the monsoon season. Water scarcity due to frequent dry spells in the rainy season resulted in poor productivity, with crop yield ranging between 500–1000 kg/ha for major cereals, pulses and oil seed. Moreover, as water for domestic use is traditionally collected by women and at large distances from home, school attendance is low.

In the cities, there is water from a large reservoir fed by the surrounding landscapes and the rivers that flow in the rainy season. Would it be feasible to retain more of the water in the landscapes themselves, fully recharging the groundwater that can be stored above the impermeable granite substrate? In fact, as elsewhere in India [1], there have been water harvesting structures (*haveli*) here in the past that helped achieve this by flooding a part of the land during the rainy season. This temporary pond also captured sedimentation from incoming surface flows, creating a fertile soil ready for a good second crop after the water was drained.

A watershed rehabilitation program facilitated by the Indian Council of Agricultural Research-Central Agroforestry Research Institute, Jhansi in India (ICAR-CAFRI) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) tried to make a difference in the Parasai-Sindh watershed, where nearly 3000 people (with their cows, buffalos, goats and sheep) live in three villages on 1246 ha, in the ways sketched above. From 2012 onwards, the local community, supported by ICAR-CAFRI, ICRISAT, and the Jhansi district administration started implementing watershed interventions in this area. By restoring the *haveli* to create an additional water reservoir that allowed groundwater recharge, and a series of checkdams to slow down streamflow, the project managed a substantial increase in water availability for a second growing season plus a year-round domestic water supply.

Figure 11.1 Location of the Parasai-Sindh watershed and its *haveli*, relative to Jhansi city and its reservoir

The value of the ecosystem service of groundwater recharge can hardly be overestimated, as the social multipliers (see below) proved to be substantial. Sustainability of the success, however, will depend on the social as much as on the technical aspects. For the land owners in the *haveli*, some form of compensation is needed that was not foreseen in the initial watershed management plan. Could a form of payments (PES) emerge to have the downstream beneficiaries of the groundwater recharge help offset those who lost a crop upstream? Or is a form of co-investment, led by the public sector an appropriate long-term solution? In this brief summary of the very complex and rich case [2], we focus on A) the water balance of the area before and after the intervention, B) the subsequent changes in land use (including the shift to agroforestry (fruit and timber trees), C) the social multipliers on the ES value generated, D) those (potentially) losing out in the *haveli* and the managers of the downstream reservoir, before E) discussing the co investment (or PES) options.

11.2 Positive impacts of tree domestication

The technical interventions involved a series of checkdams on the main streams, with a joint storage capacity of 115,000 m^3(9 check dams; 3 gulley plugs, 1 *haveli* renovation, 1 community pond, 1 farm pond). The *haveli* harvests water from about 51 ha and involves a temporary pond of about 8 ha. The checkdams and other impoundments keep the equivalent of roughly 20 mm of surface runoff (i.e. 250,000 m^3 in two fillings) in the landscape, recharging groundwater. The groundwater table increased on average by 2.5 m, varying from 2.0–4.0 m according to toposequence position [3]. This additional water has increased cropping intensity as nearly 150 ha of fallow land were brought under cultivation and even increased crop yields by 30–50% during the post-monsoonal season, when crops require 250–350 mm of water, 100–150 mm of which is met by supplemental irrigation.

Figure 34.2 Elements of the modified water capture system at sub-watershed scale

11.3 Land-use consequences

The additional water supply not only allowed a substantial increase in the area that can be cropped twice a year, but also allowed a shift to the use of perennials, including fruit trees such as guava, citrus, and pomegranate as well as timber species. The livestock population increased substantially, especially buffaloes, which are used locally as a source of milk and are readily sold to Jhansi city.

11.4 Social benefit multipliers

Several social multipliers made that the human benefits derived from this change in ecosystem structure and function went beyond the 'provisioning' service of additional food production. The second cropping season stemmed the seasonal (poverty-driven) migration to look for urban jobs in the dry season. The landless people in the watershed can now find agricultural employment. Availability of well water meant that girls can now attend schools. Social capital and sharing of water resources for domestic use increased.

Figure 11.3 Human benefits from the increased groundwater availability included increased school attendance by girls and reduced dry-season migration to towns by the poorest segment of the population

11.5 Keeping all stakeholders engaged

Yet, not all stakeholders have been the winners. Two groups specifically perceive that they lost out. The first group are the farmers who own the land now ponded in the wet season by the *haveli*. They essentially lost their wet-season cropping opportunity. At the start of the program, they asked for financial compensation, but this was not provided for by the project, as it was seeking long-term sustainable solutions and no direct way of generating recurrent compensation was deemed feasible. Instead, the water management committee explored alternatives, such as investing in the creation of a fishpond downstream of the *haveli*, to be used by the *haveli* farmers and providing them with a direct incentive to secure year-round water supplies.

During a recent visit to the site as part of a training on ecosystem services in agroforestry, the *haveli* farmers asked to develop additional dams within the *haveli*, shifting the primary water harvesting structures to the shallower and less fertile soils of the upper catchment. This proposal will be further evaluated by the local water management committee with the support of ICAR-CAFRI researchers.

A second stakeholder group that is losing out, but so far not yet articulating demands, are the managers of the large reservoir that previously harvested water from the Parasai-Sindh watershed, only to find that a quarter of the rainfall is used for crop and tree evapotranspiration. So far, the argument that they will also ultimately benefit from more base-flow may have sufficed, but if all their catchments would follow the Parasai-Sindh example, further discussions on complex rights issues are likely to follow. It seems likely that pre-human natural vegetation used as much water as the current hydrologically restored subcatchment does, but the reservoir and its water users have had the benefits from the area becoming an effective 'rainwater harvesting' domain.

11.6 Discussion: the public business case for co-investment

The case demonstrates that, from a public policy perspective, there is a clear business case for the investments made, which apparently stayed within the norms the Government of India has set for projects. Rather than financial transfers within the community to compensate *haveli* farmers, alternative investments were explored, such as a fishpond which would create a clear benefit linked to water storage.

Enhancement of the ecosystem service of groundwater recharge (W3 in the scheme presented by Lusiana et al [4]) has clearly had human beneficiaries, with considerable social benefit multipliers. Government resources were combined with local agreements to use communal land for an additional reservoir and communal labour to physically reshape the hydro-ecological infrastructure. In this way, it qualifies as a co-investment [5], but proof of its longer-term sustainability will depend on the local water management committee and its ability to deal with current and possible future challenges to the balance of perceived fairness and efficiency. There are interesting parallels between the various scales of water harvesting involved: the *haveli* farmers want to shift the dams upstream to fully benefit from the fertile soil derived from past sedimentation, the Paranai-Sindh watershed now benefits from water harvesting in the haveli, but the downstream reservoir has lost some of its water harvesting subcatchments. From a fairness and rights perspective [6], it may help to establish a historical baseline relative to which change is quantified. A natural vegetation reference, rather than the degraded situation derived from this, seems to be appropriate, but will need further discussions in local context. More explicit documentation of local knowledge systems may help to establish such a baseline [7].

The watershed also provides an interesting opportunity to see how the Indian national agroforestry policy [8, 9] works out in practice. In a neighbouring subcatchment with higher forest cover, the base-flow fraction of river flow is reportedly higher but the total water yield per unit rainfall probably less [10]. The agroforestry policy could serve as a basis to assign water use rights to trees in the restored subcatchment.

Figure 34.4 The groundwater restoration has increased opportunities to keep buffalo's in the landscape and sell their products in the nearby town of Jhansi. Photo: World Agroforestry/Meine van Noordwijk

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Restoration of tree cover

Restoration of tree cover in pastures can achieve multiple goals.

Photo: World Agroforestry/Meine van Noordwijk

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CHAPTER TWELVE

Restoration through agroforestry in Brazil: options for reconciling livelihoods with conservation

Andrew Miccolis, Fabiana M Peneireiro, Henrique R Marques

This is a shortened version of a published article[1] and is based on a manual on Portuguese[2]

Highlights

- The Brazilian Law for the Protection of Native Vegetation (2012) obliges farmers to restore degraded lands on all rural properties, which can be done through agroforestry systems as long as they maintain ecological functions in addition to social functions
- Among the different types of Agroforestry Systems (AFS), biodiverse and successional systems are most suited for restoration since they are capable of providing multiple environmental benefits and improving livelihoods while offsetting the high costs of restoration
- Ultimately, upscaling these requires co-designing solutions tailored to the socio-ecological contexts, particularly with regard to biophysical conditions, farmer objectives, input requirements, and the enabling environment (markets, policies)
- This chapter presents five examples of agroforestry options suited to commonly occurring contexts in the Brazilian Cerrado and Caatinga biomes, which vary in terms farmer objectives, labour and input requirements, farmer objectives, and key species and management practices

12.1 Introduction

The Brazilian Law for the Protection of Native Vegetation (known as the new Forest Code)[3] set a series of provisions regulating land use on all privately-owned rural areas, including obligations for restoring protected areas, known as Permanent Preservation Areas – PPAs and Legal Reserves – LRs (Box 12.1). While Brazilian law has required the conservation and restoration of these areas since 1965, compliance has historically been very low due mainly to low enforcement, lack of clear regulations, and the fact that PPAs, which include riparian zones (as well as springs and steep hillsides) are often the most humid and fertile areas and hence most useful to farmers. This conundrum is especially relevant for smallholders, or 'family farmers', in Brazil.

Figure 12.1 Illustration of an agroforestry system that can meet legal restoration requirements in Permanent Preservation Areas[2]

Box 12.1 Key definitions in the Brazilian legal framework[3]

Agroforestry Systems – AFS: Land use and occupation system in which woody perennials are managed in association with herbaceous, shrubs, trees, crops and forage plants managed in a single management unit, according to spatial and temporal arrangements, with a high diversity of species and interactions among these components.

Permanent Preservation Area – PPA: A protected area, covered or not by native vegetation, with the environmental function of preserving water resources, the landscape and geological stability and biodiversity, facilitating gene flows of fauna and flora, protecting the soil and ensuring the well-being of human populations.

Legal Reserve – LR: A percentage of all private rural properties, which varies according to biome, delimited according to the terms of Article 12, with the function of assuring sustainable economic use of natural resources on rural properties, aid in conserving and rehabilitating ecological processes and promoting biodiversity conservation, as well as shelter and protection for wildlife and native plants.

To address this issue, the new norms, passed in 2012, afford a series of special rights and conditions for using PPAs and LRs targeting family farmers, whose farm size can vary legally from 20 to 440 ha (depending on municipal economic indicators). First, it allows them to use agroforestry systems – including a maximum of 50% of the area with exotic species – for restoring PPAs, provided the agroforests maintain basic ecological functions and structure similar to the native vegetation. Second, it allows medium to large landholders to use LRs through agroforestry systems as long as annual and fruit crops – including alien tree species – are mixed with native tree species, while at the same time imposing stricter regulations for using PPAs for this category of farmers. Lastly, the new law establishes specific provisions stating that PPAs and LRs can be utilized to meet both environmental and social functions. The new law does **not** specify, however, how – or what type of – agroforestry systems can be used in these different contexts, what alien species can be intercropped with native species and which management practices can or should be adopted at different stages of growth.

These knowledge and policy gaps have thus left a wide margin for interpretation, leading to many uncertainties that have discouraged technicians from making recommendations and farmers from adopting AFS in these areas. Meanwhile, environmental enforcement and rural extension agencies tend to take a conservative stance that also discourages farmers from playing a more active role in restoration processes. One of the main obstacles for restoring these 'protected areas' on private lands in Brazil, especially in the context of smallholders, is the lack of understanding of the economic costs and benefits of forest restoration and the lack of clear regulations on which alien species can be planted to generate additional income and improve the livelihoods of farmers on these areas.

To contribute to filling these knowledge gaps, this study analyses the most commonly occurring contexts in the Brazilian Cerrado and Caatinga biomes and proposes agroforestry options tailored to these contexts that can enable restoring degraded lands in Brazil while also complying with the provisions of the new forest law. To achieve this aim, we set out to address three main questions:

1. Are agroforestry systems suitable for restoring and conserving PPAs and LRs?
2. What are the most suitable types of agroforestry systems, management practices and species for reconciling ecological and social functions in these different contexts?
3. How to develop suitable options, design elements and species selection that can be applied to different contexts?

12.1.1 The context of the Cerrado and Caatinga biomes

The Cerrado

The Cerrado, known as the Brazilian Savannas, spans across the vast plateaus of Central Brazil, forming a myriad of landscapes and amid mesas and valleys, rolling hills, and vast plains. The vegetation ranges from grasslands to woody savannahs and dense gallery forests. Often called the cradle of Brazil's waters, its springs feed eight of the country's twelve major river basins[4,5] over a vast expanse of some 200 million hectares, nearly a quarter of Brazil's land mass. The rainy season generally lasts six months (from October to April), followed by six months of very little or no rain, with annual rainfall ranging from 800mm in areas near the semiarid region to 2,000 mm in transition zones near the Amazon and Atlantic rainforests[6]. Today, the region has some 470,000 small farms, most of which belong to family farmers and traditional communities[7].

Figure 12.2 Characteristic landscape of "Vereda" vegetation typical of wetlands in the Cerrado. Photo credits: ISPN/Peter Caton

Brazil's Cerrado is the world's most biodiverse savannah, with 13,140 plant species, approximately 3,000 vertebrate animal species[8] and 67,000 species of invertebrates[9]. It is also the source of livelihoods for a wide variety of traditional peoples and communities, including extractivists, indigenous peoples, *quilombolas* (maroon communities), family farmers, among others[10], each with their own cultural diversity. Some of those communities have lived in the region for hundreds of years, often interacting with indigenous peoples, and learned over time to live with its diversity and extract its natural resources in a sustainable manner, while others still depend on traditional slash-and-burn practices to enable their production. There are still over 80 indigenous ethnic groups in the Cerrado, and another 70 in the Caatinga (described below).

The Cerrado is one of the world's most endangered biomes due to the expansion of industrial agriculture, including vast plantations of soybeans, maize and cotton, as well as cattle, eucalyptus for pulp and charcoal, and hydroelectric dams[6,5,11]. As a result, some 30,000 km^2 of the Cerrado are cleared every year[11] and only 55% of this biome's natural vegetation cover remains[12].

Figure 12.3 Caatinga and Cerrado as part of Brasil[2]

Figure 12.4 Characteristic landscape of the Caaatinga dry forest. Photo: Do-Design

The Caatinga biome occupies most of north-eastern Brazil (Figure 12.2), with several distinct vegetation types, from open fields to shrubby and tall forests, many thorny and succulent plants. This exclusively Brazilian biome is home to around 2,000 plant species, 300 of which are endemic to this environment. Its fauna is also very diverse, with 178 mammals, 591 birds, 177 reptiles, 79 amphibians, 241 fish and 221 bee species[13]. Average annual rainfall varies from as little as 300 mm in the driest areas to over 1,500 mm in zones that transition to other biomes[14,15].

Most of the Caatinga has shallow soils, an extremely hot climate and irregular rainfall, which makes the environment extremely sensitive and prone to desertification. With a population of over 27 million people, the land is occupied predominantly by smallholder family farmers and traditional communities whose livelihoods depend on local resources. The Caatinga's irregular rainfall pattern makes life extremely hard for these farmers and requires strategies for adapt to and co-existing with the semiarid[14].

Since early European colonization, the region's forests have been cleared for livestock, small-scale farming and charcoal production, still the mainstays of rural livelihoods and the main causes of degradation of the Caatinga's ecosystems[16,14]. Recently, parts of the Northeast in the region known as MATOPIBA, have become the new frontier of agricultural expansion. By 2009, 50% of its vegetation have been cleared and measures taken to restore and conserve the biome have been few and far between[15]. Of all of Brazil's biomes, the Caatinga has the fewest conservation units (protected areas), which cover only 7.5% of its territory.

12.2 Research methods

To tackle the basic question of whether AFS can indeed be a feasible approach to reconciling conservation goals with farmer aspirations and livelihoods needs, we examined evidence in the literature and experiences on the ground. After identifying the provisions in the legal and policy framework pertaining to the use of – and concepts surrounding – agroforestry, we conducted a literature review to shed light on the social, environmental and economic benefits and challenges of upscaling agroforestry systems for the purposes of conservation and restoration. We then engaged multiple stakeholders at three stages through:

1. semi-structured interviews with experts;
2. a national workshop, and
3. field visits on previously selected farmer experiences in the Cerrado and Caatinga biomes (Fig. 12.3).

The workshop, which was attended by 69 farmers, technicians, experts and policymakers from throughout the country produced a series of recommendations on principles and criteria for species selection and systems design in different contexts. Additionally, 19 farmers' experiences were analysed in-depth with the help of technicians, practitioners and/or scientists and later systematized by the authors to draw out key lessons about practical options for reconciling conservation with production. As a next step, 14 experiences led by innovative farmers (some of which were identified during the workshop) were visited by researchers to gain more in-depth knowledge on the factors underlying success and challenges. Based on these various inputs, we then developed an analytical framework (Fig. 12.5) and proposed systems, practices and species suitable to some of the most commonly occurring contexts in these two biomes.

12.3 Results and Discussion

12.3.1 Benefits of agroforestry systems for restoration in Brazil

In Brazil, despite the scarcity of scientific literature with balanced assessments about the challenges faced in the wider adoption and dissemination of agroforestry, some authors have recommended AFS as an adequate solution for ecological restoration and recovering degraded lands[17,18]. Some studies have shown agroforests increase the occurrence of native tree species and promote forest succession[19,20] with characteristics like secondary forests. The role of AFS in maintaining and improving soil fertility, especially through the use of high biomass-producing species in nutrient deficient soils, has also been documented[18]. Similarly, complex and well-managed AFS increase the litter layer and thus create favourable environments for soil macrofauna[21].

Despite the scarcity of studies assessing the economic feasibility of agroforests in Brazilian protected areas such as PPAs, some authors point to the high economic potential of such systems in production-oriented areas throughout Brazil[22,23]. However, achieving economic success hinges on a series of enabling conditions, namely: adequate planning, administration and the adoption of appropriate management practices. An economic analysis of 77 agroforestry systems in different regions of Brazil shows that the systems with a broader range of species in different successional groups reap the best benefit–cost (B/C) ratio[24].

Some types of simple AFS do not manage to meet restoration criteria as established by Brazilian law due to low levels of biodiversity[25] and structural complexity needed to provide other ecosystem services, while others are clearly quite effective at providing such functions. In this regard, high biodiversity or 'successional' agroforests stand as the most advanced option in terms of structure and function. These systems were developed and widely disseminated by an agroforestry farmer and researcher, Ernst Götsch, who has spearheaded and inspired a series of innovative practices throughout different Brazilian biomes[20,26,27]. It is important to underscore that the high species diversity and functional heterogeneity of these successional systems requires intense management, selective weeding and successive pruning, which entails availability of labour as a main input and access to knowledge on management practices.

Despite these challenges, the 'complex', 'biodiverse' or 'successional' agroforests are the most suitable to meeting[28,29] environmental functions required for restoration of PPAs and LRs. Nonetheless, these systems cannot be seen as panaceas applicable to all contexts; rather, they must consider contextual variability, not only in biophysical conditions such as soil, topography and rainfall, but also in social conditions, such as aspirations and livelihoods strategies, access to labour, markets and policies such as credit and extension services.

12.3.2 Understanding the context: constraints for restoration in the Cerrado and Caatinga biomes

In the Cerrado, the main biophysical constraints are a long dry season (usually lasting around 6 months), which limits crop options in rain-fed systems; torrential downpours and flash flooding during the rainy season, leading to soil erosion and water logging in some soil conditions and potentially annual crop losses, low soil fertility and highly acidic soils with aluminium toxicity, which is aggravated by overgrazing, mechanized large-scale farming and the widespread use of fire; and low ecological resilience of degraded lands due to the combination of these factors.

In the Caatinga, where annual rainfall is typically below 800mm, averaging 300mm in some regions, with protracted droughts that sometimes last two or more years, the main biophysical constraints are: low water availability, high evapotranspiration rates and a very short planting window for annual crops. On the other hand, the low-lying Caatinga soils tend to be more fertile and less acidic than the oxisols of the central plateaus where most of the Cerrado is located.

There are, however, significant differences between family farmers in these two biomes. In the Caatinga, farm sizes are generally much smaller and tend to be more susceptible to extreme weather events, particularly droughts but also flooding, and face higher levels of extreme poverty. Nonetheless, the vast majority of farmers in both biomes face similar social and governance-related constraints, including: low access to knowledge and information about innovative and best agroecological practices; low access to inputs (especially chemical fertilizers and pesticides) due to their high costs and long distances to towns; low availability of labour; scant access to rural credit, especially for agroforestry and ecological agricultural systems; low access – due to high distances – to markets and poor infrastructure; cumbersome and onerous administrative and licensing procedures that make it difficult for farmers to organize themselves in cooperatives and obtain licenses for processing goods.

Agroforestry options must thus be tailored not only to the biophysical conditions but also to these other variables: farmer objectives, input and labour requirements, which can vary in space and over time, as well as access to knowledge, credit, and markets.

12.3.3 The options x context framework

The options x context[30] framework as developed in Brazil (Figure 12.3) begins by understanding how these constraints play out at the household/farm or local level to guide the design of systems, selection of management practices and key species that are manageable by – and suited to – each family or group of families. In addition to family (men, women, youth) objectives, key considerations in systems design and species selection across contexts should be agroecological suitability, labour requirements, marketing opportunities and biomass production, as well as resilience to extreme climate events, particularly droughts.

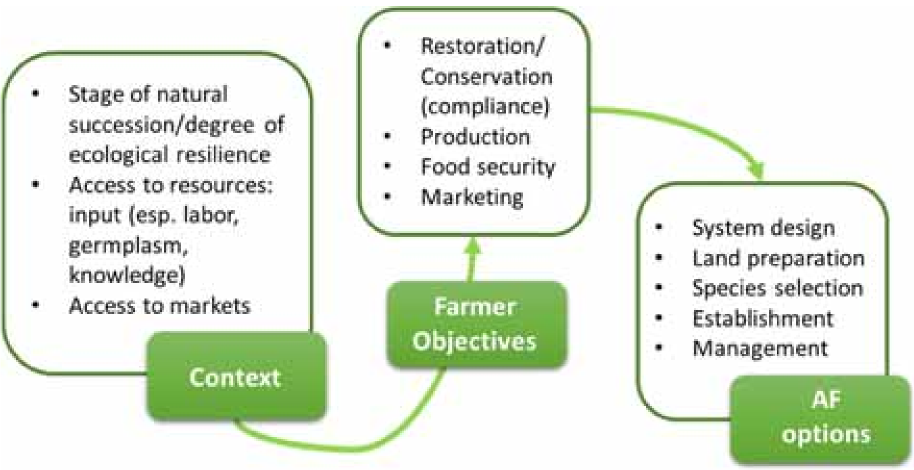

Figure 12.5 'Options x context' scheme used in the analysis

To balance the different social and environmental functions needed in these systems, priority should be given to species that:

- the farmer wants to cultivate, i.e., has experience with and likes;
- grow and produce well in that area, considering climate, soil, lighting, water and available inputs;
- are known to improve the soil and the conditions for the next plants in the succession;
- the farmer can manage with the locally available work force;
- have a potential for marketing; and
- are compatible with other species in the guild, in terms of the space they occupy over time.

In the Caatinga, for instance, species with a high capacity for storing water can be vital for coping with dry spells that can sometimes last for years. Succulent plants that swell to absorb water in their structures, such as cacti, can be important sources of water for animals, plants and even people. They keep the landscape green when all the rest has turned grey.

Other desirable features are high production of biomass and good response to pruning and ease of management. Examples of such species in the Cerrado include: eucalyptus, inga *(inga sp.)*, *mutamba* (*Guazuma ulmifolia*), Mexican sunflower (*Tithonia diversifolia*), yellow mombin (*Spondias mombin*). Some examples in the Caatinga are gliricidia (*Gliricidia sepium*), mesquite (*Prosopis juliflora* (SW) DC), *sabiá* (*Mimosa caesalpiniaefolia* Benth.), sisal (*Agave sisalana*), and pear cactus (Opuntia ficus-indica). In addition to choosing the right species, options must also adopt management practices and techniques suitable to that specific context.

Based on an analysis of the most commonly occurring contexts, particularly in the Cerrado and Caatinga, we propose a series of 11 options with a basic structure that can and should be adapted in terms of key species, design elements and management practices, 5 of which are summarized below.

12.3.4 OPTION 1: successional agroforestry for the cerrado with intensive management[a]

This option is very suitable for farmers whose primary objective is production for marketing, particularly in contexts where there is high access to inputs, labour, knowledge and markets. It can be adopted even on degraded soils with low ecological resilience, provided they are flat to enable easy management and mechanization. Such systems provide a high and quick return on investment and can accelerate restoration of tree cover and basic environmental functions, however, are extremely intensive in management, inputs and knowledge.

[a] This option is based on the AFS established by Juã Pereira, at the *Sítio Semente, Núcleo Rural Lago Oeste, Federal District,* inspired by the teaching and guidance of Ernst Götsch

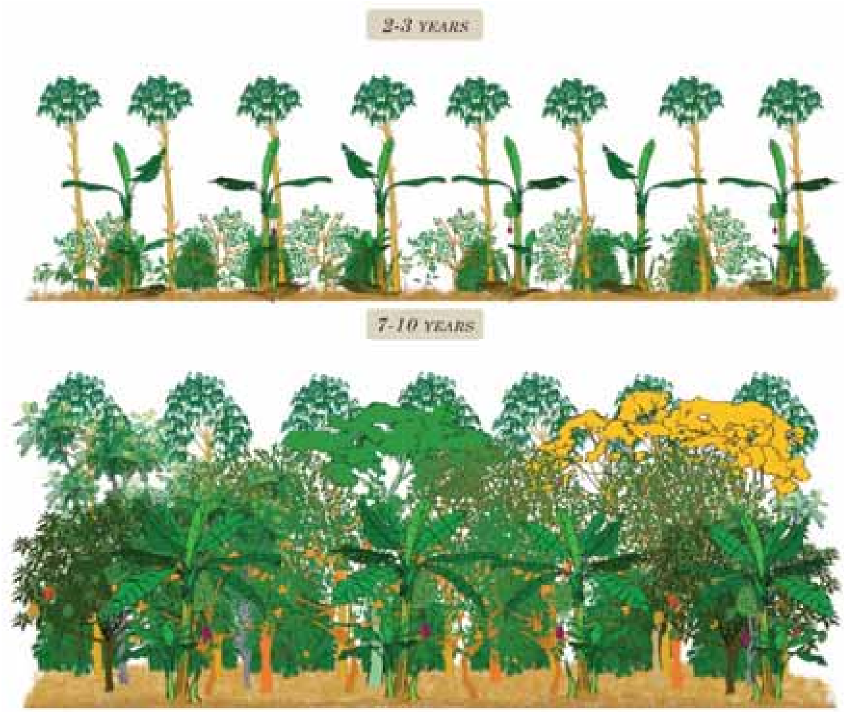

Figure 12.6 Successional agroforestry for the Cerrado with intensive management at two different moments (2-3 years, 7-10 years)[2]

Every 5-6m, rows of eucalyptus and bananas, which are intensely pruned, also concentrate citrus, coffee, and assorted fruit, such as mango (*Mangifera indica*), jackfruit (*Artocarpus altilis*), with 3 rows of garden beds in between, including a rotation of vegetables and annual crops (e.g. maize, beans) followed by tubers (cassava, taro or sweet potatoes) and later occupied by more citrus or coffee or other fruit trees such as *jaboticaba (Plinia cauliflora)* and Surinam cherry (*Eugenia uniflora*)), depending on market conditions and farmer interests. After three or four years, vegetables and herbs dependent on sunlight are withdrawn, while the emerging trees and shrubs remain, and the eucalyptus is gradually replaced by other biomass-producing trees and native trees (e.g. West Indian Locust (*Hymenaea courbaril*), copaiba (*Copaifera langsdorffii*), and cedar (*Cedrela fissilis*)). This system is systematically pruned and mulched to maintain sunlight in the understory and soil fertility. The management relies on the concentration of biomass, particularly from pruning the trees and bananas, whose material is cut up or shredded and used to mulch both the beds and the strips in between them. Depending on the situation, fertilizer trees may continue to be pruned for a few years to maintain the production of the rows of fruit trees. Slower-growing native trees are left alone until crowns begin to overlap, when they can either be allowed to close the canopy or be pruned to let light in for commercial species in the middle and lower strata.

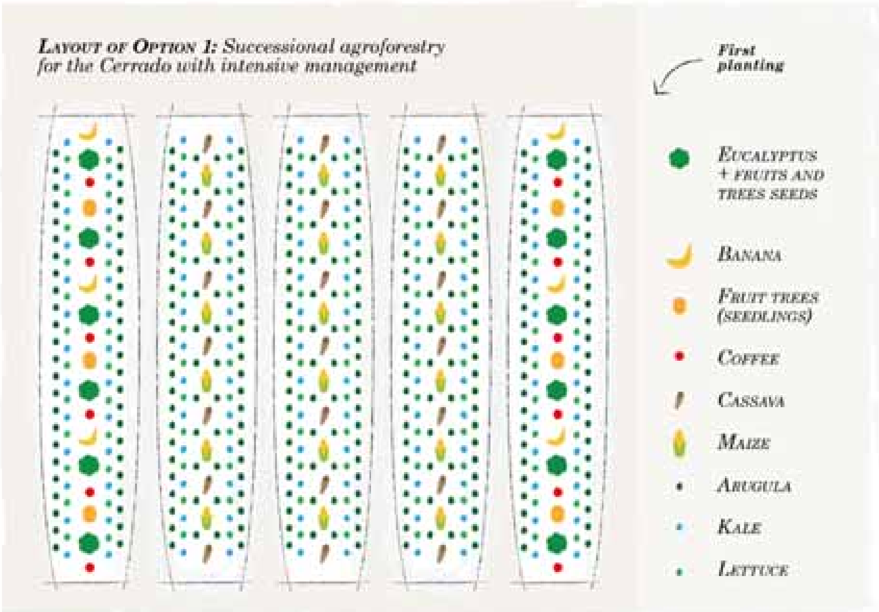

Figure 12.7 Layout of Option 1 Successional agroforestry for the Cerrado with intensive management[2]

12.3.5 OPTION 2: biodiverse successional agroforestry for restoration of riparian zones[b]

This option is ideal for contexts where the goal is to restore riparian zones that have been cleared and taken over by grasses, farmers have low labour availability but enough market access for some of the key products (tropical flowers and fruits, coffee). Annual food crops including maize, cassava, squash and hearty greens (bur cucumber (*Cucumis anguria*), mustard, okra, and parsley), along with bananas, create the basic conditions for establishing intercropped trees, followed by tropical flowers and medicinal plants in the understory.

No agrochemicals (pesticides or chemical fertilizers) or heavy machinery are used in these environmentally more sensitive areas. Rows of fruit, timber and biomass trees with bananas are intercropped with food crops and shade-loving medicinal herbs, shrubs and tubers (e.g. taro, turmeric, ginger and cardamom) and ornamental plants in single-species rows, including torch flowers (*Etlingera elatior*), and heliconias (*Heliconia rostrata*), and/or elephant ears (*Xanthosoma sagittifolium*), which occupy most of the understory, maintain a microclimate and replace the grasses, thus contributing to prevent the spread of forest fires and providing supplementary income. Fruit trees and shrubs (e.g *jaboticaba*, mango, jackfruit, coffee) can also be introduced in the lower and middle stories. Some examples of species that can meet biomass-production objectives in this context are ice-cream bean (*Inga edulis*) and other riparian *ingás*, achiote (*Bixa orellana*), *pau pombo (Tapirira obtusa)* and *pimenta de macaco (Xylopia aromatica).* These pioneer species will create the conditions needed by timber species such as ipe (*Handroanthus spp.*) and West Indian Locust to prosper. While this option can be

[b] A successful example of this option was established by Marcelino Barberato, at the *Sítio Geranium* in Taguatinga, Brasília, based on the teaching and guidance of Ernst Götsch

economically appealing to farmers, it is much less intensive in terms of inputs and labour - and generally less profitable - than Option 1 as it focuses more on commercially valuable shade-loving perennial species, but also provides key environmental functions needed in riparian zones.

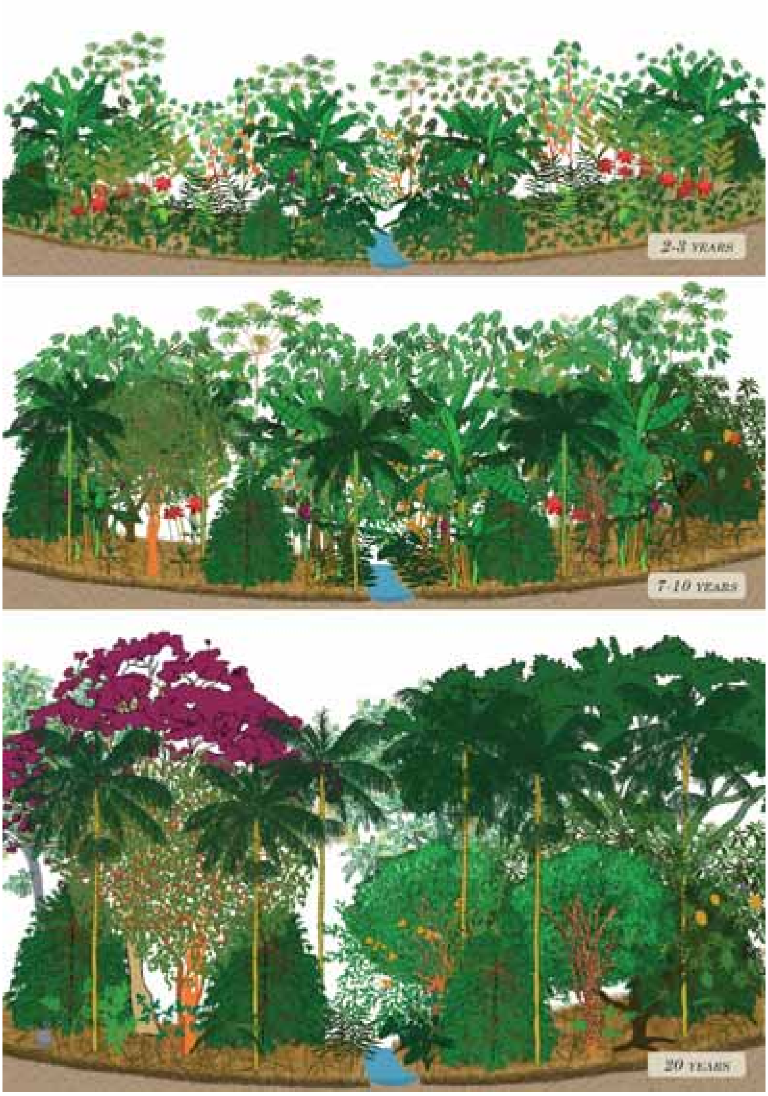

Figure 12.8 Biodiverse successional agroforestry for restoration of riparian zones at three different moments (2-3 years, 7-10 years. 20 years)[2]

12.3.6 OPTION 3: agroforestry to reconcile enrichment of natural regeneration with food production[c]

This option is ideal for farmers who need to reconcile low-input food production with restoration, particularly in the context of fallows (secondary growth) that have been degraded over time by logging, slash-and-burn farming and forest fires. The secondary growth is

[c] This option is a combination of options 3 and 4 in the Guidebook Restoration through Agroforestry: reconciling conservation with production. Options for the Cerrado and Caatinga biomes[2]

managed selectively by pruning trees and shrubs and weeding or cutting grasses to enable the introduction of multi-functional species, either in rows or “islands of fertility” (Figure 12.9).

Figure 12.9 Islands of fertility comprised of short-cycle crops and fertilizer species in the beginning to establish fruit and timber trees[2]

Fast-growing species such as bananas, cassava, mulberries or tithonia are planted in the same island (or strip) along with short-cycle crops such as corn, beans, and squash, to optimize fertilizer and labour, along with fruit and native trees planted either by sowing seeds directly or by planting seedlings. As the islands or strips grow, the fruit and timber trees become part of the overstory, increasing biological diversity and ecosystem function while also providing food and supplementary income for farmers. Beekeeping is also a very promising alternative in this context. This option is meant to require low inputs and labour so that whatever fertilizer is available can be concentrated in the islands or strips along with valuable seedlings.

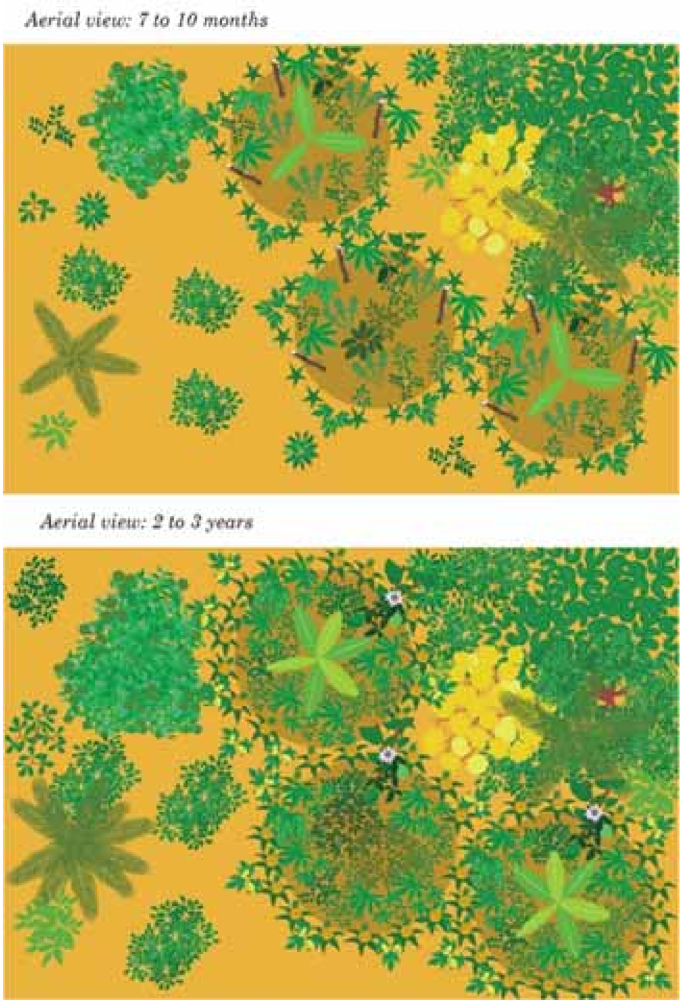

Figure 12.10 Enrichment of fallows and food production with agroforests at two different moments (3-4 months, 2-3 years)[2]

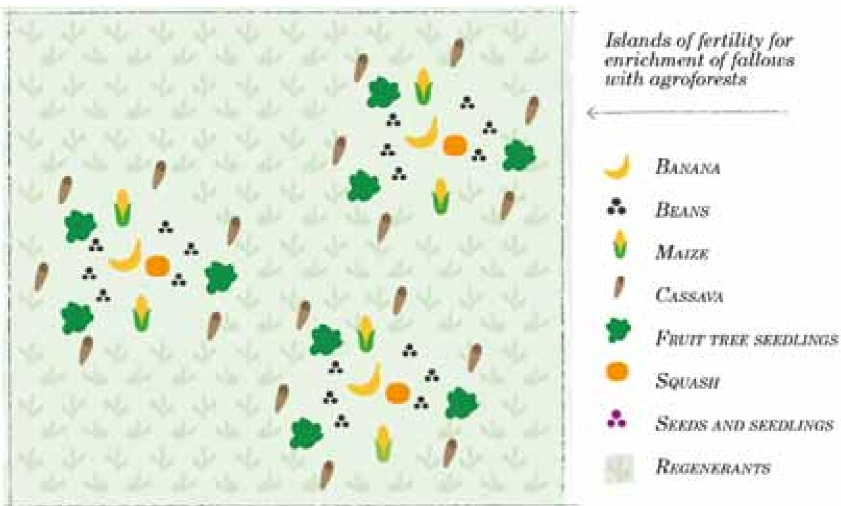

Figure 12.11 Islands of fertility for enrichment of fallows with agroforests[2]

12.3.7 OPTION 4: agroforestry to restore degraded areas with fertilizer and food species[d]

This option is ideal for farmers who wish – or are required by law – to restore pastures back into forests but aren't able or willing to spend too many resources (labour, fertilizer and germplasm). This system requires low-intensity management as compared to other biodiverse systems and can produce enough to at least offset the restoration costs, albeit without requiring markets close by. While some hearty greens, vegetables and grain (maize, millet or sorghum) can be grown in the first year or two, depending on soil fertility and/or availability of fertilizer, the focus is more on perennial species such as bananas, fruit and timber trees intercropped with hearty fertilizer species.

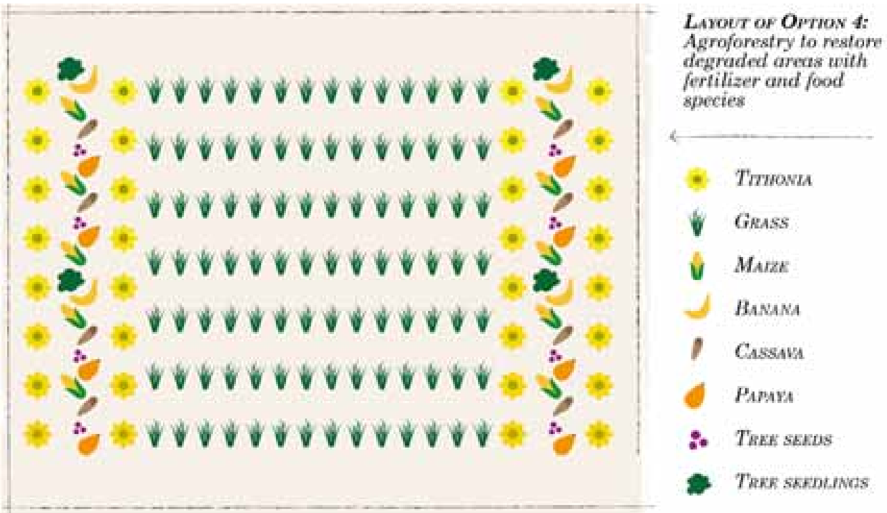

Figure 12.12 Layout of Option 4 Agroforestry to restore degraded areas with fertilizer and food species[2]

In cases where enough labour and fertilizer are available, biomass can be concentrated in rows 5-6m apart, whereas more resource-constrained farmers can opt for investing the little they have in islands or nuclei. These guilds enable establishing a wide diversity of crops in a small space and are highly efficient strategies for establishing fruit and timber trees in the middle of pastures. Their circular, concave shape concentrates fertility and increases water available in the system during the dry season while also providing tiny ecological niches both for plants that require more humidity (e.g. bananas, taro) and for tubers (e.g. cassava) that don't tolerate waterlogging during the rainy season. The basic principle is systematic concentration of biomass in the row of trees or around nuclei with bananas and/or papaya/ + maize + squash + cassava + pineapples, intercropped with fertilizer species such as tithonia, gamba grass (*Andropogon gayanus*), guinea grass (*Panicum maximum*), gliricidia, sthylosanthes, pigeon peas (*Cajanus cajan*), and crotalaria. Overall, species should be well adapted to poor soils and the fertilizer species should be fast-growing, highly efficient in producing biomass and relatively easy to manage.

[d] This option is based on the AFS established by Fabiana Peneireiro at the *Ecovila Aldeia do Altiplano*, in Altiplano Leste, Federal District and was inspired by the teaching and guidance of Ernst Götsch

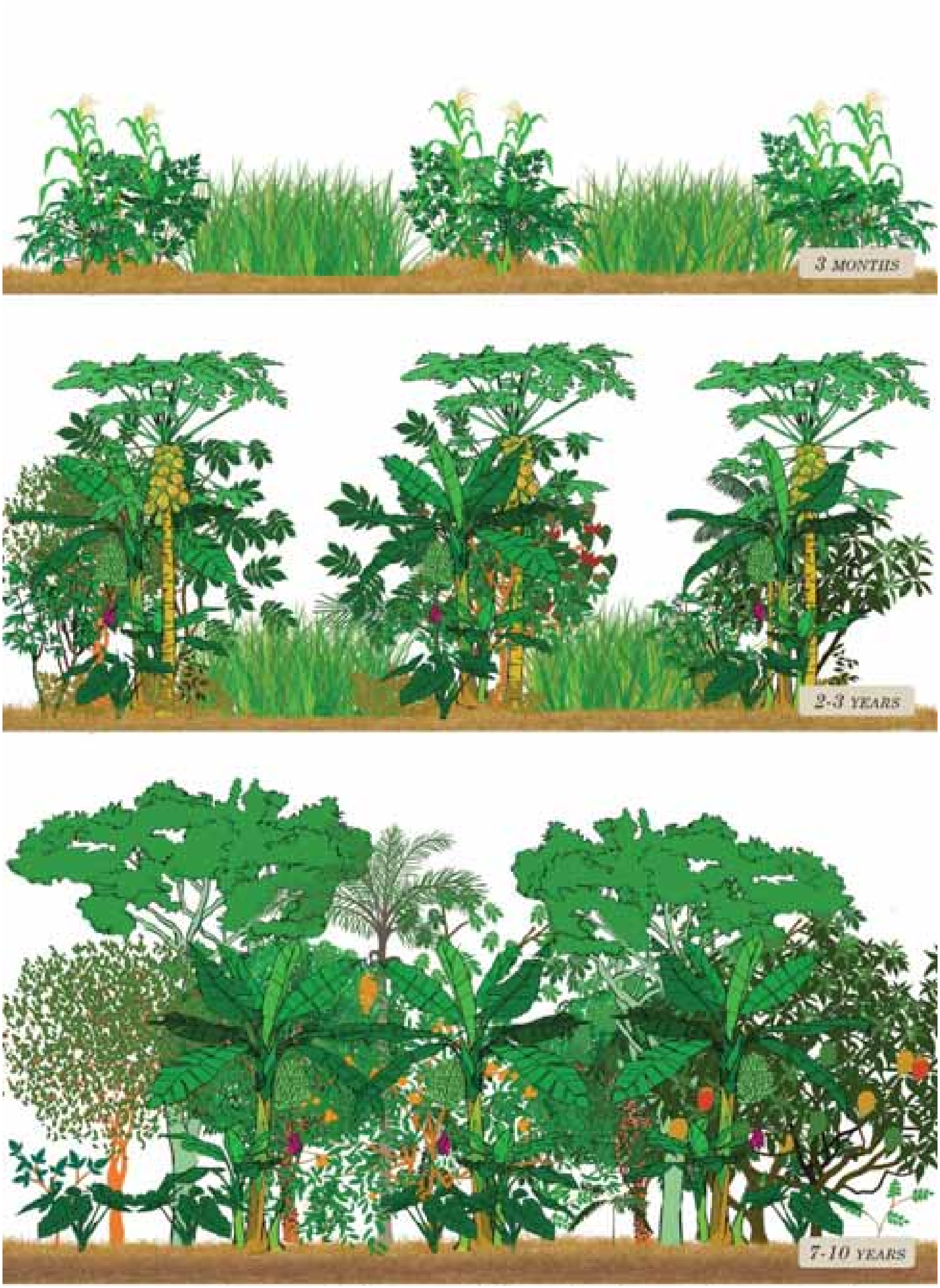

Figure 12.13 Agroforestry to restore degraded areas with fertilizer and food species at three different moments (3 months, 2-3 years, 7-10 years)[2]

12.3.8 Option 5: restoring degraded areas in the caatinga drylands with biodiverse agroforests[e]

This option is suitable for farmers wishing to restore degraded lands in the drylands characterized by low to medium fertility soils, low regeneration and potentially undergoing desertification, while also producing food, storing water in the vegetation and feeding livestock. These systems are highly efficient at restoring areas in advanced stages of degradation, including those in the process of desertification. Soil properties are recovered, and economic species are established initially through "engineer" species that are extremely hearty and drought-resistant, have a high capacity to store water, and can also be used for forage, such as pear cactus (*Opuntia ficus-indica*), sisal (*Agave sisalana*), gliricidia (*Gliricidia sepium*), and leucaena (*Leucaena leucocephala*).

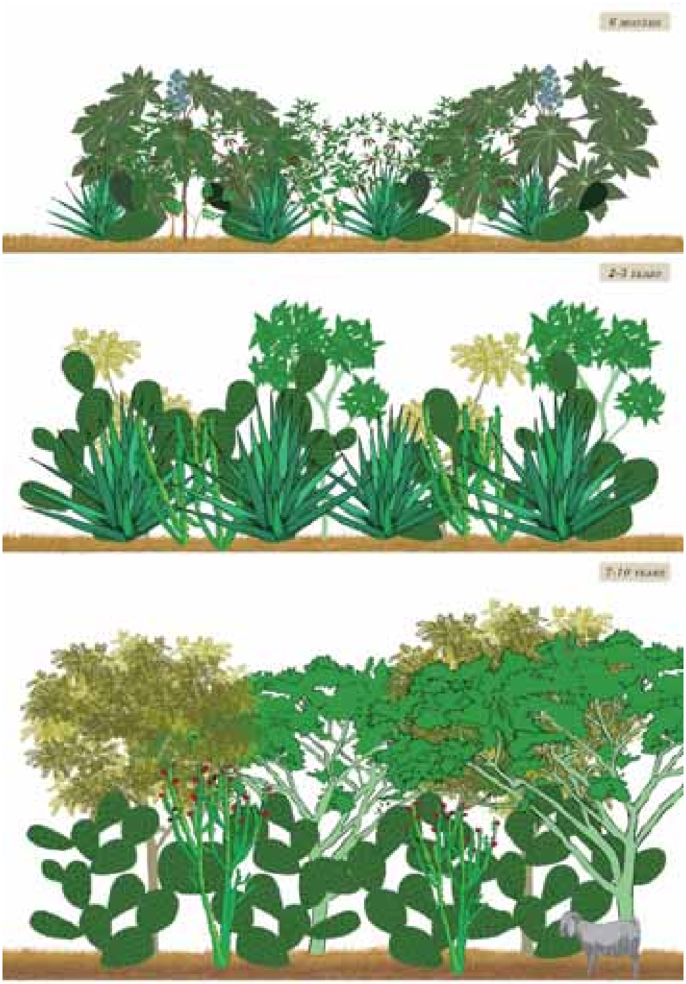

Figure 12.14 Agroforestry to restore degraded areas in the Caatinga drylands at three different moments (3 months, 2-3 years, 7-10 years)[2]

[e] This option is based on the experience of Henrique Sousa, with guidance by Ernst Götsch, in Cafarnaum, Bahia

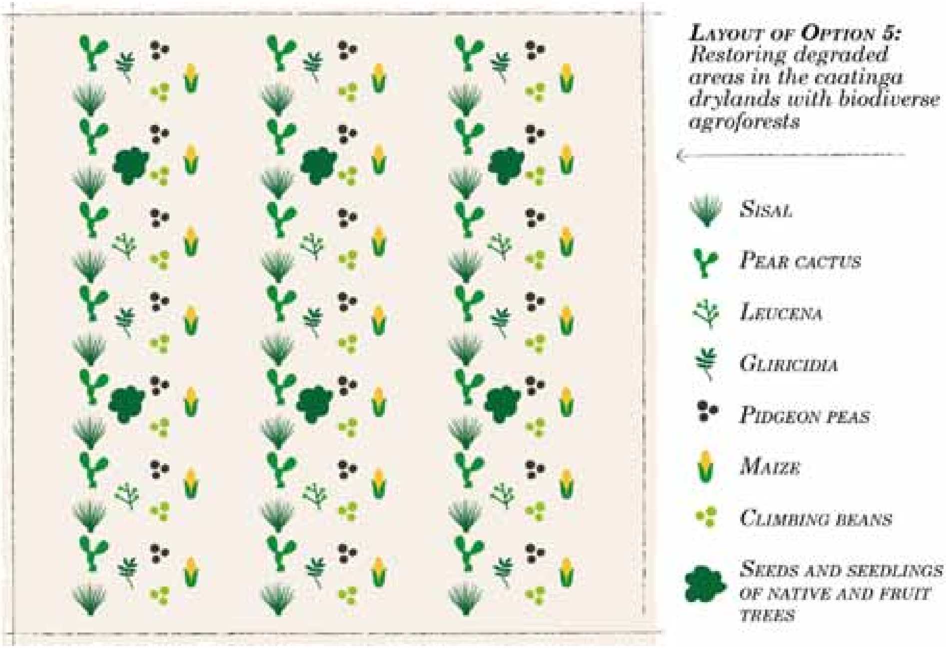

Figure 12.15 Layout of Option 5: Restoring degraded areas in the caatinga drylands with biodiverse agroforests[2]

These engineer species are planted very densely in rows and regularly pruned for mulch and/or feeding livestock, in varying proportions depending on the farmer's objectives over time. Fruit and native trees such as *umbu (Spondias tuberosa)*, yellow mombin (*Spondias mombin*), cashew (*Anacardium occidentale*), *emburana (Amburana cearensis)*, *juazeiro (Zizyphus joazeiro), catingueira (Caesalpinia pyramidalis), and sabiá (Mimosa caesalpiniaefolia),* among others, are then sown directly by seed (or planted by seedling in the second year) alongside the rows of engineer species or in a mixture with leguminous shrubs such as pigeon peas (*Cajanus cajan*) or climbing beans (*Phaseolus vulgaris*), in addition to maize or sorghum and castor beans (*Ricinus communis*).

12.4 Conclusions

This study confirms that agroforestry systems can indeed provide practical solutions for turning the onus of restoration into a bonus for farmers. Among the wide variety of agroforests adopted by farmers in Brazil, biodiverse successional systems are most suited to reconciling the various environmental goals of Legal Reserves and Permanent Protection Areas (e.g. erosion control, nutrient cycling, ecological corridors, buffers for riparian zones, increasing and regulating water flowing) with their social function (e.g. food, fodder, income). How they are planned and managed, however, will determine the extent to which their impact swings one way or the other, or towards a middle ground solution. As seen in the five agroforestry options presented here, some systems are more production-oriented and others more geared towards conservation goals though all of them perform both functions to varying extents and enable shifting objectives.

The challenge to striking the right balance between these goals at the plot/farm level lies in adopting management practices and selecting key species that accelerate ecological processes and increase resilience along with species and practices that meet farmer aspirations and take their capacities and vulnerabilities into account. Since access to labour and knowledge are common constraints across most contexts, systems need to be simple enough – and appropriately sized – to be manageable yet complex enough to ensure key ecosystem functions desired are maintained over time. Oftentimes complex systems can be implemented using simple techniques that optimize scarce resources (e.g. labour and fertilizer), such as direct sowing of tree seeds, planting of cuttings, slash and mulch (as opposed to slash and burn) and use of highly efficient pioneer species to help raise others that come later in the succession.

Achieving impacts beyond the plot/farm to the landscape scale entails organizing stakeholders around common objectives and strategies and drawing connections between farms, but adopting the right combination of systems, practices and species for the reality of each farm. This entails co-designing a set of solutions aimed at mini-contexts and functions within the landscape by drawing together technical expertise and traditional agroecological knowledge, promoting farmer-to-farmer learning and participatory innovation. In some contexts, supplying basic training and initial inputs such as seeds and seedlings can be enough for farmers to get started on developing their own systems.

Meeting ambitious restoration goals at the national, subnational or biome level will require recognizing and regulating these best practices for reconciling conservation with livelihoods. In addition to establishing basic ecological indicators and protocols for monitoring restoration, state governments will also need to tackle the thorny but crucial issues of the composition between exotic and native species, how – and how much – trees can be cut or pruned, and what sorts of inputs can be used at different stages of restoration, among other factors. Moreover, mainstreaming these practices into rural credit, extension and environmental regularization policies will be instrumental to overcoming some of the key vulnerabilities faced at the farm level.

Ultimately, restoring millions of hectares of pastures and degraded lands in Brazil with scarce resources will require combining biodiverse agroforestry practices with more passive and inexpensive methods such as natural regeneration, simpler agroforests aimed at environmental functions, or mixed solutions mingling passive and active methods on the same plot or within the same landscape. Whatever the combination of methods, the key to restoring all this land lies in including people in the restoration process, in ensuring that they reap direct benefits in addition to the collective benefits they provide to others in the landscape and to the planet.

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Small-island agroforestry

Agroforestry is the provider of many basic needs on small islands.

Photo: World Agroforestry/Meine van Noordwijk

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CHAPTER THIRTEEN

Small-island agroforestry in an era of climate change and sustainable development goals[a]

Meine van Noordwijk

Highlights

- Absence of a forest-agriculture divide has made small-islands fore-runners of agroforestry policies
- Specific forms of agroforestry match the ecological and social characteristics of small islands
- Ecologically, small islands share proximity to sea, limited freshwater reserves and low but globally unique ('endemic') biodiversity as characteristics
- Social characteristics are continued relevance of diversified subsistence support, limited economies of scale in participation in global markets and strong sense of identity

13.1 Introduction

Small islands exist in a wide range of absolute sizes, making counts of the total number of small islands that exist in the world uncertain. Indonesia, for example, is said to have more than 17 thousand islands, but although some of these are among the largest in the world (Borneo, Papua, Sumatra), it is not clear how many are classified as 'small'. A relevant distinction exists between those that are permanently inhabited and those that are not, but that criterion has borderline cases as well[b]. Being normally above sea level is a criterion for being an island, but an occasional flooding event (so that the island is not permanently above sea level) does not take it out of the island category. While there have been several initiatives

[a] With thanks to the organizers of and participants in the seminar "Agroforestry, small islands and climate change" at Pattimura University, Ambon (Indonesia) in November 2016 and to ICRAF colleagues who shared ideas, incl. Jonathan Cornelius, Jim Roshetko and Andre Ekadinata

[b] The definition of district and provincial borders hinges in some parts of Indonesia on the evidence whether or not specific islands where permanently inhabited at some point in the past; the discussion affects revenue sharing rules for resource extraction and can be hotly contested, similar to international issues in the S China sea that relate to settlement history

to represent the shared interests of small islands in global policy arena's, there is no universally agreed definition of what is small; among small island nations claims of leadership tend to be expressed by the largest among them, that may be least representative; the issues of small islands that are part of larger nations (such as Indonesia or the Philippines) differ partly from those that have nation status. Politically, small island nations, have achieved a clear voice in the climate change debate via the AOSIS association of small island states, some of which are expected to disappear with continued sea-level rise[1,2]. Some members of this grouping have 'mainland' or 'large island' parts as well (Figure 13.1). Indonesia as a country may have the largest number of 'small islands' of any country of the world, but does not belong to the AOSIS association. The concerns derived from a high vulnerability to sea level rise and climate change, however, apply to the small islands (inhabited or not) of small island states and archipelagic nations alike, as well as to the densely populated coastal zones of large islands and continents.

Figure 13.1 Small island states and other small islands of the world

Small islands share some properties with all coastal zones (proximity of the sea-land interface, vulnerability to climate change) and some with mountains (high-elevation islands of cool and wet climates, separated and surrounded by a sea of hotter lowlands) and the inhabited valleys ('inverse islands') between them (lower elevation peninsula's in a sea of non-vegetated rocks): remoteness, specific biodiversity values[c], lack of economies of scale. Yet, within a set of common characteristics, the history and cultural identity of the small islands in the Caribbean differs essentially from those in Southeast Asia and the Pacific, as their current population represents West Indian, African and European roots[3].

Agroforestry has a special character and possibly significance on small islands. In reflection on the special circumstances of small islands that can justify separate attention to the social-ecological systems that function on small islands, and that may imply a role for specific forms

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[c] Volcanoes, some are both islands and mountains, have added an episodic destruction of local life followed by recolonization from outside to this "small island" dynamic, as described in the island biogeography literature

of agroforestry, seven points emerged, three ecological, three social and one integrated, forward looking one. These form the core of this chapter, after clarifying what the era of climate change and sustainable development goals entails.

13.2 An era of climate change and sustainable development goals

The world is in need of integrative concepts, as counterforce to the natural tendency of human institutions to fragment into self-contained silos. The wording for such integrative concepts may change faster than their core content, with sustainable development, green growth, planetary boundaries and low emission development as elements of current policy discourse (Figure 13.2). The acceptance in September 2015 of the UN 2030 agenda with 17 Sustainable Development Goals (SDG's) has provided new momentum to a debate that was initially shaped by the Brundtland report in 1987[4]. The 17 SDG's can be interpreted as belonging to two groups: 12 that relate to the land use nexus of income, food, water, energy, climate and biodiversity, and 5 that relate to the human dimensions of inequity, fairness, gender, education, conflicts and cooperation (Figure 13.3). On further analysis the 12 SDG's in the land use nexus may be represented by six aspects of land use that have clear interactions, opportunities for synergy and risks of conflicts and unavoidable tradeoffs (Figure 13.4). Agroforestry concepts can play a role in achieving these six SDG synergy opportunities[5]

Figure 13.2 The need for integrative approaches at the interface of basic needs, livelihoods, planetary boundaries, policy issues, landscapes and project cycles in theories of induced change

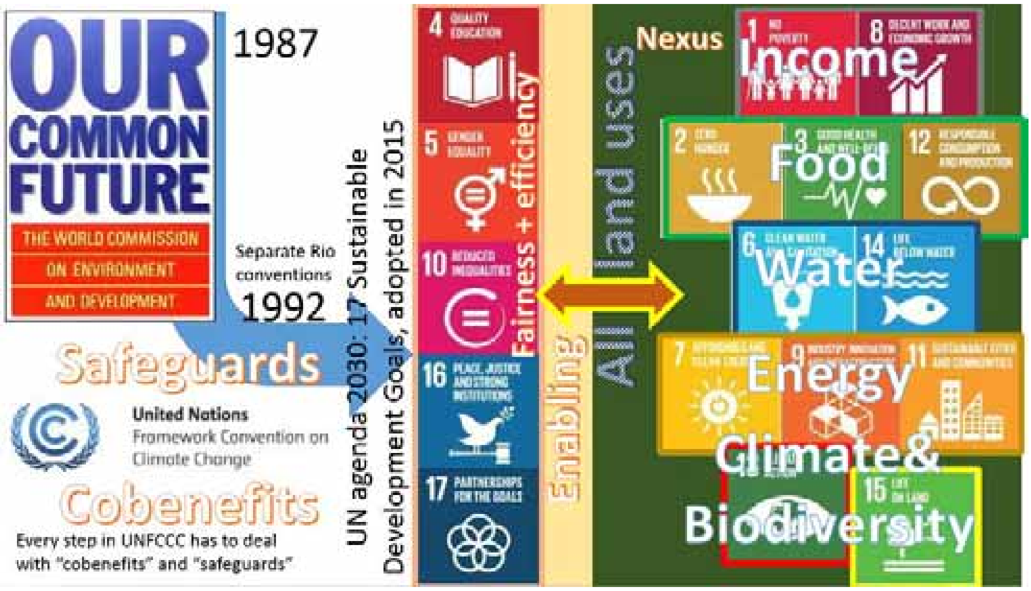

Figure 13.3 Pathway that led to the current set of 17 Sustainable Development Goals[6]

SDG's	Poverty, economic growth 1+8	Food, health, diets 2+3+12	Water, oceans 6+14	Energy, infrastructure, cities 7+9+11	Climate change, UNFCCC 13	Biodiversity and land health, CBD and UNCCD 15	4+5+10 + 16+ 17
1 + 8	Efficient transition to service-based economy in rural-urban continuum	Stronger value chains for food; income-based food security	Water footprint of traded commodities	Rural-urban continuum; renewable energy as growth engine; natural hazards contained	Low-emission development, ptotecting high-carbon stocks land cover	Biodiversity-friendly and non-degrading commodity production	Empowerment of underprivileged; fairness; transparency
2+3+12		Sustainable agriculture providing for healthy, affordable diets and adjusting demand	Blue water for irrigation; productive use of green water; wetlands, mangroves	(Peri) urban agriculture; waste reuse and reduction; integrated bio-energy	Climate-smart agriculture	Biodiversity-friendly agriculture; utilize both land sparing and land sharing opportunities	
6 + 14			Protect clean water sources, avoid pollution	Avoiding flood damage; grey water reuse; coastal zone health	Continental rainfall recycling; mangrove integrity	Water towers, springs, riparian zones, wetlands, mangroves	
7 + 9 + 11				Efficient use of renewable energy; no un-used waste	Climate smart cities with cool trees	Spatial planning of infrastructure & conservation	
13					Maximize high C stock land cover, CC buffering	Conserving, restoring high C-stock + high biodiv.habitat	
15						Min.20% fully protected; minimize loss elsewhere	
World Agroforestry Centre	Distributional, gender-equity and non-area based goals interacting with all the above: 4+5+10+16+17 a) equitable land use planning, rules for access, guarding from environmental spillovers b) education, access to dynamic, relevant knowledge; governance transparency; scrutiny of SDG progress						→

Figure 13.4 Interaction table between groups of Sustainable Development Goals (SDG's) and opportunities for integrated landscape solutions using agroforestry[4]

Box 13.1 Coconut: small island colonizer, multipurpose tree and agroforestry symbol

Across all tropical islands coconuts are a prominent part of the vegetation, and have become part of the 'visual brand'. With floating and sturdy fruits, it colonizes beaches easily. It provides protection (shelter), building materials, food, and income to island and coastal populations. Intercropping in coconut plantations, and their transformation to agroforestry, was linked to a shortage of other land and fluctuating copra prices in surveys in the Philippines[14].

Coconut palms can also be tapped as source of sugar – if there is sufficient fuelwood, but the woody petioles can also be used. Photos: World Agroforestry/Meine van Noordwijk

Seven characteristics of the social-ecological systems of small islands

For many of the Small Island Developing States (SIDS) of the Pacific Ocean, trees outside forests (TOF) and agroforestry constitute, perhaps, the single greatest foundation for the life and health[7]. Island soils, rivers, beaches, coastlines, people and the other plants and animals depend on it. The protection and planting of TOF and the protection and enrichment of traditional agroforestry systems and associated traditional knowledge can serve as a basis for addressing deforestation, forest degradation, 'agrodeforestation' and the loss of biodiversity (Box 13.1). In this analysis it may help to first identify which combination of environmental and social aspects define the 'small island' character (Fig. 13.5).

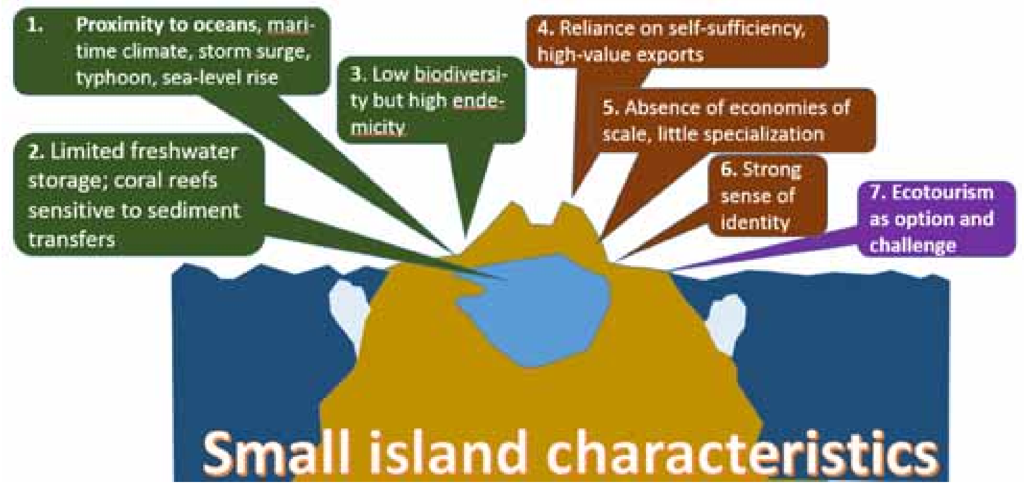

Figure 13.5 Seven specific aspects of social-ecological systems on small islands that provide context for agroforestry options

When considering small islands as social-ecological systems[8], we can distinguish a number of aspects of 'context' that are closely related to 'issues' within the globally agreed set of 'goals', and that shape the types of 'options' that have the best chance of 'induced change' in a desirable direction. As indicated in Figure 13.5, we found seven aspects (three ecological, three social, one integrated forward looking one) to be of particular relevance here.

Three **ecological** aspects imply high vulnerability to climate change and a specific place in the global biodiversity debate:

I. The coastal zone identity of small islands implies proximity to oceans, benefitting from the temperature and humidity buffering of large water masses in a maritime climate, but also involving exposure to the hurricanes and cyclones that are formed over heating surface water. They are also subject to the tsunami's that follow from sub-surface marine earthquakes, especially in the global ring of fire where tectonic plates clash. The maritime climate is subject to periodic shifts and long-term trends in global oceanic circulation and temperature differentiation (El Nino/La Nina, Indian Ocean Dipole and similar effects elsewhere). Human vulnerability to sea-level rise and episodic storm surges depends on access to higher elevation places to escape to. The contrast between day-night cycles in temperature between land and sea parts of the coastal zone may generate the air movement that brings rainfall to the islands, with specific roles for coastal forests, according to some authors[9].

II. Limited (fresh) groundwater storage, short (and thus 'flashy') rivers, saltwater intrusions in response to groundwater extraction and challenges to year-round water supply, especially where tourism increased the number of people and per capita water requirements. Coral islands[10] may be the group where limited freshwater supplies are most readily identified as constraint.

III. High endemicity (globally unique species) coupled to low species diversity (when compared per unit area), high extinction rates (dominating overall anthropogenic extinctions so far) and vulnerability to invasive species, while nearly all of global flora and fauna are by definition exotics. Most of the diversity of small islands is "between" rather than "within". Islands can be considered to be 'test tubes' for flora and fauna — simple systems with multiple replicates that can be used to understand ecological community dynamics in more complex mainland systems[11,12].

Three **social** (economic) aspects, posing challenges to mainstream economic development trajectories, but also offering some protection to the common negative side-effects of such:

IV. Limitations on transport imply a greater reliance on self-sufficiency for human livelihoods, with multi-purpose trees (coconuts as prime example[13,14]), and integrated marine-terrestrial resource use of coastal zones. Participation in global markets mostly based on non-perishable, high-value-per-unit-volume commodities (spices, sandalwood, metal mines).

V. Absence of economies of scale in resource exploitation and plantation development, coupled to limited human resource specialization and cultural-religious resistance to immigrants.

VI. A human population that reflects multiple waves of immigration, with those established earlier claiming "indigenous" status relative to newcomers. Across the islands of Southeast Asia and the Pacific evolution of linguistic diversity mirrors biological speciation and extinctions (including those where the loss of canoe-grade timber closed down the escape routes)[d]. There tends to be strong attachment to place and sense of in-group identity[7].

A jointly shaped opportunity for social-ecological systems in sustainable development:

VII. Shifts from resource extraction and primary production to service sector jobs and livelihoods primarily linked to tourism provide opportunities for the "early movers" (Box 14.2), but tends to have a "shifting cultivation" character, constantly looking for the "pristine" frontiers, leaving strongly modified, degraded places in its wake.

[d] The "Easter island" theory that human settlement overused the vegetation and especially exhausted trees large enough to make canoes that allow people to move on to the next island

Box 13.2 Small islands, (eco)tourism and the multiple values of nature

The realization that 'small islands' have more economic potential in an 'eco-tourism' pathway than through agriculture has come at various points in history in different parts of the world.

> *"Sixty years ago nobody yet thought that 'wilderness' could be as valuable for our people as first-class wheat-lands. If our island keeps its current beauty, we'll soon see that the income from tourism more than compensates for any lost income from foregone reclamation for agriculture or afforestation. Not even counting the moral effect on our visitors, while the latter is the most important part."*
>
> *Jac-P Thijsse 1924, commenting on Texel[i].*

This quote pre-dates current debates on 'valuation' of Nature, asserting that the 'moral' benefits of (urban) tourists getting at least some experience of the birds, flowers and landscape beauty of 'wild' islands outweigh any gains from 'productive' land use, for the local as well as national economy. The quote also indicates a strong critique on the 'afforestation' programs that tried to replace moving sand-dunes ('desertification') by monoculture pine plantations. Scattered trees in the landscape and around the farms were certainly appreciated as part of the cultural history.

Jac-P Thijsse, a primary school teacher by training and an educator at heart, pioneered both environmental education and area-based nature conservation in the Netherlands, a century ago, influencing public policy discussions and attracting funding for 'Nature Monuments'.

i. Quoted in: Deen M. De Wadden: een geschiedenis. Thomas Rap, Amsterdam.

Agroforestry options in the light of the seven characteristics

Agroforestry[15], the presence and explicit use of trees in agriculture and as part of livelihoods strategies, is an important part of historical human adaptation to small-island conditions. A range of names describes specific forms of agroforestry in the eastern parts of Indonesia, including[16]: *Oma, Rau, Amarasi, Kamutu luri, Budidaya lorong, Sikka, Kebon, Ongen, Uma, Napu, Nggaro, Ngerau, Omang wike, Mamar, Okaluri, Pada Mbanda.* All of these can continue to share adaptive responses by:

1. Coastal zone management with mangroves and other coastal tree cover as protection from storm surges (climate or earthquake induced) as quantified for the 2004 Tsunami in Sri Lanka[17] and Indonesia[18], respectively, and for tropical cyclones in the Philippines[19]. Coral reefs in front of a coast may provide stronger protection from waves than any tree-based coastal vegetation, but coral reefs may disappear unless the sediment load of rivers is controlled – a service in which tree-based land use helps as part of a ridge-to-reef concept of land/seascape management.

2. The relevance of agroforestry and tree cover for protecting water resources on small islands is not essentially different from that on larger land masses and their

watershed management as a social-ecological priority, linking biophysical cause-effect relationships with local knowledge and socio-economic benefit streams[20,21,22].

3. Biological diversity of high vulnerability to invasive competitors, predators, pests and diseases calling for strict phytosanitary standards and *ex ante* studies preceding any planned introduction. Special *Tectona grandis* (teak) populations developed on Muna island (south of Sulawesi) with affinity to other Sulawesi provenances and likely human spread from mainland SE Asia in the past 1000 years[23]. A large-seeded Kenari (*Canarium indicum*) population was identified on Nissan island[24]. Banana's and plantain have followed human settlement across small islands[25]. Explicit attention to genetic diversity within species of a human-induced dispersal history can be rewarding, especially where it links to local knowledge[26,27,28].

4. Retain local production of perishable goods (vegetables, fruits) while potentially outsourcing major, storable staples; spice-agroforestry as historical focus on high value goods to join in global markets. The accounts of agroforestry in the eastern parts of Indonesia[29] and the Pacific[30] by make this point. The Dusun systems of the Maluku have a long history of combining spices with high-value per unit weight, with food crops for local use, including fruit trees and sago[31]. On the isolated Indian Ocean island of Soqotra (Republic of Yemen), an arid tropical climate and an annual period of isolation as winds weren't conducive for sailing boats, have moulded the local livelihoods and culture, with a prominent role for homegardens[32].

5. Lack of institutional segregation of 'forestry' and 'agriculture' due to their obvious and tight integration in the land- and seascapes, avoiding some of the challenges of continents and larger islands. While rainforests of the Solomon islands had often been described by Western scientists as untouched, pristine or virgin, they are actually sites of former settlement, with evidence of extensive forest clearance, and agriculture based on both swidden and intensified irrigation practices[33]. Where historically agriculture and forest were seen as part of an integrated land use pattern in many small islands, integration of such islands in unitary states has posed new challenges. Swidden cultivators and sago extractors living on the edge of lowland rainforest in central Seram, Maluku, have had to counter threats to their traditional agroforestry resource base posed by government-sponsored settlement and logging[34,35]. The traditional resource management rules known under the term 'Sasi' in Maluku are under pressure but can offer new meaning in the current re-appreciation of ecosystem services[36]. The main challenge in this respect is to reconcile local knowledge, the concepts on which public policy is based, and science-based quantification of environmental service functions rather than form and compliance with definitions[37].

6. Human diversity on small islands is associated with localized identity, and rich ethnobotanical and local ecological knowledge as basis for a wide range of location-specific agroforestry systems[38,39]. Clarke[40] commented on the irony that modern, aid-funded attempts to promote externally designed agroforestry in the Pacific, a region where agroforestry systems were developed thousands of years ago and where hundreds of species of trees are still used in a be wildering variety of ways.

Lazrus[2] discussed the perspective that island communities are not merely isolated, small, and impoverished but that they are often deeply globally connected in ways that reject such simple descriptions and will be essential for the world to accept just and equitable climate solutions[41].

7. Once the primary obstacles to transport are overcome, forms of (eco)tourism are a major opportunity to capitalize on the favourable climate, local identity, scenic beauty and social coherence of small islands. This pathway to development, however, can also be a challenge because of excessive demands on local resources, privatization of previously communal assets, increased social stratification, invasive exotics and global homogenization. The stories of how trees have been traditionally integrated with local culture and livelihoods can certainly be used to strengthen a marketable branding.

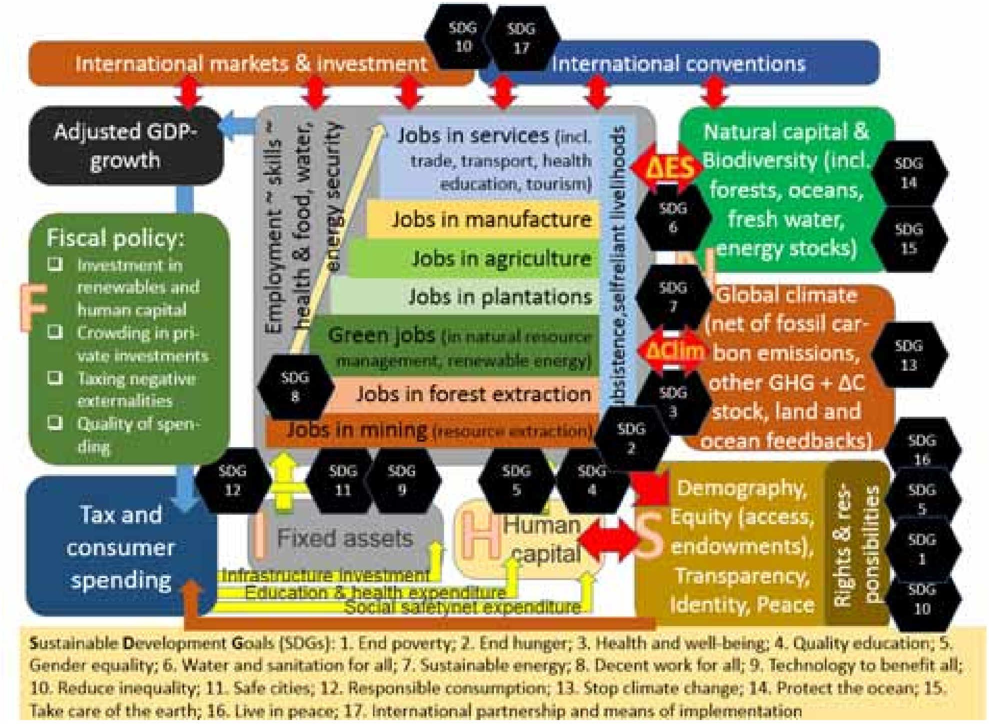

Figure 13.6 Outline of a dynamic model of the five capitals (N, H, S, F, I; natural, human, social, financial and infrastructural, respectively) in a national (or jurisdictional) economy[4]

13.5 Discussion

The sustainable development debate can be approached from many angles, but a focus on the sources of livelihoods, jobs and employment can be a powerful way to communicate with governments from local to national levels. In an outline of a dynamic model of a regional economy (Figure 13.6) four main types of jobs can be recognized, that are based on: A) resource extraction (incl. much forest management), B) primary production (incl. much of agroforestry attention so far), C) value-addition and manufacturing (that the 'value chain' and agroforestry-market line of research explore), and D) service-sector jobs. Where economic development can generally be understood as based on a progression from A to D as dominant segment of economic activity, small island extractive industries are restricted to high-value products (A), primary production is not easily shifting from meeting local to global market demands (B), while the economies of scale for stage C are limited. The logical step is to rapidly progress to D, before failed efforts in A, B or C have destroyed too much of the local ecosystem services as potential selling points for ecotourism.

The Ecosystem Services paradigm[42] is first of all a service-sector concept (see the language used), but one that interacts with the other three: trying to contain and control the extractive sectors, nudging the primary production sector into more ES friendly forms (incl. the certification debates[43]), controlling negative aspects of industries in stage C. New perspectives on the way small-island agroforestry can reinvent itself in an era of climate change and sustainable development goals can build on the positive dimensions of local identity and biodiversity in shaping eco-tourism as an advanced economic sector initiative.

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Melda

It all started as we like Katuk ...

KIPRAH AGROFORESTRY 18,
ICRAF, Bogor

INTERMEZZO 5

Edible hedges that became a good business and a farmer group success story

The Tani Hambaro farmers group in Nanggung (Bogor, W. Java, Indonesia) consisted of 20 women when it started, but now many more want to join, as explained by the group's leader Ibu Melda. Their main business success so far: growing and selling planting material of a productive local hedge species: katuk (*Sauropus androgynus*).

It all started when project staff came to the village to explore which local plants might be worth investment and experimentation to support local livelihoods. The Katuk hedges are known as a good source of iron and vitamins, a healthy component of local diets and they are easy to grow. But as space is limited, they often are grown as understory of fruit trees and it wasn't clear how much shade they can tolerate. For the on-farm experimentation a lot of planting material was needed – and this wasn't available on any of the local markets. So, ibu Melda started to produce it herself to sell to the project – but then continued to grow it for others. By chance they discovered that there actually was demand for the planting material, as katuk became one of the targets of more health-conscious revival of local foods, after a long period of neglect.

Starting a farmer group led by women met with initial prejudice. But when the initial idea appeared to work, the group became interested in further innovation and in sharing, not only the products of the group, but also the experience of success and the confidence that can give to participants. The katuk, a very useful plant that had been 'invisible' started a local story that continues to this day.

Hedges that provide a healthy vegetable whenever you need it – the starting point for an innovative women farmers group

Based on "Bermodal tekad mambangun Tani Hambari" by Aunul Fauzi 2009. KIPRAH AGROFORESTRI 4, ICRAF, Bogor

One year after Tsunami Aceh

The coastal areas of Aceh, the northern tip of Sumatra, were directly hit by a Tsunami in December 2014. Conversion of coastal vegetation to urban settlements had made many people vulnerable and mangroves or other tree cover were seen as important to prevent future disasters. One year after the event, trees were back, but natural resource extraction also recovered and became more extensive, with new mining, land conversion, and logging underway.

Photo: World Agroforestry

Suggested citation:

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CHAPTER FOURTEEN

How can agroforestry be part of disaster risk management?

Meine van Noordwijk, Kurniatun Hairiah, Hesti L Tata, Rodel Lasco

Highlights

- **A**groforestry and wise use of trees in rural and urban landscapes can reduce human vulnerability to disasters
- Separate hypotheses relate to reduced exposure to and increasing resilience in the face of natural and partially anthropogenic disasters
- Examples from Asian landscapes in the past two decades provide nuance to the hypotheses

14.1 Introduction

A common definition of a disaster is: "a sudden, calamitous event that seriously disrupts the functioning of a community or society and causes human, material, and economic or environmental losses that exceed the community's or society's ability to cope using its own resources. Though often caused by nature, disasters can have human origins."[1] Disasters can be of many types, based on the elements (Earth, Water, Wind, Fire and Biota) involved, the spatial and temporal scale affected and the degree to which they are natural or (partially) manmade.

The human response can be understood on a before/during/after timescale. Awareness, prevention and avoidance of risky times and places is a strategic, long-term response. The tactics of fleeing, hiding and surviving form the immediate responses, while the resilience or bouncing back afterwards has both material and immaterial (motivational) dimensions. With current understanding of the human causation of as part of global climate change[2], the categorization into 'natural' and 'manmade' disasters is further blurred, but such distinctions still play a role in policy responses and insurance coverage. The recent Lombok earthquakes show that the negative repercussions for international tourism of declaring the damage to be a 'national disaster' are an argument against such designation and in fact delay the recovery process.

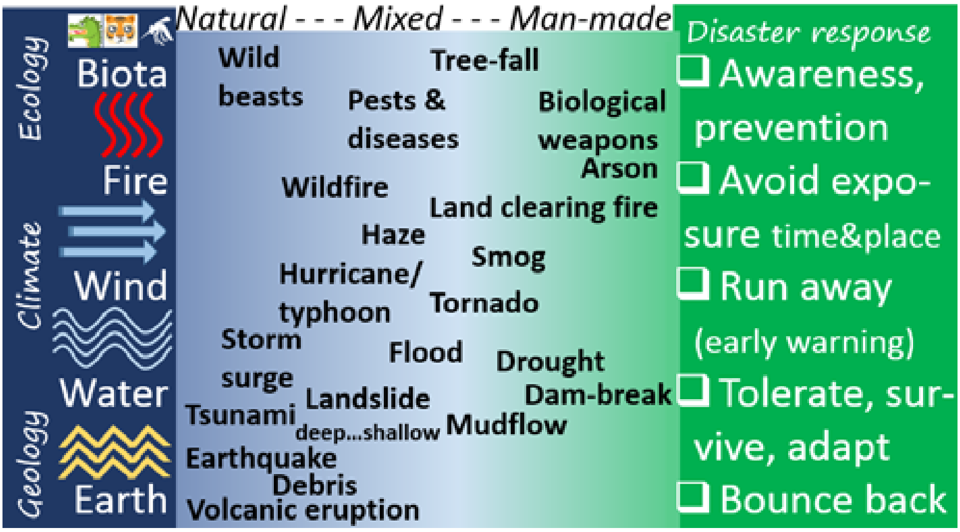

Figure 14.1 Examples of disasters classified by 'element' causing it and degree of human causation

Agroforestry as a concept has evolved from a focus on specific ***technologies*** for using trees on farm, towards an understanding of multifunctional ***landscapes*** with trees in multiple roles, and more recently efforts to harmonise agricultural and forestry ***policies*** in a holistic approach to land use for achieving sustainable development goals (SDGs)[3,4,5].

Our key hypotheses here are that:

1. Agroforestry, or the wise use of trees, can play a role in reducing exposure in risk-aware land use planning.
2. It can also help to retain or restore buffer and filter functions in the landscape that reduce and localize disturbances, such as surface flows of soil particles derived from erosion or volcanic debris.
3. Through its mitigating effects on global climate change, agroforestry also contributes to countering the current increasing trend in disaster prevalence due to climate change.

A number of studies will be briefly reviewed here that have quantified the positive and negative aspects of trees in landscapes affected by natural disasters and/or considered to be at risk:

- Tsunami (W. Aceh)
- Volcanic ash (Kelud)
- Shallow landslides (W. Java)
- Kebun lindung, protective agroforests on sloping land
- Flood risks in headwater catchments
- Haze prevention through peatland paludiculture

14.2 Tsunami (W. Aceh)

With more than 200,000 human victims, the Tsunami that hit Aceh in December 2004 was high on the global list of deadliest disasters since 1900[6]. Directly after the scale of the devastation became clear, public discussion focused on the role of mangrove conversion in the degree of avoidable damage done[7]. Two aspects were key here: building houses in locations that used to be mangrove proved to be a high-risk land use choice, while remaining mangrove between people in the hinterland and the coast provided protection from the wave impact by absorbing part of the momentum. A further analysis of the damage and victims in W Aceh, however, showed[8] that positive protection effects of trees between people's locations and the coast were largely offset by negative impacts of trees beyond where they lived. Such trees blocked escape routes and contributed to the back-and-forth debris flows that characterize a tsunami and make it hard to survive, unless one escaped to higher grounds (or climbed a strong tree) on the first warning signs (having felt the earthquake that caused the tsunami). This analysis combined data for mangrove with other coastal tree vegetation, based on a 'roughness' parameter that represented the wave impact of various types of vegetation. In hindsight, much of the mangrove planting that was part of the early disaster response might have fulfilled a ritualistic function, but did not contribute much to future risk avoidance, as the survival rate of the trees was low (for various reasons) and people still preferred to rebuild houses close to the coast[9] (Fig. 14.2).

Figure 14.2 Murals in Meulaboh (W. Aceh, Indonesia) developed as part of the recovery process for survivors, showing the destruction by the waves, the efforts to escape, the international support that we triggered and the vision for the future (fishing plus houses between the coast and trees...)

Rather than planting 'any tree', specific attention to species choice and quality of planting material through local 'nurseries of excellence'[10] helped in the economic recovery process in coastal areas[11]. In assistance of local governments, reinventing spatial planning through use of models that build in explicit risk factors[12] made a contribution to a more rational weighing of the risks (small probabilities but huge impacts) of a next Tsunami and more immediate livelihood opportunities. Across coastal areas of Indonesia the technical options for early warning, effective communication and clarity on escape routes have been replicated. There has been some progress on mangrove rehabilitation along part of the coast, especially where local communities were involved from the earliest stages[13] but the lack of a strong land use planning discipline means that the risks of a next Tsunami disaster still exists in Indonesia, and elsewhere in SE Asia.

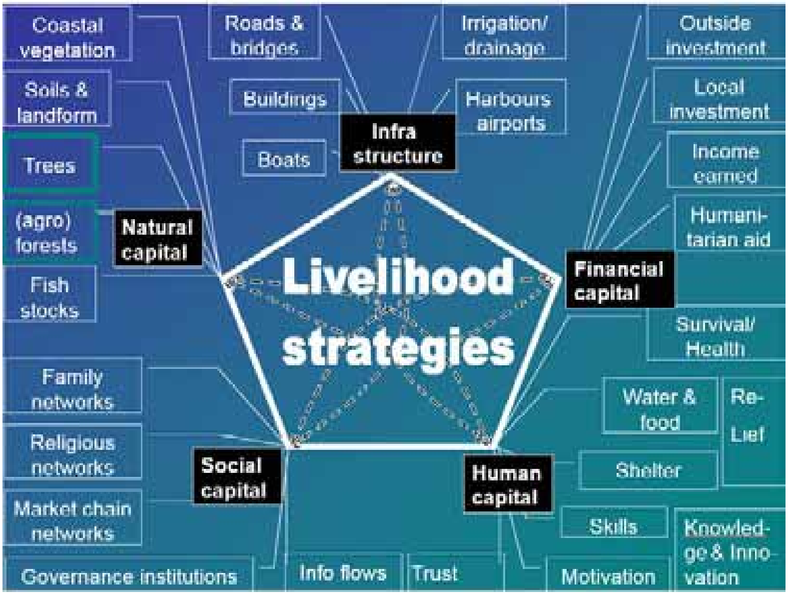

Figure 14.3 Result of a focus group discussion with local government staff of the livelihood context of Tsunami recovery in West Aceh (Indonesia), leading to stronger sectorial integration and coordination

Although its primary cause differs, storm surges after typhoon landfalls in the Philippines have similar effects on coastal populations. The degree of damage brought in 2013 to Leyte by typhoon Hainan[14] sparked interest in mangrove rehabilitation as well, with similar findings as earlier documented in Indonesia[15]. Because typhoon frequencies and pathways are influenced by ocean temperatures, there is a clear anthropogenic risk induction dimension to the storm surge debate. Strengthening tree-based coastal defence is now seen as a valid component of climate change adaptation[16].

14.3 Volcanic ash (Kelud)

In the 'ring of fire'[17] plate tectonics are the underlying cause of the vast majority of the world's earthquakes and active volcanoes. Southeast Asia has about 750 active and potentially active volcanoes, with different frequencies of eruption[18]. Eruptions, especially before the current era of monitoring of volcanic activity, caused disasters for people living on the slopes and direct surrounding, while the ash and debris deposits affect land use over much larger distances, and climatic effects of stratospheric ash have affected global climates several times per century[19], with disastrous impacts in historical records at least once per millennium. Yet, volcanic ash is also the basis of some of the most fertile soils (Andosols). Such andosols, however, develop after weathering of the ash and involve the incorporation of large amounts of carbon, challenging farming in the years directly after landscapes are blanketed by ash[20].

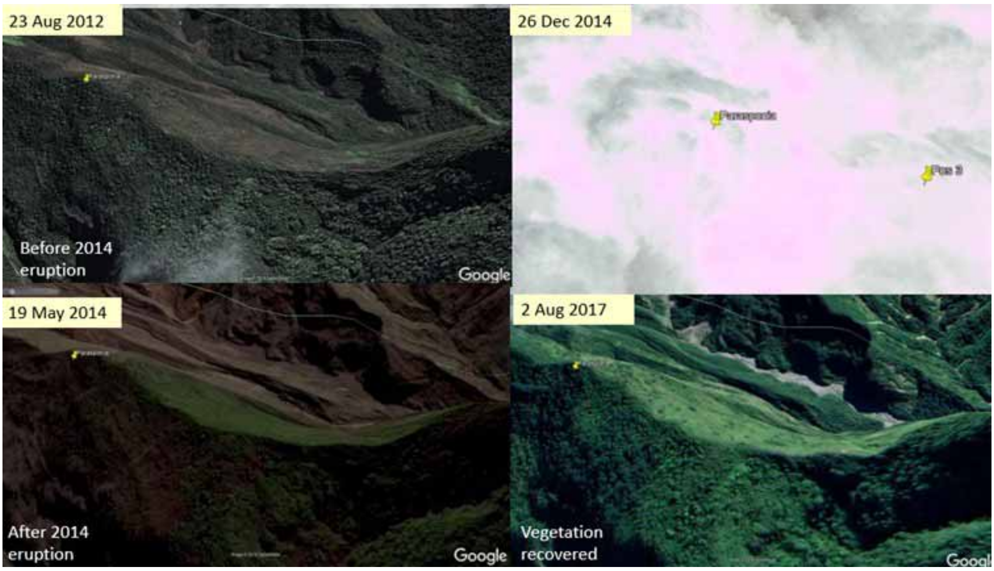

Figure 14.4 Google Earth imagery of the E slope of Mount Kelud before, during and after the most recent eruption and ash deposit that was a major disruption for many villages in the Kali Konto landscape

Only a limited number of trees can withstand the high sulphur emissions and other conditions on volcanoes, and play, through tolerance and rapid recovery after ash deposits, a role in the stabilization of fresh ash deposits, preventing mudflows and further disasters downstream in the following rainy seasons. On volcanoes with a high frequency of ash deposits a biologically remarkable genus of trees, *Parasponia*, is among the few that can tolerate and even thrive in these conditions. It is remarkable, because it is in early stages of evolution of a symbiosis with *Rhizobium* bacteria that allows it to fix atmospheric nitrogen in an otherwise N-limited environment[21]. Ongoing research on Mount Kelud in East Java explores how *P. andersonii* can be used in coffee agroforestry systems on the volcanoes slopes and direct surrounding, providing a positive twist to the regularly occurring disturbance of lives and landscapes by the ash[22].

Figure 14.5 *Parasponia andersonii* and the nodules it formed three years after this landscape position was blanketed by ash on Mount Kelud

14.4 Shallow landslides (W. Java)

Recent earthquakes in Lombok have again confirmed that man-made buildings from brick and concrete are far more vulnerable than trees when the earth shakes. Traditional wooden houses are reportedly much better adapted, absorbing the wave energy and shaking, but not collapsing. Trees also add coherence and anchoring to soil layers on slopes, shifting the threshold at which landslides occur when soil gradually accumulates over time. Because of this function, landslide risk increases after deforestation, peaking after a few years when the main woody roots have decayed. If landslide have not happened by that time, the soil compaction and reduction of infiltration rates is likely to protect the soil from landslides after that point in time. Deep landslides, beyond the reach of tree roots will still occur if soil accumulation has proceeded for a long time.

Not all trees are equally effective in preventing shallow landslides, as it depends on the architecture of the root system. Relatively simple methods have been developed to characterize tree roots in their relative share of vertical ('anchoring') and horizontal ('soil binding') roots[23]. There is a tendency for smaller trees to have rela-tively larger root systems (based on cross-sectional area of proximal roots relative to that of the stem, Fig. 14.6B)

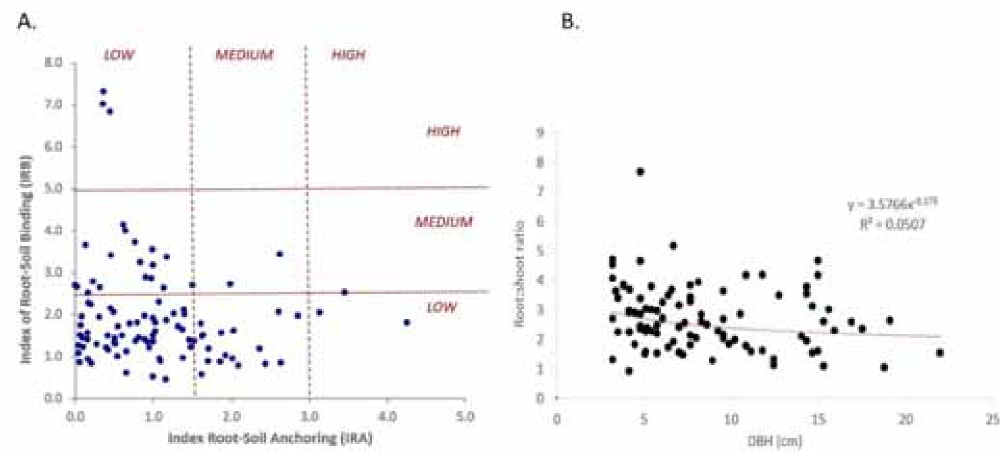

Figure 14.6 A. Tradeoff between deep anchoring and horizontal soil binding roots, and B. Reduced investment in roots with increasing stem diameter, in recent fieldwork in E Java[24]

14.5 Kebun lindung, protective agroforests on sloping land

In Indonesia land is classified first of all as forest versus non-forest, where the first is under state control (even when the legal requirements of gazettement have only been completed for a fraction of the total area claimed[25, 26,27]), and the second without substantial legal restrictions to 'environmental externalities' of private land use decisions. Both of these issues limit the options to reconcile 'development' and 'sustainability' in land use patterns. Based largely on criteria of slope, part of the forest domain is classified as 'protective forest' (*hutan lindung*; the common English translation as 'protection forest' is less accurate; the term used in a colonial past referred to 'shielding' forest), implying that it is out of bounds for logging. It also means, however, that forest management authorities have few means to implement the mandated control of external pressures. A small fraction of the national 'protective forest' now has community management agreements, with limited use rights linked to effective protection, mostly for securing local 'environmental services' as incentive. Negotiations between local communities and forest authorities have been complex and slow, because existing regulations prescribe 'solutions', rather than clarify objectively verifiable functions[28,29,30,31].

Part of the community- or privately owned non-forest land still has substantial tree cover, and on slopes acts as 'protective garden' (*kebun lindung*). Interests of downstream stakeholders in maintaining (or enhancing) the existing 'protective' functions may deserve voluntary Payments for Environmental Services, but despite promising pilot schemes, there still are substantial bottlenecks in mainstreaming such[32,33,34,35].

Effectiveness of the two types of 'kebun lindung' (the community-managed parts of 'forest' plus the privately controlled non-forest, tree-based systems) has been shown in studies of landscape-scale sediment transport[36]. A diverse tree cover contributes to landslide prevention, while a continuous litter layer protects soil from erosion and feeds the soil biota (incl. earthworms) that help to main high infiltration rates[37], thus reducing flooding risks.

14.7 Flood risks in headwater catchments

Floods are high on the list of economic damage and public health risks, even if the number of human victims is modest (different from the mudflows that were considered under 'landslides'). In fact, temporarily high water levels are a regular feature of downstream river systems, geomorphologically classified as 'floodplains'. As long as these are maintained as wetlands, they protect areas further downstream from flooding. If they are converted to urban areas, protected by dykes, this implies flooding risks both for the areas themselves (unless the dykes are high and strong), and their downstream neighbours. The greatest economic damage by flooding tends to occur in such converted floodplains – and in the public discussion of the causation of such floods 'deforestation' has been a popular 'scapegoat'.

Evidence in small-scale paired catchments has generally pointed at an increase of both total annual and peak flows when forests were logged or converted to other land uses. This is due to both a lower water use by evapotranspiration (leading to less replenishment potential of soils before they are saturated), a sealing of the soil surface and a decline in soil macroporosity, jointly determining the actual infiltration rate, depending on rainfall intensity. As there has been less convincing evidence of effects of land cover change on flood frequency[38], there has been a considerable gap between public perceptions (readily attributing disastrous floods to 'deforestation') and hydrological evidence. With a more sophisticated metric, however. The change in 'flashiness' of river flow records (Fig. 6) can now be characterized and linked directly to the part of peak rainfall events that is transferred immediately to rivers[39]. With the 'flow persistence' metric changes in land cover in the mosaic of catchments can be quantified, in interaction with climate variability and possibly climate change, showing that the buffering and temporary water storage capacity of wetlands is key to flood prevention. Beyond integrity of headwater catchments, wetlands (with or without trees) are key.

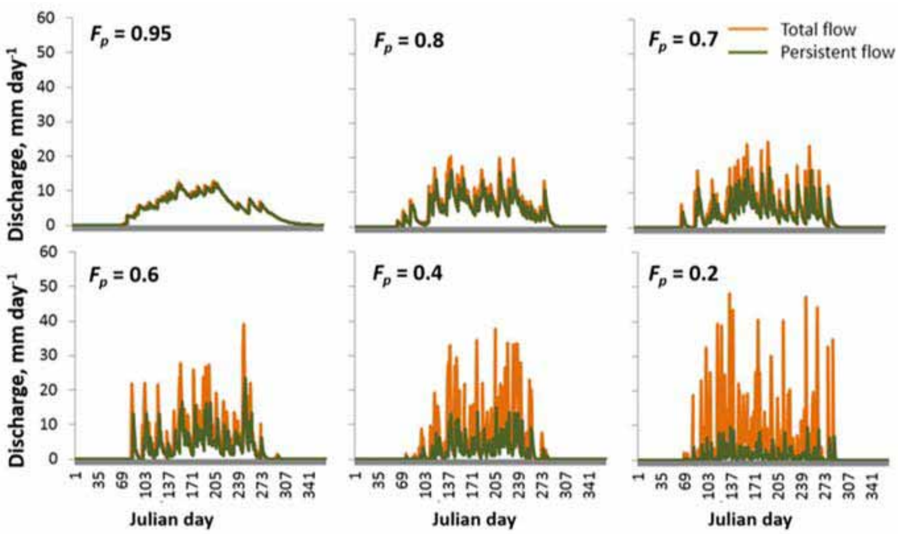

Figure 14.6 Changes in daily river-flow records when the 'flow persistence' metric (F_p) decreases from the value above 0.8 typically found in forested catchments, to values around 0.6 found in open agricultural landscapes and the lower values of urbanized, sealed subcatchments[26]

14.8 Haze prevention through peatland paludiculture

Estimates of the total economic damage by the 2016 haze episode vary[40], but the major disturbance to public health and disruption of economic activities and transport within Indonesia, plus the damage to neighbourly relations with countries affected by the haze, has been sufficient to set up a national coordinating 'peat restoration' body to make sure that such disasters won't happen again. The political momentum this achieved was hard to imagine before the 2016 event[41,42], and showed that disasters have to get over a threshold before they spark corrective action.

As landscape-level drainage for agricultural development plus canals to facilit6ate log transport were a major contributor to the peat fires, much of the attention since has been given to forms of 'canal blocking'. To be acceptable to local communities, however, the shortage of 'kebun lindung' options for wet environments has been a bottleneck. Only a few trees with internationally traded products are known to thrive in undrained peat, and their markets are relatively shallow[43].

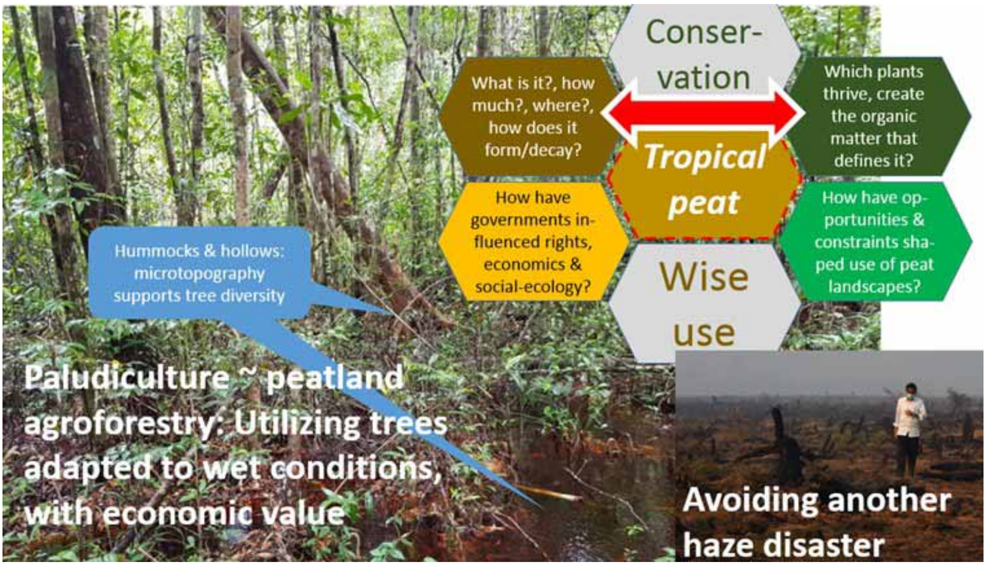

Figure 14.7 Aspects of the ongoing search for paludiculture forms of 'kebun lindung' on undrained peat

Cultivation on peatlands is constrained by saturated low pH of soils, while many tree species with high economic value needs suitable condition for living. Therefore, water on peat swamp ecosystem is drained through a canal, which reduce water table on peatland. Drained peatland causes many consequences, such as fosters decomposition rate, subsidizes the peatland[44] increases emission of greenhouse gasses[45] fire susceptibility in drought season[46,47] and floods in the rainy season[48]. Owing to human intervention and mismanagement, peatlands condition in Indonesia has degraded fast.

In the national peatland restoration programme, three approaches were employed, namely rewetting, revegetation and revitalization of local livelihoods[49]. A zonation, which is based on the depth of peatlands, is established in a peatland hydrological unit (PHU). A PHU is divided into two zones of function, those are protection and cultivation functions[108]. The regulation on peatland restoration targeted the maximum ground water level in the cultivation function of peat hydrological unit (PHU) is 40 cm below the surface. While in the protection function of PHU, the water table is suggested to be near the surface.

Paludiculture or cultivation on rewetted peatland with native tree species offers a solution to reduce emission, improving land cover and offering livelihood options. Cultivation on peatlands with a minimum or none drainage may tackle two disasters, namely fire risk in drought season and flood in rainy season. On a drained peatland in the protection function, canal has to be permanently blocked by canal backfilling. While in the production function, canal can be blocked with spillway. With the increased of water level in the rewetted peatland, only selected species can be planted. Several plant species have been recommended to be planted as paludiculture practice in Indonesia[50,51]. Recommendation of tree species selection is based on two potential risks (e.g. fire and flood risks), their economic values, and availability of potential market[110].

14.8 Mitigating global climate change as source of risks

The third hypothesis ("Through its mitigating effects on global climate change, agroforestry also contributes to countering the current increasing trend in disaster prevalence due to climate change.") has been reviewed both for its soil[52,53] and aboveground components[54,55]. Recent analysis of the way forests and treebased systems interact with global climate has pointed at effects linked to the hydrological cycle that may be (even) more important for actual climate change, and that may provide a much more direct relation between local and global benefits of enhancing functional tree cover[56].

In the last few decades, economic losses from weather- and climate-related disasters have increased[57]. While these losses cannot be definitively attributed to climate change, the possibility that they are related cannot be ruled out. In the 21st century, it is expected that climate change-related risks from some extreme events, such as heat waves, will increase with higher temperatures[2]. It is likely that average tropical cyclone maximum wind speed will increase, although the global frequency of tropical cyclones will either decrease or remain essentially unchanged[49]. Agroforestry systems offer compelling synergies between adaptation and mitigation[58]. Multiple evidence from a number of countries show that agroforestry systems improve resilience of smallholder farmers through more efficient water utilization; improved microclimate; enhanced soil productivity and nutrient cycling; control of pests and diseases; improved farm productivity; and diversified and increased farm income while at the same time sequestering carbon[59].

14.9 Discussion

Based on the six examples we can now review the three hypotheses. In all six cases we found specific evidence for hypothesis 1 ("Agroforestry, or the wise use of trees, can play a role in reducing exposure in risk-aware land use planning"), with variations in the degree of prominence of avoidance of human settlement in high-risk locations (e.g. the likely pathway of mudflows, floodplains or low-lying coastal areas) can be supported by the allocation of such lands to economically interesting tree-based land uses.

For a number of the potential ‘disasters’, we also found evidence for hypothesis 2 (“It can also help to retain or restore buffer and filter functions in the landscape that reduce and localize disturbances, such as surface flows of soil particles derived from erosion or volcanic debris.”). Beyond that, there are circumstances in which trees help in rescue and recovery stages by providing escape options (trees to climb into), trees that provide emergency food[60] when areas are cut off from the outside world by disasters, or lianas that are sources of safe drinking water in similar settings. There are, however, various tradeoffs between the functional traits if trees that are involved in the various functions (Fig. 8). These tradeoffs may be the strongest argument so far, to maintain tree diversity as a higher-order buffering mechanism, as we often deal with multiple potential disaster categories.

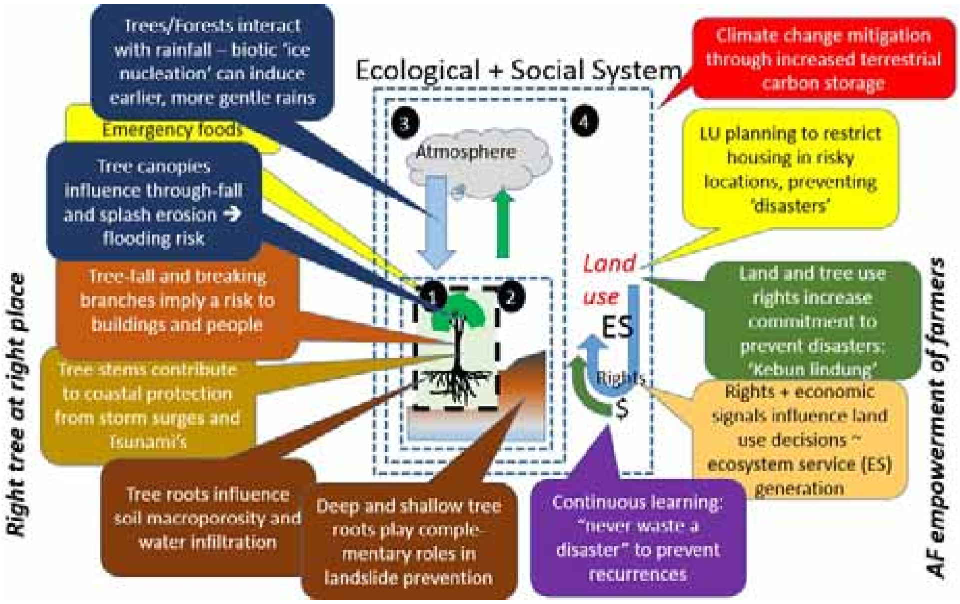

Figure 14.8 Summary of some of the disaster-relevant functional traits of trees involved, at the nested system scales of trees (1), trees + soil (2), trees + soil + climate (3), that interact with the social-ecological landscape scale (4) in shaping disaster avoidance and management

Maintaining tree diversity throughout agricultural and urban landscapes generally has positive effects on disaster risk reduction[61], but trees or their branches falling on people or buildings are a risk that requires specific attention through choice of species, regular inspection and targeted management actions. Major improvements towards ‘sustainable development’, whether at local, national or global scales, have been triggered by disasters. Without a direct demonstration of the damage and human suffering, it is difficult for public policy making to take warning signs seriously. A variant to Winston Churchill’s "Never let a good crisis go to waste” can thus be “Never waste a disaster”. In the aftermath of a disaster questions of causality and avoidability come up, and (over)simplified perceptions can shape responses beyond the immediate rescue and recovery phases. Research results need to be ready for such ‘windows of opportunity’, as there is no time to fully explore evidence in the short timespan before a next issue or crisis takes priority in public discourse. Maintaining diverse tree cover in agricultural and urban landscapes is usually a ‘no regrets’ solution, with details on the most desirables set of tree traits depending on context.

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A degraded forestry landscape in Cameroon

A degraded forestry landscape in the western highlands of Cameroon.

Photo: World Agroforestry/Charlie Pye-Smith

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CHAPTER FIFTEEN

Community forestry as a green economy pathway in Cameroon[a]

Peter A Minang, Lalisa A Duguma, Serge M Piabuo, Divine Foundjem-Tita, Zac Tchoundjeu

Highlights

- Community Forestry (CF) was introduced in Cameroon through an extensive forestry reform process in the early 1990s
- The objectives at the time were three-fold: to grant communities rights to surrounding forests, enable them to improve their livelihoods, and to promote sustainable forest management
- Twenty years on, about 450 CFs exist in the country, 285 of which have final management agreements, showing success in the first objective of granting community rights to forests
- Results on the livelihood and sustainable forest management objectives have been mixed
- New initiatives are needed to make community forestry an engine for a viable green economy

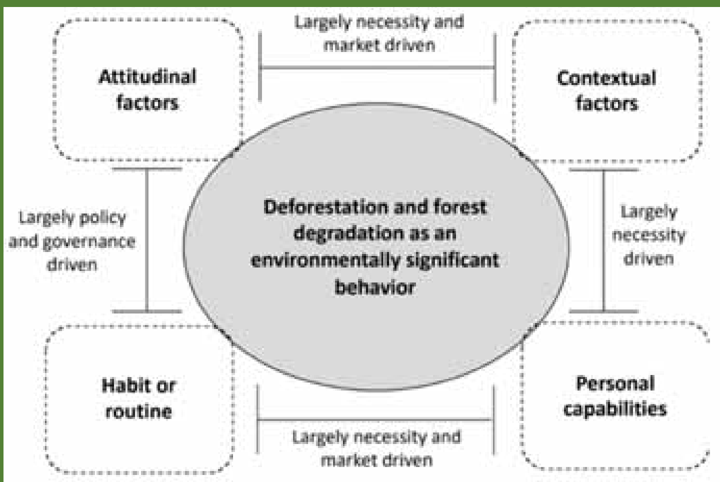
Agroforestry, as well as its 'parents' agriculture and forestry, relate to the portfolio of 17 Sustainable Development Goals in multiple ways, as indicated in chapter 17. On-going efforts in Cameroon to breathe new life into the 'Community-Based Forest Management' efforts by connecting the policy reform of local forest management more clearly to agroforestry and local business development, can serve as an example of the ways SDG 16 (governance) interacts with SDGs 15 (terrestrial ecosystems, including forests), 12 (responsible production and consumption) and 1 (income). Where smallholders are part of the problem of forest degradation and deforestation (See Box 15.1), solutions are unlikely to work without involving them at the level of rights, incentives and motivation. The Cameroon example demonstrates

[a] Minang PA, L A Duguma, S P Mandiefe, D Foundjem, Z. Tchoundjeu. 2017. *Community forestry as a green economy pathway: two decades of learning in Cameroon*. ASB Policy Brief 53. Nairobi: ASB Partnership for the Tropical Forest Margins and the World Agroforestry Centre

how landscape level and national level constraints together shape the issues, and how further synergy is needed to resolve them.

Box 15.1 Beyond blaming smallholders for forest degradation and deforestation[1]

Deforestation and forest degradation (D&D) in the tropics have continued unabated and are posing serious threats to forests and the livelihoods of those who depend on forests and forest resources. Smallholder farmers are often implicated. Based on case studies in the Menagesha Suba Forest in Ethiopia and the Maasai Mau Forest in Kenya, data analysis indicates that factors that forced farmers to engage in D&D were largely contextual, i.e., sociodemographic, production factor constraints, as well as policy and governance issues with some influences of routine practices such as wood extraction for fuelwood and construction.



Those factors can be broadly aggregated as ***necessity***-driven, ***market***-driven, and ***governance***-driven. In the forests studied, D&D were largely due to necessity (basic needs) and governance challenges. Though most factors are intrinsic to the context of smallholders, the extent and impact on D&D were largely aggravated by factors outside the forest landscape. Therefore, policy efforts to reduce D&D should carefully scrutinize the context, the factors, and the associated enablers to reduce forest losses under varying socioeconomic, biophysical, and resource governance conditions.

15.1 Introduction

According to the 1994 Cameroonian Forest Law, community forests refers to "…part of non-permanent forest estate (not more than 5000ha) that is the object of an agreement between government and a community in which communities undertake sustainable forest management for a period of 25 years renewable"[2]. In order for a community forest to be granted communities have to fulfil the following obligations:

- Constitute a legal entity (a Common Initiative Group (CIG), an Economic Interest Group, an Association or a Cooperative) and appoint a community forest manager who shall represent them in negotiations with government in matters of community forestry;

- Delineate and map the intended community forest area prior to approval;
- Present a management plan as part of the conditions for approval. The simple management plan has to be reviewed every 5 years;
- A manual of procedures details out rules and procedures for community forestry from creation through to management, including conditions for annual exploitation in the case of timber.

Since the inception of community forestry a number of major reviews have taken stock: one in 2003 by the Ministry of Environment and Forests[3]; another by Tropenbos International in 2006[4], and subsequently by the Ministry of Forestry and Wildlife (MINFOF)[5]. This chapter takes a systems perspective and lays emphasis on the role of community forestry in a viable green economy, one in which community forest enterprise is the primary vehicle for taking rural poor people out of poverty while enhancing ecosystem service benefits from community forests. It is based on a review of more than 100 publications both peer reviewed (55%) and grey literature in the form of reports, monographs etc (45%). Methods such as content analysis, systematic reviews and historical timelines are employed in the analysis.

Box 15.2 Required synergy between change inside and outside multifunctional landscapes[6]

Landscapes have emerged in the past decade as a specific scale for interventions, intermediate between 'farms' and 'national policies', interacting with various levels of local or sub-national governance. Landscapes typically interact with both private and public sectors operating at wider scales, and modulate participation in value chains for goods and services. They can connect local action to global concerns, especially where globally traded commodities are derived from the landscape; in such cases the private sector parts of the value chains, and the national governments are intermediate to 'supply' and 'demand'.

The expectation that attention for landscape scale interventions could mediate between local, national and global stakeholders has received empirical support. However, when a group of 'landscape approach' practitioners in Indonesia was asked to rank statements with possible answers to the question 'why are landscapes not functioning as well as they could', they identified constraints at landscape level and those to be addressed at national scale as approximately equally important. This points to the need for policy coherence from local to national levels as key requirement for sustainable development[7].

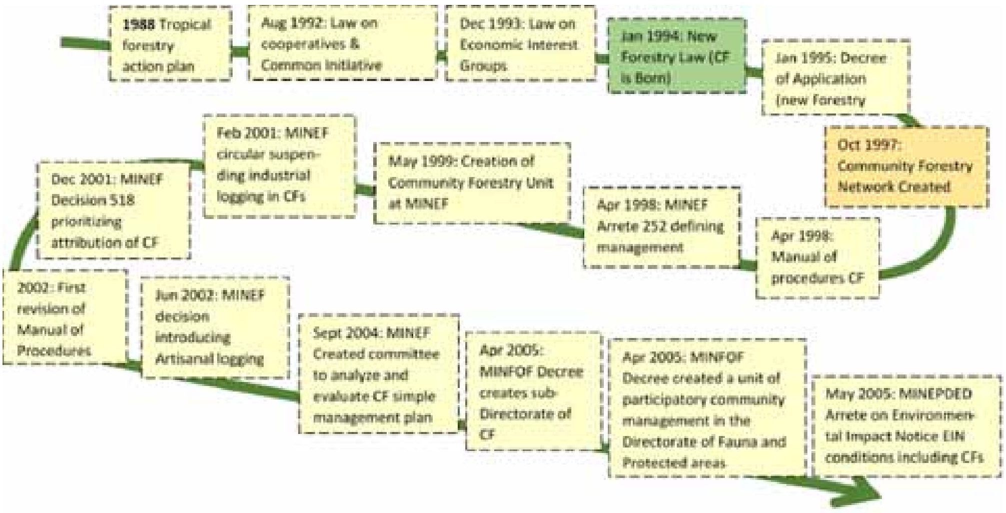


Figure 15.2 Timeline of key events in the legal and institutional landscape for community forestry in Cameroon since the early 1990s

15.2 Progress made

Tremendous progress has been made on policy processes and frameworks allowing about 1.8M ha of forests to come under community forestry. Significant progress has been recorded in the legal and institutional landscape for community forestry in Cameroon since the early 1990s. Table 15.1 summarises key milestones in the regulatory and policy reform processes in the last 20 years. Figure 15.2 shows a timeline of key events. Very little innovation has been recorded in the area of community forest management practice, especially in terms of enterprise development. Key areas of inertia in community forestry include community forest enterprise practice and collaboration between multiple CFs[8]. Evidence suggests that the majority of community forests have been without activity. A good number of CFs have been involved in subcontracting logging to partners on terms that have been deemed largely disadvantageous[9]. No evidence has been seen of non-timber forest products (NTFP) exploitation at scale or with reasonable value addition within CFs.

A unique case of ecosystem services enterprise development was seen through a Centre for Environment and Development (CED) led project recently, but there has been no marketing, nor certification of any services (i.e. REDD+ Credits) as intended. There were encouraging signs of collaboration between more than one community forest especially in the East Region with the creation of community forestry cooperatives, e.g. Cooperative Agroforestiere de la Trinational (CAFT), but we have seen little documented evidence of actual collaboration. The community forestry network contributed tremendously to legal and institutional reforms but has little to show in terms of joint actions.

Table 15.1 Summary of key progress domains/areas in community forestry in the last two decades

Progress domain	Description	Comments
Institutional Enhancement	Manual of the Procedures and Norms for the management of community forestry (MINEF, 1998)	Perhaps the most influential piece of legislation on community forestry, given that its promulgation saw a quick spike in the number of community forests in the country
	Community Forestry Management Unit created in 1997	The creation of this unit confirmed the commitment from the government that the community forestry agenda is taken seriously
	Creation of Sub-Directorate of community forestry in the Ministry in Charge of Forestry	This sub-directorate has played a significant role in anchoring the community forest agenda into the bigger forestry strategy of Cameroon. The sub-directorate also played a crucial role in facilitating the process of institutionalisation of community forestry
Enhancement of Rights	Introduction of pre-emption rights for communities in which communities were prioritized in the attribution of potential community forest areas in the face of competition from sales-of-standing volumes and other classic forest licensing options in the same non-permanent forest areas	In effect the introduction of this right was a giant leap in giving communities the confidence and opportunities in the face of competition from commercial logging companies
	Introduction of the provisional management plan alternative for communities further allowed communities without the necessary resources to proceed with exploitation of forests within a period of 2 years, for the purposes of raising the necessary funds to develop a simple management plan required for the final management agreement	While this was seen as remarkable progress, it led to a slowdown in the drive towards full management agreements. Less than 10% of CFs created after the pre-emption rights have moved beyond the provisional management agreement compared to almost 100% compliance prior to its introduction
Enhancement of Sustainable Forest Management	The ban on industrial logging and modalities and conditions for artisanal logging in community forests by ministerial circular in February 2001 and the Ministerial Decision No. 1985/D/MINEF/SG/FC respectively	These measures have been contested as illegal on grounds that a simple ministerial letter cannot overwrite a law passed in parliament
	Introduction of Environmental Impact Notice (EIN) in lieu of Environmental Impact Assessment	The EIN is the main tool to ensure activities proposed in the CFs do not result in negative environmental outcomes. Its introduction

Progress domain	Description	Comments
	(EIA) as an exploitation requirement for community forestry was a cost saving measure for CFs. Reducing costs from a maximum of about 16 Million CFA to a maximum of 2,500,000 CFA (more than six times)	therefore is welcome if properly implemented. The development and adoption of certification standards for community forestry initiatives in Cameroon (FSC 2010) https://www.scribd.com/document/45761832/FSC-Std-CFCameroon-Final

Benefit generation, partnership, monitoring, policy support and technical support came up as the top five variables, followed by financial support, practices, institutional factors and governance in an extensive analysis involving 46 papers on community forestry in Cameroon [10]. It is important to note that strong associations and dependencies were observed between these factors. These results have some implications for how we catalyse CF development going forward. Resources to support community forestry could be focused on the most important variables in order to obtain the best results. However, due to interdependencies observed among the variables, a holistic approach especially at policy level is necessary.

Several factors have been cited for the inertia in enterprise development namely: (i) Limited size of CFs, with 5000 ha proving to be too small for viable enterprises on a number of products; (ii) Institutional formats that are ill-adapted for enterprise, given lack of clarity on tax and other issues under Common Initiative Groups and Association formats within which more than 90% of all CFs currently operate; (iii) Lack of finance (especially start-up capital); (iv) Lack of knowledge and business development and management skills.

A few good cases of community social and livelihoods benefits have been recorded, while evidence of real economic and environmental benefits has been scarce. Meanwhile overall governance within CFs remain poor.

There is also evidence that CF management has contributed to forest cover increase e.g in the Kilum-Ijim Mountain area in the NW region- from 10500ha in 1983 to 20000ha in 2015[11]. This is one of the few documented positive environmental outcomes of CF in Cameroon. More negative outcomes were recorded indicating that governance remains a huge challenge. Accountability and equity emerge as the least respected good governance principles. Elite capture and power tussles between CF managers and traditional authorities were among key poor governance drivers. The areas with positive outcomes need to be encouraged, while challenges need to be tackled urgently[12].

15.3 Recommendations

A number of policy reforms might help catalyse innovations in CF enterprise and potentially generate envisaged economic, livelihood and environmental benefits such as jobs, revenues etc- hence contributions to SDGs 16, 15, 12 and 1. These include:

Defining and allowing simplified, yet compatible corporate institutional frameworks for CF could potentially reduce transaction costs and enable formation of enterprises:

Associations and Common Initiative Groups under which most CFs operate have been alleged to be non-compliant with taxation requirements of the Ministry of Finance (MINFI) and therefore not very suitable for business. On the other hand, current cooperatives and economic interest group procedures might be complex for community forests. Simplified cooperatives have been suggested in the past as potentially viable option amongst many. This and others need to be considered seriously.

Engaging MINPMESSA and MINFI on the terms for enabling a social enterprise status for CFs with favourable tax regimes, and targeted institutional capacity, technical enterprise and governance support could be helpful in eliciting social, economic and environmental benefits:

Even if current institutional deficits are sorted, a dialogue between MINFOF, MINMPESSA, MINFI and other relevant ministries is needed to clarify taxation issues on CFs with the aim of defining a favourable tax regime for CF[13]. Given the poor rural nature of the communities and vis-à-vis multiple social, economic and environmental objective envisaged, considering a social enterprise status for CFs is worth considering. This will allow for wider MINMPMESSA actions and other social investments in the form of capacity building, training, institutional support as well as grants that can potentially stimulate enterprise development.

Consider increasing the size of community forests beyond 5000 ha and/or allow species-based exploitation beyond compartments. In order to render community forestry more productive, it might be useful for policy to consider increasing the maximum area of CF beyond 5000ha:

A 5000ha CF exploited over 25 years for timber in compartments implies about 200ha per year, which would be grossly insufficient in most cases to meet minimum financial viability. This is further complicated by the fact that many CFs are found in secondary or previously logged forests and therefore degraded and resource poor. Another option could be for policy to allow exploitation by species across entire CF areas (instead of multiple species in small compartments as currently practiced). This might allow species rich forests a better chance of meeting scale requirements for financial viability. This option might also be suitable for community forests that have no possibility to expand the area of the CF under any future increased maximum area of CF, though this might come with increased risks of “illegal logging”.

Enable co-investments from climate and ecosystem services initiatives such as REDD+, GCF and eco-certification with multiple sustainable benefits:

In an era of scarce financing, enabling CFs access to diverse funding would be helpful. REDD+, BioCarbon Funds, Green Climate Fund (GCF) as well as premium prices for CF commodities through certification could provide much needed finance. Accessing any of these funds would require ramping up the monitoring and reporting capacity of CFs. In case of certification, the demands for better quality products will increase significantly also needing overall capacity enhancement to enable delivery of required quality in terms of environmental services such as climate regulation (carbon sequestration and emission reductions and biodiversity conservation[14][15].

Finally, with more than 450 CFs and millions of potential beneficiaries in rural communities, a soft financing programme in partnership with banks might be worth considering:

Instituting incentives that will target salient governance challenges including: catalysing progress beyond provisional management agreement, encouraging gender equity and participation, timely processing and issuance of annual exploitation permits and others. The introduction of pre-emption rights rules, allowing issuance of provisional management agreements have enabled communities hold on to forest areas and generate resources for completion of dossier required for final management agreement. However, more than 90% of CFs post pre-emption rights have not moved beyond the provisional management agreement stage. This stalemate needs to be addressed if any of these community forests would be sustainably managed for the benefit of communities.

Options could include (i) considering a special project that would help these community forests move forward: (ii) simplifying CF management plan requirements so more community forests can access it; and (iii) to consider increasing the length of exploitation under provisional management agreement. All options should be duly considered and supported by evidence in order to make sure that they bring on the desired impact. Conditional finance, institutional support, and capacity building type incentives could be deployed to encourage communities address accountability, equity, gender and other challenges[16][17]. Meanwhile some specific disincentives alongside "sermon" type incentives- e.g. education and awareness raising to minimize elite capture should be developed.

The proposed policy and policy implementation reforms could potentially enhance the contribution of CFs to multiple SDGs in Cameroon.

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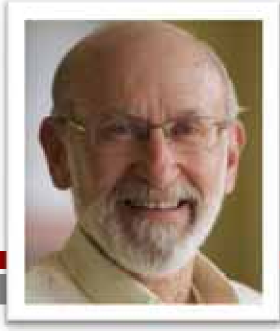
Dennis Garrity



INTERMEZZO 6

Call to action from ICRAF's (the World Agroforestry Centre's) fourth Director General (2001-2011)

"Agroforestry has now come of age as an integrative science, and it is now recognized as a very common land use system around the world. It is also now recognized as being at the heart of the solution to many of the world's most intractable problems. But let's get to heart of the matter: The fight against climate change has just become extremely more urgent and critical. The latest report by the Intergovernmental Panel on Climate Change (IPCC 2018) makes it clear that (1) we must immediately decarbonize the entire global economy and (2) we must recapture very large quantities of carbon back out of the air. Or else the extreme heat waves, and severe droughts, that are already causing havoc in many parts of the world right now, will soon be drastically worse."

The IPPC concluded that biological approaches to carbon capture are by far the most promising ones. These measures include protecting current forests, restoring degraded forest lands, increasing tree cover on agricultural lands through agroforestry, and increasing the biomass production of pasturelands. They are projecting the conversion of up to 500 million hectares of agricultural land and up to 800 m ha of pastureland into bioenergy crops, while also increasing the global forest area by up to 1 billion hectares. Unfortunately, such an enormous conversion in land use, particularly from annual crop production to bioenergy production with perennials, is not feasible. It would endanger the whole ability of the food production system to keep up with increases in population growth.

The good news is that nearly half of agricultural land already has greater than 10% tree cover, and it is accumulating 0.74 billion tons of CO^{2} annually. Millions of farmers are establishing leguminous shrubs and trees in their crop fields in many countries throughout the tropics. They harvest the foliage to fertilize their crops, provide fodder for their livestock, and provide fuelwood for household energy or for sale. These agroforestry techniques have been pioneered by World Agroforestry and its partners for the last three decades. These systems are currently being massively scaled-up in many countries in Africa. This source of bioenergy is already providing substantial electrical power generation in Sri Lanka. The offsetting gains in agroforestry carbon stocks can be further accelerated, because they are low cost, and they have high income, livelihoods, and resilience benefits for the farming populations, particularly in the tropics.

We must immediately promote progressive stretch goals for increasing agroforestry through the United Nations Convention on Climate Change and the Sustainable Development Goals. If the rate of increase of overall tree cover on agricultural land were to be quadrupled, if. agroforestry with leguminous shrub systems were implemented on 30% of global croplands.

We must also better protect current forest areas and restore the vast areas of degraded forest lands throughout the world through assisted natural regeneration. This could capture another 30% of current global emissions, bringing the total to 60% via nature-based solutions. 1.5-2.0 degrees C is our global goal to forestall catastrophe. But the experts give us only very slim chances of hitting it. We must launch a global crash program to develop evergreen bioenergy carbon capture and storage. Agroforestry must lead the way.

Gliricidia known as ‘fencing plant’ in Zambia

In Zambia, Gliricidia commonly known as 'fencing plant' improving soil fertility and yields in addition to reducing soil erosion and control pollution.

Photo: World Agroforestry

Suggested citation:

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CHAPTER SIXTEEN

Agroforestry's role in an energy transformation for human and planetary health: bioenergy and climate change

Meine van Noordwijk, Ni'matul Khasanah, Dennis P Garrity, Mary Njenga, Juliana Tjeuw, Atiek Widayati, Miyuki Iiyama, Peter A Minang, Ingrid Öborn

Highlights

- Sustainable and clean rural energy is essential for a coherent SDG portfolio on health, climate, food, jobs and terrestrial ecosystems
- Improved cooking stoves and policy support for charcoal production are still 'work in progress'
- Biodiesel derived from oil-rich seeds has created hope-hype-crash cycles and faces hurdles in accounting systems that include 'indirect land use change'
- Bio-ethanol production and large-scale wood-based energy focus on low-cost bulk production
- Rural evergreen electricity supply from coppiced fast-woods offers agroforestry synergy and prospects of integrated solutions at multiple scales

16.1 Climate change, energy transitions and agroforestry

When agroforestry was ten years old as formal term, the Brundtland report[1] on Sustainable Development reviewed many of the aspects that are still part of the current discussions – but it did not have the 'global climate change' issue on its agenda yet. Energy was amply discussed, however, and there the issue of carbon emissions was getting attention. Remarkably soon after that report, in 1992, the Rio conventions put climate change, biodiversity and desertification (land degradation) at the same level of priority and global commitments were made. It has taken the next 25 years to come to grips with implementation modalities and reframe the commitments as the 2030 Sustainable Development Goals (SDGs) of 2015, that presented access to energy, human health, climate change and integrity of terrestrial ecosystems at the same level as food, water, jobs and income (Figure 13.3).

Within the climate change discussions, the need for a decarbonization of the worlds' energy systems has been widely accepted, but its interactions with changes in terrestrial carbon stocks (including forests, mineral soils and peatlands) have been more contentious. Part of the problem is the different basis of accounting, at national scale, for energy-related greenhouse gas emissions at the 'demand' side of the equation, while changes in terrestrial C stocks are accounted at territorial or 'supply' level. With the connecting global trade outside accounting systems and the political interpretation of the agreed 'Common But Differentiated Responsibility'[2] controversial, there was no easy way to agree on effective measures. Initial resistance to seriously discuss 'Adaptation', as some had hopes that 'Mitigation' would be effective in curbing global climate change, was finally abandoned, but had led to firewalls between mitigation and adaptation at implementation and budget level (Fig. 16.1). Where agroforestry was already early on identified as relevant at the interface[3], there was little institutional space to follow through on synergies[4,5,6]. The focus on Reducing Emissions from Degradation and Deforestation (REDD+)[7] was on forests in their institutional definition and the concept of Reducing Emissions from All Land Uses (REALU) didn't get the early traction it might have deserved.

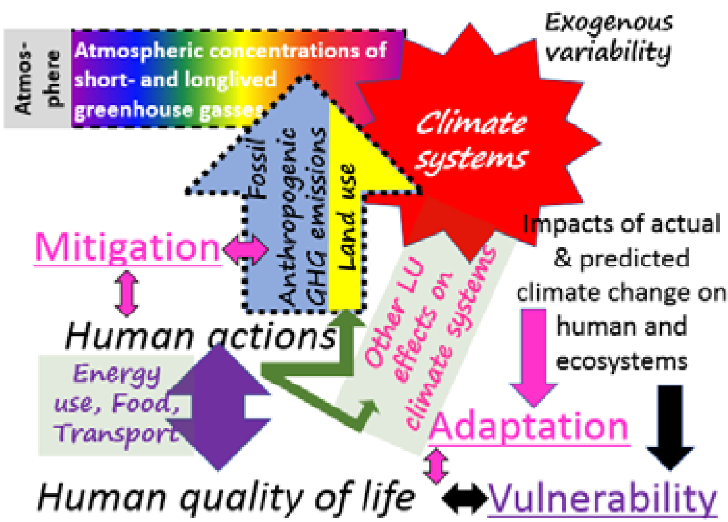

Figure 16.1 The logical loop of human actions aimed at increasing quality of human lives, but through use of fossil fuel and land cover change changing greenhouse gas (GJG) concentrations that change the global climate, with increased human vulnerability as a consequence; recognized intervention points are defined as emission reduction ('mitigation'), primarily through decarbonizing the economy, and dealing with the consequences ('adaptation'); direct effects of land cover on hydro-climate and temperature are discussed in Chapter 17; figure modified from[8]

Early surveys of farmer practice in relation to climate change[9,10] emphasized the relevance of trees and agroforestry. For farmers the association between 'trees' and 'climate' is obvious, as trees provide shade during the hottest part of the day, reduce windspeed and provide temporary shelter during rain. The effect of trees on climatic variables was so obvious that standard weather stations are operating at sufficient distance from trees to make their effects appear to be negligible. Yet, the 'microclimate' research that relates the actual conditions at the level of a plant, animal or human being to the vegetation and build-up structures was slow to connect with the global climate debates[11]. Global change as science had its origin in the data generated at synoptic weather stations and their change over time. Early criticism that part of the change in recorded data could be due to a changing context of the weather stations was seen as distraction – although stations that had obviously become part of 'urban heat islands' were taken out from the datasets studied. At the farmer level the microclimatic effects of trees are much more immediate and tangible than any role trees may have in global climate change – but the emergence of the 'climate smart agriculture' concept allowed local and global concerns to reconnect. At the interface of 'mitigation', 'adaptation' and 'vulnerability' the concept of 'climate smart agriculture' gained traction.

Beyond Mitigation and Adaptation, Agriculture and Forestry have to be jointly considered to link local solutions to global relevance[12], and in doing so their interactions with the 'energy transitions' agenda is at the heart of the matter.

16.2 Energy transitions

Cooking has been one of the biggest leaps forward in human history, and as trees often provide the fuel required, a close association between crops and trees to make sure there's something in the cooking pot and something to heat it (in other words: forms of agroforestry) has been as old as agriculture. When crop fields were scattered in a vegetation of recovering fallow plots, one didn't have to walk far to find firewood, but when cropped fields became contiguous and fallow periods short, maintaining firewood supply required specific efforts. In parts of the world hedgerows developed that combined functions in keeping straying animals from cropped fields, with microclimate effects and provision of wood for farm implements and as fuel. Traditional European agroforestry had strong rationale in wood energy security[13], an aspect recently gaining attention through emission accounting rules[14].

Energy is used for many aspects of modern lives, with cooking probably as oldest invention, requiring control over fire and its fuel. Energy can also be classified by its source, with solar energy driving many processes on Planet Earth, with nuclear transformations as driver of geothermal energy the main other source. However, much of the solar energy currently used has been stored in fossil fuels and can only be used by releasing CO_2. A tentative two-way classification of energy use (Fig. 16.2) can help to trace many of the historical energy transitions, and discus the way forward.

The steam engine was the first alternative to strongly location-bound hydropower as source of looms, and led to a drastic shift of the economic geography of textile industries. When steam engines were put on rails and became mobile a shift from woody biomass to fossil fuels of higher energy density was a step forward. The discovery of electricity and practical means to get it under control, led to a preference for coal as cheapest fossil fuel for electricity generation, and oil as basis for mobile engines. Woody biomass retained a significant share in the total mix only in countries of low population density. Average per capita energy use has only quadrupled from 1820 to 2010[15], but its energy source has shifted and (the 20 GJ p.p.p.y. in 1820 was nearly all from biofuels, the 80 GJ GJ p.p.p.y. in 2010 only for one-third), and the human population increased eightfold. Substitutions of biofuel involved coal, oil and natural gas, with a slow rise of hydroelectricity and a small role overall for nuclear energy sources.

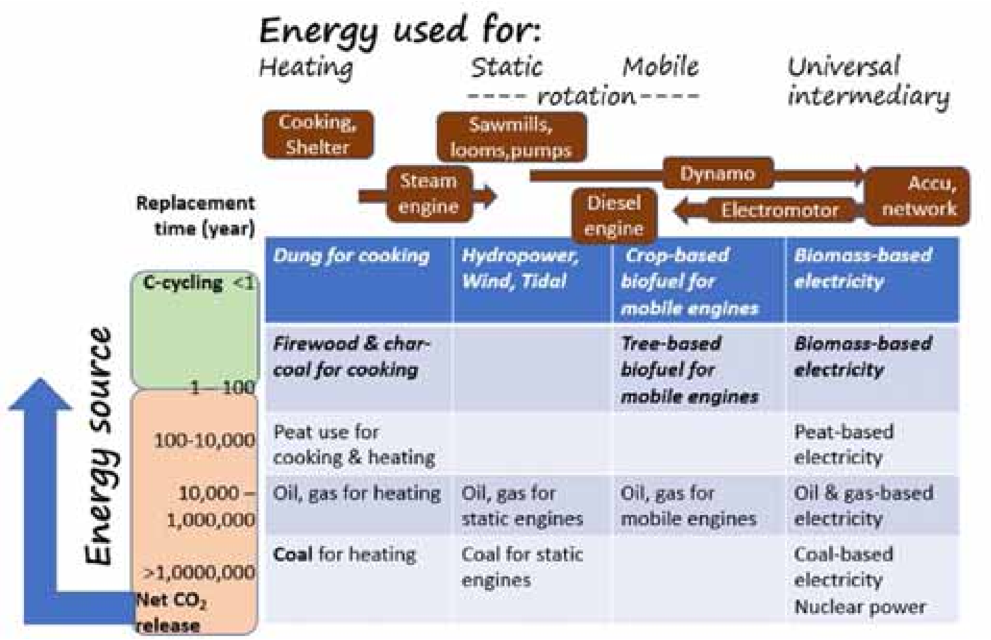

Figure 16.2 Historical energy transitions have involved both a shift in the types of energy used and the replacement times of the energy sources (linked to sustainability and net C emissions to the atmosphere)

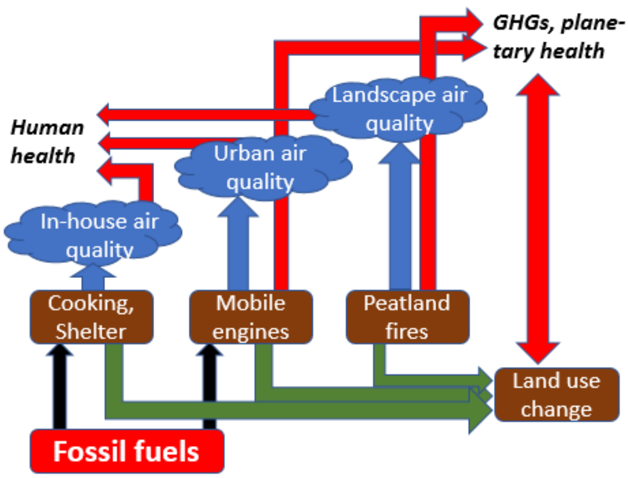

Figure 16.3 Relations between planetary health, human health effects of fuelwood use in closed kitchens, fossil fuel engines in urban areas and landscape level effects of peat fires

The search for emission-saving energy sources initially focussed on the undisputed relevance of mobile engines and their need for high-density energy carriers. Biodiesel and bio-ethanol became the targets. However, this ran into a number of challenges:

- When mainstream crops (maize, soybean) were used as source of oil in biodiesel production, the actual energy yield per ha of crop land was low, and barely compensating for the emissions needed for agricultural inputs to maintain production,

- Yet, the increased use as biofuel interacted with a fragile supply-demand balance and led to increase in food prices; in response the emphasize shifted to non-food fuel sources, preferably those that can be grown on land not suitable for crops,
- The productivity of such crops, despite initial claims to the contrary was low and they became part of a hope-hype-bust cycle[16],
- The most economically viable current source of biodiesel, palm oil, expanded rapidly, but became associated with both social and environmental concerns; especially where the expansion shifted to tropical peat soils (relatively free of human conflict), the carbon emissions exceeded any possible emission saving from replacing fossil fuels.

Meanwhile, the substitution of coal or oil for electricity generation by wood pellets became one of the main ways advanced economies tried to meet their emission reduction commitments – with serious questions about the sustainability of such biofuels and the accounting rules that make them appear to be carbon neutral.

In seeking 'carbon neutrality' in energy sources there is agreement that sequestration and emission within a single year can be ignored, but of the time periods relevant for woody biomass (say 5, 30 or 100 years) only for the first (e.g. fast-wood plantations or coppiced woodlots) can a 'neutrality' assumption be justified within currently agreed accounting schemes. The current 'rediscovery' of the relevance of energy derived from current solar radiation (or that of the recent past), meets parts of the world where the main energy transition pursued is still substitution of 'traditional and dirty' by 'modern and clean' fuels. A major human health concern over smoky kitchens has indeed promoted fossil fuel sources as clean substitutes. Are improved cooking stoves able to connect traditional fuel sources with modern standards and lifestyles? Concerns over air quality in cities now pushes governments to declare the end of fuel-using cars and their substitution by electrical cars. Can the fossil fuel phase of development be shorted by a more direct transition to electricity generation from (woody) biomass? If so, how does this relate to current accountability at production and consumption level?

There are still optimistic voices: "Well-designed bioenergy systems can contribute to several objectives, such as mitigating climate change, increasing energy access, and alleviating rural poverty. With adequate technical assistance and land management, farm yields and income can be increased, food security strengthened, carbon sequestration improved, and pressure for land clearing reduced. There are, nonetheless, risks involved on bioenergy production and several initiatives worldwide have failed to achieve proposed positive outcomes. Overreliance on monoculture plantations, negative land-use change impacts, and use of cereal crops as feedstocks are among the main causes. Agroforestry systems and practices can address most of these risks and thus play an important role in sustainable production of several bioenergy outputs, including efficient solid biomass, biogas, liquid biofuels, and dendro power (*Gliricidia pyrolysis*)."[17]

In a nutshell, the Climate Change agenda requires an energy transition, weaning off current fossil fuel dependency. Biofuels can be an important part of the solution, but the direct use of fuelwood, the biodiesel and ethanol type 'biofuels' and the current use of wood pellets for large-scale energy generation all have issues and problems associated with them.

Can agroforestry (in its connections between field/farm level AF1, multifunctional landscape level AF2 and governance/policy level AF3) be of help here? It can conceivably operate between the 'mitigation' and 'adaptation' side of the existing UNFCCC (SDG 13) rules and seek synergy with public health (SDG 3) and food supply (SDG 2) concerns. In this chapter we will review four possible pathways:

- Improving traditional wood-based energy sourcing, securing local health benefits,
- Hydropower, addressing the land requirement and impacts on local land use,
- Biofuel (bioethanol, biodiesel), acknowledging the failed silver bullets of the past,
- Rural wood-based electrification,

interacting with the accountability and accounting rules that apply.

16.3 Fuelwood, charcoal and human health

The four-fold increase in per capita energy consumption as global average between 1820 and 2010 is surpassed by current differences between national averages. Declines in fuelwood with increasing HDI (Fig 16.4) are offset by increased consumption of forest fibre, while fossil energy use rises faster than fuelwood declines with mainstream progress in human development.

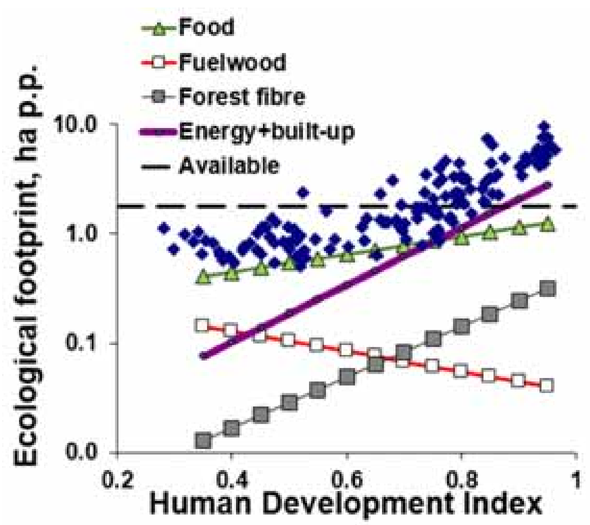

Figure 16.4 Ecological footprint (essentially the per capita area of forest supposedly able to re-absorb CO_2 emissions) of human consumption in relation to Human Development Index for countries of the world, with four main components: food production, use of fuelwood, use of forest fibre (timber, paper) and fossil energy use (plus cement) for a 'modern' economy (data for 2005)[18]

Woodfuel plays a critical role in energy provision in sub-Saharan Africa (SSA), and is predicted to remain dominant within the energy portfolio of the population in the coming decades[19]. Although current inefficient technologies of production and consumption are associated with negative socio-economic and environmental outcomes, projected charcoal intensive pathways along with urbanization may further accelerate pressures on tree covers[20].

In rural areas firewood is used as such (and often not problematic, except nearby protected areas[21]), for transport to and use in urban centres, charcoal is preferred (for its higher energy density, cleaner and more easily controllable burning). Yet, charcoal is more controversial than firewood, being blamed for a rapidly expanding circle of deforestation around Africa's urban growth centres. In the debate five commonly held perspectives on charcoal have been identified as myths[22] that are perpetuated by different stakeholders and actors, namely, that: 1) charcoal is an energy source for the poor; 2) charcoal use is decreasing; 3) charcoal causes deforestation; 4) the charcoal sector is economically irrelevant, and; 5) improved charcoal cook stoves reduce deforestation and GHG emissions. For each myth there may be specific reasons that it is perpetuated against the existing evidence, leading to misguided policy responses and intervention approaches.

Indeed, analysis of the charcoal value chain in Kenya showed that most of the value urban consumers pay had to cover for transport and illegal levies along the way (or levies justified by the illegality of the transport, depending on perspective)[23]. Policy reform based on reliable data might create stronger incentives for sustainable production, as well as reliable supply to urban consumers[24]. A systematic review[25] assesses what's known on the status of the fuelwood sector in SSA and estimates the magnitude of impacts of increasing wood demand for charcoal production on tree cover, which will be obviously unsustainable under business-as-usual scenarios (Fig. 16.5).

Agroforestry through use of prunings harvested periodically from multipurposes trees such as those produced for timber is making farmers self-sufficient with firewood [26]. This practice reducecs women's drudgery in gathering firewood from forests and avoids soil nutrient mining from collection of dead wood. Agroforestry, if widely adopted as an integrated strategy together with improved kilns and stoves, can have a significant impact to reduce wood harvest pressures in forests through sustainably supplying trees on farm. Further integrating agroforestry with improved kiln and stove technologies could significantly reduce global warming potential from charcoal and firewood production and use[27]. A systematic approach is required to promote multi-purpose agroforestry systems compatible with farmers' needs under local farming systems and current dryland socio-economic contexts.[28]

Despite decades of attention of rural development and 'appropriate technology' projects, there is a widespread sense that results have been disappointing. For example, a large-scale randomized trial in India, on the benefits of a common, laboratory-validated stove with a four-year follow-up showed that smoke inhalation initially falls, but that this effect disappeared by year two. Households used the stoves irregularly and inappropriately, failed to maintain them, and usage declined over time[29].

Attention has shifted to gasifier cookstoves, and where livestock is held, biogas production as cleaner and sustainable rural energy sources[30].

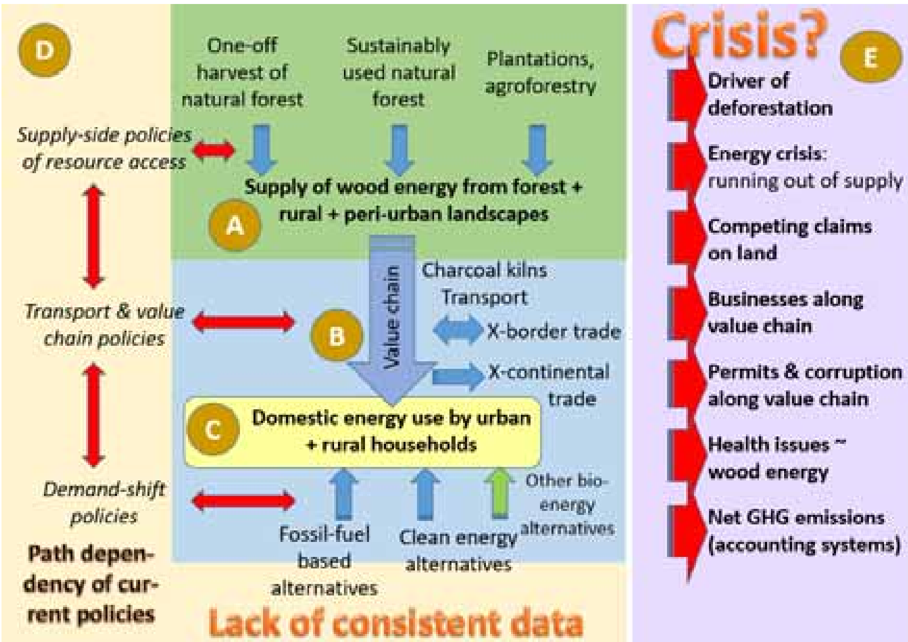

Figure 16.5 Conceptual diagram of the questions surrounding supply and demand of fuelwood and charcoal in the rural-urban continuum in relation to existing laws and regulations

16.5 Hydropower from healthy landscapes

Hydropower makes use of the global water cycle, driven by solar energy and modulated by vegetation. Watermills have existed for thousands of years, as evidenced by reconstructions of ancient mobile sawmills on the Tiber river in Rome. Some of the first active interventions in stream flows were to secure a stable supply of rotational energy, used for early industry, including looms for weaving.

After a phase of large reservoirs for combined generation of hydropower and regulated supply of irrigation water, the various environmental and social impacts led to a reconsideration and focus on smaller units, often with run-of-the-river designs. Still, such projects had major social impacts (compare Chapter 9), especially when conflicts over upstream land use erupted. Sedimentation, and hence reducing the economic life-time of the reservoir is the main issue in the large projects, while run-of-the-river with are highly dependent on flow regularity (compare Chapter 17). Plans for large interventions still exist for various parts of the world and remain controversial[31].

16.6 Liquid biofuels and biogas

Initial reports on the productivity of Jatropha curcas as source of oil-rich seeds, suitable for conversion to biodiesel sounded 'too good to be true'. And they were[32]. Interest in 'second generation', non-edible vegetable oils emerged around 2005, with Jatropha as its 'silver bullet' solution[33,34]. Technically these oils were ready for use[35], but the amount of policy support they received was out of balance with actual track records of productivity.

A number of authors have contributed to the 'post mortem' of the crash, focusing on technical shortcomings[36,37], or using a political ecology lens[38,39]. Existing knowledge of Jatropha productivity and constraints was not effectively used in the debate (Box 16.1). Others still see opportunities once research has resolved the low-productivity issue[40].

The economic potential of biofuel production from oilseed trees in small-scale agroforestry systems is often overestimated as profitability studies commonly ignore key methodological issues such as quantitative uncertainty analysis, full accounting for opportunity costs, and inclusion of all value chain actors[41].

Despite all this, still positive evaluations of Jatropha opportunities have been reported for Mali[42]. Elsewhere, attention has shifted to other oil-rich seeds[43], including those from the tree Pongamia (*Millettia pinnata), with greater attention to the production ecology, social-economic aspects*[44]*, pricing policies*[45]*, and basic requirements for farmer adoption.* Cross-sectional survey data on adoption of oilseed tree mixtures in smallholdings in Hassan district, South India, examined the impact of a biofuel extension program and farmer characteristics on adoption[46]. The findings revealed that tree cultivation is much more prevalent than oilseed collection, and that various activities of the biofuel extension program only stimulated the former. Low seed prices and high opportunity costs of labour are major factors impeding households to collect seeds from planted or wild oilseed species. The paper concluded that the program succeeds as an agroforestry program but not as a biofuel program.

A study in Tanzania[47] of income effects of agricultural biomass production for bioenergy purposes in comparison to firewood production found that the highest income effect for the poorest households derived from agroforestry, which households use as a source of firewood and fruits for sale or home consumption, followed by *Jatropha curcas*, sugarcane and finally cassava. Agroforestry in general has been also found to substantially release the pressure on public forest reserves.

A study for Indonesia[48] emphasized the relevance of geographical context: "The geographic focus for bioenergy development should take into account competitiveness with fuel and power generated from fossil fuels. Yet in areas where electricity is very expensive per kilowatt-hour and the fossil-fuel price is very high, which is typically the case in the outer islands, bioenergy is more likely to be competitive".

Multifunctionality of the specific plant or species options were taken into account as part of the context. Options prioritized here are nipa palm and 'nyamplung' (*Calophyllum inophyllum*) for coastal protection or restoration and for bioethanol and biodiesel production, respectively. Rice straw, rather than being burned as currently done, can be a feedstock for biogas. Albeit challenges, bamboo through biomass combustion or thermal mode, was a good potential for its abundance and being part of degraded land restoration approach.

Box 16.1 Jatropha hope-hype-crash[49]

Interest in jatropha as a biofuel crop has been driven by economic concerns over limited oil reserves and the global price of crude oil, by the global relevance of clean sources of renewable energy and by advantages Jatropha was claimed to offer from the national to individual household levels. Jatropha proponents further claimed that Jatropha production does not impact on food security due to its toxicity, whilst offering the added benefits of erosion control, soil enrichment, water infiltration and flood reduction, carbon storing, and the possibility of earning carbon credits. Many of the claims put forward were based on optimistic assumptions, especially regarding yield and the early warning signs and calls for caution were largely ignored, buried or overtaken by the wave of hype. Jatropha has been through multiple hype cycles dating back to 1945-50. The disappointment observed during the first hype could simply be attributed to a very specific need that was no longer relevant. The second and subsequent cycles share many similarities and resemble other 'miracle' crops. A combination of market pull (society, economy, environment and government mandates, subsidies, land allocation, and investors) and technology push factors were responsible for the disappointment. The push factors (oil processing and value adding) were not sufficiently well prepared or developed; they also were not implemented within the framework and guidelines necessary for realistic commercial development. Research in Indonesia highlighted the fact that many actors exploited the system for personal gain. Policies were often influenced by a network of powerful entrepreneurs who manipulated the process for personal gain. Companies and NGO's were able to access subsidies or bank loans and investment funds to develop large or smallholder jatropha plantations, while brokers successfully managed to get a piece of the subsidy cake. Researchers were able to access numerous research funds. While smallholders were often depicted as victims of land grab there were many who joined in the exploitation of jatropha. In hindsight it is easy to see why the jatropha hype ended in disappointment. From our review it is clear that jatropha was introduced without a comprehensive understanding of crop development and performance and market supply and demand.

It will be important that any strategies developed for similar crops be designed to foster energy development and improve socioeconomic conditions so as to instill the confidence necessary to once again adopt jatropha or any alternative crop. The biophysical results from this study highlight a need for high yielding jatropha varieties suitable for areas that do not compete with existing food crops. Production management systems that maximize commercial potential will also need to be developed, but not at the expense of the environment. Our jatropha – maize intercropping results showed that different management practices such as fertilizer, pruning, and planting density can reduce competition and/or enhance complementarity. Popular belief is that if the objective is to maximize jatropha yield, then maize yield suffers, and vice versa, although this may not be the full story. While intercropping with maize has been the study focus there may be other more suitable crops. In essence there is no single, generic or even correct solution so for growers to maximize plant growth and yield relative to their location and circumstances, they must understand that trade-offs are a necessary part of any multiple objective system. In reality for farmers it is simply yield and what combinations will provide the highest return on investment. The yield and social benefit uncertainties outlined in our study confirm that jatropha should not be promoted as a smallholder or plantation crop. Only when the underlying causes of the jatropha hype and disappointment have been addressed and satisfied will we see improved commercial performance and socioeconomic conditions and environmental concerns conducive to a successful biodiesel industry

A study of factors affecting landowners' preferences for bioenergy production in Central Kalimantan[50] indicated that 76% of landowners preferred well-known species that have a readily available market, other than as source of bioenergy, such as sengon (*Albizia chinensis*) and rubber trees (*Hevea brasiliensis*) for restoration on degraded land. Only 8% of preferred nyamplung (*Calophyllum inophyllum* L.) for bioenergy production, as they had additional jobs and income, or had migrated from Java where nyamplung is prevalent.

Technically palm oil (*Eleais guineensis*) has been the main success story as feedstock for biodiesel, but the success has created problems of its own[51,52,53] and only partial success in self-regulation by the industry through standards and certification mechanisms[54]. We will come back to this in the section on accountability and accounting systems.

16.7 Bio-electricity for flexible uses

16.7.1 Creating EverGreen Food-Energy Systems for Rural Electrification

Prospects may be far better for small-scale electricity production for rural electrification. Six hundred million people, two-thirds of the population of sub-Saharan Africa, are still without electricity. In Malawi, for example, only 7% of the population has access to electrical power. This is an enormous drag on rural economic growth, and on improved outcomes in food production, health, and education. Ninety-percent of the sub-Saharan African population currently relies on firewood and charcoal as their primary source of energy for cooking, heating and other uses.

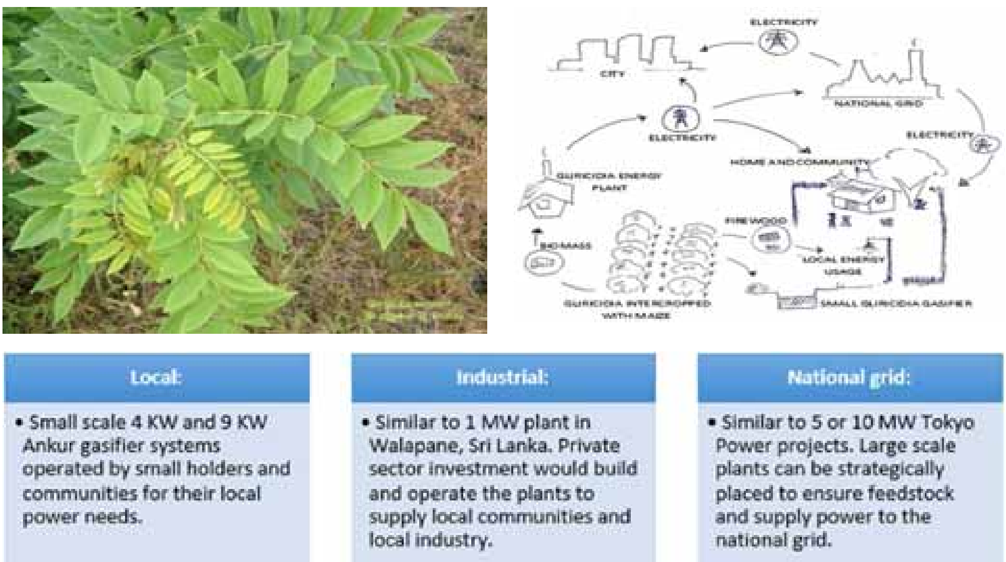

Figure 16.6 Opportunities at local scale, industrial areas and the national grid of a gliricidia-based electricity production

Experience now shows that tree-based systems can simultaneously provide electrical and bioenergy for the home and for industry, while also providing biofertilizers for crop production, and better-quality fodder for livestock production. These systems have the potential to transform livelihoods and food security, and enhance economic development while conserving the environment.

The approach overcomes concerns that growing crops for bioenergy might compete for resources with food production. On the contrary, through the concept of EverGreen Energy, fertilizer-fodder-fuel wood trees are incorporated into crop fields to provide the feedstock for power generation, while at the same time they directly increase crop yields, provide enhanced high-quality livestock fodder, improve vegetative soil cover year-round, increase soil fertility, and buffer crop production from drought and higher temperatures due to climate change. They also store much greater quantities of carbon in the soil and enhance biodiversity.

16.7.2 Gliricidia power generating systems in Sri Lanka

Similar to Africa, much of Sri Lanka's rural population is completely off-grid and without any electrical power. This situation has fostered a real innovation in the power sector. During the past 25 years, partners have worked to develop a dendro power industry, largely based on gliricidia as a feedstock. Gliricidia is so widely grown by Sri Lankan farmers that it is officially designated as the country's fourth plantation crop (along with coconut, tea and rubber). Lanka Transformers Limited (LTL) installed a 35 kW generator operating exclusively on gliricidia wood as a demonstration unit. Upon achieving operational success, LTL together with Ankur gasifier systems (Ankur Scientific Energy Technologies Pvt.Ltd) launched community-scale 4 KW and 9 KW systems using Gliricidia feedstock from smallholders for electricity generation.

Figure 16.7 A. Gliricidia intercropped with coconut in Sri Lanka. The trees are pruned every eight months to provide the biomass feedstock for electrical power generation; B. a 290 kW gliricidia fueled power plant in Sri Lanka, C. D. A 1.5 MW gliricidia fueled power plant in Sri Lanka

The Ceylon Tobacco Company (CTC) then established a commercial-type 1MW power plant in Walapane. This plant demonstrated all aspects of converting gliricidia to supply the national electricity grid. The success of this plant sparked the interest of the private sector. The Bio-Energy Association of Sri Lanka was formed, and through the Sri Lanka Sustainable Energy Authority, established the inclusion of dendro power to meet national energy demand.

In 2009, Tokyo Power constructed and commissioned a 10 MW gliricidia-fueled plant in Trincomalee, Sri Lanka. Following its success, the company recently commissioned a second plant of 5 MW capacity in Mahiyanganaya early in 2014. There is a 500 kW plant in Thirappane (Anuradhapura) and a 15 MW plant in Embilipitiya. It is reported that there are several more glircidia-based power plants now under development.

16.7.3 Gliricidia Systems in Southern Africa

Gliricidia is already widely distributed in farming systems throughout Africa, having been introduced four centuries ago. Research during the past three decades has demonstrated its value as a superb fast-growing nitrogen-fixing fertilizer tree. In Malawi, gliricidia is a major species underpinning the scaling-up of fertilizer trees for increasing crop yields in maize-based systems through the National Agroforestry Food Security Program. Practical systems for intercropping trees in maize farming have long been developed, and they are currently being extended to hundreds of thousands of farmers in Zambia and Malawi. They are being massively scaled-up in eastern Zambia, where 25 million trees were planted by smallholders during 2013 alone.

The development of food-energy electrification projects would be a natural extension of the type of crop production systems practiced in these two countries. The species has also been widely tested and is well-adapted for such food-energy systems in Tanzania, Kenya, Ethiopia, and many other countries across the African continent.

16.7.4 Addressing a Perfect Storm of Challenges to Food Security

African agriculture must be transformed in the coming decades. With a population burgeoning to 2 billion people, at least twice as much food must be produced per year by 2050 to avoid widespread starvation. But food production per capita has been declining since the 1960s, and cereal crop yields have remained stagnant. In the face of this dire situation, observers are pointing to a perfect storm of further challenges.

EverGreen Agriculture is now emerging as an affordable and accessible science-based solution to regenerate the land on small-scale farms, and to increase family food production and cash income. EverGreen Agriculture is a form of more intensive farming that integrates trees into crop production systems at the field, farm, and landscape scales. The vision is sustaining a green cover on the land throughout the year.

The next step will be to foster South–South learning as a means to generate viable and successful development initiatives. We aim to facilitate the sharing of knowledge and experiences from Sri Lanka with interested parties across Eastern and Southern Africa (governments, communities, investors and power plant developers). In so doing, strong relationships across national and intercontinental borders will be fostered, allowing for ongoing cross-country sharing and co-learning to occur in the future beyond the life of the project.

Feasibility analyses and public-private partnerships will be developed to pave the way for attracting and harnessing substantive levels of commercial and public sector investment in the development of an agroforestry-based energy industry in Eastern and Southern Africa, with an emphasis on implementing new commercial-scale projects that can fully demonstrate the potential for wide expansion.

Box 16.2 A resource for firewood as seen by Evergreen Agriculture proponents

The gliricidia systems increase the on-farm production of firewood, a resource which is increasingly short supply in Africa smallholder agricultural systems. Farm production of adequate fuelwood saves the drudgery of women and children in travelling long distances to collect it, and this releases time and energy for other income-generating activities. It also reduces the destruction of natural forests by reducing the need to collect firewood from public lands. The increased supply of fuelwood that will be produced in association with the commercial production of glricidia for power generation will also ensure that the cooking and heating energy needs of the communities are amply met.

Our vision is a fully-fledged, integrated and sustainable tree-based food-energy system (EverGreen Energy) that is operating and providing benefits to numerous communities across Eastern and Southern Africa. We envision that the systems will be providing rural electrification benefits to 'powerless' communities, enhanced income generation from growing the feedstock, increased crop production with enhanced soil fertility, and greater wood-fuel availability in rural areas.

16.8 Accounting and accountability issues

While the earlier debate and policy formulation was mostly at the level of the plant species used for bioenergy production, subsequent analysis showed that footprints (emissi0ns caused per unit product) varied more widely within than between types of feedstock[55]. Palm oil was found to be both the best (most productive with low emissions when grown on mineral soils replacing low-C-stock vegetation) and the worst (when converted from forest on deeply drained peat soils)), within a range of tropical and temperate feedstock sources.

That defines a problem for the accounting. If the type of product is not a good predictor of the emissions savings, should rules apply at the national scale of a country of origin? A region within a country? A company that is transparent about all of its production? A specific, certified plantation? In the biofuel debate the issue of indirect land use change became specifically controversial (Box 16.3).

Box 16.3 Accounting challenges palm oil[56]

The public debate on oil palm heated up by the increasing options for use of palm oil as non-food product. Emerging demand for palm oil from European countries followed from policies to reduce their attributed CO_2 emissions through the use of biofuels, with associated carbon emissions outside their books. Based on earlier critiques, biofuels must (from 2018 onwards) lead to at least 60% emissions saving at global scale in order to be included in the EU policy, but the assessment of such emissions (at sector, national, company or plantation scale) is still debated.

Calculations of the palm oil carbon footprint for biofuel consider three phases of the production process and four types of emissions: (i) the initial conversion of preceding vegetation into an oil palm plantation, usually based on 'land clearing', leading to a 'carbon debt' defined as the difference between time-averaged C stock of the subsequent plantation and that of the preceding vegetation, (ii) the emissions due to production of external inputs, such as fertilizer, (iii) the growth cycle of the oil palms (typically around 25 years) and its management and fertilization practices that lead to the yield, direct fertilizer-related emissions and an aboveground and belowground time-averaged C stock of oil palm that influences the carbon debt and repay time, (iv) post-harvest processing including transportation until the product reach the end user.

Palm oil used for biofuel and produced in plantations derived from low (below 40 t C ha^{-1})[57] C stock land covers on mineral soils[58] and second-generation plantations (without attributable carbon debt) can achieve current targets for emissions saving when compared to the use of fossil fuel, when fertilizer levels are adjusted[59].

Based on the sampled companies with good agriculture practices, 25% of Indonesian palm oil production can meet the 60% emissions savings standards for net emission reduction when used as biofuel. This is more than what is currently exported to the EU for that purpose. When the EU threshold will increase to more than 70% in the near future further efficiency increases, including in the use of N fertilizer and in dealing with emissions at the mill will be needed.

The rationale for the “Indirect Land Use Change” ILUC debate is that even if the footprint of specific products used in biofuel matches the existing standards, its use as biofuel might displace current other uses of the same product (e.g. in the food industry) and lead to expansion of production elsewhere. As such, it is not informed by data of the types presented and discussed here. As ILUC calculations are generic, they don’t provide any incentives for or recognition of attempts to improve practice on the production side. Their primary target is the consumer/user side, nudging away from commodities with high ILUC tax (such as vegetable oils with current (or at least recent) expansion in high-carbon-stock density parts of the world) and towards those with low ILUC tax (such as vegetable oils grown in areas where conversion took place long ago). A major challenge of the ILUC concept, however, is that the choice of the level at which it is applied (commodities such as ‘palm oil’ with its global markets and expansion) appears to be arbitrary. One could equally argue that a generic ILUC tax should apply to all vegetable oils that are interchangeable for at least some of their uses.

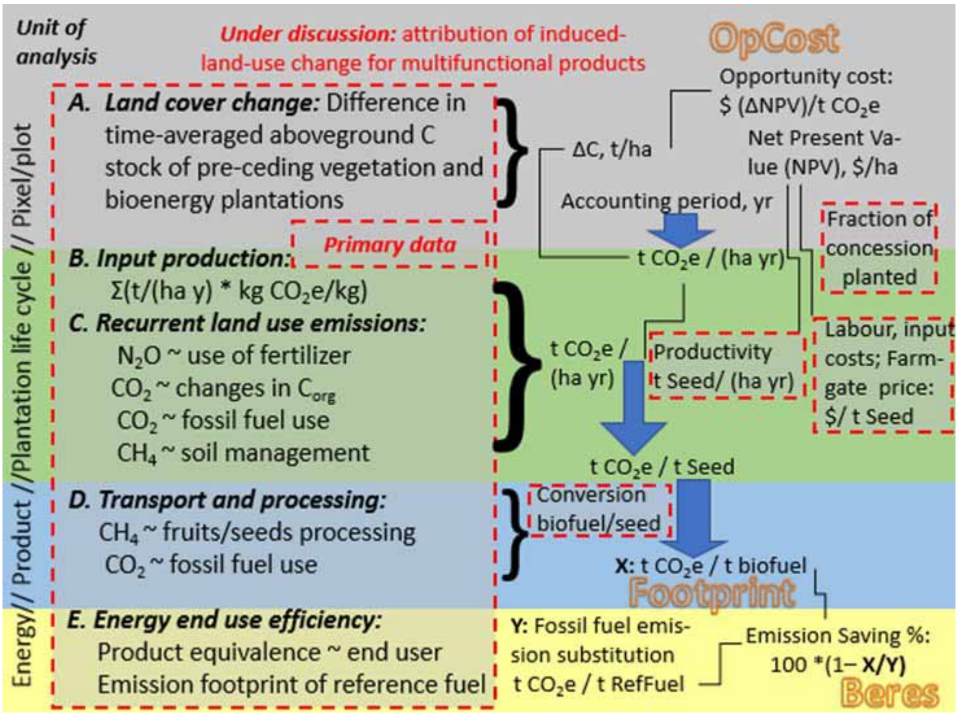

Figure 16.8 Biofuel Emission Reduction Estimation Scheme (BERES) as used for quantifying palm oil footprint in Indonesia

Oil palm as one of biofuel feedstock with relatively cheap price compared to other vegetable oils was found to be both the best (most productive with low emissions when grown on mineral soils replacing low-C-stock vegetation) and the worst (when converted from forest on deeply drained peat soils). Photo: World Agroforestry/Ni'matul Khasanah

While the BERES scheme (Figure 16.8) can be used for consistently comparing any biofuel source that has potential to substitute for fossil fuels, there are challenges where global trade is involved. Where carbon is sequestered in the country of production and released in the country of consumption, the emissions embodied in trade will have to be accounted for in a transparent overhaul of the current rules[60]. Currently well-intended actions by individual consumers in importuning countries ('individually determined contributions', such as a palm oil boycott) are not directly linked to area-based accounting and Nationally Determined Contributions in producing countries (Fig. 16.9).

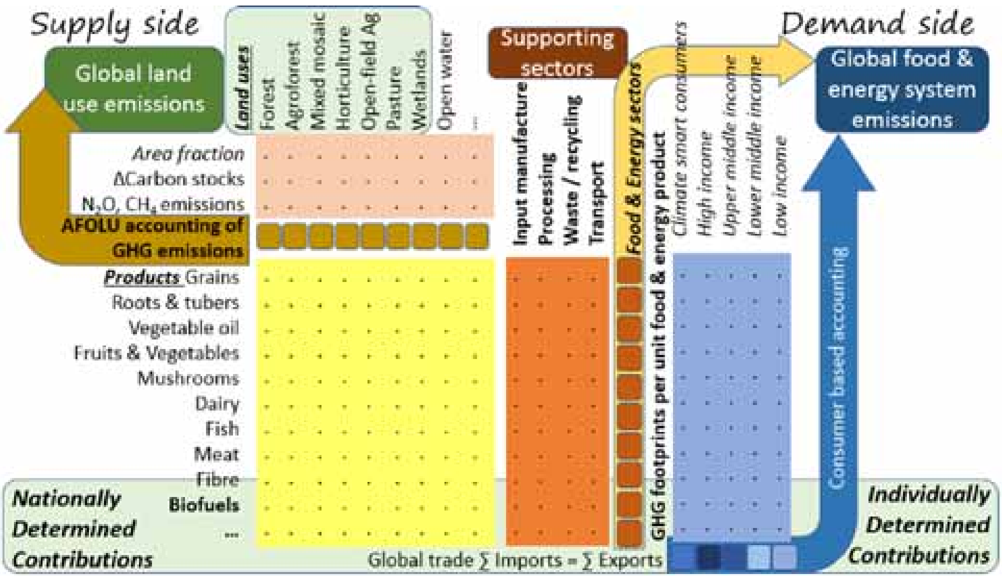

Figure 16.9 Accountability through the supply side of land use, interacting with that through the demand side of consumption, with challenges for coherent accounting of nationally and individually determined contributions to climate change mitigation, especially where global trade is involved (embedding emissions in tradable goods)[61]

Rural energy is clearly a key aspect of 'sustainable development' and conversion of biomass to electricity may offer the access to clean energy-demanding applications. But solutions need to be analysed in their regional 'green growth' context, as will be further explored in Chapter 21.

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Nature-based water management

Nature-based solutions for stabilizing the banks of an irrigation channel in Bali (Indonesia)

Photo: Brawijaya University/Eka Purnamasari

Suggested citation:

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CHAPTER SEVENTEEN

Trees as part of nature-based water management

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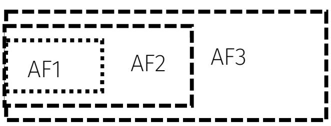
Highlights

- Trees link local to regional and global water cycles through their modification of infiltration, water use, hydraulic redistribution of soil water and their roles in rainfall recycling
- Nature-based water management is complemented by technical interventions for water retention, redistribution, flow regulation and recycling, but it generally is more resilient and adaptive than concrete and steel structures
- Understanding forest (and tree) water relations can be characterized by three paradigms: 'paradise lost', 'blue-green water competition' and 'full hydrological cycle'
- Agroforestry can contribute to enhancing nine specified 'ecosystem services' that relate to water, with priorities depending on context and ten prototypes for coinvestment
- Four types of 'boundary work' are recognized at the governance level, to link local solutions to global and (sub)national problems

17.1 Introduction



Water has been explicitly (or sometimes implicitly in its climate relationships) discussed in nearly all preceding chapters. Water links the plot, landscape and governance scales of the three agroforestry concepts (Chapter 1), it is a key determinant of tree growth and adaptations (Chapter 2), relevant traits can be a target of tree domestication (Chapter 3); water is an important component of soils (Chapter 4) and tree-soil-crop interactions (Chapter 5). The pantropical analysis of agroforestry (Chapter 6) found climate (and specifically the ratio of rainfall and potential evapotranspiration) to be a major determinant of tree cover on agricultural lands. All the landscape examples dealt with water, through restoration and modification of microclimate (Chapters 7, 8 and 12), through contested land use rights and watershed functions (Chapters 9, 10 and 11). One of the key features of small islands (Chapter 13) is a shortage of freshwater storage, while excess and deficits of water are at the basis of many disasters (Chapter 14). In this chapter we will discuss how the shift in agroforestry concepts (from field/farm-level AF1, to landscape level AF2 and governance level AF3, as detailed in Chapter 1) has interacted with research and contributed to an increased understanding of the way all water-related aspects are interlinked, urgent in the current sustainable development discussion, and open to a wide range of tree and agroforestry- based interventions (with several examples of how such interventions have backfired where understanding was incomplete). Hydrological, ecological, social, economic and policy aspects of trees as part of various land uses in relation to water, are tightly linked (a Gordian knot?). Yet, the relationship between tree cover and human water security is strongly contested[1] (Fig. 17.1), with 'pumps' versus 'sponges' as key features of forests[2] and atmospheric recycling as arena of debate[3].

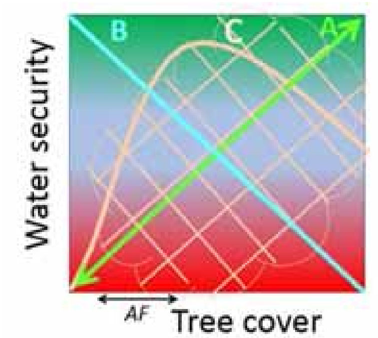


Figure 17.1 Contrasting perceptions of the relationship between tree cover and human water security: A. All loss of forest implies loss of security, B. Focus on maximizing blue water yield by minimizing green water use, C. Full hydrological cycle, with optimal tree cover concepts depending on context, trees and weakest links (e.g. quality, quantity, flow regularity, rainfall induction) in water security

Laymen's discussions of water often express high expectations on the roles of forests and trees for specific aspects of human water security (Fig. 17.2). There is considerable history to this[1,4].

Figure 17.2 Questions related to forests, trees, water, people and climate (change)

Policy discussions on forest, trees, water and rights to land have changed over time, but with only a limited role for science-based understanding[1,5]. In the colonial period presumed hydrological functions that can only be provided by 'forest' became a major rationale for the state's claims on any land not yet converted, for example in Indonesia[6]. Ecohydrological discussion in the 1930's focussed on unique functions of **forests** as sponge (retention) versus an appreciation of multiple land uses that secure infiltration (dependent on terrain, geology and surface conditions) and allow **soils** to act as sponge[7]. The debate tried to reconcile practical experience with mechanistic understanding of the water balance, with important implications for the types of forests to be conserved and/or restored. The debate was left unfinished at the end of the colonial period and replaced by other priorities. Space for agroforestry and partial tree cover, and for the agroforesters whose livelihoods depends on 'state forest land' had to be created by tackling both the scientific understanding of hydrology, and the power relations between national and local stakeholders of well-functioning landscapes (compare Chapter 9). Elsewhere, colonial policies to enforce soil conservation became part of the struggle for independence in East Africa, and it took long before the negative stigma of top-down prescribed solutions could be replaced by bottom-up initiatives, adjusted to local context. Currently, three forest-water paradigms coexist[1] (Figure 17.3). They have been labelled 'Paradise lost' (line A in figure 17.1), 'Blue-green water trade-off' (line B in Figure 17.1) and 'Full hydrological cycle' (Area C in Figure 17.1). The latter includes the concept of an intermediate tree cover optimum at landscape scale, but also 'rainbow water' (atmospheric moisture) as part of the wider feedback system, and attributes hydrological impacts to at least five aspects of land cover (Leaf Area Index, surface litter layers, rooting depth, soil structure and specific effects on downwind rainfall). Agroforestry, seen as land use with intermediate tree cover or as a continuum between agriculture and forestry is closely associated with the latter paradigm. This aligns with a recent UN Water report[8] on 'Nature-based solutions' that seeks a more coherent approach to the various aspects of water flows (availability, quality, avoiding disasters) and storage that matter to large numbers of people around the world (Box 17.1).

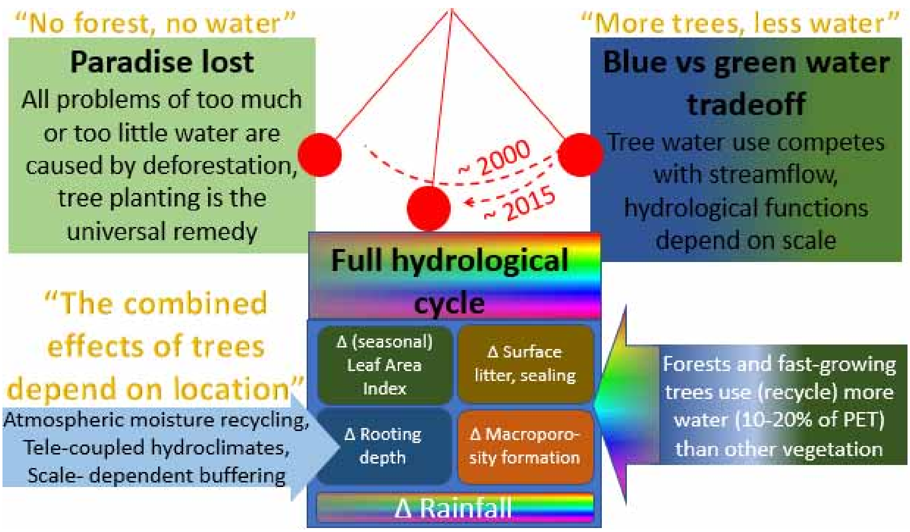


Figure 17.3 Shift between three 'forest-water' paradigms and examples of the scientific analysis and practical experience that contributed to paradigm shifts[1]

Box 17.1 Nature-Based Solutions for Water[9]

Human demand for water (agricultural, industrial, domestic) keeps increasing, while climate is becoming more variable and water pollution has worsened in almost all rivers in Africa, Asia and Latin America. The trends in water availability and quality are accompanied by projected changes in flood and drought risks. The number of people at risk from floods is projected to rise from 1.2 billion today to around 1.6 billion in 2050 (nearly 20% of the world's population). The population currently affected by land degradation/desertification and drought is estimated at 1.8 billion people, making this the most significant category of 'natural disaster' based on mortality and socio-economic impact relative to gross domestic product (GDP) per capita.

Nature-based solutions are relevant for managing

- ***water availability,*** mainly by addressing water supply through managing precipitation, humidity, and water storage, infiltration and transmission, so that improvements are made in the location, timing and quantity of water available for human needs. Reference to precipitation in this list reflects the breakthroughs in understanding 'ecological rainfall infrastructure'. The technical option of building more reservoirs is increasingly limited by silting, decrease of available runoff, environmental concerns and restrictions, and the fact that in many developed countries the most cost-effective and viable sites have already been used. In many cases, more ecosystem-friendly forms of water storage, such as natural wetlands, improvements in soil moisture retention and more efficient recharge of groundwater, could be more sustainable and cost-effective than traditional grey infrastructure such as dams. Nature-based solutions for addressing water availability in urban settlements are also of great importance, given that most of the world's population is now living in cities. Urban green infrastructure, including green buildings, is an emerging phenomenon that is establishing new benchmarks and technical standards.
- ***water quality.*** Source water protection reduces water treatment costs for urban suppliers and contributes to improved access to safe drinking water in rural communities. Forests, wetlands and grasslands, as well as soils and crops, when managed properly, play important roles in regulating water quality by reducing sediment loadings, capturing and retaining pollutants, and recycling nutrients. Where water becomes polluted, both constructed and natural ecosystems can help improve water quality. Non-point (diffuse) source pollution from agriculture, notably nutrients, remains a critical problem worldwide, including in developed countries.
- ***water-related risks*** (floods, droughts). Water-related risks and disasters, such as floods and droughts associated with an increasing temporal variability of water resources due to climate change, result in immense and growing human and economic losses globally. Around 30% of the global population is estimated to reside in areas and regions routinely impacted by either flood or drought events. Ecosystem degradation is the major cause of increasing water-related risks and extremes,

Nature-Based Solutions for enhancing water security across all aspects aim for multiplying the benefits. However, such solutions often require cooperation among multiple institutions and stakeholders, something that can be difficult to achieve. Current institutional arrangements (including agriculture, forestry, irrigation, domestic and industrial water supply institutions, and waste-water treatment plants) did not evolve with cooperation on nature-based solutions in mind.

Trees are cool[9], as can be seen in remotely sensed surface temperature records of the earth surface, largely because they intercept and transpire more water than most other vegetation would do[,10], often by having greater access to deeper soil water reserves[11]. Effects of deforestation on water flows and cycles, and the degree to which these changes can be reversed by tree planting have been discussed for at least the past two-thousand years, while the world lost 46% of the trees it had at the start of human civilisation[1] and the human population increased to more than seven billion people, with four billion of them considered to be water-scarce[12]. Approximately 1.36 trillion of current trees exist in tropical and subtropical regions, 0.84 trillion in temperate regions and 0.84 trillion in the boreal region[1]. Current hydro-climatic understanding suggests that the roles of trees depend on the climatic zone considered, as well as local topography[2], replacing previous paradigms of 'no forests, no water', as well as 'more trees, less water' as supposed general (universally valid) truths[1]. Forest and Tree - Water relations depend on context, and thus on 'Theory of Place' (which here includes seasonality and interannual variability of climate), influencing various terms of the water balance. It has taken time for the various positive and negative effects of trees on the local water balance to be understood, as the net effect depends on soil, climate and qualitative, quantitative and distributional aspects of tree cover, with a high risk of 'over-generalization'.

Globally there is no scarcity of water as such – but water of the right quality is not freely available everywhere and human appropriation of the available water resources is a valid concern. At any point in time only 0.03% of the freshwater on planet Earth is to be found in the atmosphere (Fig. 17.4), while 30% is in (deep) groundwater reserves and 69% in glaciers and ice caps. Yet, in total, freshwater is only 3% of all water on the planet, with 97% in oceans. At global scale oceans are a source of atmospheric moisture that becomes rainfall over land, and a recipient of rivers (and some groundwater flows in coastal areas). Warmer oceans imply more rainfall over land including extreme rainfall due to cyclones and typhoons. As the atmospheric moisture pool is so small, and its turnover time high (with a mean residence time of 8 – 9 days)[13], it is possible for local evapotranspiration to influence 'downwind' precipitation (as we will discuss in more detail below). A major way to increase temporal aspects of water availability for humans is protecting ecological buffering[14,15,16] and increasing rainwater harvesting and storage. Rainwater harvesting[17] interventions in spatial context[18] have been grouped as (i) rooftop water collection, (ii) surface runoff from open surfaces with storage in pans/ponds, (iii) flood-flow harvesting from watercourses with storages in sand/ subsurface dams and (iv) in-situ soil water storage systems. Although it is still common to have the source of rainfall and the fate of evapotranspiration as external to the system of study in managing water and agroecosystems for food security[19], the evidence that atmospheric moisture over continents is subject to land cover feedbacks has rapidly accumulated[20,21] and led to recognition of rainfall generation as ecosystem service[22]. The first specific applications of these insights are emerging[23]. The spatial and temporal scale of land cover feedback on rainfall remains contested with counteracting mechanisms influencing atmospheric moisture supply and the turbulence that triggers precipitation[24].

Trees use water, like all plants do. Trees, however, often have access to deeper soil layers than other plants, so they can maintain actively functioning leaves for a larger part of the year[25]. Overall, by a larger canopy interception term + transpiration (water use), forests (or vegetation with considerable tree cover) increase evapotranspiration by about 100-300 mm/year[a], when compared with a short (grass) vegetation[11]. The difference is larger when compared to bare soil, where only the soil surface evaporates water. Thus, we can expect total water yield to decrease by a similar amount. Through their litterfall and root turnover, however, trees also contribute to biological activity in the topsoil that increases infiltration and avoids sealing of the soil surface. This means that a smaller part of rainfall reaches streams as surface runoff, carrying soil particles with it ('erosion'). When surface runoff was more than 100-300 mm/year, it is possible that dry season flows increase if the soil structure improves to the point that the additional water that infiltrates into the soil exceeds the additional evapotrasnpiration from trees[26]. Whether or not trees increase dry-season flows of rivers and feed downhill springs depends on the relative strengths of these two opposite effects: increasing infiltration and increasing the direct loss after canopy interception plus use of water infiltrated into the soil. It is commonly observed that increasing tree cover, especially with fast-growing trees, reduces all aspects of streamflow; but on degraded and compacted soils, with a high surface runoff, the net effect can be positive – if one has the patience for the slow recovery of soil hydraulic properties to become effective (10-20 years, according to recent studies)[27,28,29,30]. Consequently, landscape restoration with trees will generally reduce annual water yield[31], but (in the longer run) improve water quality and regularity of flow.

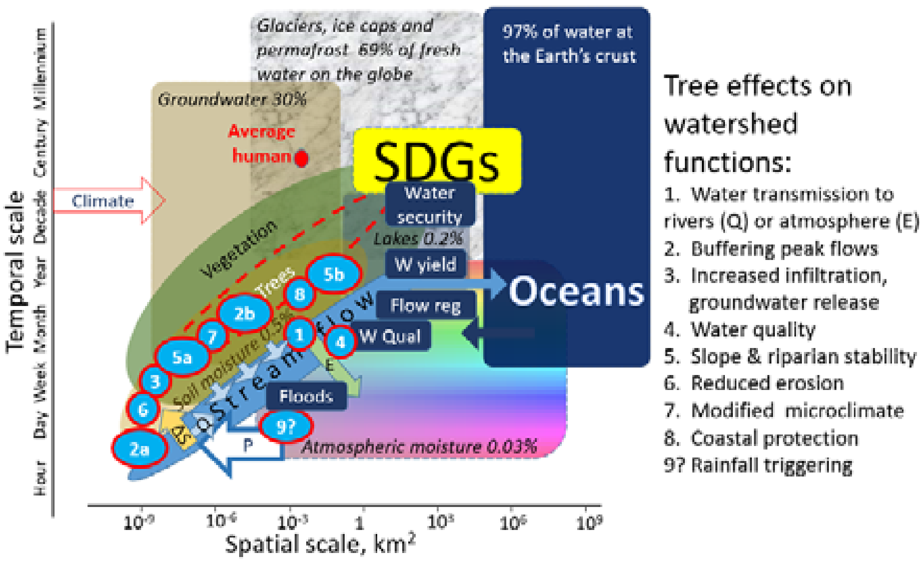


Figure 17.4 Water (as gas, fluid or solid phase) at a range of spatial and temporal scales with the associated tree effects on 'watershed functions' (modified from[1])

In the increased understanding over the past four decades of the roles trees in agroforestry have on water cycling and availability for crops, livestock and people[32,33,34], the temporal and spatial scales had to be disentangled (Fig. 17.4). Currently nine groups of tree effects on watershed functions are recognized as 'ecosystem services'[35,36], and we will use these for our review of current understanding of hydrological effects of agroforestation.

[a] This represents around two months of potential evapotranspiration, depending on local climate

The Andean snow cap, like the Himalaya and snow-capped African water towers, derives its water from terrestrially recycled plus oceanic moisture in the past and gradually releases it (but currently at an unsustainable rate due to global warming), subsidizing lowland land use systems. Photo: World Agroforestry/Jonathan Cornelius

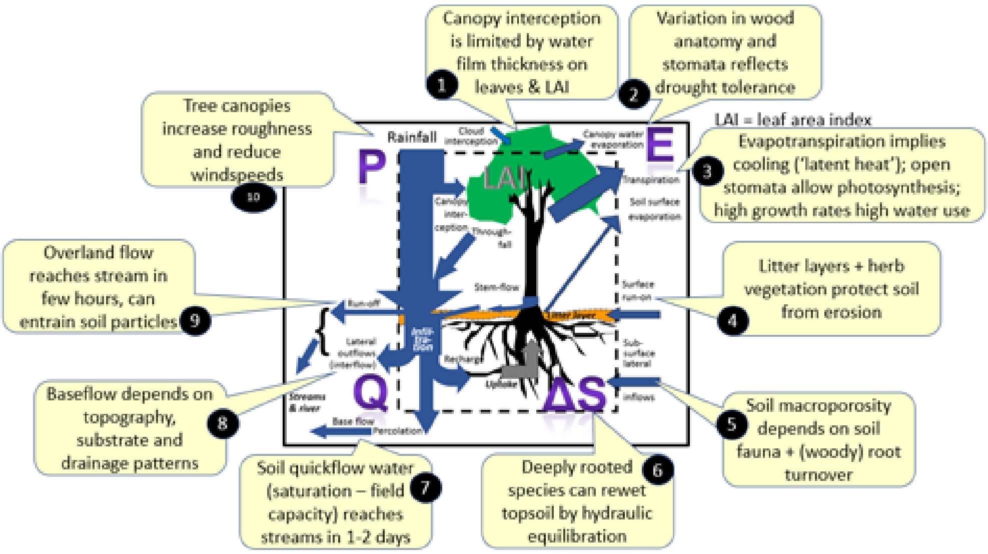


Figure 17.5 Examples of plot-level understanding of the way trees and soils interact with the terms of the water balance (P = rainfall, E = evapotranspiration, Q = streamflow or discharge, S = changes in stored water)

17.2 Plot-level science

Process-level understanding of the plot-level water balance in response to tree properties, climate and soil has increased considerably in the first four decades of agroforestry research[37]. Some highlights (Fig. 17.5) are:

1. Canopy interception depends in part on canopy (leaf area index, architecture, leaf angle distribution) and leaf traits (drip tips, hairs, compound leaves with mobile leaflets), with part of the variation not yet described in existing interception models[38].
2. There is considerable variation in ecophysiological response to (temporary) drought in trees and shrubs, related to wood anatomy[39,40,41]. There also is an increasing trend in intrinsic water use efficiency in the tropics under elevated CO_2

and climate change[42] either caused by higher photosynthetic capacity or reduced stomatal conductance[43] and thus will influence the global hydrological cycle[44].

3. Evapotranspiration means cooling[6], stomatal water use efficiency varies between plant species[45]
4. Litter layer dynamics depend on leaf area index, leaf duration, biochemical quality of the litter, abiotic and biotic factors in the decomposing environment, with interactions where mixed litter sources are produced in agroforestry[46].
5. Soil macroporosity is stimulated in agroforestry by biotic 'soil engineers' (incl. termites and earthworms) and old tree root channels[47], modifying infiltration patterns and inducing preferential flow[48,49].
6. Hydraulic redistribution[50,51] (based on equilibration) as 'complementarity' mechanisms between deep-rooted trees[52,53] and more shallowly rooted crops and grasses[54].
7. High infiltration rates, exceeding the retention (sponge) capacity, of forest soils with high macroporosity lead to 'interflow', or soil quick-flow, reaching streams in 1 or a few days after a rainfall event; soil compaction after forest conversion directly affects this property, shifting more of the flow to be overland flow[55].
8. Increased infiltration after forestation can under specific circumstances increase baseflow, where the additional infiltration exceeds the additional water use by trees[56].

Box 17.2 Beyond blaming smallholders for forest degradation and deforestation[57]

A B

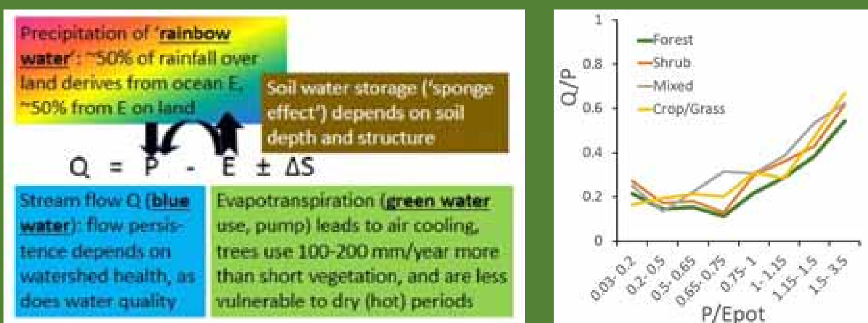


Figure 17.6 A. The 'colours of water' linked to the terms of the water balance; B. Relationship between water yield (Q/P ratio) as function of climate (P/E_{pot}) for four land cover categories in a comprehensive global case study compilation[a]

The plot-level water balance is commonly defined as $\Delta S = P - Q - E$, where P = precipitation (= rainfall for tropical conditions), Q = river discharge (plus groundwater flows where these exist), E = evapotranspiration (= bare soil evaporation + evaporation of water intercepted on biomass and surface litter + transpiration by plants) and ΔS = storage term, reflecting change in water storage (where this exists, it includes snowpack); all can be expressed in mm (= l/m2). At a daily timescale ΔS can be a large fraction of P, but when considered over an annual timescale the ΔS term tend to become small, although in dry climates with deep soils it may take decades before the ΔS term is negligible. It appears that regardless of vegetation and rainfall pattern at least 15% of rainfall ends up in streamflow, probably because rainfall intensity exceeds instantaneous infiltration capacity of the soils, which leads to the generation of infiltration-excess overland flow. This can be captured in (a modified Budyko equation):

$$Q/P = (q_0P + \max(0,(1- q_0)P-E_{Act}))/P = \max(q_0, 1-E_{Act}/P) = \max(q_0, 1-\eta/(P/E_{pot}))$$

With η = EAct/Epot = evapotranspirational index or relative evapotranspiration rate, and q0 = minimum Q/P ratio.

9. Process-level understanding of overland flow[58] has led to better understanding of erosion and sedimentation than the directly empirical universal soil loss equations and its variants. Even at low annual rainfall, however, storm events can be intense and lead to overland flow as the soil doesn't easily rewet (Box 17.2).
10. Canopy roughness, which tends to be high with partial tree cover, contributes to turbulence[59] and potential evapotranspiration.

In agroforestry systems, the key to increasing the amount of usable output per unit of water depleted is choosing the right combination of trees and crops to exploit spatial and temporal complementarity in resource use[60,61,62,63,64]. For discussions of technical aspects of 'adaptation' it is important to know which climate metric should be used for comparing the specific years of observations and experiments to the current and expected future variability. Results so far showed[65] that for freshly planted trees the duration of dry spells is the best predictor, while for older, deeper rooted trees the overall water balance matters most.

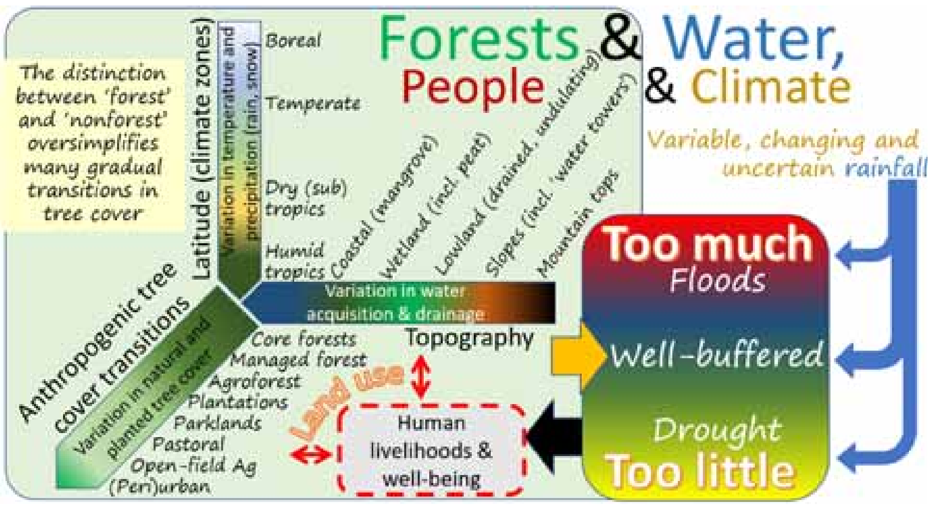


Figure 17.7 Three main axes of variation that influence biophysical tree-water relations: latitude (climate zone), topography and anthropogenic tree cover transitions, combining to the degree to which variable rainfall is buffered from a human perspective avoiding both situations of 'too much' and 'too little'

Where public discourse about water is still largely in terms of deforestation/reforestation, a more functional forest-hydrological interpretation (Fig. 17.7) requires at least three axes to describe variation in tree cover and properties: 1) Latitude (climate), 2) Topography and 3) Anthropogenic forest (or tree cover) transitions[1]. The latter may be reflected in the five key functional traits described for the 'full hydrological cycle' paradigm in Figure 17.3, with the four first interlinked through plant architecture and functioning:

Leaf Area Index as a function of time	Litter layer presence throughout the year
Rooting depth and root length density	Soil macroporosity and soil water retention
Effects on rainfall.	

17.3 Landscape-scale science

As also described in preceding chapters (9-11), landscape-scale research on watershed management has teased apart some of the social-ecological system interactions, developed new procedures and metrics, and yielded process-based models that can be used beyond the original study areas.

The first result of engagement at the landscape (c.q. watershed) scale is a tentative map of the complexity of stakeholders and the specific aspect of flow regimes and hydrological cycles in which they are most interested (Table 17.1).

Table 17.1 Examples of stakeholders and their institutional representatives for various 'watershed functions'

Examples of stakeholders	Net primary productivity	W1. Water yield	W2. Peak flows	W3. Base flow	W4. Water quality	W5. Slope stability	W6. Sedimentation/ erosion	W7. Microclimate	W8. Coastal protection	W9. Rainfall triggering	Examples of institutions influencing decisions
On-site farmers/ forest managers	XX										Forestry, Farmer groups, Agriculture, Local govt
Down**hill** inhabitants						XX					Local govt Disaster agency
Down**stream** reservoir managers		XX			X	X	XX				Public works
Down**stream** water users				XX	XX		X				

without reservoir											
Down**stream** hydro-power generation without reservoir				XX			XX				Run-of-the-river hydro-power
Down**stream** water users with reservoir		XX					X				Public works Irrigation Drinking water Industrial water
Down**stream** hydro-power generation with reservoir		XX					X				Hydropower
Down**stream** flood plain inhabitants			XX				X				National, local governance, Disaster agency
Down**stream** fisheries & wildlife			X	X	XX						Fisheries Nature conservation Recreation
Down**stream** transport			X	X							Shipping, transport agency
Down**wind** inhabitants								X			Health Climate
Down**wind** land & water users										X	All of the above
Coastal zone inhabitants									X		Local govt Disaster agency
Marine life (incl. coral reefs)					X		XX				Nature conserve Recreation

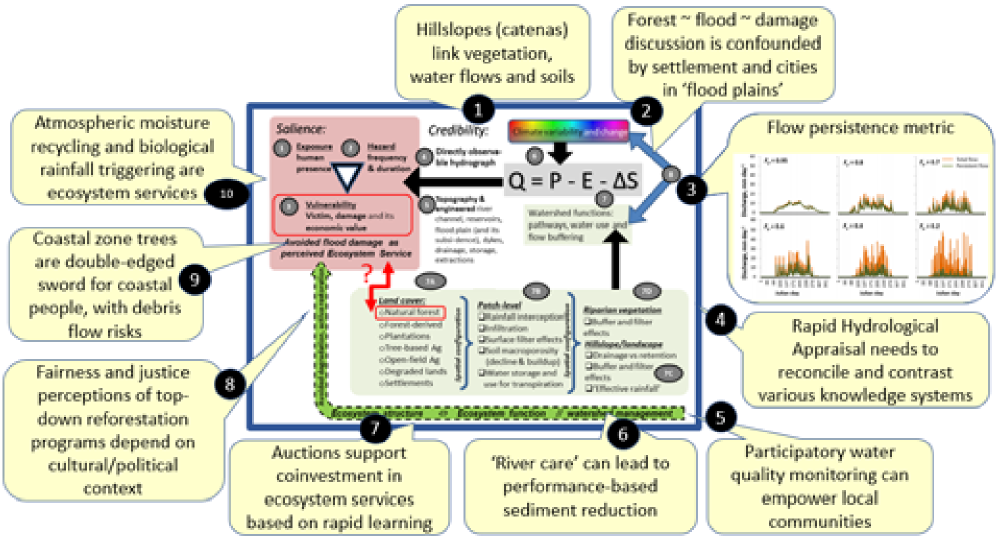


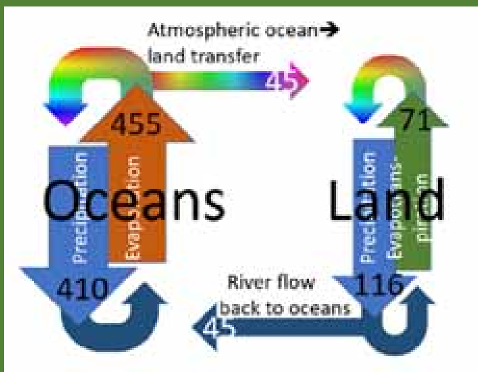
Figure 17.8 Landscape level progress in understanding how agroforestry relates to stream flow

Some of the highlights and recent examples of landscape-scale AF research on watershed functions (Fig. 17.8) are:

1. Hillslopes and their soil catena interact to generate flow regimes, and it matters what preceding land cover an expanding crop (such as rubber monocultures in SW China)[66] replaces,
2. The Forest ~ flood ~ damage discussion is confounded by settlement and urbanisation in in 'flood plains'[67],
3. The flow persistence metric[68] connects floods and drought risk to infiltration,
4. Rapid Hydrological Appraisal needs to reconcile and contrast various knowledge systems as a start of context-specific negotiations and solutions[69,70],
5. Participatory water quality monitoring can empower local communities interacting with authorities[71,72],
6. River care: performance-based sediment reduction (Chapter 9),
7. Auctions as basis for coinvestment in ecosystem services can form effective 'learning curves' for all[73],
8. Fairness perceptions of top-down reforestation programs depend on cultural/political context (Chapter 10),
9. Coastal zone trees are double-edged sword for coastal people, with debris flow risks[74],
10. Atmospheric moisture recycling and biological rainfall triggering are ecosystem services (Box 17.3).

Box 17.3 The global water cycle over land[4]

Data[75] on the global hydrologic cycle and its principal hydrologic flows show that in an average year, ~40,000 km^3 (net) of ocean evaporation enters the terrestrial atmosphere. When equally distributed, this accounts for 268 mm of rainfall. However, average annual terrestrial precipitation of 779 mm requires 116,000 km^3 of atmospheric moisture; more than 60% of this is derived from green water use by trees, forests, croplands, other vegetation, wetlands and soils, plus some evaporation of blue water from water bodies or irrigated agriculture. Atmospheric moisture has been labelled rainbow water, complementing the blue and green water terminology[76].



On average, a drop of water entering the atmosphere over land from the ocean falls 2.6 times as rainfall before returning to the ocean in river flow. There is, in fact, no compelling reason that the 2.6 value, and thus the amount of recycled rainfall, cannot increase or decline based on future land use change (via forest landscape restoration or continued deforestation). Location-and timewise, atmospheric moisture derived from blue water use in irrigation areas differs from that of green water use in water-tower forests. The teleconnections and spatial dependency implied in the recycling of atmospheric moisture over land masses can be calculated from existing observations of precipitable water, wind speeds, rainfall and evapotranspiration-ration, using robust models.

At landscape scale issues of flow regularity (and flooding risk) and water quality can be at least as important as total water yield, and increased infiltration at plot level is key to a buffered flow with reduced flood risk, as well as for better water quality (with some notable exception in soils where sub-surface salt can come into circulation if more water infiltrates than happened in the past). It matters what types of trees are involved (both their above- and belowground architecture and aspects of their physiology) and the density at which they occur. Generally faster growing trees use more water and will often be superficially rooted, while deeper rooted species tend to grow slower but can be expected to reduce dry-season flows. The relative importance of canopy interception depends on the temporal pattern of rainfall (many small versus a few big events). On misty mountain tops cloud forests can strip clouds of moisture that isn't measured in a normal rain gauge, and such forests can increase river flow because they effectively increase P[77].

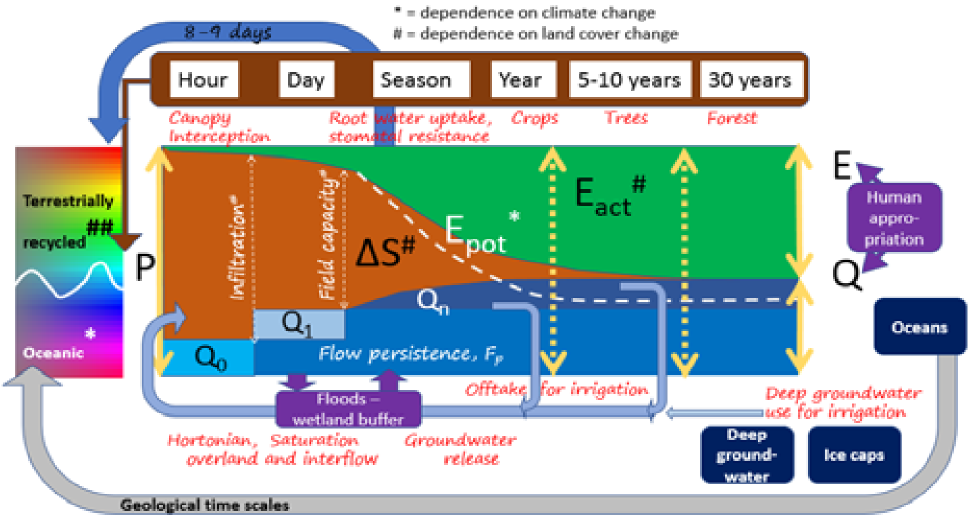


Figure 17.10 Connection between water balance processes across multiple time scales (logarithmically represented)

The landscape-scale understanding (AF2) has connected with a focus on governance and policies (AF3), mostly by embracing the concept of 'ecosystem services' as basis for negotiation and coinvestment.

17.4 Nine watershed functions to which agroforestry can contribute

This section will briefly review tree effects (through 'agroforestry' land uses) on the nine 'watershed functions' described in Fig. 17.4, that cover a range of spatial and temporal scales, before we will discuss current understanding of a right amount and diversity of suitable trees on appropriate locations (as embellishment of the 'right tree for right place' slogan and in search of the relationships A, B or C in figure 17.1).

Table 17.2 Time scale and interrelated metrics for the watershed functions (W) identified in Table 17.1, in dependence of location, topography and vegetation properties (V) as 3 axes of Fig. 17.7 (S_s = soil strength, a property influenced by root development and root decay)

	Time scale	P	E_{pot}	E_{act}/E_{pot}	Q_0	Q_1	Q_n	ΔS	S_s
Location (latitude, elevation)	Permanent	X	X						
Topography, slope, terrain	Permanent				X	X	X	X	X
V1. Leaf Area Index	Season			X	X		X		
V2. Rooting depth, root density	Multi-year			X			X		X
V3. Litter layer permanence	Season				X				
V4. Soil water storage capacity	Multi-year			X	X	X	X		
V5. Ice nucleation agency	Season?	X?			X?				
Net Primary Production	Year		X	X					
W1. Transmission/water yield	Multi-year	X	X	X					

	Time scale	P	E_{pot}	E_{act}/E_{pot}	Q_0	Q_1	Q_n	ΔS	S_s
W2. Buffering peak flows	Day (hourly?)	X				*Fp*			
W3. Infiltration ➔ base flow	Season	X	X	X	X	X		X	
W4. Water quality	Day & season	X			X			X	
W5. Slope & riparian stability	Multi-year	X			X			X	X
W6. Sedimentation/erosion	Multi-year	X			X			X	X
W7. Microclimate	Season	X	X	X					
W8. Coastal protection	Decades							X	X
W9. Rainfall triggering	Season?			X?				X?	

17.4.1 W1: Water transmission

Trees increase E, by a larger canopy interception + transpiration (water use) (Fig. 17.1). For climates with > 1000 mm/year this may amount to about 100-300 mm/year, when compared with a short (grass) vegetation (and more when compared to bare soil).

Plotting (Fig. 17.11A) a multi-year data set for natural vegetation in North American long-term ecological research sites, including desert, rangeland and forests, with the modified Budyko equation of Box 17.2, matches remarkably well with a q_0 estimate of 0.15 and an evapotranspirational index (E_{Act}/E_{pot}) of 1.0. Part of the variation may be due to interannual carry-over effects between wet and dry years, while there is also uncertainty in the use of existing E_{pot} estimates, and possible sub -surface transfers into and out of the measured watershed. For a global dataset of measured watersheds according to dominant land cover, the two-parameter model can enclose 90% of the empirical data if E_{Act}/E_{pot} is in the range 0.35-1.1 for forests (Fig 17.11C), 0.2-0.9 for mixed land uses (Fig. 17.11D), 0.2 – 1.0 for shrub (Fig. 17.11E), and 0.1 – 1.0 for crops or grass (Fig. 17.11F), with the direct surface runoff fraction q_0 estimated as 0.15. Clearly, the land cover classes show wide internal variation and considerable overlap, but on average forests are on the highest E_{Act}/E_{pot} line (but also occur at the highest P).

It matters what types of trees are involved[78], the density at which they occur[79], and the tree canopy management that is applied[80,81]. Generally faster growing trees use more water, while deeper rooted species tend to reduce dry-season flows. Trees with 'reverse phenology' have young and active leaves at times other plants use less water[82].

From the results shown in Figure 17.11 we can expect total water yield Q to decrease due to re/af- forestation by about 100-300 mm/year where precipitation is > 1000 mm/year, as has indeed been reported[83]. However, when surface runoff was more than 100-300 mm/year, it is possible that dry season flows increase if the soil structure improves to the point that all water infiltrates, as has been reported for ex-grassland sites in the Philippines[84].

An unfortunate 'natural experiment' in the form of a typhoon that destroyed a large fraction of the leaf canopy but did not affect the soils, allowed researchers to separate forest-effects-on-soil from current water demand, confirming current theory[85]. Beyond the total water yield of catchments and the tradeoff between blue (Q) and green (E) water yield, is the question of the type of products derived from the (modified) forest vegetation[86].

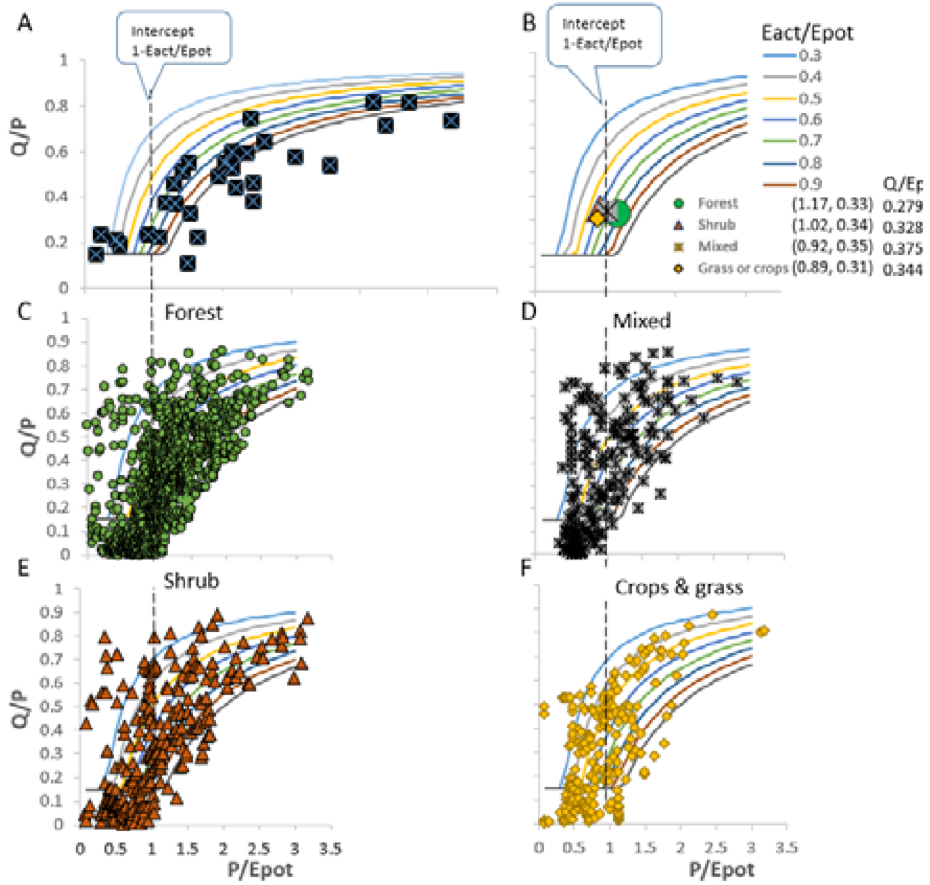


Figure 17.11 Modified Budyko plots (compare Box 17.2) for a large data set of comprehensively monitored subwatersheds characterized by dominant land cover[1]; A. North American long-term ecological research data set[87]; B...F global dataset[88]

17.4.2 W2: Buffering peak flows

At landscape scale issues of flow regularity (and flooding risk) and water quality can be at least as important as total water yield, and increased infiltration at plot level is key to a buffered flow with reduced flood risk, as well as for better water quality. There are, however, some notable exception in soils where sub-surface salt can come into circulation if more water infiltrates than happened in the past[89].

The predictability (regularity) of river flow depends on climate and terrain (topography) and is now well captured in the flow persistence (F_p) metric, that responds to changes in land cover in dependence of terrain properties[90]. It effectively links two ecosystem services: flood prevention and dry season flow, as can be understood to be equal to the weighted sum of respective F_p values for the three flow pathways (thus: $F_p = (F_{p0} Q_0 + F_{p1} Q_1 + F_{pn} Q_n)/Q$, with 0, 0.5 and ~0.95 as values for F_{p0} ,F_{p1}, F_{pn}, respectively).

17.4.3 W3 Increased infiltration, groundwater release

Box 17.4 Soil macroporosity and water infiltration

Instantaneous infiltration capacity seems to be easy to quantify: apply water to the soil surface and measure how fast it disappears. However, there are several complications to be aware of:

1. Infiltration during rainfall may be an approximately one-dimensional (vertical) process, but if a limited measurement surface is used, the flow below this surface will include a considerable (but soil texture and water content dependent) divergent lateral component that is not easily adjusted for. The standard approach to reduce the problem is the use of a double-ring infiltrometer in which infiltration rate is measured within the inner ring while the outer ring serves as a buffer to reduce lateral divergence of flow caused by capillary forces. However, this requires additional water to be brought to the measurement site, which might be difficult in many field locations.
2. The time course of infiltration is influenced by two basic soil properties: sorptivity (essentially the amount of water needed to saturate a volume of soil) and saturated hydraulic conductivity; while the interest is in the latter, variation in soil water content (due to time since last rainfall event) may dominate variation between measurement point derived from field surveys. This is why it is standard to report steady-rate infiltration values (which theoretically are not dependent on the initial soil water content) instead of actual infiltration rates.3) Preferential flow, especially where cracks or biotic macropores (caused by termites, earthworms, or decayed tree roots) are involved, causes a high point-to-point variation in infiltration measurements; in some soils a natural process of 'fingering' is expected, rather than the simple uniform wetting front that standard soil physical theory expects. The use of coloured fluids as dye solutions (e.g. methylene blue) and subsequent observations of the infiltration pattern can test for this and even be used to quantify the degree of preferential flow.
3. On many dryland soils 'hydrophobicity' or difficulties in early rewetting of soils due to algal growth and/or effects of preceding fires (leaving a type of 'soot' on the surface) cause transient problems with infiltration that may or may not be represented in the field measurements, depending on the time measurements are made.

Despite these challenges, the study of soil infiltration capacity and preferential flow is key to improve our mechanistic understanding of fundamental hydrological processes such as runoff generation and soil and groundwater recharge, which in turn are linked to flood risk, soil erosion, or streamflow regime.

With Q_1 and Q_n as consequences of infiltration, process-level understanding of infiltration distinguishes between Hortonian and saturation-overflow types of runoff. The first happens if rainfall intensity exceeds instantaneous surface infiltration capacity, the second if hydraulic conductivity lower in the profile limits the process and the soil above that layer is saturated. The latter also occurs at the base of slopes where subsurface flows resurface. Measurements in a parkland system in Burkina Faso suggested[91], from the perspective of groundwater recharge and baseflow, an intermediate, optimum tree density (a response like line B in Figure 17.1) due to positive tree effects on soil hydraulic properties influencing groundwater recharge, that are partly counteracted by additional interception and water use by trees. The direct measurement of infiltration capacity is not without difficulties, however (Box 17.4).

17.4.4 W4 Water quality

As mentioned in section 17.3, methods for participatory monitoring of water quality, including simple physical and chemical measurements plus observations on aquatic biota with a 'water quality index' score, have become widely used. Loss of water quality can have several causes, and observations along streams can identify point sources of pollution (e.g. domestic or industrial waste disposal) or sediment loading, and/or more disperse sources of nutrients (eutrophication) from agricultural fields with excess fertilizer use. Specific to tree cover along streams is the observation that water temperature (and related oxygen concentrations) have direct relevance for fish species and other aquatic fauna. Functionality of agroforestry as riparian buffer strips needs to be assessed spatially[92,93].

17.4.5 W5 Slope & riparian stability

Slope stability is at risk when infiltration rates are high, but current water use is low. Such conditions typically occur after forest clearance, with a temperature dependent time frame of loss of soil strength due to decomposition of woody roots (a few years in the tropics, 5-10 years in temperate zones)[94]. In the assessment of landslide risk (see also Chapter 14), root architecture is thus a key parameter[95,96]. Process-level 3D models of woody root architecture[97] may in future make patterns more predictable.

17.4.6 W6 Reduced erosion

Ever since Anthony Young's 'Agroforestry for soil conservation' book[98], has agroforestry been positively associated with erosion control, although the specific mechanisms involved vary with context[99], rainfall erosivity[100] and scale of consideration[101] (compare chapter 4). A study of agroforestry coffee cultivation systems in Nicaragua[102] found litter layers to effectively limit erosion, with on average 10.4% of the cultivated area affected by erosion, and a threshold determined by litter ground cover of 60–65%. Litter layer residence times tend to be less than a year, while green leaf duration of evergreen crops typically exceeds a year, making the rate of decomposition an important agro-ecosystem characteristic[32]. A study of erosion control in Rwanda concluded that the main challenge for agroforestry as soil conservation method is to produce enough biomass to mulch the whole surface[103]. Yet, landscape-scale studies of net sediment loss through rivers have pointed at different sets of processes and driving factors above the hillslope scale: effectiveness of sedimentation and filter zones, riverbed vegetation and river bank stability[104].

17.4.7 W7 Modified microclimate

Early agroforestry experiments showed that the tree-crop interface not only influences wind speed, but also precipitation[105]. Temperature effects (measured in standard, shaded conditions) of tree canopies tend to be in the 1 – 3 ºC range, with greatest effects on the days with highest direct radiation[106]. For crops grown as supra-optimal temperatures (e.g. wheat rather than maize), such microclimatic effects can lead to positive yield responses, as quantified in Ethiopia recently[107].

17.4.8 W8 Coastal protection

As described in section 7.3 under point 9, coastal zone tree cover, whether mangrove or other, does have some protective effects as it reduces run-up height for waves and (especially by breaking trees) reduces wave energy, but it also blocks human escape pathways and may give a false sense of security[108]. Where coastal fisheries benefit from moderate sediment and nutrient inputs from rivers (hence the negative effects on such biota if reservoirs trap the sediments instead of releasing them to estuaries), coral reefs (and associated tourist income) can be negatively affected by increased sediment flows into oceans. The roles mangroves in estuaries play in guarding land from sea-level rise by trapping such sediment is a current research focus.

17.4.9 W9 Rainfall triggering

Vegetation effects on P are a recent focus on hydroclimatic studies, challenging the assumption that P is an 'exogenous' (external) variable when plot-level studies are extrapolated to landscape and catchment (basin) scales. The larger the area under consideration, the more likely it is that the P term is influenced by E. Most of the land use change studies so far, however, have ignored the possibility that trees (and other vegetation) can also influence rainfall, locally (by producing potential triggers of raindrop formation[109,110] and allowing them to get uplifted to the atmosphere) and/or regionally (by recycling moisture back to the atmosphere). The latter effect increases with scale, and empirical data sets show that the negative effect of increased tree cover on total water yield gets smaller (for the same percentage land cover change) in larger watersheds. To increase water yield it may be best to convince land users in adjacent watersheds to increase tree cover, as this may increase rainfall, without the additional water use by trees affecting flow in your own watershed.

The term 'precipitationshed' describes all the land and/or ocean areas that contribute to precipitation at a given location or watershed of interest and has become part of the governance discourse[111,1,112].

While concerns about tropical deforestation continue, global data of a net 'greening' have consequences for precipitation, as documented in a recent study[113]. The global LAI enhancement of 8% between the early 1980s and the early 2010s was modelled to have caused increases of 12.0 ± 2.4 mm yr^{-1} in evapotranspiration and 12.1 ± 2.7 mm yr^{-1} in precipitation—about 55% ± 25% and 28% ± 6% of the observed increases in land evapotranspiration and precipitation, respectively.

17.5 Discussion: coinvestment in the right amount and diversity of suitable trees in appropriate locations

Water is one of the most basic aspects of life on the planet and appears to be simple in accounting of the various pools and fluxes, yet our brief stocktake has shown complex and often partly contradictory effects of land use. The dichotomy forest – nonforest has not been an effective guide to values, knowledge and rules, and we are yet to decide on the three paradigms of Figure 17.1. Although some examples of a B type response were encountered, the C space where it all depends on context, type of trees and watershed function of primary interest is the safest starting point.

The three paradigms of agroforestry (AF1, AF2 and AF3) introduced in Chapter 1 are all needed to understand tree effects on the full range of watershed services, water-related impacts on SDGs and a tentative list of 'prototype' ES enhancement and coinvestment mechanisms (Fig. 17.11), that requires a separate book[114] to fully explain.

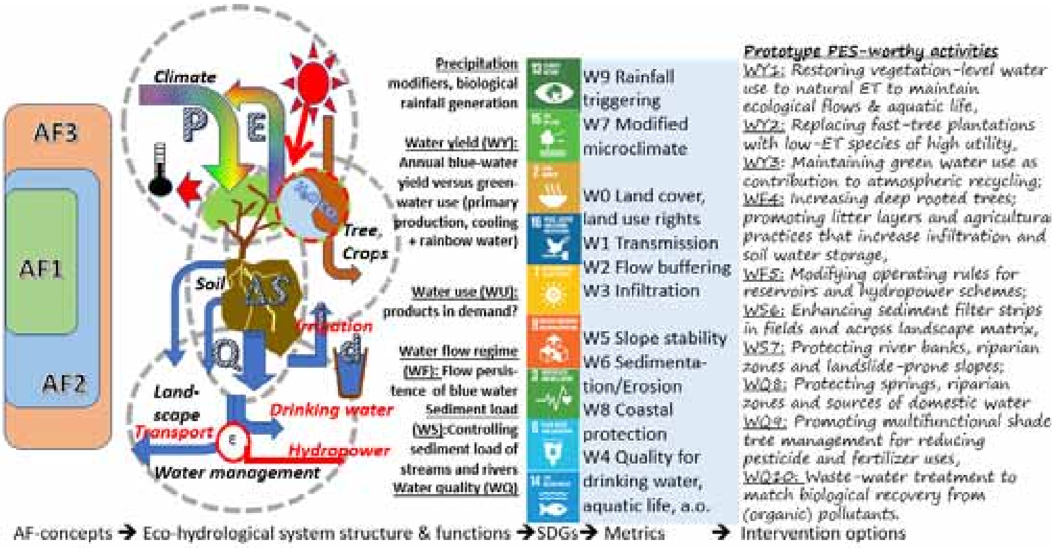


Figure 17.12 Eco-hydrological system structure and functions across subsystems (climate, plant and its stomata, rooted soil, river flow regimes and blue water management), as basis of human risks and food+water+energy+income security, and ten prototypes of interventions that can improve the key performance indicators and metrics in results-based co-investment[24,25,95]

Taken one by one, such activities can easily be misinterpreted. WY1 suggests using the overall water balance as a guideline with natural vegetation as quantitative reference. WY2 suggests, where current water use is too high from a downstream perspective, to replace fast-tree plantations with low ET species of high quality. Yet, there are indigenous, naturally growing trees that use more water than the fast-tree plantations but don't translate this into woody-stem growth. Where water use efficiency for firewood production is important, Eucalyptus has often been found to be superior. Increasing deep-rooted trees beyond the optimal capacity will also lead to ground water depletion.   Matching the right trees to the site conditions and optimal planting density of the right mix (both deep rooting and shallow rooted trees) is the target that requires site-specific knowledge and understanding beyond what generic databases can provide (compare Chapter 2).

In the specific form of the ecosystem structure, function, service, beneficiary and stakeholder cascade[95] that has been discussed in this chapter (Figure 17.13), four types of boundary work (or phases in a complete 'issue cycle') are identified as essential for an AF3 paradigm to function:

I. I = Achieving a shared understanding of the eco-hydrological functioning of a landscape (as a social-ecological system),

II. II = Agreeing between stakeholders on a locally prioritized set of services, indicators and metrics,

III. III = Understanding the polycentric governance aspects, which often involved separate national forestry, water infrastructure, agriculture, fisheries, energy, nature conservation and health entities interacting with local government (more integrated by its size) and farmers/land users.

IV. IV = Co-investment in ES in a public-private partnership after the legal (rights) and incentive (econo0mics) aspects of current land use are clarified, and entry-points for strategic interventions have been identified.

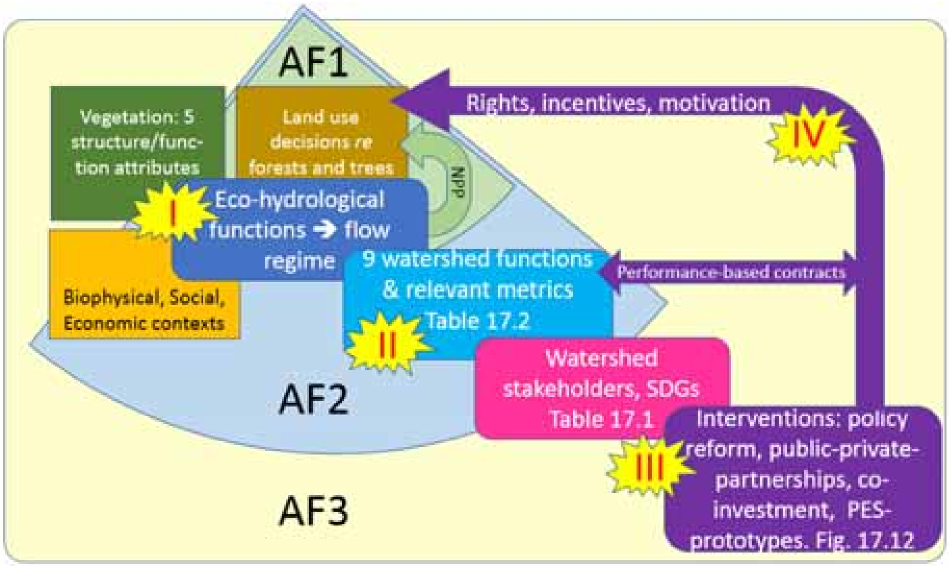


Figure 17.13 Ecosystem-services cascade as used to structure this chapter, with indications of the three AF paradigms and four types of boundary work (I = shared understanding, II = indicators and metrics, III = polycentric governance, IV = co-investment in ES)

Agroforestry as a climate-change adaptation strategy is now being recognized[115,116], especially where increased variability of water supply is the primary issue of concern. Some parts of the world will get wetter, others drier, especially where the additional river flow from melting ice caps comes to an end[117] or groundwater depletion aggravates negative rainfall trends[118]. The positive effects of restoring groundwater recharge described in chapter 11 that allow year-round fruit tree production may be under threat in such scenarios.

Decision analysis can now include uncertainty in technical, social and political aspects as part of economic and environmental feasibility, as explored for a proposed deep groundwater utilisation project in N Kenya[119]. Yet, the most complete example of the four types of boundary work in ongoing agroforestry research may well be the Rejoso watershed in East Java (Indonesia). Here a densely populated volcanic slope provides the water resources identified as essential for securing urban drinking water supplies in Indonesia's second largest megacity. All four types of boundary work were combined to understand the interacting subsystems of highland horticultural zone, mid-slope forestry and mixed agroforests and lowland irrigated rice production (with uncontrolled groundwater use) to propose zone-specific interventions that have now started their implementation phase.

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Somkit Kirikumsap

INTERMEZZO 7

ASB Voices N0. 6, 2002

"If we don't respect our traditions, it's the same as disrespecting our elders. If we disrespect our elders, it's the same as disrespecting the forest. Trees give us shade and shelter, and will provide for the next generations of our people. Water will continue to flow out of the forest, as long as the elders continue to pass on the knowledge and traditions of our culture." – **SOMKIT KIRIKUMSAP**

Somkit Kirikumsap is a lifetime resident and current village head of Phapueng, a Karen community nestled in the valleys of northern Thailand's mountainous Chiang Mai Province. As in neighbouring Karen communities in this upper watershed region, the people and land use systems of Phapueng have come under scrutiny in recent decades as production increases in lowland irrigated agriculture and associated economic growth have increased demands for water downstream. Apprehensions about the sustainability of water and other resources are on the rise, and as lowlanders search for the source of their troubles, the easy targets for blame have been ethnic mountain communities like Phapueng—commonly perceived as destroyers of forest and water resources. It is a perception that is far from the truth. Living compatibly with the natural environment and maintaining the forest as a viable community resource are values deeply embedded in Karen culture. In addition to providing natural value, the forests set aside in Phapueng for protection supply villagers with many of the materials they need for daily living. These forests also hold great spiritual value for the people. Somkit's last name, Kirikumsap—which means 'mountain full of resources'—is just one example of the intimate connection between 'nature' and 'human nature' that prevails in Phapueng. There are numerous other examples of connections between humans and the environment, reflected in the spiritual traditions that are intrinsic to Karen life. Somkit explained that villagers are highly protective of their 'umbilical forests'—so-called because selected trees within this forest are encircled by the umbilical cords (wrapped in bamboo) of community members.

Just as a human umbilical cord is the string of life for a newborn, the umbilical forests are considered integral to the community's survival. In another example, villagers perform ceremonies to ordain—as they would a Buddhist monk—trees of particular value within the community.

Beginning last year, Somkit and other villagers have collaborated with ASB researchers to monitor rainfall, soil erosion, temperature, aquatic invertebrates, stream flow and other environmental indicators with the objective of linking these science-based measures to local knowledge. For example, villagers know that if small crabs appear on the banks of the river, or if red ants build their nests high up in the bushes by the river's banks, rains soon will follow. Using basic, lowcost scientific indicators, villagers can verify, record and validate their own local knowledge—and preserve this knowledge for future generations. Phapueng members also hope that the monitoring of selected environmental indicators—like water quality and stream flow—can help resolve disputes and provide a tool for negotiation in a region where growing competition for resources has resulted in heightened economic, political and ethnic tensions.


Agroforestry interspersed with corn and fruit trees

A farmer shows his typical agroforestry farm in Peñablanca, Cagayan, Philippines: planted with corn interspersed with mango and banana.

Photo: World Agroforestry/Regine Evangelista

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CHAPTER EIGHTEEN

Policy guidelines for agroforestry development adopted by ASEAN[a]

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Highlights

- All ten member-countries of the Association of Southeast Asian Nations (ASEAN) agreed that agroforestry development can increase their prosperity, connectivity, resilience and security
- The guidelines support focused policies and programs for agroforestry in Member States as part of the Vision and Strategic Plan for ASEAN Cooperation in Food, Agriculture and Forestry 2016–2025
- The guidelines support collaboration between Member States in sharing technical and policy developments, promoting increased trans-border trade in agroforestry products and bolstering the enhancement of ecosystem services, in keeping with the vision of the ASEAN Economic Community
- The guidelines include 3 institutional, 2 economic, 2 environmental, 3 socio-cultural, 2 technical design and 2 communication and scaling principles
- The guidelines, adopted by ASEAN Ministers of Agriculture and Forestry, were developed in a collaborative process with a wide range of partners from national government agencies, international, regional and national research and academic institutions, non-governmental organizations, and civil society groups

18.1 Introduction: the process

Getting agroforestry on negotiation tables where global, regional, national and local policy responses to current 'issues' are discussed takes patience and time. Yet, without such investment, flexibility in the language to be used, and persistence and consensus on the core

[a] Adopted from: ASEAN Guidelines for Agroforestry Development. Jakarta, ASEAN Secretariat, December 2018

aspects, agroforestry practitioners will continue to face hurdles because policy documents don't refer to it as a potential contribution.

Considerable progress was made in recent years in the Southeast Asian context where ASEAN (the Association of Southeast Asian Nations) with its ten Member States engaged in a process of consultations that led to a set of principles and associated implementation guidelines were endorsed at Ministerial level. The document itself has no legal power (there are sanctions or dispute settlement rules), but serves as an expression of commitment and intent, and provides a framework for cooperation amongst Member States. It can help in dealing with cross-border issues as they exist on both the agricultural and forestry side of agroforestry. The principles and guidelines will offer little, if any, surprise for readers of the preceding chapters of this book, and indeed much of the research results reviewed here was summarized at the start of the policy process in a 'white paper'[1]. Much of these guidelines can apply in other regions of the world, but as in any science-policy interface, the 'boundary work' of consultations and a participative process is as important for the legitimacy dimension of the resulting 'boundary object', as the credibility of the underlying evidence and the relevance (salience) of the recommended courses for action.

The main part of this chapter is the list of principles and guidelines formulated, but we will first describe the process followed to ensure ownership by the relevant authorities. For the readership of this book, the list of suggested references of the ASEAN document has here been used in the sections where they are most relevant.

18.2 Background and scope of the guidelines

The Vision and Strategic Plan for ASEAN Cooperation in Food, Agriculture and Forestry 2016–2025, as endorsed by the 38th ASEAN Ministers of Agriculture and Forestry meeting in 2016, aims to ensure that, 'forest resources are sustainably managed at the landscape level to meet societal needs, both socio- economically and culturally, of the present and future generations, and to contribute positively to sustainable development'.

Recognizing the contribution of agroforestry in achieving food security, enhancing climate-change adaptation and mitigation, and reducing land degradation; to many of the Sustainable Development Goals; and to strengthen links between forestry and food production through an integrated approach to landscape management as well as enhancing sustainable forest management, the 20th ASEAN Senior Off of Forestry meeting agreed to develop ASEAN guidelines on agroforestry. The 39th ASEAN Ministers of Agriculture and Forestry meeting adopted the recommendation to develop the guidelines as one of the key deliverables of ASEAN cooperation in forestry in 2018.

The World Agroforestry Centre was requested through the ASEAN Working Group on Social Forestry to prepare — together with the Food and Agriculture Organization of the United Nations (FAO) and the partners of the ASEAN-Swiss Partnership for Social Forestry and Climate Change project — a set of guiding principles in support of agroforestry development in ASEAN Member States. The guidelines are deemed necessary to achieve the ASEAN Food, Agriculture and Forestry Sector's Vision and Strategic Plan, particularly Strategic Thrust 4, 'Increasing resilience to climate change, natural disasters, and other shocks', and Action

Programme 5, pertaining to the 'expansion of resilient agroforestry systems where they are ecologically and economically appropriate'.

Consultations with many stakeholders, including researchers, academics, practitioners, technical experts, forestry- agriculture- environment sector representatives from national governments, and farmers' associations, were facilitated since June of 2017. The authors and contributors would like to emphasise that the Guidelines are designed to ensure that agroforestry development is based on the unique contexts of ASEAN Member States. Individual Member States' socio- economic, policy and environmental conditions will need be to given equal consideration in the design of any agroforestry intervention.

The Guidelines are intended to be applicable to all types of land or ecosystems targeted for agroforestry interventions within ASEAN Member States, whether forests, farms, watersheds, uplands, lowlands, coasts, wetlands or peat. It is not a technical guideline for establishing agroforestry but, rather, a framework for facilitating dialogue in the design of agroforestry policies, programs, projects and investments between, and within, ASEAN Member States. Implementation of the Guidelines is voluntary and neither add to, nor replace existing formal regional agreements or treaties, national laws and policies, but align with the ASEAN Multi-Sectoral Framework on Climate Change: Agriculture and Forestry towards Food Security, and all other ASEAN sectoral guidelines relevant to agroforestry.

The principles and guidelines described in this document, although intended for ASEAN Member States, represent a broad philosophy that can be adopted by States outside ASEAN.

Box 18.1 Objectives of the guidelines

1. Promote the role of agroforestry in simultaneously achieving economic, environmental and social outcomes at farm, household and landscape levels.
2. Guide the formulation of agroforestry policies, strategies and programs of ASEAN Member States and private- sector investments, as well as higher education agroforestry curriculum and programs.
3. Help ASEAN Member States achieve their targets related to food security, 'green' or sustainable growth, reduction of greenhouse-gas emissions, land restoration, watershed protection, gender equality, social/community forestry, climate-change adaptation and mitigation and, more generally, the Sustainable Development Goals.
4. Strengthen partnerships among ASEAN Member States through joint action on agroforestry development.

The intended primary users of the Guidelines are ASEAN Member States' policy makers and, secondarily, program and/or project planners at national and sub-national levels, domestic and foreign investors, institutions for higher learning, and local and international non-governmental organizations involved with agroforestry and development. The Guidelines can be also used by civil society groups for advocacy purposes.

Box 18.2 International context of the guidelines

The guidelines adhere to all legally- and non-legally-binding international conventions, agreements and treaties as well as global programs and frameworks that ASEAN Member States have committed to. These include, but are not limited to, the following.

- The 17 Sustainable Development Goals were adopted by world leaders in September 2015. Built on the success of the Millennium Development Goals, the Goals are mobilizing efforts to end all forms of poverty and inequalities, and tackle climate change while ensuring that 'no one is left behind'.
- United Nations Framework Convention on Climate Change (UNFCCC) aims to stabilize greenhouse-gas concentrations in the atmosphere to prevent dangerous interference to the climate system, without any binding greenhouse-gas limits or enforcement mechanisms for countries. The framework outlines how specific international treaties (called protocols or agreements) may be negotiated to specify further action towards the objective of the UNFCCC.
- The Paris Agreement came out of UNFCCC negotiations, and aims to bolster global efforts to lower the projected temperature increase to 1.5°C above pre-industrial levels, increase the ability to adapt, foster climate resilience and low- emissions development without threatening food production, and create financial flows that support these aims. Through Intended Nationally Determined Contributions, countries create actions consistent with their own national circumstances, capabilities and priorities.
- Convention on Biological Diversity (CBD) outlines the principles governing the conservation of biological diversity, sustainable use of components and fair and equitable sharing of benefit arising from the use of genetic resources.
- United Nations Convention to Combat Desertification (UNCCD) is a 10-year strategy (2008–2018) with the goal of forging a global partnership to reverse, and prevent, desertification and land degradation and to mitigate the effects of drought to support poverty reduction and environmental sustainability. The UNCCD collaborates closely with the CBD and the UNFCCC to meet the complex challenges, with an integrated approach and the 'best possible use' of natural resources.
- The Bonn Challenge is a global effort to restore 150 million hectares of the world's deforested and degraded land by 2020 and 350 million hectares by 2030 to realize existing international commitments, including the CBD Aichi Target 15, UNFCCC REDD+, and the Rio+20 land degradation neutrality goal.
- Ramsar Convention on Wetlands is an intergovernmental treaty providing a framework for national action and cooperation in the conservation and utilization of wetlands and their resources.
- Rio Declaration on Environment and Development details principles that guide countries in balancing environmental and developmental considerations in policies and actions.
- Code of Conduct of Germplasm Collection and Transfer is a global voluntary framework that provides for the rational collection and sustainable use of genetic resources.
- International Panel on Forests proposes actions for sustainable forest management.
- Global Plan of Action for the Conservation and Sustainable Utilization of Plant Genetic Resources is a voluntary global framework that provides for the conservation and sustainable use of plant genetic resources for food and agriculture.
- Millennium Declaration and Millennium Development Goals aimed to uphold human dignity and equity, eradicate poverty, protect the common environment, support human rights and democracy, promote gender equality and good governance and form a global partnership for development[a].

- Sendai Framework for Disaster Risk Reduction (2015–2030) aims to achieve substantial reduction of disaster risks and loss of lives, livelihoods and health. The Framework was adopted at the Third United Nations World Conference on Disaster Risk Reduction in Sendai, Japan on 18 March 2015.
- United Nation strategic plan for forests (2017-2030) (UNSPF) serves as a reference for the forest- related work of the UN system and for fostering enhanced coherence, collaboration and synergies among UN bodies and partners towards the following vision and mission, as well as a framework to enhance the coherence of and guide and focus the work of the International Arrangement on Forests (IAF) and its components.

18.3 Guiding principles

The guiding principles are interlinked, representing a broad philosophy that guides the development of agroforestry interventions (for example, policies, programs, projects and business investments) throughout ASEAN Member States, in all circumstances, irrespective of changes in their goals and strategies.

18.3.1 Institutional principles (1-3)

Principle 1: Create an enabling environment

Considering the lack of clear institutional home for agroforestry in many countries in Southeast Asia, it is important to provide an enabling institutional and policy environment within which the development of agroforestry policies, programs and investments can be facilitated[2,3]. In all accountability, inclusiveness must be adhered to, at all levels of planning, decision-making and implementation of agroforestry interventions. The guidelines include, but are not limited to, the following.

Guideline 1.1. Abide with existing international and regional treaties, frameworks, agreements, strategies and programs when developing agroforestry programs, projects or policies.

Guideline 1.2. Examine national laws, regulations, strategies and programs with respect to agroforestry and formulate new, or amend existing, policies to ensure the development of agroforestry has clear policy and legal support.

Guideline 1.3. Establish an institutional 'home' for agroforestry. Assess existing circumstances, principles of good governance adopted by different sectors including FAO's responsible governance of tenure of land, fisheries and forests (transparency, equity, institutional structures and assign a suitable, or create a new, institution with relevant ministries in ASEAN Member States in charge of agroforestry development with duties, roles and responsibilities clearly defined

Guideline 1.4. Develop national agroforestry programs, strategies or road maps and support development at sub-national and local levels.

Guideline 1.5. Provide enabling conditions and procedures that encourage and reward adoption of agroforestry, such as security of land tenure, enhanced market access and improved infrastructure.

Guideline1.6. Explore different means to provide appropriate, and continuing funding to support agroforestry development.

Principle 2: Ensure effective organizational capacity

With reference to Principle 1, capacity development of the designated or newly created institution, agency or department with relevant ministries and their key partners is necessary to effectively share knowledge, transfer technologies, conduct research, provide support services and facilitate planning. Guidelines include, but are not limited to, the following.

Guideline 2.1. Strengthen the capacity of the institution in charge of agroforestry and its partners at national and sub-national levels to effectively deliver knowledge and skills, provide technical guidance, facilitate participatory planning and decision-making at various levels, and monitor results and impacts.

Guideline 2.2. Identify and mobilize individual and institutional experts to enhance technical capacity for agroforestry development at various levels.

Guideline 2.3. Enhance national research capacity to conduct participatory agroforestry research and link knowledge to policy through direct engagement in policy and planning processes.

Guideline 2.4. Enhance national extension capacities to facilitate knowledge and skills' transfer between, and amongst stakeholders, support dialogue, plan agroforestry programs and projects, and design agroforestry options for different contexts.

Guideline 2.5. Strengthen collaboration for research and outreach between national research and extension systems and international research and development organizations, including academe.

Guideline 2.6. Encourage agroforestry education by providing support to colleges and universities in developing agroforestry curricula through existing networks of higher education in the region.

Guideline 2.7. Identify specific needs of different stakeholders and provide tailored support services for the various needs of large landholders (concessionaires, corporate farms) and smallholders.

Principle 3: Support effective cooperation and participatory decision-making

Taking into consideration the multifaceted nature of agroforestry, its evolving concepts and interfaces with agriculture, forestry and other land uses; its landscape-level interactions and links to other sectors (for example, livestock, energy, aquaculture, water, climate change, and rural livelihoods), a landscape approach to planning agroforestry interventions and inter-sectoral cooperation and integrated decision-making, as outlined in the ASEAN Multi-Sectoral Framework on Climate Change: Agriculture and Forestry towards Food Security, are needed for effective development of agroforestry. Guidelines include, but are not limited to, the following.

Guideline 3.1. Promote participatory approaches and participation of all stakeholders at appropriate levels of planning and decision- making for joint planning, targeting and implementation of agroforestry interventions, particularly, at smallholder level. Stakeholders could include policy-makers and planners from relevant sectors: private industry, investors, and concessionaires; researchers; non-government organizations; international donors and partners; farmers' organizations and cooperatives; indigenous peoples' or ethnic minority groups; and women's and producer groups (linked to Principle 8).

Guideline 3.2. Ensure that agroforestry interventions, and their products and services, are better understood and included in sectoral strategies.

Guideline 3.3. Design agroforestry interventions in the context of a whole landscape and in relation to future changes in climatic regimes as well as economic and policy shift to ensure that on- and off-site, short- and longer- term impacts are considered, managed and monitored in accordance with social, economic and environmental standards adopted by ASEAN Member States (linked to Principle 11).

Guideline 3.4. Include and reconcile often divergent goals, interests and accountabilities of diverse stakeholders in landscapes targeted for agroforestry, including smallholders, small- and large-scale producer groups, community-based forestry groups, large-scale concessions, and state entities (linked to principles 8, 9, 11)[4,5,6].

Guideline 3.5. Use spatially-explicit tools to determine areas best suited for agroforestry in a landscape, according to environmental, social and economic suitability to ensure large-scale, benefits and impact (linked to Principle 11).

Guideline 3.6. Respect, utilize and/or combine traditional knowledge systems in scientific research, planning and decision-making (linked to Principle 8).

Guideline 3.7. Ensure the contribution of agroforestry to local goals and alignment with national goals, ASEAN frameworks, strategies and action programs, as well as international conventions, treaties, agreements, goals and strategies.

18.3.2 Economic principles (4, 5)

Principle 4: Recognise the value of goods and ecosystem services

Agroforestry provides many benefits in the form of goods and ecosystem services for markets, households and the environment. Agroforestry is often a traditional practice in which farmers act as custodians of the land, for which they should be recognized, rewarded or compensated for their long-term investments, such as through direct income from agroforestry products and/or through rewards for ecosystem services' schemes. Guidelines include, but are not limited to, the following.

Guideline 4.1. Promote all types of agroforestry goods (for example, raw commodities and products for consumption and sale) with, for example, unique branding and/or certification, such as Fair Trade or 'green' commodities, and strengthen support for smallholders to aggregate and thereby achieve economy of scale to benefit more from agroforestry value-chains.

Guideline 4.2. Respect local knowledge in the use of agroforestry products for various purposes, including for food and nutrition security, bio-prospecting and commercialization, and ensure equitable sharing of benefit between stakeholders (linked to principles 8, 9).

Guideline 4.3. Provide longer-term incentives[7], payments[8] or rewards for the range of ecosystem services[9,10]provided by agroforestry[11] that are essential to watershed functions, land restoration, carbon sequestration and biodiversity enhancement, most of which are public goods (linked to Principle 6).

Guideline 4.5. Integrate agroforestry data into global, regional and national databases, for example, trees on farms, agroforestry typologies and carbon, disaster risk reduction potential, geographic distribution, productivity, profitability and adoption profiles.

Farmers in Tỏa Tình Commune, Tuần Giáo District, Điện Biên Province, Viet Nam taking seedlings to their farms for planting in their agroforestry systems. Photo: World Agroforestry/Nguyen Van Thach

Principle 5: Enable environments for agroforestry investments and markets

Creation by ASEAN Member States of enabling environments with direct and indirect incentives encourages corporate and smallholding investors to make longer-term investments in agroforestry. Such investments can be oriented toward markets except in the case of subsistence production in areas in which access to markets and other factors, provide high barriers. New market mechanisms may be needed but can have contradictory social and economic effects, hence, the development of enabling environments for agroforestry investments must be consistent with the ASEAN Guidelines on Responsible Investment. Guidelines include, but are not limited to, the following.

Guideline 5.1. Identify and develop financial schemes, including pro-poor credit schemes (for example, with longer payback periods and lower interest rates) to support agroforestry business models for smallholders and small- and medium-sized enterprises.

Guideline 5.2. Provide policies that support longer-term but flexible investments and land- use planning at national and sub-national levels to provide confidence to financiers to invest in agroforestry.

Guideline 5.3. Provide technical and trade promotion support to develop agroforestry value chains and create market links (linked to Principle 4)[12].

Guideline 5.4. Provide transparent and simple procedures for processing and marketing agroforestry products to stimulate small- and large-scale investments.

Guideline 5.5. Remove economic distortions emanating from other sectors that reduce the value of agroforestry products, or which limit opportunities for agroforestry investors, especially, smallholders.

Guideline 5.6. Provide a range of direct and indirect incentives for agroforestry interventions that benefit society (linked to Principle 4).

18.3.3 Environmental principles (6, 7)

Principle 6: Maintain and enhance ecosystem services at farm and landscape scales

Agroforestry farms are often located in landscapes that serve multiple purposes at the same time. In many cases, they are in critical upland and watershed areas. Thus, agroforestry practices will, in addition to producing goods, have an impact on the provision of multiple ecosystem services. Because of this, agroforestry development should ensure that ecosystem services emanating from these landscapes are conserved, restored or improved [13]. Careful planning and proper management of agroforestry should be promoted to achieve targeted ecological benefits without undermining economic and other benefits. Guidelines include, but are not limited to, the following.

Guideline 6.1. Ensure that agroforestry interventions are planned with the purpose of achieving multiple benefits simultaneously — economic, social and environmental — at various scales from farm through to landscape levels (linked to principles 3, 11)[14],[15].

Guideline 6.2. Recognise and assess positive impacts of agroforestry in the maintenance and enhancement of ecosystem services, including in the restoration of forest and landscape functions, rehabilitation of degraded land, abatement of soil erosion, mitigation of climate change, and combating of desertification (linked to principles 4, 11).

Guideline 6.3. Conduct environmental impact assessments before implementing large-scale agroforestry interventions, including establishing baselines by which to monitor effects on ecosystem services.

Guideline 6.4. Facilitate a comparable biodiversity gain to compensate for any losses or unavoidable damage caused by the development of agroforestry after having applied mitigation measures.

Guideline 6.5. Develop and implement standard operational fi practices in the establishment and management of agroforestry interventions to ensure their contribution to ecosystem services (linked to principles 11, 12).

Principle 7: Understand and manage trade-offs

A trade-off is a balancing of benefits that are not attainable at the same time[16]. Understanding and managing trade-off is of importance when introducing agroforestry where trees, crops, fish and livestock are integrated on the same land unit. Trade-off arise both spatially regarding the arrangement of different components in agroforestry, and temporally, for example, the integration of trees as part of a farming system may result in a longer period between investment and return. To better understand and manage trade- off guidelines include, but are not limited to, the following.

Guideline 7.1. Use participatory methods to understand smallholders', medium- and large-scale and corporate farmers' decision-making both for short- and sustainable long-term production, with consideration of the needs of different household members (especially, women and youth), industry and markets (linked to principles 3, 11, 12).

Guideline 7.2. Project the magnitude of potential trade-off and support decision-making by quantifying the economic and environmental costs and benefits of agroforestry interventions. Costs are inputs such as land, labour and financial investments whilst benefits are outputs such as trees, crops, fish and livestock products and/or ecosystem services (linked to principles 4, 6).

Guideline 7.3. Consider foregone income of farmers and investors, especially during initial years of agroforestry establishment, and seek ways and means of reducing and managing trade-off for example, through longer-term credit, lower interest rates, tax holidays, insurance premiums, and incentives for the provision of ecosystem services (linked to principles 4, 5, 6).

18.3.4 Socio-cultural principles (8-10)

Principle 8: Recognise and respect local knowledge, traditions and choices

Social norms, cultural value systems, and local/traditional knowledge systems should be taken into consideration in planning and implementing agroforestry interventions. Guidelines include, but are not limited to, the following.

Guideline 8.1. Recognise and respect local, traditional or customary value systems, including indigenous knowledge and practices, of communities targeted for agroforestry interventions (linked to principles 4, 10).

Guideline 8.2. Secure local stakeholders' buy-in to major agroforestry investments through a process of free, prior and informed consent (linked to Principle 10)[17].

Guideline 8.3. Ensure that local knowledge and choices regarding agroforestry options (for example, tree and crop species, livestock breeds and types), purpose and practices are taken into consideration when conducting research, and during planning and decision-making (linked to principles 3, 4, 10, 11, 12).

Guideline 8.4. Recognise and address local people's unique needs for training, technology, land and resource rights, physical infrastructure, and market information, especially for indigenous peoples and ethnic minorities (linked to Principle 3).

Guideline 8.5. Establish socio- economic-cultural baselines for monitoring progress and evaluating impact as well as for compliance with social- welfare laws and investment guidelines adopted by ASEAN Member States and applicable international laws.

Guideline 8.6. Prevent displacement or alienation of local communities by major agroforestry investments (linked to principles 3, 8, 9).

Principle 9: Support gender equity and social inclusion

Social inclusion and gender equity should be considered when craft policies and when planning and implementing agroforestry interventions. These must be accessible to all types of social groups, including marginalized groups, such as indigenous peoples and ethnic minorities, as well as youth. Gender differences should be considered, and gender synergies promoted in agroforestry. Implementation of the guidelines to this principle should align with the ASEAN Guidelines on Gender. Guidelines include, but are not limited to, the following.

Guideline 9.1. Acknowledge the importance of gender equity and social inclusion in decision-making, design and implementation of agroforestry interventions.

Guideline 9.2. Ensure beneficial participation in agroforestry interventions by smallholders and socially-marginalized groups, such as indigenous peoples/ customary people/ethnic groups, displaced residents.

Guideline 9.3. Ensure that socially- marginalized groups benefit from, or are not adversely affected by, large-scale or corporate agroforestry investments (linked to principles 8, 10).

Guideline 9.4. Ensure that agroforestry interventions reinforce gender equity by understanding differences in gender roles, decision-making, constraints and opportunities, and seeking to improve women's access to agroforestry opportunities (including information, technologies, fi) and associated benefits

Guideline 9.5. Ensure that introduced agroforestry options or technologies are gender sensitive especially when it comes to the labour required from women.

Guideline 9.6. Strengthen the capacity of national research and extension systems and non-governmental organizations to undertake socially- and gender[18]-inclusive agroforestry interventions (linked to Principle 2).

In this photo, women in East Sumba District, Nusa Tenggara Timur Province, Indonesia are playing a game devised by ICRAF staff to help them identify which species are best for domestic and commercial purposes. Photo: World Agroforestry/Iskak Nugky Ismawan

Principle 10: Ensure safeguards and tenure rights

Agroforestry interventions will most likely create tensions amongst stakeholders in areas where rights to land and natural resources are unclear. Safeguarding tenure rights is, thus, important to ensure that agroforestry interventions do not jeopardize community rights or adversely impact the social fabric and livelihoods of local communities. Guidelines include, but are not limited to, the following.

Guideline 10.1. Understand tenure rights of stakeholders in areas targeted for major agroforestry interventions, especially those by corporate investments[19].

Guideline 10.2. Engage stakeholders in dialogues when planning major agroforestry interventions, respect their aspirations and rights and ensure farmers engaged in agroforestry, are not threatened or involuntarily displaced by large-scale agroforestry investments (linked to principles 3, 7, 8, 9).

Guideline 10.3. Ensure security of land-tenure rights of stakeholders involved in, and/or impacted by, agroforestry interventions to avoid social conflicts and secure returns on investments.

Guideline 10.4. Ensure free, prior and informed consent of rights holders who could be adversely or otherwise affected by major agroforestry interventions, and just compensation for any unavoidable damage inflicted (linked to principles 7, 8).

18.3.5 Technical design principles (11-12)

Principle 11: Design agroforestry options based on context

A variety of agroforestry systems and options exist, with their success being dependent on effective designs based on local contexts linked to sub-national, national and global conditions. Achieving economic, socio-cultural and environmental benefits simultaneously is the main goal of agroforestry. Trade-off often exist but well-designed agroforestry can simultaneously provide multiple benefit and satisfy the needs of different stakeholders. To achieve optimal benefits in agroforestry, guidelines include, but are not limited to, the following.

Guideline 11.1. Provide user- friendly, decision-support tools [20]for stakeholders to collectively assess information, identify opportunities and constraints, and make informed choices about agroforestry options. Decision support includes information and datasets of biophysical parameters — such as topography, land use, soil, temperature and rainfall — and socio-economic statistics including gender, market information, infrastructure issues and related policies.

Guideline 11.2. Ensure that agroforestry options are selected based on the specific needs, interests or purposes of individual (smallholders, large- holders, corporations) and public (government, non-governmental organizations) stakeholders, considering possible changes in future climatic regimes, economic conditions and policies (linked to principles 3, 7, 8, 9).

Guideline 11.3. Design agroforestry options based on local contexts in relation to biophysical, socio- economic (including labour availability and affordability), cultural, infrastructural, market and policy conditions (linked to guideline 12.2 and principles 3, 5, 9, 10), and considering temporal (for example, rotation of trees, crops, livestock, fi and spatial (for example, spatial arrangement of the components in the system) dimensions of agroforestry.

Guidelines 11.4. Aim for optimal benefits by ensuring agroforestry options are designed to provide economic benefits simultaneously with socio- cultural and environmental benefits, taking into consideration local contexts, including socio-cultural conditions (linked to principles 2, 9) and the land-tenure status of direct stakeholders (linked to Principle 10).

Guideline 11.5. Ensure that selected agroforestry options are implemented in combination with applicable conservation and climate-smart agricultural technologies[21], such as contour ploughing (especially on steeply sloping land), cover-cropping, mulching, ridge or zero tillage, drought-resistant varieties, and water-saving technologies.

Guideline 11.6. Provide technical guidance to ensure proper management of selected agroforestry options through training and extension material to support continuous education and lifelong learning (linked to principles 2, 6).

Principle 12: Select agroforestry components in a participatory manner

Selecting and deciding on tree, crop, livestock and fi aquatic components with respect to the spatial and temporal dimensions of agroforestry is crucial to success. Depending on the goals (short to medium or long term) of small-, large-holding and corporate farmers, their productive resources (land size, labour, capital) and other considerations, such as tenure and markets, the careful selection of components in agroforestry should be based on the concept: 'The right species of trees, crops, livestock and/ or fi in the right place for the right purpose'[22]. Guidelines include, but are not limited to, the following.

Guideline 12.1. Identify plant, livestock and/or aquatic species and varieties that match the biophysical conditions (temperature, rainfall, elevation and soils) of areas targeted for agroforestry by noting their existence in the areas and at similar sites (linked to principle 11)[23],[24] [25]. Consider future changes in climatic regimes when selecting species, varieties and breeds included in agroforestry systems. It is best to accompany this process with a market survey of the species and varieties to identify their markets and better design strategies for marketing the agroforestry products (linked to principle 11).

Guideline 12.2. Conduct a survey or workshop with local stakeholders to identify their preferential uses (goods and services) of trees[26], crops, livestock, fish and the species they want to cultivate, ensuring that the process is inclusive and equitable. When necessary, organize separate survey groups for men, women, youth and marginalised groups to ensure all can provide input (linked to principles 8, 9, 10, 11).

Guideline 12.3. Examine and apply existing technical guidelines adopted by ASEAN Member States concerning germplasm selection, quality, sourcing, distribution and management as well as those concerning selection of livestock and aquatic species and breeds. Ensure native plant, livestock and aquatic species and/or breeds are not adversely affected by introduced exotic species and/or breeds in the agroforestry systems.

Guideline 12.4. Ensure active participation of key stakeholders, particularly farmers, investors, extension workers and government agencies in decision-making regarding the components in agroforestry systems.

18.3.6 Communication and scaling principles (13,14)

Principle 13: Effectively communicate agroforestry knowledge

Taking into consideration a general lack of detailed knowledge about the development and management of agroforestry among ASEAN Member States and the varied and complex nature of agroforestry practices, managing knowledge and communicating it is critically important for policy makers, farmers, investors and market actors, to encourage widespread adoption, and continuous development, of agroforestry. Guidelines include, but are not limited to, the following.

Guideline 13.1. Identify knowledge and communication needs and gaps of all stakeholders — including farmers, extension and advisory agencies, local and national governments, market actors, investors — through participatory methods to provide tailored support as required.

Guideline 13.2 Communicate clearly between all stakeholders in a landscape and/or value chain in preferred languages and formats — including, but not limited to, written and audio- visual material, large and small meetings, skills' workshops, field training and demonstration plots — to better understand the issues facing adoption of agroforestry.

Guideline 13.3. Strengthen the knowledge management and communication capacity of institutions in charge of, and those already involved in, agroforestry, including their partners at national and sub- national levels, so as to more effectively create and share knowledge and skills, provide technical guidance, facilitate planning and decision-making at different levels, monitor results and impact, promote methods, results and achievements specifically and widely, and support financial mobilization for research and development of agroforestry.

Guideline 13.4. Adequately provide resource knowledge management and communication to ensure all stakeholders are informed, can engage in discussion, are able to increase their knowledge and skills and can continuously adapt and improve.

Principle 14: Plan for effective scaling up and sustainability

In consideration of the context-specificity of agroforestry interventions, scaling-up agroforestry must be carefully planned and take into account universal and contextual perspectives. The requirements for scaling-up agroforestry to achieve lasting impact must be thoroughly determined. Guidelines include, but are not limited to, the following.

Guideline 14.1. Engage stakeholders and sectors in planning for scaling agroforestry interventions (linked to principle 3).

Guideline 14.2. Understand the highest potential for, and limits to, scaling agroforestry by examining internal and external opportunities, including biophysical, social, cultural, labour and market conditions, as well as the strategies and plans of related sectors that may have an impact on the proposed scaling up.

Guideline 14.3. Ensure that the requirements for scaling are understood by stakeholders and are wholly or partially addressed at targeted sites.

Guideline 14.4. Understand the focus of scaling, which could be either the technical or institutional aspects of agroforestry or both. Technical aspects include selection of trees, crops, livestock and/or aquatic species' system components, design and management practices, and expected farm- and landscape- scale impact. Institutional aspects include organizing smallholders, building partnerships, training approaches and funding mechanisms.

Guideline 14.5. Agree on appropriate modalities for scaling contexts, including the key actors to be involved, for example, local governments, private companies, producer groups, extension agencies.

Guideline 14.6. Review scaling approaches, processes and achievements periodically to address gaps, issues and opportunities or devise recourse measures.

Box 18.3 Current understanding of agroforestry

Agroforestry is the interaction of agriculture and trees (forestry), including the agricultural use of trees. This includes trees on farms and in agricultural landscapes, farming in forests and at forest margins, and tree-crop production. Interactions between trees and other components of agriculture such as livestock, fish and aquatic species is important at a range of scales: in fields (where trees and crops are grown together), on farms (where trees may provide fodder for livestock, fuel, food, shelter or income from products, including timber)[27] and landscapes (where agricultural and forest land-uses combine in determining the provision of ecosystem services)[28]. At national and global scales, forestry and agriculture interact ecologically and through policies relating to land use and trade and are important with respect to climate change and other environmental concerns[29]. Agroforestry embraces an agro-ecological approach emphasising multi- functionality and the management of complex systems and polycultures rather than focusing exclusively on monoculture[30]. The word 'tree' is used inclusively to refer to trees and shrubs, all woody perennials, palms and bamboos. Similarly, the word 'agriculture' is used inclusively to refer to a human activity carried out primarily to produce food, fibre and fuel by the deliberate and controlled use of plants, animals and aquatic species. Agroforestry has proven benefits in areas of food security and family nutrition, energy supply from fuel wood, climate-change adaptation and mitigation, watershed regulation, land restoration, and agri-biodiversity improvement, among others. Agroforestry also helps farmers spread economic and environmental risks, providing important income sources for rural households, especially in the face of climate change. Farmers in Southeast Asia have for a long-time practised agroforestry and the types of agroforestry can be distinguished by their origin in the region.

The importance of forests for the health of the planet is well acknowledged but trees outside forests also have a vital role to play in landscape restoration and in achieving ambitious international and national targets in areas dominated by agriculture. There are many ways to rehabilitate degraded landscapes, but few can restore biodiversity and ecosystems while also delivering food and nutrition security, income and other ecosystem services through engaging and empowering local communities in the way that agroforestry does. When used as a tool for forest and landscape restoration, agroforestry can enhance physical, chemical and biological soil characteristics thereby increasing soil organic matter and fertility, enhancing nutrient cycling, controlling soil erosion and regulating water. The restoration of degraded landscapes with agroforestry can increase the resilience of communities to shocks, including drought and food shortages, and help adapt and mitigate climate change[31].

Today, agroforestry is increasingly recognized to achieve many international conventions, frameworks and targets that ASEAN Member States are all committed to. Among others, the Paris Agreement that came into force on 4 November 2016 provides a global framework for advancing agroforestry because trees in forests and on farms are central to climate-change mitigation and adaptation. Because of trees' capacity to sequester carbon, agroforestry can contribute to achieving ASEAN Member States' Nationally Determined Contributions. Agroforestry can also be instrumental in reaching the Sustainable Development Goals, helping to eradicate hunger, reduce poverty, support gender equity and social inclusion, provide affordable and cleaner energy, protect life on land, reverse land degradation and combat climate change.

18.4 Implementation considerations

These principles and guidelines form a framework that can facilitate discussions about the formulation of agroforestry policies, strategies, programs and projects by ASEAN Member States. They also provide guidance for agroforestry investments by the private sector. For implementation purposes, technical guidelines relevant to agroforestry that are tailored to specific ecological and socio-cultural zones in ASEAN Member States should be followed. Some considerations for implementation are discussed below.

18.4.1. Institutional roles and arrangements

Governments and agencies at different levels of ASEAN Member States, non- governmental organizations, farmers' associations and cooperatives, community-based organizations, the private sector (small- or large holders, small- and medium-sized enterprises, corporations) and others all have different roles to play. Concerted effort is needed in creating an enabling environment, enhancing organizational capacities and participatory inter-sectoral collaboration and decision-making (principles 1, 2, 3). Identifying key stakeholders and understanding their roles, needs and aspirations is a necessary first step toward an enabling environment for agroforestry.

Successful agroforestry interventions require government support through policies and funded programs, given competing interests from commercial monoculture agricultural production. As elaborated in Principle 1, ASEAN Member States should identify a dedicated institution responsible for agroforestry development in their respective countries. Social Forestry is amongst many national programs and mechanisms in which agroforestry can be implemented with policy backing and funding support. Many ASEAN Member States have social forestry programs with plans and targets to improve forest peoples' livelihoods while protecting and sustainably managing forest; agroforestry plays a critical role in achieving these goals.

Private-sector investors play crucial roles in agroforestry development, particularly, agri-industrial companies with an interest in sustainable production that are aiming for certification that will enable them to brand their products as 'environmentally friendly'.

National research and academic institutions need to be engaged in agroforestry research, training and education to 1) continuously generate agroforestry knowledge and evidence needed for adjusting and/or refi technical and policy recommendations; 2) develop tools and methods for knowledge generation, monitoring and impact evaluation; and 3) support continuous learning, education and knowledge dissemination. Basic and applied research in agroforestry should be carried out in a participatory manner (principles 3, 8, 9).

The forestry and agricultural extension or rural advisory services in ASEAN Member States also play crucial roles in sharing knowledge and experience, training and building cadres of extension workers with the right skills to facilitate agroforestry planning, implementation, monitoring and evaluation.

Farmers'associations and cooperatives and community- based organizations are also vitally important in the co-production of agroforestry knowledge, farmer-to- farmer sharing of knowledge and experience, adoption of agroforestry options best suited to their own contexts in relation to biophysical, socio-economic, cultural, market and policy conditions, consolidation of the aspirations, concerns and products of the farmers, and fostering dialogue amongst stakeholders, including policy makers and investors.

Members of the CGIAR, a global partnership for a food-secure future, also play a role by aligning their research programs with ASEAN Member States' agroforestry agendas and/or directly conducting research together with regional and national partners.

Finally, United Nations' organizations, particularly FAO, play crucial roles in providing technical assistance, policy advice and, where possible, funding toward the implementation of these guidelines.

18.4.2 Planning and financing

Since agroforestry is not explicitly in the hands of either agriculture or forestry, ASEAN Member States aspiring to develop a national agroforestry program should, first, consider the institutional infrastructure required to make a national program successful (principle 1). Headed by designated institutions within relevant ministries, a special multi-sectoral committee or taskforce could be created to facilitate planning. This approach aligns with the ASEAN Multi-Sectoral Framework on Climate Change: Agriculture, Fisheries and Forestry towards Food Security, which provides a mechanism for coordinated actions.

Planning for an agroforestry vision and road map by ASEAN Member States is desirable to show the way forward. There are many ways to drive agroforestry development in the region, including creating a favourable investment environment with supportive policies that stimulate market openings for agroforestry products and mainstreaming agroforestry in existing strategies, plans and targets, for example, sustainable or low-emissions development plans, national REDD+ action plans, rural development plans, land restoration programs, land-use planning, and Nationally Determined Contributions. International development and bilateral partners of ASEAN Member States can be sought to align their development programs with, or directly provide funding support, to Member States' agroforestry programs.

Planning for agroforestry programs or projects at national and sub- national levels requires scoping and situation analyses to identify issues, challenges, gaps and opportunities. If positive signals give potential investors (smallholders, large-holders, corporations) the confidence to invest in agroforestry, financial feasibility studies and long-term strategic and medium-term management planning needs to be undertaken. Planning at the local community, farm or fiish level should be facilitated by extension agents trained in agroforestry (Principle 2) and include selection of a number of agroforestry options best suited for specific contexts, considering their specific environmental, social, cultural, market and policy conditions (principle 12).

18.4.3. Research and continuous learning

Continuous learning and research are needed for the co-production of agroforestry knowledge not only to underpin efforts to scale best practices but also to enable adjustments of existing agroforestry technologies and practices to address changes in local contexts, including future changes in climate regimes and influences from external factors (principles 3, 12). Documenting and taking stock of success and failures of past and existing agroforestry models is a good start to prioritize research in various aspects of agroforestry. Research should be action oriented and carried out in a shared-learning and participatory mode with stakeholders. Part of the planning process could be to identify research and academic institutions involved, or wanting to be, in agroforestry research and rally their support to undertake coordinated efforts to ensure complementarity rather than duplication of research efforts. Development of agroforestry curricula should be supported to ensure agroforestry is taught in institutes of higher education, building upon the work of the Southeast Asian Network for Agroforestry Education that was established by the World Agroforestry Centre in the late 1990s with funding from the Swedish International Development Agency, as well as other higher education networks existing in the region. Such efforts should also be aligned with the broad goals of the Southeast Asian Ministers of Education Organization's Southeast Asian Regional Center for Graduate Study and Research in Agriculture.

18.4.4. Monitoring and evaluation

In view of agroforestry's potentially large addition to Nationally Determined Contributions, Land Degradation Neutrality targets, food security and other goals, targets and strategies where agroforestry potentially contributes, ASEAN Member States can include agroforestry in their monitoring, reporting and verification schemes. Any monitoring process should ensure that the following principles are addressed by agroforestry programs:

1) Continuous learning: the program should embrace an iterative process of gaining feedback and informing stakeholders. The program should be adaptive in accepting feedback to improve its activities.
2) Participatory and user-friendly monitoring: the development of monitoring tools is best done in a participatory manner to ensure friendliness for users.
3) Strengthened stakeholder capacity: effective participation requires technical, social and financial skills and abilities. Strengthening these capacities can increase stakeholders' involvement in monitoring, especially with farmers' organizations and cooperatives, and forest user groups

At ASEAN level, monitoring the uptake of this framework by Member States should be coordinated by the ASEAN Food, Agriculture and Forestry sector using applicable monitoring instruments already adopted by ASEAN, such as the ASEAN monitoring on food security, environment and climate change. The ASEAN Multi- Sectoral Framework on Climate Change: Agriculture, Fisheries and Forestry towards Food Security can also be used for monitoring and assessing the uptake of the guidelines by Member States, particularly in regard to multi-sectoral cooperation within Member States.

FAO may also consider monitoring and assessing progress of implementation of these Guidelines by ASEAN Member States, in view of its global database on tree cover and trees outside forests.

18.4.5. Knowledge management

One of the many issues raised in the development of agroforestry is a lack of information and knowledge sources in ASEAN Member States. This is linked not only to the lack of institutional home for agroforestry research and development in many ASEAN Member States but also because agroforestry knowledge is often available only as scientific articles, which are not readily accessible to policy makers and planners. In relation to Principle 13, agroforestry knowledge must be communicated effectively but it cannot be effectively managed and communicated unless responsibility is delegated to appropriate bodies. It is thus important for ASEAN Member States to create a facility for managing agroforestry knowledge effectively, and ensure such knowledge is readily accessible to a broad range of users. The tasks of this facility would be to collect and categorise agroforestry knowledge, establish a knowledge-oriented technology infrastructure, such as web portals, and monitor use (linked to monitoring and evaluation in Section 5.4). Knowledge management of agroforestry is a task that can be delivered by the designated or newly-created institution referred to in Principle 1. This task can be shared with many knowledge owners and brokers, such as research institutions and academe, as well as non- governmental organizations.

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Transformation of forest function

Transformation of Costa Rican forest functions from a focus on logging to one on ecotourism as backbone of the country’s economy (mural in roadside restaurant)

Photo: World Agroforestry/Meine van Noordwijk

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CHAPTER NINETEEN

Policies for ecosystem services enhancement

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Highlights

- Policies and policy frameworks for ecosystem services (ES) are relatively weak and still emerging, interacting with sectoral policies for specific ES
- Individual and specific ES such as those related to biodiversity and water benefit from existing sector-driven policies, while less tangible and cross-sector ES such as pollination and climate have less policy support and instruments
- Climate regulation services which includes carbon sequestration and climate resilience have been catalysed by international policy instruments
- A few countries (e.g. Costa Rica and Vietnam) have developed specific policies for ES enhancement; however, there have been challenges with such attempts as a single policy falls short of addressing multiple ES and ecosystem functions
- Determining appropriate policy instruments and the right mix of instruments requires rigorous evidence-based analysis and understanding of the trade-offs and synergies between instruments, especially when decision-making requires balancing multiple ecosystem services

19.1 Introduction

Ecosystem services have increasingly been highlighted as central to human wellbeing[1,2,3]. Ecosystem services refer to the various benefits that humans gain from nature and functioning ecosystems. Four groups of ecosystem services are commonly recognized: provisioning (e.g. food, drinking water, fibre), regulating (e.g. climate, disease control, flood prevention, waste-water self-cleaning), supporting (e.g. nutrient cycling, crop pollination, maintenance of genetic diversity), and cultural (e.g. recreation, spiritual)[4] services. These together play a key role in determining overall economic, social and environmental development[5]. As a result, interest in various aspects related to maintaining and enhancing ecosystem services, with research on characterization and valuation taking centre stage[6,7]. Several recent publications have highlighted the paucity and need for research on policies and policy frameworks for maintaining and enhancing ecosystem services[8,9]. Such policies may need to support four processes of linking knowledge with action[10]:

1) Awareness, diagnosis of issues and (international) agreements on monitoring progress,

2) Political will and commitment to deal with them ('willingness to act'),

3) Synergy with the totality of existing policy instruments ('ability to act'), and

4) Support for continuous innovation in the search for fair and efficient solutions.

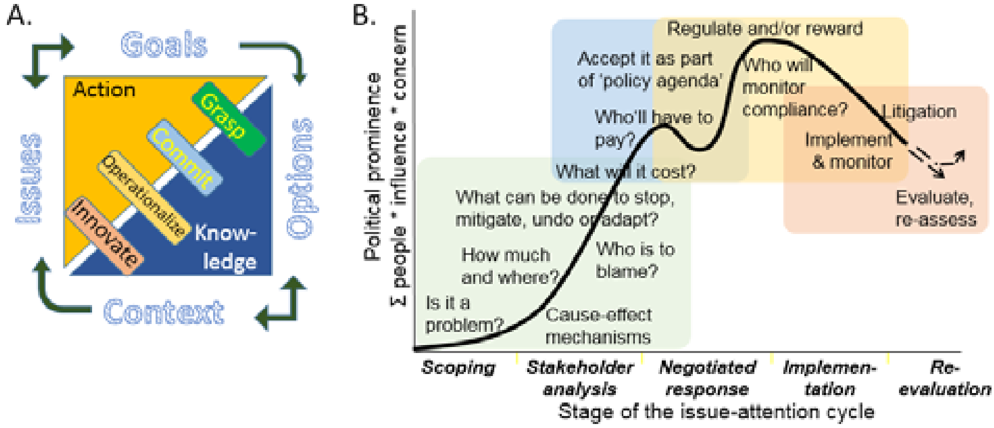

Figure 19.1 A. Four aspects of linking knowledge with action[10] in relation to B. the policy attention or issue cycle[11,12] (with colour coding of the four aspects)

As a consequence of a wide range of 'issues' that went through the stages of awareness, denial, diagnosis and acceptance of their importance by a sufficiently large part of the public discourse, political commitment has been expressed to deal with them. Given the sequence in which this happened in various countries, a patchwork exists for dealing with issues with a specific area focus and generically (within the jurisdiction of the institutions that have emerged), as shown in Table 19.1.

Table 19.1 Different models used to study interactions in mixed tree–crop systems and their main characteristics

Type of decisions	Specific area focus	Generic (within jurisdiction)
Avoiding negative effects on nature	Dams and other water infrastructure Mining and other resource extraction Regulated hunting/ fishing/ logging/ grazing Environmental Impact Assessments (EIA) for all 'projects'	Pesticide admission Water pollution control Air pollution control Soil pollution control Greenhouse gas emission control (climate mitigation) Invasive species control Land use zoning & planning Strategic Environmental Assessment (SEA) Adjusting perverse subsidies & taxation rules Boycotting destructive 'value chains'
Supporting positive	Protected area designation & management	Environmental education Environmental accounting

effects on nature	Ecological corridors Restoration of 'degraded lands'	Supporting 'certified' trade Developing clean technologies
Adjusting benefit distribution from well-functioning ecosystems	Respecting & recognizing indigenous territories PES and coinvestment in environmental stewardship Integrated Conservation and Development Programs Local conservation contracts Sloping land conversion actions	Benefit sharing rules for bioprospecting (incl. pharmaceuticals) Devolution of resource management governance Global Environmental Fund (and related) transfers

A study of the effectiveness of policies in sustaining and promoting ecosystem services in the Indian Himalayas[13] reviewed existing policy instruments in the forest, wildlife and environment sectors from 1927 – 2008. The narration showed an evolution from the production-focused instruments that dominated between 1927 and 1972, followed by a focus on protection-oriented instruments between 1972 and 1988, community-participation dominated instruments between 1988 and 2006 and a climate and globalization dominated approach from 2006 onwards. The study concluded that a mix of complementary instruments that ensure and incentivize stakeholder participation across sectors would be most effective and potentially efficient in sustaining ecosystem services. The way targeted policy instruments interact with all existing rules, incentives and norms shapes the citizen's response.

Measurement of 'policy relevant' ES issues, such as the rate of peat subsidence in smallholder oil palm landscapes. Photo: World Agroforestry/Ni'matul Khasanah

Policy literature and ES policy literature in particular suggests three major groups of policy instruments- regulatory, market-based instruments and information and knowledge-based instruments[14],[15],[16]. Regulatory instruments seek to regulate the use of natural resources. This could include rules for planning, management, granting of permits, controls etc. Market-based instruments seek to change behaviour by influencing prices directly and indirectly. Subsidies, taxes, payments, penalties, fees, and auctions represent examples of market-based instruments. Information and knowledge-based instruments seek to change behaviour through raising awareness and provision of knowledge. Education, training, extension, research and communication on matters related to human actions and environment are among the main instruments in this category. The above categorizations are not mutually exclusive in practice but rather used to highlight the possible distinctions to guide the discussion. The bulk of the instruments in this chapter fall in at least one of the above-mentioned categories. Tradeoffs need to be recognized at multiple levels[17], as key to effective policy designs and reforms. Often the last category (benefit distribution) is combined with either or both of the others, in forms of 'coinvestment', enhancing the local benefits from well-functioning ecosystems (rather than paying for the services provided as such).

This chapter explains ES policies and policy frameworks with a view to providing guidance on effective, efficient and equitable policy options for pro-poor payment for ecosystem services (PES). It examines sector-based policies to enhance targeted ES as a dominant paradigm of ES policies, and a more generic national ES support policy as an emerging paradigm. Backed by examples, the chapter discusses challenges for both paradigms and suggests innovative and flexible policy instruments for enhancing ecosystem services.

19.2 Sector-based ecosystem services policies

Given that ES is a relatively new concept, few countries have so far addressed ES specifically. Most countries have had very sector-specific policies often tied to a given ES. We briefly show a set of policies that target ES from different sectors and sub-sectors in the literature, typical of the global landscape namely, water, forests, carbon and pollination. The first two are largely established, while the last two have been growing. Table 19.2 below summarizes the set of instruments largely used in each of the sectors.

Table 19.2 Examples of policy instruments for ecosystem services enhancement

Instrument Category	Water	Forests	Carbon	Pollination
Regulatory restrictions on land use and resource exploitation	• Water Funds • Watershed Management Boards (local) • River Basin Commissions (Trans-national) • Integrated Basin and watershed management plans	• Protected Areas • Forest Zoning Plans • Spatial Land Use Plans • Forest Management Plans • Trade rules (*Forest Law Enforcement, Governance and Trade*, Lacey Act)	• REDD+ (Reducing Deforestation and (forest) Degradation) • Nationally Determined Contributions (NDCs)	• Pesticide regulatory standards • Crop risk assessment rules • Pollination and pollinator monitoring regulations

Market-Based Incentives	• User fees • PES • Utility taxes (water, electricity/hydro)	• PES • Fines (illegal harvesting, etc.) • Certification schemes • Penalties • Fees • Taxes • Duties	• PES • Certification	• Insurance schemes • Recognition and valuation of pollination as agricultural input
Information, Norms of behaviour	• Water Users Associations	• UNFCCC Subsidiary Body for Implementation (SBI), • Subsidiary Body for Scientific and Technological Advice (SBSTA) events, • Conferences of Parties (COPs)	• REDD Readiness[18] • Global Climate Fund readiness support • Climate Technology Centre and Network	• Pollination Strategy Documents • Integrated pest management • Agro-ecology (ecological intensification and diversification)

Generally, policies for water management are domestically and locally initiated rules for access to, and avoidance of pollution (as a 'disservice') of surface water given its centrality as a 'utility' to daily activities and development. Water policies tend to focus around four main areas, namely- planning and management rules, privatization and public management, water rights, and market policies including pricing. Various national and subnational levels often have to make choices along the lines of the four areas listed in the preceding sentence. Rules for less visible resources such as groundwater have been slower to develop, and the differential water use by different types of land cover (including forest plantations) is only regulated in a few, water-scarce countries[19]. In almost all countries complex laws govern water services management at multiple levels, broadened from an initial focus on agriculture (irrigation), engineering (flow regulation and storage), urban and industrial water supply, and/or waste-water treatment[20]. In transboundary river basin management, basin-level multi-country agreements constitute another layer of coordination in policies. No policies and institutions exist yet to coordinate atmospheric moisture transfers as key element of global climate systems[21,22,23].

Forest policies have also remained largely domestic. And have evolved tremendously overtime. Prior to the 1970s forests were meant to generate revenue for development. As a result, forest policy was centralized and heavily sectoral in nature, with forests designated as sources of revenue, land for agriculture and or forest reserves largely. Since the early 1970s, with rising awareness of dependence of local communities on forests as sources of livelihoods and the growing importance of small-scale forest enterprise in local economies, forest policies have sought to integrate forests in rural development. This ushered in participatory, collaborative and community approaches to forest management.

With growing competition between forests and larger economic interests such as a plantation agriculture, international interests in shaping forest policies has grown exponentially. Hence, forest policies have been centre stage in the sustainable development discourse in the last three decades. The Convention on Biodiversity (CBD), the Aichi Targets, Forest Law Enforcement Governance and Trade- FLEGT, Reducing Emissions from Deforestation and forest Degradation (REDD+) within the UNFCCC are examples of international instruments that shaped forest policies at global and national levels. Payments for ecosystem services and certification are among mechanisms that have grown and continue to grow in the forest policy arena.

The influence of global climate policy is even greater since the UNFCCC[24] and the Kyoto Protocol in 1997 moved towards climate instruments, first only for 'reforestation' and 'afforestation', but subsequently also incorporating forest carbon stock protection. Efforts to learn lessons from 'integrated conservation development projects' informed the design of carbon emission control[25] , but the capacity to understand and effectively deal with all aspects of effective policy design and its subsequent implementation varied substantially between countries[26]. As evidenced in India[13], climate concerns became a new 'discourse' for redressing existing policies, rather than a start from a clean slate.

Pollination policy or policy action on the other hand is at infancy. A few European countries have developed policy papers and strategies, with the EU attempting actions towards enhancing pollination services. Ten types of policies have been identified[27] that governments can take to safeguard pollination services. These include, raising pesticide regulatory standards; promoting integrated pest management; including indirect and sub-lethal effects in genetically modified crop risk assessments; regulating movement of managed pollinators; developing incentives such as insurance schemes to help farmers benefit from ecosystem services instead of agrochemicals; recognizing pollination as an input into extension services; supporting diversified farming systems, conserving and restoring 'green infrastructure' (a network of habitats that pollinators can move between) in agricultural and urban landscapes; developing long-term monitoring for pollinators and pollination; and funding participatory research on improving yield, diversified and ecologically intensified farming.

A major disadvantage of sectoral policies is that they sometimes displace degradation activities to other sectors with weak or no regulation. In the climate change literature such displacement is described as 'leakage'. Often times they are spatially targeted and land cover / land use type specific and therefore unlikely to be effective if not designed and implemented as part of a larger land use plan. Another challenge is that specific ES sector policies often suffer poor financing, especially when the base sector is weak in revenue generation. In forested countries, forests and agriculture tend to have more resources, while water, carbon and others are very weak. A national level policy can overcome this through cross-subsidization.

19.3 National ecosystems services policies

In the last 2-3 decades, national level ES policies have emerged as an option for enhancing ES. These policies largely target multiple ecosystem services and are modelled around payments for ecosystem services. We briefly introduce two case studies here in after – i.e. Costa Rica (Box 19.1) and Vietnam (Box 19.2). It is hoped that this will highlight the key features of national level ES as currently practiced.

Visitors to Costa Rican rainforest as inspiration for forest policy reform. Photo: World Agroforestry/Meine van Noordwijk

Box 19.1 Costa Rica

Costa Rica has a history of deploying incentives in forestry going back to 1979. This including soft credits and forest payment certificates of various forms. However, PES was only enshrined in forestry law in 1996. The new national forestry law recognized biodiversity, watershed functions, scenic beauty and GHG mitigation through carbon storage and sequestration as ecosystem services[28,29]. These could be achieved through a number of land use modalities (i) reforestation through plantation, (ii) protection through existing forest, (iii) natural forest regeneration, and (iv) agroforestry systems.

By 2008 over 668, 369 ha had been protected under this scheme. Payments ranged from USD 41/ha -for natural forest regeneration, to USD 800/ha for 10-years reforestation plantation contract. For agroforestry, payments were about USD1.3 per tree. Budgetary provisions for PES in Costa Rica averaged around USD 13 Million or about 0.43% of the country's budget in 2006[28].

Box 19.2 Vietnam

Vietnam instituted a nationwide Payments for Forest Ecosystem Services-PFES in 2010 with the aim of improving forest quality and quantity, increasing the forest sectors contribution to the national economy, reduce the state's financial burden in forest protection and management, and improving social wellbeing. PFES requires users of forest ecosystem services to make payments to suppliers of these services. Users include water supply companies, hydropower plants, tourism companies, and suppliers are forest owners including individuals, households, communities and organizations holding forest land titles. Services outlined in the Decree 99 include, water protection; natural landscape beauty protection and biodiversity conservation for tourism; forest carbon sequestration and the reduction of GHG through prevention of deforestation and forest degradation; and the provision of forest hydrological services for spawning in coastal fisheries and aquaculture.

Following a series of over 20 legal instruments, Forest Protection and Development Funds –FPDFs have been set-up at national and provincial levels for the purposes of implanting PFES. Provincial level FPDFs sign contracts with buyers and collect payments, prepare payment plans, release payments to service suppliers, monitor performance and report to the national FPDF.

Since creation, PFES has guaranteed[30] USD 162 Million with record disbursements to ES suppliers of above 75%. For most families PFES payments often surpassed financial support of around VND 200000 / ha / year provided to forest owners for protection and development through state budget[29]. A variant of PFES specifically for watershed functions that was tested in Son La province received USD 35 Million (at a USD 1 per cubic meter as a nationwide price). Based on a formula known as the K-Factor, payments ranged between USD 5-10 per ha for forest conservation activities[31]. In this case 10% of funds was allocated to management at every level of government.

While national policies offer opportunities for cross-sectoral actions, cross-subsidization and coordination, the two case studies in Box 32.1 and 32.2 demonstrate that transactions costs might be quite high. Involving several sectors, different levels of government and monitoring for multiple types of services and actors (producers and beneficiaries) can be expensive. Capacity requirements for national level planning, implementation and monitoring can be difficult in poor, data-scarce environments in developing countries. This challenge was reported in both Vietnam and Costa Rica cases[27,29]. Both Costa Rica and Vietnam national policies were based on PES as the key instrument and there is emerging evidence that they may not be effective in instances where opportunity costs are higher than what government PES is offering rendering the scheme inefficient and ineffective[16,28]. It is thus imperative to find flexible, innovative and cost-effective policy options going forward. The preceding chapter discussed this for water-related policies in East Africa[32].

Towards flexible and innovative policy mixes

Sectoral policies have their limitations. Attempts at developing ES policies at national level in Costa Rica, Vietnam and elsewhere have also had challenges in attracting non-public financial resources[33] and interacting with global commodity trade through certification[34].

In order to be effective, efficient and equitable in the management of natural resources a more integrated approach has been recommended[16,35,36,37]. Such an approach must be flexible, innovative and allows for mixing of policy instruments in an adaptive way with room to retool, adopt and aggregate across sectors and local, meso and macro levels.

Several key dimensions/ features are necessary for the development and implementation of a successful integrated ES policy. (i) A flexible mix of instruments to choose from, (ii) choosing the right set of instruments, (iii) equity, participation and political feasibility of the instruments, and (iv) The role of technology and innovation policies. We briefly examine each of these below.

One of the beneficiaries of Costa Rican PES policies: a brightly coloured, highly toxic "Blue jeans" frog or known as Strawberry Poison-dart frog that has habitat loss and human use of its toxic skin for poisonous darts as threats. Photo: World Agroforestry Centre/Meine van Noordwijk

Instrument Choice

Choosing the right set of instruments that are compatible and complement each other is critical for delivering ecosystem services[16]. A number of factors deemed important in the choice of instruments have been cited in literature including, effectiveness, economic efficiency, equity (distribution of costs and benefits across groups) and political feasibility[38,39,40].

Figure 19.2 The 17 Sustainable Development Goals provide an overarching policy framework within which the case needs to be made that well-functioning ecosystems are essential for achieving any of the goals[41]

It is important to have some data and understanding of the impacts of the above-mentioned factors and their implications, before making decisions on what instruments to apply. Often, a clear view of the uncertainties involved is also necessary in the decision-making process. This can be a challenge in data-scarce and resourced challenged environments in developing countries. However, attempts at understanding these to the best extent possible is advisable. It is also important to understand the externalities of various instruments as we consider their deployment. The Sustainable Development Goal framework has emerged as a way to address synergies and tradeoffs at the level of national commitments to balance 'development' and 'sustainability', with its ecological, social and economic dimensions (Fig. 19.2).

Equity, Participation and Political Feasibility

Who gains and who losses in the implementation of any policy instruments is often a determinant of (especially political) feasibility. Often interests of various stakeholder groups and the way they would absorb benefits or costs of any instrument would vary. Poor vulnerable groups and minorities are often losers. It is therefore useful to ensure that their benefits and costs are well understood and taken care of through appropriate safeguards[42]. Participation and inclusion of all stakeholders in policy development and implementation at all stages has been evidenced as an effective way of ensuring that potential losers and winners are understood and that the political feasibility is guaranteed[43].

The Role of Technology, Research and Innovation

Some of the greatest opportunities for enhancing ecosystem services are linked to technology /technical innovations and practices. Climate smart agriculture practices, smart watershed management practices and innovations in forestry can help improve ecosystems productivity[3]. In Pro-Poor PES, this is particularly important because developing country environments face tremendous challenges in terms of technological developments. Technological innovation is often fuelled by research, therefore policies that promote investments in 'boundary work' research[10, 44] relevant for ecosystems services is important for the mix of policies and instruments needed.

19.4 Conclusion

This chapter set out to explore policies and policy frameworks for ES enhancement. It pays particular attention to PES as an instrument in the ES policy arena. Two ES policy paradigms are distinguished. Single sector ES policies and national PES policies. While sector specific policies are well established in the water, biodiversity and forest sectors, carbon and pollination are still in development. Hence, PES is established in water and in the biodiversity sub-sector to some extent but is yet experimental in the carbon sector and almost non-existent on the pollination arena. These sectoral policies are limited, poorly funded and often displace degradation related activities outside the sector.

While national PES presents opportunities for cross-sectoral actions and for cross-subsidization of sectors, it also lies at the interface of multiple sectors, with accompanying challenges of generating interest and agreement and meeting high transactions costs of multiple sectors. Like all PES, funding and financing must enable payments beyond what competing options offer, else it would become ineffective. This suggests that for PES to be effective, efficient and equitable, it has to be part of a wider policy mix that is flexible and innovative for application at all scales.

Four recommendations for developing flexible and innovative frameworks for ES enhancement are suggested. These are,

(i) Build up experience with diverse instruments so that there is a flexible mix to choose from, depending on context; be aware that working across existing sectors takes time and special efforts;

(ii) Choose appropriate instruments once the various, possibly partly conflicting, public goals have been articulated;

(iii) Throughout the 'issue cycles', ensure equity, participation and political feasibility of the emerging instruments and their implementation; and

(iv) Foster the role of technology and innovation policies so that emerging issues can refer to basic understanding of cause-effect mechanisms and monitoring of long-term changes.

Coherence between the four aspects of linking and action, as described in Figure 32.1, in effective boundary work can help enhance pro-poor PES in the future, beyond current 'recipes'.

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Murti'ah

Sustainability means maintaining the flow

KIPRAH AGROFORESTRI 18, ICRAF, Bogor

INTERMEZZO 8

Ibu Murti'ah, a coffee farmer in Ngantang (Malang, East Java, Indonesia) has answers to all questions of students who want to understand agroforestry as source of livelihoods and well-functioning landscapes. The students find that topics that are taught in separate courses at the campus all connect when talking to a farmer in her plot.

The agroforestry plot is small, only 0.25 ha on the map, but has many components, and provides a continuous flow of products. Ibu Murti'ah manages the plot based on a simple concept of space: when there is an open patch, she plants something new; if she has found something worth trying, she makes some space for it. The main concept is interplanting ('sisipan' in the Indonesian language), rather than rotations and land clearing. As a result, every day there's something to cook, eat and sell.

She also has a number of tree commodities that provide income, especially coffee and clove trees. With the coffee she found that the difference in farmgate price between fresh and processed, dried beans is such that it is worth the work. She also tried the 'Luak' coffee that is harvested and pre-processed by the civet cats that still live in the landscape. Such coffee has been promoted as a specialty product (maybe as much based on an interesting story as on objectively verifiable quality) and fetches a high price in tourist-oriented restaurants, but Ibu Murti'ah found that the Luak excrements from which coffee beans are collected are smelly and after considering the extra work in collecting and washing the beans, the price premium was actually very small.

She told the students that clove trees from which once a year flower buds can be harvested, dried and sold were more interesting. She is also happy with her 'Petai' (*Parkia speciosa*) trees, as the pods always fetch a good price, and the seeds add a nice flavour to the food. Among trees that provide timber the 'Chinaberry' tree (*Melia azedarach*) is her favourite, as it grows fast and can already be harvested with a stem diameter of around 30 cm after 5-6 years. These trees really are a savings account, providing large amounts of cash (equivalent to 1000 USD) when needed.

"So why don't you just focus on growing such trees?" ask the students. "I can't wait that long", she explains, "I need a garden that is flowing continuously into my kitchen and purse". Trees are also good as source of fodder, along with grass collected elsewhere in the landscape. She has three cows that provide milk that can be sold to the local dairy cooperative, while the biogas tank supports the kitchen fire when needed. The cows are only a few hundred m from the agroforestry plot, so fodder and manure can be moved back and forth. She experimented with growing ornamentals (flowers) for the local market (mostly people from Surabaya city), but currently likes the coco-yams best, as they can be harvested when needed.

She inherited the land from her parents, already in 1968 and has farmed here ever since. She explains to the students that the birds in the landscape and the earthworms in her soil help to keep the soil fertile and the landscape a pleasant place to be. Sustainability is first of all a matter of maintaining the flow.

Based on "Agroforestri pas-pasan... pas butuh, pas ada" by Kurniatun Hairiah, Heni Melsandi, Wahyu Ningtyas 2015. KIPRAH AGROFORESTRI 18, ICRAF, Bogor

Cultivated lands with mostly native trees

Cultivated lands with mostly native trees in boundaries and coutours - Pacobamba, Apurimac-Peru.

Photo: University of Bern/Sarah-Lan Mathez-Stiefel

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CHAPTER TWENTY

Methods in agroforestry research across its three paradigms

Meine van Noordwijk and Ric Coe

Highlights

- Methods in agroforestry research have evolved along with the paradigms and scales of interest
- For the field-level AF1 paradigm (What?, Where?, How?, Who?) methods have been derived from soils, microclimatology, forestry, agronomy and agricultural economics research, along with social science and geographical methods to describe typologies and spatial patterns
- Methods for the landscape-level AF2 paradigm (So what?, Who cares?, Why?) have been derived from those used in hydrology, ecology and social-ecological system analysis
- The policy-oriented AF3 paradigm requires additional methods for interaction with public attention issue cycles and boundary work

20.1 Introduction

Methods, subject to scrutiny of underlying assumptions and sources of bias, define the scientific approach to knowledge more than any other aspect, but they are driven by questions and judged by the results (data) they generate and the implications these are considered to have. Agroforestry research methods are 'horses for courses'; there is no single method that stands out across all purposes of research. Similarly, there are no research methods that are unique to agroforestry, and few that are completely new rather than modifications of something used earlier. Agroforestry research, like all applied research, has borrowed, used and sometimes improved methods from other fields – with all the hidden assumptions and potential biases these methods may have. The borrowing has not always been easy. For examples, methods from agronomic research may not be feasible with trees that take 30 years to mature. The value of method in advancing the field of agroforestry research is judged not only on credibility of results – judged, for example, by those assumptions and biases – but also their feasibility determined by cost, practicality in field conditions or ease of learning them. In this chapter we will give examples of how research methods have evolved alongside the articulation of the second (landscape) and third (policy) agroforestry paradigm (see Chapter 1), while enriching those that are used within the first (field/farm level) paradigm.

Research questions at the AF1 scale are primarily those about ***what?*** (agroforestry typology, tree diversity), ***where?*** (spatial context, including climate, topography, soils, accessibility), ***how?*** (understanding of growth, yield and plot-level interactions between trees and crops in relation to inputs and management) and ***who?*** (farmer typology). At AF2 level three additional questions are asked: ***So what?*** (Ecosystem service consequences), ***Who cares?*** (Stakeholders and their involvement) and ***Why?*** (Drivers of change, points of leverage and intervention). At AF3 level the last two questions are further enriched with a 'public attention issue cycle' concept with its own dynamic and points of intervention and learning.

20.2 Methods for research of field and farm level paradigm AF1

20.2.1 Typologies of agroforestry practices (what?, where?)

Agroforestry practices, where trees are intimately associated with agricultural components at a field scale, are often part of farming systems that include other components as well. The purpose of a general classification of agroforestry practices is to have logical labels for different types and to group those that are similar, thereby facilitating communication and the organized storage of information[1]. A generic scheme uses a primary classification based on relative dominance of (and priority amongst) naturally established or planted trees, tree crops, annual crops and livestock, and a secondary classification based on dispersed versus zoned tree distribution. Temporal dimensions of practices (length of rotations, sequential or simultaneous interactions) provide another classification. The specific agroforestry experience in Asia and Latin America, with high tree diversity agroforests, provides additional insights and lessons for an Africa-focussed typology[2]. In North America agroforestry developed a partially separate terminology and typology[3]. In European countries administrative structures that consider only agriculture or forestry as legitimate have resulted in the loss of agroforestry practices (and systems?) and an impoverishment of the benefits that they provide. Typology and nomenclature may need to be adjusted to make agroforestry possible within the existing land use concepts[4].

In the analysis of tree diversity in various agroforestry practices, the concepts of 'planned' and 'tolerated' diversity can help[5], as does the insight that agroforestry farm components may represent past + present + future value-determining elements (see Chapter 2).

20.2.2 Allometry and characterization of trees, soils, crops, livestock (what?, how?)

Research methods for characterizing biomass, carbon and nutrient cycling in agroforestry systems have been developed in parallel with those for other complex agro-ecosystems[6,7]. Tree biomass is generally derived from allometric relations with stem diameter established for trees growing in close stands[8,9], but may need to be adjusted for solitary trees[10] and shrubs[11]. A specific interest in agroforestry is in the belowground part of tree biomass, using common root research methods[12], as well as methods based on (fractal) woody root architecture derived from 'proximal root' diameters and angles[13]. Gains in prediction efficiencies of belowground biomasss allometry over 2000 measurements of belowground biomass using species-specific models were negligible[14]. However wood density, though not constant within a species, does vary by species and global data bases can be used in widescale assessments (compare Chapter 2).

20.2.3 Complementarity and competition in tree-soil-crop interactions (where?, how?)

Early research on agroforestry tried to understand under what conditions complementarity between tree and crops (or more rarely trees and pasture) could exceed competition for a net positive effect on usable biomass production[15] (see Chapter 5). Process-level studies led to models that linked tree and crop architecture and physiology to soil and climatic conditions, as well as management[16]. Experiments used a 'replacement series' concept of earlier intercropping analysis, with adjustments for the different sizes of trees and crops. However, a number of adjustments were needed to make the agronomic tradition of replicated small-plot trials with randomized treatment allocation feasible. Plot sizes had to be considerably enlarged, and the interference above- (e.g. microclimatic effects) and below-ground (horizontally scavenging roots) called for wide buffer zones between plots (linked to tree height) and/or root trenching to reduce the scavenging[17].

Agronomic field experiments have been used for more and 150 years based on the hypothesis that there is a 'treatment effect' to be estimated by rejecting a 'No-effect' null-hypothesis, in the face of spatial and temporal variation in yield. Statistical techniques (pioneered by Fisher in the analysis of the long-term fertilizer trials at Rothamsted, UK) were targeting a precise and unbiased estimate of the effect size, while variation around the effect was seen as 'error'. Factors that could possibly increase variation were controlled as much as possible, while replication and averaging reduced the impact of the variation. A major assumption thus was that spatial variability of fields makes it harder to assess 'treatment effects' but would not influence the treatment effect as such. This assumption has been rejected where the 'safe operating space' between adequately fertilized crops and nutrient leaching beyond water quality standards is involved[18]. Spatial variability within fields that are managed as a single unit can increase the likelihood of positive 'agroforestry effects' by meeting a risk reduction criterion based on correlation between component yields[19].

A recent surge of interest in heterogeneity effects 'beyond averages' has focussed on risks of technology success and failure[20]. The definition of the population of contexts to be used in assessing risks proved to be controversial and open to multiple ways of data interpretation[21,22,23].

Development of measurement methods were important for understanding of processes plot-level interactions: sap flow, root activity, litter and root decomposition, easy logging of light and water, as reviewed in chapters 4 and 5. During the first two decades of ICRAF many of the contentions in research methods, particularly experimental design, centred on trying to use agronomic experimentation paradigms when they could not be adapted to agroforestry. When looking at a specific process-based hypothesis then it was (still is) feasible, with enough ingenuity, to come up with a viable experiment. But much agronomic practice is based on empirical experimentation to derive 'recommendations' for farmers. AF research was dominated by agronomists who tried to use the same methods and often failed. They failed not only because of plot size and land heterogeneity problems, but also because of system interactions, challenges to defining sensible 'controls' or baselines, the genetic variably of the trees, the edges that should and should not be included. More fundamentally, the issue probably was failure to identify useful questions.

20.2.4 Production ecological perspective on yield gaps (where?, how?)

Where the focus is on annual (or tree) crops, the concept of a 'yield gap' between actual and potentially achievable yields has become popular[24]. It commonly partitions the yield gap in three parts, attributed to water, nutrient and pest & disease limitations, respectively, suggesting that yield gap closure depends on pest & disease control, fertilization and irrigation & drainage (Fig. 20.1.A). As the distinction between these three limitations may reflect the skill of crop simulation models in predicting effects of interventions, rather than a real hierarchy and independence of the three types of cause, two alternative interpretation of yield gaps split them i) in the gap between potential and attainable under economically justifiable use of inputs (of any type), and a management-defined gap between actual and attainable yields, and ii) in a gap due to environmental rules that prevent Y_{pot} being achieved, and a sustainable intensification gap that indicates progress possible beyond Y_{act}.

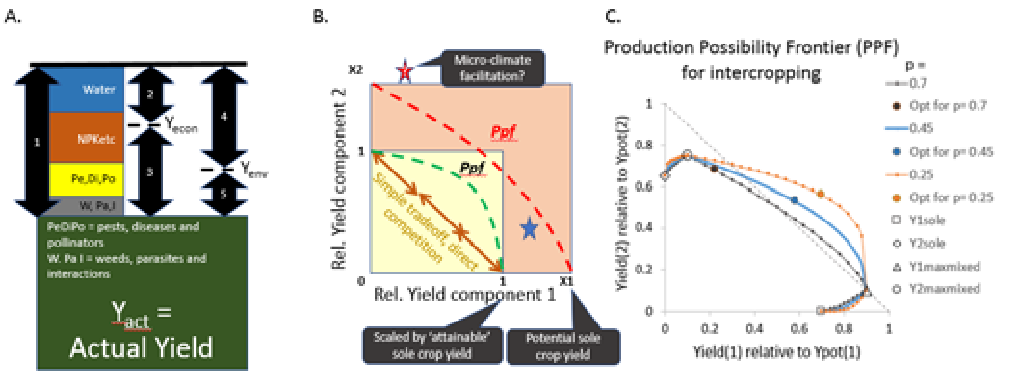

Figure 20.1 A. Five ways of interpreting 'yield gaps', between four yield concepts[a]; ; B. Attainable and potential sole crop yields as two possible reference points for production possibility frontier (ppf) derivation and calculation of Land Equivalent Ratio (LER); C. Possible ppf shapes where attainable yields of sole crops are exceeded by complementarity effects

These concepts of actual, attainable and potential production levels are also relevant for the way intercropping experiments are analysed. In the tradition of Land Equivalent Ratios, where the combined yield of two (or more) crops in combination is compared with that of the respective sole crops, it is common practice to use actual (or attainable) sole crop yields. LER values of around 1.2 are feasible, especially where a longer effective cropping season is achieved[25]. In the combination of timber and food crops, in settings where the trees can benefit from fertilizer inputs to the crop while sole-tree fertilization is not economically

[a] **Y_{pot}** = Potential Yield for specific **G**enotype in radiation, temperature&[CO_2] **E**nvironment and ***maximized*** **M**anagement ; **Y_{econ}** = Yield level of Econ farmers, economically ***optimized*** M ; **Y_{env}** = Yield meeting all Environmental regulations

feasible, LER values up to 1.8 have been suggested[26]. Microclimatic effects can also lead to high LER values in suboptimal climates[27]. The overall conclusions about farm-level benefits of specific forms of agroforestry thus depend as much on the choice of controls (or comparators), as they do on the yields achieved in experiments.

20.2.5 Participation by researchers in farmer experiments (how?, who?)

The experiments and analysis discussed so far have not explicitly included the farmer and her management choices as part of the system and within the boundary of analysis. Keeping the farmers out is a way to 'control' variation (and increase the specificity of definition of treatments applied) but contributes to 'yield gaps' between experiments and farm practice on often more heterogenous plots. Keeping the farmer and management choices explicitly involved in the experiments makes the data obtained more realistic, even though they will likely be harder to interpret[28].

Recommendations for research methods for multistrata agroforestry systems with coffee and cacao[29] included (but all may need to be re-evaluated with current understanding):

- Research focused on characterization and production studies (of crop and timber including border areas) of traditional systems should assess the whole plot, including the border areas, and not some subjectively selected central area which supposedly represents unit area productivity.
- Uncontrolled crop, tree, and management heterogeneity limited extrapolation of early on-farm research results to other farmers' fields.
- On-station research included the use of systematic spacing designs to test extreme shade tree density treatments of coffee. Most nutrient cycling studies were also carried out on-station, using service and timber shade species over coffee and cacao to evaluate the ability of these agroforestry systems to maintain nutrient reserves and diversify production.
- Plot size (even 36 × 36 m) was limiting for long term research because of inter-plot interference, both below- and above ground, when using fast growing, tall timber trees as shade. These experiences suggest a minimum plot size of 2,500 m^2 . Individual tree designs and tree-crop interface studies (e.g. regression analysis of data taken along transects) are promising experimental/sampling approaches that need further development.

Participatory research that combines the knowledge of farmers and researchers promotes the development of a variety of agroforestry options that may meet the various needs of different farmers, and thus exploits one of the greatest strengths of agroforestry - its plasticity[30]. On-farm research has been a main driver of agroforestry research over its four decades[31,32,33] , as it was realized early on that to study existing agroforestry systems and their complexity, to learn from farmers' knowledge and experience, to access representative site conditions, or to elicit farmer evaluation of new technology all required such direct farmer-researcher interaction. Methods were used and adapted based on concepts and experience from other areas of research. New elements added by agroforestry included participatory tree species selection and improvement (see Chapters 2 and 3) and linking community seedling production to on-farm research.

Figure 20.2 Clarity of terms and definitions is easily assumed, but higher-level categories are often interpreted to include different specific entities

20.2.6 Farm economics

Interest in the economic side of agroforestry as integral element of many studies emerged in the first agroforestry decade[34]. After a phase of literature reviews, qualitative, and purely descriptive quantitative research based on small sample sizes, and often struggling with the categorization of goods and services (Figure 20.2), more rigorous statistical analyses of better and larger data sets started to emerge twenty years ago[35]. Methods for valuing agroforestry systems[36] require a good understanding of farmer decision making, rather than being objectively measurable quantities that guide decision making and scaling up of agroforestry practices[37]. There often is a two-way adjustment between 'rationality' concepts (which can well go beyond profitability) and 'decision making' (Fig. 3). Financial analysis of agroforestry practices needs to be adapted to farmers' objectives such as feeding livestock, providing firewood, or improving soil fertility[38,39]. Agroforestry practices provide by-products and services which are difficult to value, such as border markings, improved animal health and calving rates, firewood and curbed soil erosion in the case of fodder shrubs, or improved soil structure and moisture retention in the case of improved fallows. Rotational woodlots may reduce deforestation, as home-produced firewood is substituted for firewood cleared from the forest and trucked to the farm. As part of the rotational woodlot experiments in Shinyanga (Tanzania; compare chapter 7), researchers were in for a surprise. After 4 or 5 years of fast growth, researchers plan was to cut down the trees for firewood and crop the area assumed to have improved soil fertility. But farmers saw multiple other options, such as coppicing for regrowth, use as a grazing reserve, letting the trees grow on to produce timber or simply leaving them because they look nice.

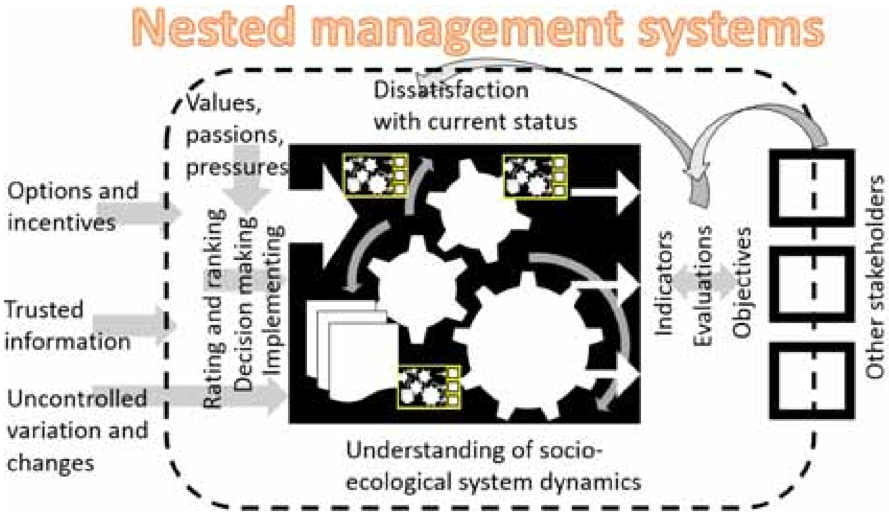

Figure 20.3 Understanding of decision making as a management concept, driven by a contrast between actual performance and objectives, within the range of options known, rated and ranked

For many AF systems the low requirements for financial investment and likely reduction of risk in the face of climatic variability form additional considerations. Accounting for all direct costs and benefits in existing practices, together with sensitivity analysis to variation in the woody component, can, after choosing an appropriate discount rate for future benefits relative to current costs, lead to Net Present Value (NPV) comparisons, as well as 'returns to labour'. On-farm trials are useful for measuring benefits, because agroforestry practices can be readily compared with alternative ones[40]. Researcher-designed, farmer-managed trials appear most appropriate for financial analysis. Because these trials are designed by researchers (in consultation with farmers), non-experimental practices (such as weeding) are relatively uniform across treatments. This uniformity ensures that differences among treatments are caused by the practices being tested and not by extraneous variables. The standardization of plot size and purchased inputs in such trials also helps facilitate the collection of data on the use of labour. However, labour (e.g. person days of work) remains one of the most complex inputs to measure, as the number of hours of actual work per day varies and there are issues on how to account for weather or other conditions that prevented a planned labour input to happen, but also prevented alternative use of the time allocated. The problems in measuring and valuing labour in small farm contexts are not restricted to agroforestry research[41].

In contrast, farmer-designed trials vary greatly among farms in size, types of inputs, and management and thus contain several feedbacks from farmers' perceptions of profitability. In farmer-managed trials measurement of inputs and outputs more realistically reflects farmers' experiences with the practices, interacting with 'objective' profitability[42]. Tenure is not only a precondition for planting trees but can also be obtained by doing so[43], further complicating the assessment of 'profitability'. One more complication results from the time lag between input and benefits, with little evidence that economists' use of discount rates is connected to farmers' ways of making decisions. Focus group discussions can be used to check the rational and estimate the key elements of cost benefit comparisons in a participatory way (see LUPA method described below), but doesn't circumvent the need for replication and statistical rigour in subsequent analysis.

20.2.7 Adoption through adaptation: research in development (what?, where?, how?, who?)

Local and indigenous knowledge, beyond its role in economic decision analysis, has been a long-term interest in agroforestry research, with early articulation of the need to combine qualitative and quantitative, participatory but researcher-led, and formal data and informal collection methods as they provide complementary and supplementary perspectives on a complex reality[44].

Encyclopedia-style enumerations of ethnobotany (and ethnozoology) of all the plants (and animals) involved in forest/agroforestry/agriculture transitions showed a rich diversity, and helped in understanding how generic 'local' knowledge can be (restricting 'property rights' claims to such knowledge in many cases). A different set of methods was developed for describing and analysing explanatory knowledge, seeking to understand the 'logic' became a separate line of research[45,46,47,48]. A combination of enumerative and explanatory knowledge was used, for example, in assessing shade composition of multistrata coffee systems in Mexico[49]. For selection of candidate species of the local forest flora suitable for dry-season fodder banks a recent analysis used three types of knowledge: farmers, bromatological science and cows (in their actual feeding behaviour)[50].

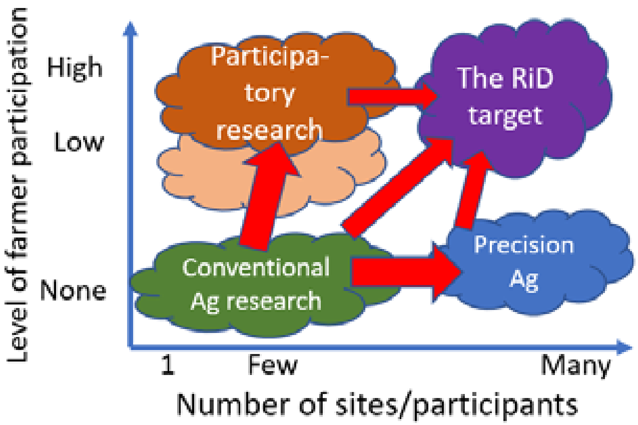

Figure 20.4 Trends in agronomic experiments towards more inclusion of site variability and farmers, with 'research in development' (RiD) as target to reduce 'implementation gaps'[51]

Overall, current trends in field-level experimentation (Fig. 20.4) is towards 'Large N, participatory' trials that include as much of the variation in context as is feasible within the likely 'extrapolation domain' of a candidate technology to be assessed[52]. The challenges of working with many farmers who may all give a different interpretation to the treatments to be tested are managed in part by explicitly describing and analysing farmer ratings and rankings, alongside measurements as part of experiments[53].

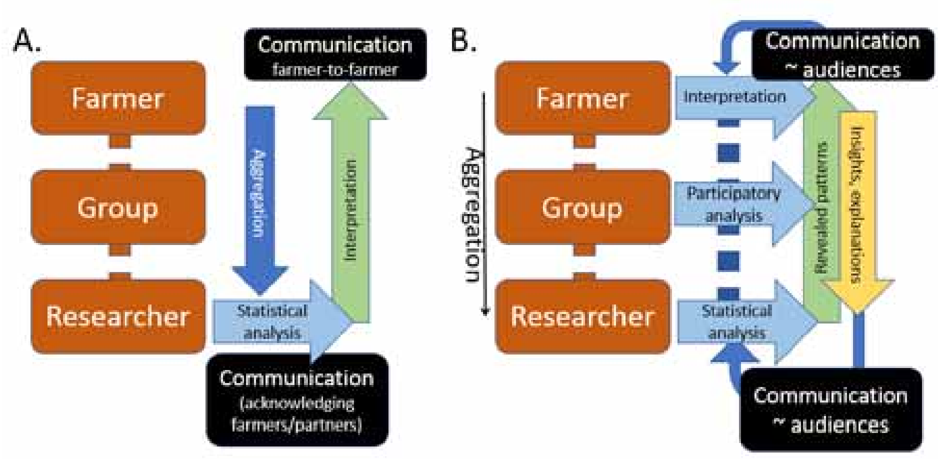

Figure 20.5 A. Conventional approach to data from on-farm experimentation with researchers aggregating data, doing a statistical analysis and communication results back to farmers. B. Alternative iterative approach that incorporates farmers' individual and group-level perspectives and explanations.

A decade ago, a method review for multistrata system research found[54] little evidence of research on complexity at several scales, but limitations were not only methodological. There has been at least some progress since that time. For example, the diversification trajectories in the cocoa belt of West Africa were found[55] to differ between men and women with the most profitable trajectory controlled by men, and gender-based inequalities negatively impacting agricultural productivity.

20.3 Methods for research of landscape-level paradigm AF2

In the first agroforestry decade, the implementation of newly developed agroforestry techniques in various places all over the world, led some researchers already to the realization that[56]:

- Problem solving cannot be limited to the individual farmstead or plot level from a social and ecological point of view,
- Existing landscapes present both constraints and opportunities for further land development,
- More appropriate agroforestry techniques can be applied by classifying landscape units and existing land-use systems,
- Planning is necessary because agroforestry requires a holistic perspective to be sustained during the long time necessary for implementation.

Yet, a 'landscape approach' took some time to become formally articulated[57,58] and embraced[59]. The choice of research methods has been directly linked to the conceptualization of system components, interactions and boundaries. Three concepts that found wide application are the ecosystem structure/function/services cascade (Fig. 20.6A), the drivers, pressures, states, impacts, response (DPSIR) framing of causal chains (Fig. 20.6B, 20.7) and the options, context, issues, goals cycle across scales (Fig. 20.6C, 20.6).

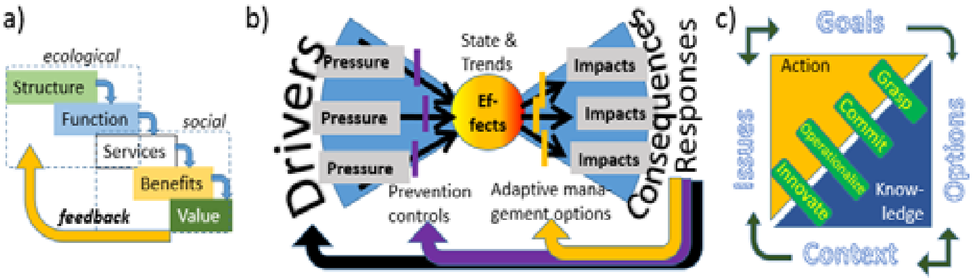

Figure 20.6 Analytical frameworks for landscape level understanding of agroforestry (AF2)

Various typologies for ecosystem services have been used in agroforestry research[60,61]. Quantification of lateral flows became the basis for understanding non-area-based scaling rules for processes such as net sediment movement by erosion[62,63]. New metrics provided ways of analysing evidence in the longstanding debate on flooding risk and tree cover[64].

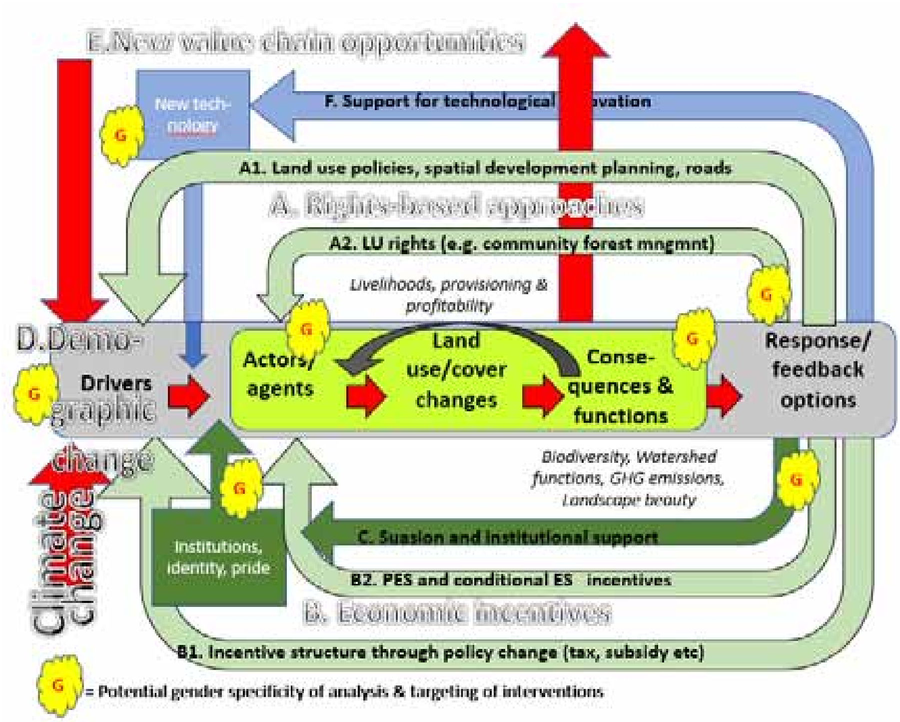

Figure 20.7 Embellishment of the Drivers-Pressures-State-Impacts-Responses (DPSIR) framework with multiple feedback loops and external influences[65]

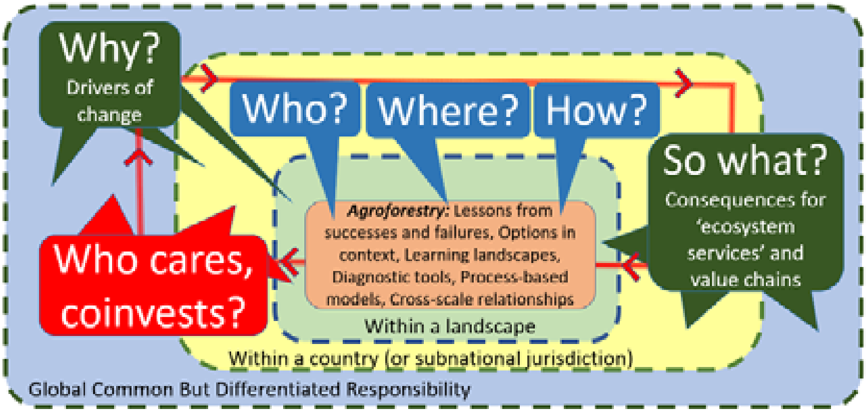

Figure 20.8 Cross-scale relations in the determinants and consequences of agroforestry land use choices

The landscape scale of Social-Ecological Systems is a meeting point for bottom-up local initiatives to secure and improve livelihoods from agriculture, agroforestry and forest management, and top-down concerns and incentives related to respecting planetary boundaries to human resource use[66]. Sustainable development goals require a substantial change of direction from the past when economic growth was usually accompanied by environmental degradation, with the increase of atmospheric greenhouse gasses as a symptom, but also as an issue that needs to be managed as such. In landscapes around the world, active learning takes place with experiments that involve changes in technology, farming systems, value chains, livelihoods' strategies and institutions.

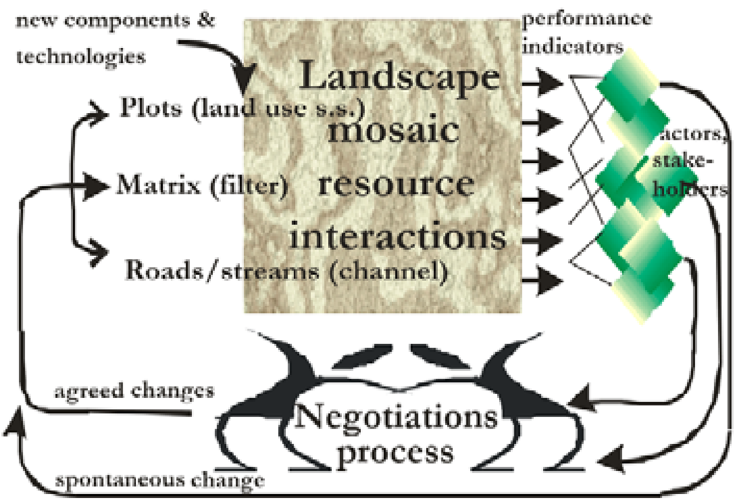

Figure 20.9 Early portrayal of Negotiation Support Systems (compare Chapter 9) as dependent on shared understanding of landscape mosaic-resource interactions as perceived by multiple stakeholders, and a negotiation process for planned change (in the face of spontaneous change)

An overarching hypothesis that is being tested is: Investment in institutionalising rewards for the environmental services that are provided by multifunctional landscapes with trees is a cost-effective and fair way to reduce vulnerability of rural livelihoods to climate change and to avoid larger costs of specific 'adaptation' while enhancing carbon stocks in the landscape.

Such changes can't come overnight. A complex process of negotiations among stakeholders is usually needed. The divergence of knowledge and claims to knowledge is a major hurdle in the negotiation process.

A collection of tools (Box 20.1) - methods, approaches and computer models - was shaped by over a decade of involvement in supporting such negotiations in landscapes where a lot is at stake. The tools are meant to support further learning and effectively sharing experience towards smarter landscape management. The terminology of Negotiation Support Systems (NSS)[67,68] emerged as complement to Decision Support systems that target a single decision maker.

The Land Degradation Surveillance Framework (LDSF)[69] is primarily based on 'objective' 'ground-truthing, remote sensing and advanced processing of large data sets[70]. In doing so it deliberately (and makes a bias-reducing virtue of) sampling land as if people are not involved. While this is fine for some questions (e.g. overall extent of land with specified biophysical properties), it may not be the most effective and efficient way to unpack social x biophysical interactions. Field tests suggest that land users may not share the same priorities, in terms of where, when and how to address degradation, with other actors involved in restoration initiatives, which implies a need for negotiation, and suggests that impacts of restoration activities are likely to be socially differentiated[71].

Games[72] and Agent-Based Models (ABM's) have become important tools for understanding the social interactions that shape landscape-level land use decisions (Fig. 20.8).

Auctions for economic incentives for enhancement of ecosystem services[73],[74] have become a next step, beyond 'games', to explore the way land use decisions involving agroforestry can be 'nudged'.

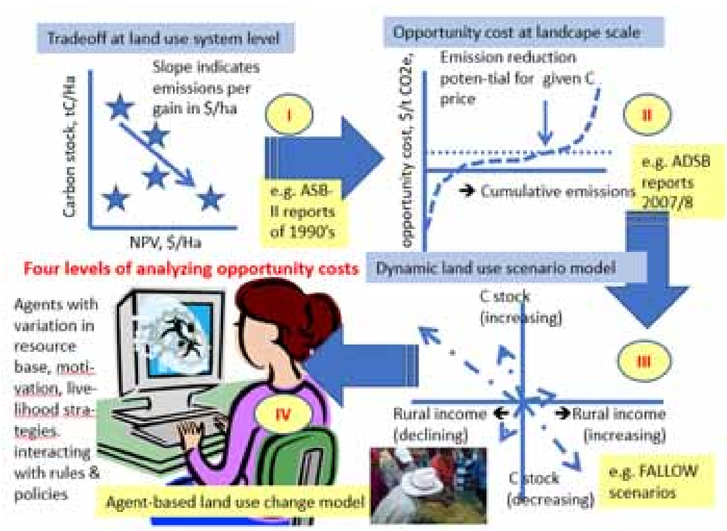

Figure 20.10 Four ways of analysing opportunity costs of retaining landscape-level carbon stocks: I. trade-off between NPV and time-averaged C stock of land use systems (RACSA plus LUPA method in Box 20.1), II opportunity cost curves based on actually observed land cover change (adding ALUCT data, using ABACUS), III. Using dynamic land use change models such as FALLOW, IV. Using agent-based land use change models that include actor variation.

Box 20.1 Negotiation Support Systems toolkit[75]

I. Understanding context: multifunctional landscape mosaics

- Participatory landscape appraisal (PaLA)
- Participatory analysis of poverty, livelihoods and environment dynamics (PAPoLD)
- Rapid appraisal of drivers of land-use change (DriLUC)

II. Lives, land use and livelihoods: trees, agroforestry technology and markets

- Rapid appraisal of agroforestry practices, systems and technology (RAFT)
- Local ecological knowledge: agroecological knowledge toolkit (AKT5)
- Land-use profitability analysis (LUPA)
- Rapid market appraisal (RMA)
- Gender roles in land use and value chains (GRoLUV)
- Tree diversity and tree–site matching (WhichTreeWhere?)
- Gender perspectives in selecting tree species (G-TreeFarm)
- Access to trees of choice (NotJustAnyTree)
- Climate-change opportunities offered by local trees (CoolTree)
- Tree and farming system resilience to climate change and market fluctuations (Treesilience)
- Functional branch analysis (FBA): tree architecture and allometric scaling
- Simple light interception model (SLIM)
- Water, nutrient and light capture in agroforestry systems (WaNuLCAS): at the plot level
- Spatially explicit individual-based forest simulator (SExI-FS): for management of agroforests
- Adopt and learn: modelling decision making and information flow

III. Landscape: ecosystem services, trade-offs

- Analysis of land-use and -cover trajectory (ALUCT)
- Trade-off matrix between private and public benefits of land-use systems (ASB Matrix)
- Rapid hydrological appraisal (RHA): watershed functions and management options
- Rapid landslide mitigation appraisal (RaLMA): managing trees for improved slope stability
- Participatory water monitoring (PaWaMo)
- Rapid agro-biodiversity appraisal (RABA)
- Quick biodiversity survey (QBSur)
- Rapid carbon stock appraisal (RaCSA)
- Reducing emissions from peatlands (REPEAT)
- Re-assessing oxygen supply and air quality (ROSAQ)
- Biofuel emission reduction estimator scheme (BERES): land-use history, production systems and technical emission factors
- Generic river flow at landscape level (GenRiver)
- Flow persistence (FlowPer)
- Rainfall Simulator (RainyDay) and Spatial Rainfall (SpatRain)
- Land-use Change impact assessment (LUCIA)
- Polyscape
- Forest, agroforest, low-value landscape or wasteland (FALLOW)
- Ecological corridors (ECor): a distributed population model with gender specificity
- REDD Abacus SP

IV. Transformations: governance, rights

- Rapid land tenure assessment (RaTA): understanding land tenure conflicts
- Why No Tree? (WNoTree) analysis of agroforestry constraints
- Fair and efficient REDD value chains allocation (FERVA)
- Rapid assessment of institutional strengths, networks and actors (RISNA)
- REDD/REALU site-level feasibility appraisal (RESFA)
- Trade-off analysis for land-use scenarios (TALaS)
- Scenario tools: land-use planning for low-emissions development strategies (LUWES)
- Capacity-strengthening approach to vulnerability assessment (CaSAVA)

V. Negotiation support as process

- Assessing and adopting social safeguards in all planned programs (AASSAPP)
- RUPES role-play game (RPG)
- Conservation auction and environmental services' enhancement (Con$erv)
- Multi-scale payments-for-environmental services' paradigms (MuScaPES)

20.4 Methods for research of policy-level paradigm AF3

Policy-oriented agroforestry research starts with listening to current discourses in policy debates, and trying to present existing knowledge in the 'flavour of the day'[76,77]. Rather than assuming either 'science' or 'policy' has a monopoly on 'truth', the tradition of boundary work[78] (Fig. 20.8) has emerged as a specific way of analysing the interactions. Research methods on 'discourses' that combine qualitative and quantitative aspects, such as the Q-method[79,80] have become part of the agroforestry research toolbox. To further describe and understand changes in public attention issue cycles, scales for four parallel changes (grasp, commit, operationalize, innovate) have been proposed, awaiting further testing (Fig. 20.9).

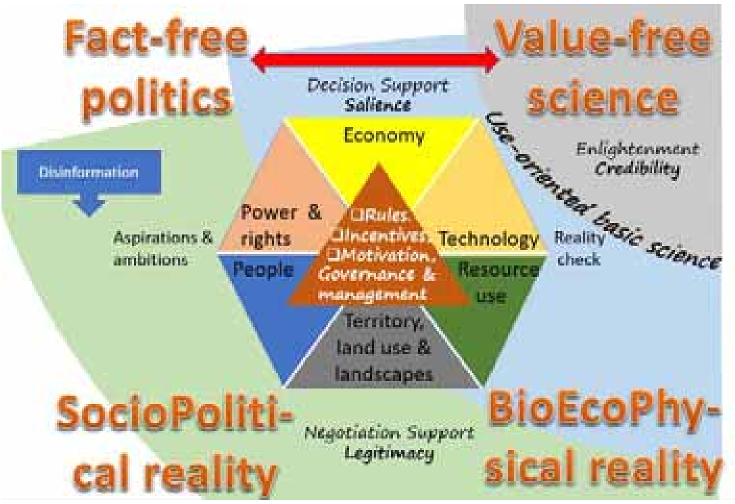

Figure 20.11 Three aspects of knowledge (credibility, salience and legitimacy) in relation to boundary work between Bio-Eco-Physical reality, value-free science, fact-free politics and socio-political reality

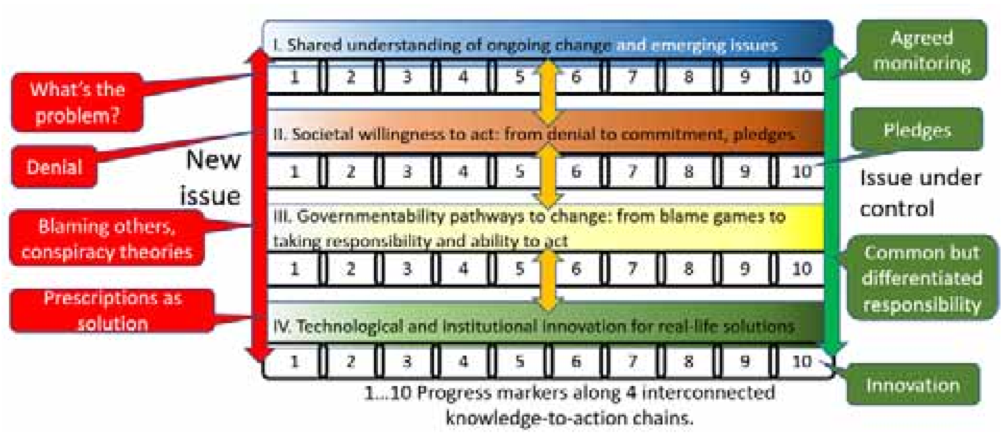

Figure 20.12 Four parallel processes that jointly determine progress on public attention issue cycles in terms of shared understanding, commitments, implementation and innovation[81]

There has been considerable effort and progress in 'true-cost accounting' in agrifood systems[82]. Apart from many issues at the operationalization level, such methods, however, stay within a narrowly financial concept of value that cannot be universally applied. As discussed by Mazzucato[83] (2018), in "The value of everything: making and taking in the global economy", the concept of value has been central to economic theory in the past, but became (in the transition from 'classical; to 'neoclassical' economic theory) replaced by market prices, losing the distinction between the creation of value and the appropriation of 'rent'. Her analysis tries to revive concepts that the grandfathers of economic science introduced, but that subsequently became lost by a 'monetary value only' framing. These include Adam Smith (who included moral judgements in the distinction between 'rent' obtained from control and 'value' obtained from production), Ricardo (who distinguished value concepts for reproducable from that for non-reproducable goods and services) and Pareto (who focussed on consumer satisfaction as driver of economic decisions). The new school of behavioural economics[84] has established a 'bottom-up' perspective on actual decisions made, often contrasting with the 'rationality' assumptions that dominated economic analysis in the past. Perceptions matter at least as much as 'facts', and 'communication strategies' are at the core of AF3 research, rather than an afterthought. Repetition of messages and attention to the persons voicing them (e.g. in public panels) is key to success. The ASB Partnership developed a specific format for its policy briefs (around four salient findings and their policy implications as a 1-pager, followed by the supporting evidence and references) that according to existing evaluations matched expectations of at least part of the target audience (Box 20.2). Attempts were made to stay as close to 'current debate' as feasible, often opportunistically defying the mandates of advance project planning.

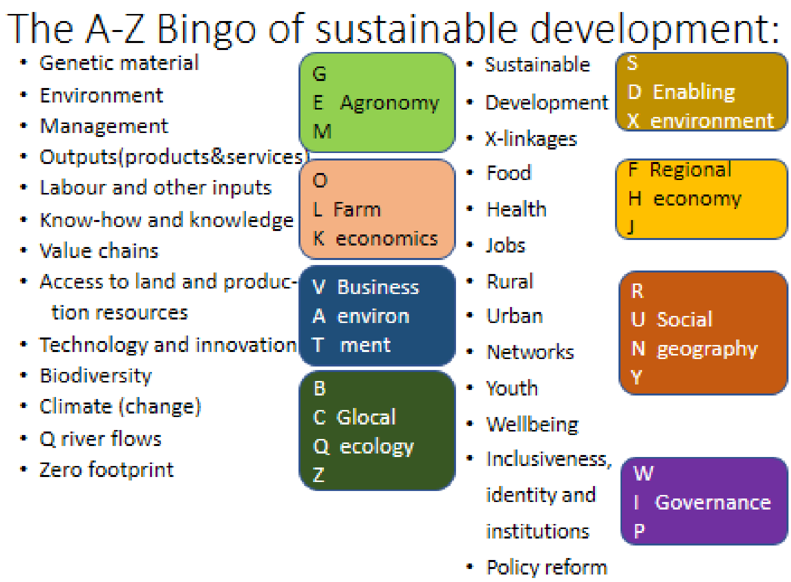

Figure 20.13 With the realization that the AF3 concept requires a basic understanding of a large number of subsystems and their interactions, an alphabet Bingo game can help to list and group 26 aspects that modern agroforestry research needs to be at least aware of

Table 20.1 Achievable goals for researchers interracting with policy issue cycles

Stages of Policy Cycle	Researcher goals	Impact looks like...
Problem alert	Spotting new social and environmental problems or phenomena that (someone believes) limit progress to development goals such as SDGs	Raised interest and concern among researchers (and others? Activists?)
Problem scope and basis	Understanding: - Extent of the problem (areas, people affected) - Drivers and mechanisms - Connections to current or new theory	Either: Increasing numbers of people aware of and understanding nature of the problem and why it matters Or (if it turns out to be an unimportant problem): Efforts redirected to areas with more potential effect
Potential solutions and interventions	Show that there are actions that will alleviate the problem and policies that will promote those actions	Pilot projects that excite people, increase demands, generate more nuanced research
Political Agenda setting	Get relevant policy makers interested and pushing towards policy change	Convincing demonstration that problem impacts on things they care about and that policies proposed will help
Policy formulation	Systematic investigation of a problem and thoughtful assessment of options and alternatives	Convincing policy options formulated
Selection Process	(Decisions making) Prioritization of available options given, cost/benefits and compromise across diverse stakeholder interests	New policies adopted and followed
Implementing	Introduce actions based on policy aimed at changing the problem	Change in state of problem
Evaluation and monitoring	Confirm that the problem is under control (or tracking in the right direction) and remains so	Problem is solved – extent of 'fix' and role of the policy.

New insights in public/policy issue cycles lead to many ways of targeting stepwise progress towards a final impact of reducing the intensity of problems identified, but there often is the challenge that the time-line of research is such that an issue cycle has moved on by the time results have been obtained (let alone analysed and published). Without claiming the arrogance of foresight, research design will have to try to anticipate what might emerge, and convince its funding sources that investment is needed. As there seems to be no limit to the number of subsystems and associated knowledge with which AF3 research may have to interact (Fig. 20.13), the conventional concept of a 'generalist' needs to be expanded, with network abilities to quickly team up with a wide range of specialists.

Box 20.2 Samples of Policy Briefs produced by the ASB partnership in the tropical forest margins[85,86]

Generic sustainable development concepts

53. Minimizing the footprint of our food by reducing emissions from all land uses.

50. Trees as nexus for Sustainable Development Goals (SDG's): agroforestry for integrated options

47. Ecological rainfall infrastructure: investment in trees for sustainable development

46. Transforming REDD and achieving the SDGs through support for adaptation-mitigation synergy

42. The ASB Policy Brief Series: Reflections from Twenty Years of ASB Partnership

26. Agroforestry in REDD+: Opportunities and Challenges.

25. Drivers and consequences of tropical forest transitions: options to bypass land degradation?

23. On-farm timber production for emission reduction with sustainable benefits at the tropical forest margins.

19. Linking scientific knowledge with policy action in Natural Resource Management.

17. Emissions Embodied in Trade (EET) and Land use in Tropical Forest Margins.

16. Reducing emissions from deforestation inside and outside the 'forest'

15. If we cannot define it, we cannot save it.

14. Perceptions of Fairness and Efficiency of the REDD Value Chain

13. Reducing Emissions from All Land Uses (REALU): The Case for a whole landscape approach.

10. The Opportunity Costs of Avoiding Emissions from Deforestation.

8. Deforestation and the multiple functions of tropical watersheds.

7. Participatory development of methods

6. Deforestation has no single cause but is the outcome of a web of factors whose mix varies greatly in time and space.

5. Balancing development and global concerns over the environmental consequences of tropical deforestation

Country-specific land use issues in relation to climate change discourses

51 Peat and land clearing fires in Indonesia in 2015: Lessons for polycentric governance.

49 When can oil palm production qualify for a 'carbon neutral' claim?

45 Stopping haze when it rains: lessons learnt in 20 years of Alternatives-to-Slash-and-Burn research in Indonesia

41. Planning for low emissions developments efforts in Ucayali, Peru.

40. Climate smart landscapes: Integrating mitigation; adaptation and development in Shinyanga region Tanzania.

39. Linking development pathways and emission reduction at local levels: An analysis of feasibility in the Efoulan municipality, Cameroon

38. How feasible is a landscape approach to REDD+ in Vietnam?

36. Reassessing peat-based emissions from tropical land use.

35. Land-use planning for low-emission development strategies (LUWES).

34. Reducing emissions from all land uses in Indonesia: motivation; expected funding streams and multi-scale policy instruments.

33. Hot spots in Riau; haze in Singapore: the June 2013 event analyzed.

32. What drives reforestation in Viet Nam.

31. REDD+ readiness in Vietnam: a rapid assessment and its implications.

30. Incentives for Reducing Carbon Emission from Illegal Logging in Cameroon.

24. Why smallholders plant native timber trees: lessons from the Philippines.

22. Recognizing traditional tree tenure as part of conservation and REDD strategy: Feasibility study for a buffer zone between a wildlife reserve and the Lamandau river in Indonesia's REDD Pilot Province.

Box 20.2 Samples of Policy Briefs produced by the ASB partnership in the tropical forest margins[85,86]

4. Smoke pollution is a serious public health problem and disrupts livelihoods in large areas of the humid tropics.	21. Hot spots of confusion: contested policies and competing carbon claims in the peatlands of Central Kalimantan; Indonesia.
3. Removing restrictions on the marketing of timber from agroforestry systems in the humid tropics: a rare 'win-win'	20. Co-existence of people and orangutan in Sumatra. Stabilising gradients for landscape multifunctionality
2. Creating fair and effective policies and institutions to govern land and tree tenure.	18. Stewardship agreement to reduce emissions from deforestation and degradation (REDD) in Indonesia.

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Tony Simons

Agroforestry at 40

INTERMEZZO 9

Perspective from ICRAF ('World Agroforestry')'s fifth Director General (2011-2021) and CIFOR-ICRAF Executive Director (2019-present)

The institutional evolution of ICRAF for the two thousand and tens decade is a combined outcome of sound planning and serendipity. The decade started in a highly disrupted way with the world still reeling from the triple food, fuel and financial crises of 2008-9. On a note of positive disruption, it also started with the CGIAR reform and the creation of CGIAR Research Programmes (CRPs) with expanded funding. In particular, the creation of the Forest, Trees and Agroforestry CRP was very useful in helping raise the profile of Agroforestry and ICRAF.

ICRAF's Board of Trustees guided two corporate strategic planning exercises in 2012 and 2017 and approved ICRAF's first ever Corporate Business Plan in 2018. These documents laid out the clear logic of the why, what, how and where of our institutional agenda. They also importantly helped focus and categorise our work more clearly. The development challenges which we prioritised and the value propositions of ICRAF became more closely linked by deliberately tying in our diverse revenue streams with our changing cost structures. We became more conscious of our quadrophenic identity in research, development, policy and delivery. Whilst our ultimate target beneficiaries and national counterparts stayed constant our key partners became a much wider group. Here we expanded our engagement particularly with the private sector, sub-national governments, and mainstream INGOs.

One highly innovative approach that ICRAF pioneered in this decade is linking the science of discovery with the science of delivery. We successfully sourced several large grants (>$5 million) to investigate the scaling up and scaling out processes of technical, social and policy agroforestry solutions. This has positioned ICRAF well in the blended finance and private investor spaces with growing demand for bespoke project design, decision support, risk identification and delivery options.

ICRAF staff competencies and business processes also evolved substantially in the two thousand and tens decade. Our administrative and support staff became a more connected group of enablers, and greater subsidiarity was seen in our thirty strong country and regional offices. Weaving all this together with a fit for purpose Enterprise Resource Planner (ERP) is still a work in progress. However, with increased risk awareness and due diligence demands the ERP remains a priority management task.

The latest and most significant positive disruption of the decade though is the merger of CIFOR and ICRAF from January 2019. This voluntary move to create a bigger and more impactful single organisation is built on the 40 successful years of ICRAF's history and the 25 years of CIFOR's history. Together we are confident we can leverage all the rich content of our research, development, policy and delivery efforts to accelerate our impact and better drive institutional effectiveness.

In this period, we remain most grateful to our donors, scientists and agroforestry practitioners who have developed our work around highly salient and innovative topics including: landscape approaches, geospatial science, capacity development, gender, SHARED approach, ecosystem services, biomass energy, tree germplasm, rainbow water, agroforestry systems, tree commodity value chains, research methods, land health, landscape governance, African Orphan Crops, impact investing, rural resource centres, green economy, integrated policies, impact assessment and knowledge management. With all this in place, the next decade is looking even more promising.


Agroforestry into its fifth decade

Palembang, South Sumatra Province, Indonesia's first Master Plan for Renewable Resources-Driven Green Growth. This photo was taken on Mt Dempo (3159 metres above sea level) in Pagar Alam District, South Sumatra Province, Indonesia. Tea gardens at varying stages of growth bordering coffee agroforestry make for a delicately patterned, sustainable landscape.

Photo: World Agroforestry/Arga Pandiwijaya

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CHAPTER TWENTY ONE

Agroforestry into its fifth decade: local responses to global challenges and goals in the Anthropocene[a]

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Highlights

- In its fifth decade agroforestry is a drive to greater policy synergy between technologies, landscapes, rights and markets to achieve restoration of multifunctionality in a Sustainable Development Goals (SDG) context
- Bottom-up interest in sustainable and profitable land use interacts with concerns at livelihood and landscapes scale (rights, migration, livelihoods and ecosystem services) and nation al and international policy agendas with their top-down goal-setting and instruments
- Three broad groups of SDG coexist: A) articulating demand for further human resource appropriation, B) sustaining the resource base, and C) redistributing power and benefits
- The FEWI (food, energy, water, income) agenda can be reflected in a broadened LER (land equivalence ratio) concept of land-sparing through -sharing in multifunctional landscapes
- A new 'Anthropocene equation' relates planetary boundaries to population, affluence, life style, waste and land use technology, with multiple resilience concepts as connections with a new agroforestry agenda
- Synergy between agriculture and forestry can evolve from recognizing coexistence and agreed boundaries towards joint land use programs and innovation in a circular economy

[a] Expanded and updated from reference 1

21.1 Introduction

Chapter 1 outlined the evolution of agroforestry as a concept at plot/farm, landscape and policy scales, with all three coexisting in the current links between praxis, knowledge and policy. Chapter 19 ended with the need for policies that seek and support SDG synergy in pursuit of landscapes that not only produce goods for existing markets, but also provide the services that 'downstream' stakeholders have in the past taken for granted but do miss when they are affected. We will here focus on the third agroforestry paradigm and the need for reinventing the interfaces between agriculture and forestry in the food, energy, water and income nexus[1] as part of addressing the challenges of the Anthropocene, the geological era dominated by a single (our own) species.

The formulation of Millennium Development Goals, precursor to current Sustainable Development Goals (SDGs) brought the ending of poverty and the need for environmental sustainability on the same 'goal' level in high-level discourse[2]. It allowed multifunctional land uses, such as agroforestry, to gain wider support[3]. With the SDG agenda[b] of the United Nations, agreed upon by 193 countries in September 2015, the debate has shifted from 'willingness' to 'ability to act'. Because the human brain is challenged when a list contains more than 3-5 items, there have been many attempts to group the 17 SDGs[4,5]. One way (Figure 19.2) is to recognize five groups: 1) SDG 1-5 deal with multiple dimensions of poverty (food, income, health, education, gender), 2) SDG 6-9 with development infrastructure (water, energy), 3) SDG 10-12 with the fairness-efficiency balance, 4) SDG 13-15 with ecological infrastructure, and 5) SDG 16 and 17 with institutions. A further grouping sees a group of goals that articulate increased demand for resources (including food, energy, water)[6], a group that tries to maintain the resource base and a group modifying access to resources, power and benefit distribution (including gender and youth-based distinctions beyond homogeneous household perspectives)[7]. Despite critique on the goals ("By attempting to cover all that is good and desirable in society, these targets have ended up as vague, weak, or meaningless")[8] and comments from the science community[9] that were only very partially taken to heart, they are still the most legitimate attempt at global governance so far, deserving efforts to try and make it work[10].

Progress within each of these SDG groups probably requires efforts that are at least compatible with goals in the other groups (being neutral to or with modest trade-offs), while providing the focus and clarity needed to address a specific target. Having 17 single-goal implementing policies is not efficient; the Tinbergen rule about the need for the number of policy instruments to match the number of goals[11] can be softened where goals in practice (at least in a given local context) align. Central to all groups of SDGs is 'land use' as a meeting point for material and immaterial needs. Sustainable land use as target has been debated since long ago[12,13], but could still be the key to progress. It connects the need for further human appropriation of resources, the efficiency with which existing land is used for achieving agricultural and forest production of goods and services, and the rights and governance agenda of who decides, controls and benefits.

[b]http://www.un.org/sustainabledevelopment/development-agenda/

As described in chapter 1, the concept of agroforestry was from its very beginning aligned with 'restoration' and linking farmers' knowledge, objectives and expectations to desirable environmental change. Four decades of agroforestry research and development, as reviewed in the chapters of this book, have deepened the need for reconciling local interests and opportunities at farm level, with the global agenda for nature, forests, agriculture and urban land use as agreed on in the 17 Sustainable Development Goals (SDGs) (Figure 21.1, Figure 21.2).

Figure 21.1 Bottom-up interest in sustainable and profitable land use (based on Genotype x Environment x Management or GxExM interactions involving trees) interacts with concerns at livelihood and landscapes scale (rights, migration, livelihoods and ecosystem services) and nation al and international policy agendas with their top-down goal-setting and instruments

Throughout the chapters we have seen that the interest in what agroforestry has to offer has evolved along with 'issue cycles'[11]: the entry point for public debate and policy responses has varied within the multifunctional landscape, but 'solutions' become 'next-generation problems' unless the totality of functions is understood and considered. The tendency of academic researchers to tackle problems one-at-a-time and defend the territorial boundaries of disciplines is not particularly helpful in this context. Present-day agroforestry science takes its clues from integrative fields such as 'agro-ecology'[14] and 'boundary work'[15]. It participates in and builds on integrative science-policy assessments such as those on agricultural science and technology[16], forests, food and nutritional security[17] and forests and water[18]. It also benefits from integrative concepts such as the co-adaptation of people and trees to climate change[19] and treesilience[20].

The debate on planetary boundaries[21],[22] as next step beyond limits to growth[23] has connected current human resource appropriation to a 'carrying capacity' perspective on what the energy, water, nutrient, pollutant and further cycles can afford. Similar to earlier carrying capacity debates[24], the agility of humankind to adapt and modify technology can shift the hard limits proposed. There are, however limits to adaptation[19,25] and current progress may be hindered by a fall back to earlier 'denial' phases by important stakeholders in the debate. The planetary boundaries concept, just as the earlier limits to growth may be most useful if it is a self-unfulfilling prophecy that triggers a just-in-time human adaptive response. Smarter technologies, however, need to go hand in hand with efforts to contain current global environmental change by enhanced and sustained agility[26,27], once goals have been set.

The various SDGs have from their start and political platform in the discussion, been associated with existing sectoral perspectives. SDG2 for example is seen as the domain of 'agriculture' and SDG15 of 'forestry'. It seems logical to relate SDG2 on 'Zero hunger' primarily to agriculture. However, current understanding of the multiple dimensions of food security (adequacy of supply, economic and physical access by all, absence of factors restricting utilization, stability and sovereignty[28]), has opened up to wider perspectives[29]. The concept of 'outsourcing' of staple foods (but not of other elements of healthy diets) in tropical forest margins[30], has pointed at rural income security as basis of food security. A wide range of forest and tree crop products can be a basis for income and thus food security. In many countries, food insecurity and under-nutrition are not the result of a lack of availability of food but are related to unequal distribution of resources and unequal access to healthy natural resources, productive inputs, credit, social protection and information. Lack of clean water (SDG6) or energy to cook (SDG7) link forests and trees to underachievement of SDG2. Efforts to achieve food security and nutrition thus require dealing with challenges in production, distribution, pricing and information, access to healthy land and water. However, it also deals with problems of insufficient health care and education, inadequate sanitary systems, or factors such as economic decline and climate change impacts on production and distribution[31]. Rural societies need to deal with all SDGs, rather than SDG2 alone, just as they deal with agriculture, forestry and everything in between.

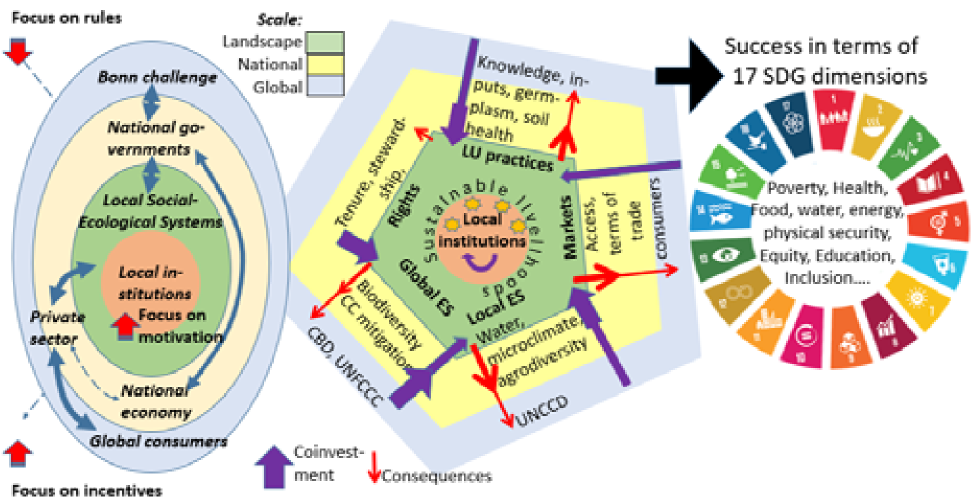

Figure 21.2 Linkage of global concerns to local change in land use can start from rules, incentives or motivation (left panel), but to be effective it will need to address all sides of the pentagon (middle panel) and be directed towards the totality of 17 SDGs

21.2 Agroforestry concepts, impact pathways and theories of change

As described in Chapter 1 and formalized in a set of hypotheses[32], agriculture and forestry have a long history as separate and often antagonistic sectors[33], but reality in the landscapes shows a much smoother continuum. In the four decades of its existence[1], agroforestry as a concept has been understood and defined by reference to various system scales of interest: trees (Chapters 2 and 3), soils[34] (Chapter 4) plot-level interactions (Chapter 5) and management practices[35], development goals[36] or climate change[19]. Where earlier definitions of agroforestry focused on the technology of plot-level integration of trees[37] (AF1) (see Chapter 6 for the regional variation in tree cover in agricultural lands). Subsequent interpretations of agroforestry as an element of multifunctional landscapes, have embraced a much larger share of the natural resource management and rights agenda[38,39] (AF2), as described for different parts of the tropics in Chapters 7 – 12. Finally, it led to current perspectives on how the land-based sectors using the principle of agroforestry knowledge and practice (AF1 and AF2) can contribute to the achievements of SDGs by removing the conceptual and institutional barriers between agriculture and forestry (AF3)[40]. Chapters 13-19 have discussed various policy lenses through which agroforestry may appear to be part of solutions to be pursued.

The relationship between the agriculture and forestry sectors has in the past largely been analysed as competition for space in a zero-sum (land-sparing) game[41] and power, but the existence of wider 'planetary boundaries' than space as such, including the causation of climate change, may urge for a reanalysis[42,43] of the underlying discourses. Discourses are shared, structured ways of speaking, thinking, interpreting, and representing things in the world[44], and represent one of the highest level 'leverage points' identified by systems analysis[45]: from parameter settings to the dynamic structure of feedback loops, their strengths and time-lags, to differential information access, goal setting, paradigms and self-organization. Publicly held paradigms and existing segregated institutions are key bottlenecks to SDG attainment.

The SDGs call for new alignments across sectors that don't have a history of smooth cooperation in many countries[46,47], including agriculture and forestry as part of natural resource management. The opportunities for a coherent SDG approach to 'all land uses' across the full spectrum of human use intensity and measurable tree cover, will be bounded by the degree of success in overcoming institutional divides. A seven-point scale has been proposed to describe interactions between goals[48], ranging from 'Cancelling' (-3) through 'Neutral' (0) to 'Indivisible' (+3). This interaction scaling can be applied on how agroforestry at the agriculture/forestry interface on the various contexts contributes to climate change adaptation with co-benefits for mitigation within SDG 13, while addresses food, energy and water issues of SDGs 2, 7, 6 along with human health (SDG3) and healthy terrestrial ecosystems (SDG15), while never loses economic progress (SDG1) out of sight. An earlier analysis described how the way adaptation and mitigation dimensions of the global climate change debate can move from competing silo's towards complementarity and further to synergy[49] and took stock of current practice in developing countries in this regards[50].

Following earlier agroforestry reviews of food security and climate change in Africa[51,52], water and climate change adaptation in Indonesia[53], nitrogen fixation as SDG friend or foe[54], and multifunctional agriculture[55], the rest of this review focuses on the need for a comprehensive 'land use' SDG agenda, transcending existing sectoral views on agriculture and forestry. Four steps in such a process of enhancing synergy can be coupled to the four knowledge-to-action chains[11,56] that relate understanding of 'public concern' issues to willingness to act, ability to act and capacity to innovate:

Progress in resolving issues of public concern can be constrained by any of these four chains[5].

21.3 Science-based understanding of prioritized issues and their trade-offs

Increased demand for food and healthier diets, renewable energy and reliable clean water, as part of the SDG portfolio, all imply claims on land. Increased functionality per unit land is needed to reconcile footprints and available space. Intensification (greater use of inputs and energy per unit land to obtain more output) has been the main strategy in agriculture and production forestry to reduce competition for land with other societal functions. In trying to close 'yield gaps', however, a common pathway to intensification has widened other 'efficiency gaps'[57]. In a major review of the diversity of impact pathways by which (international) agricultural research can increase rural prosperity[58],18 pathways were identified. The first five describe the traditional core area of such research in the Genotype x Environment x Management interactions of high-yielding germplasm and associated input markets (Figure 21.3A). The next eight broader issues of natural resource management, property rights, gender, skills and value chains, and the last five policies relating to health, safety nets, food waste and international trade (Figure 21.3B). The three interpretations of agroforestry (Chapter 1) relate to the first five (AF1), the first nine (AF2) and the full set (AF3).

Current understanding of the complexity of the forest-rural and rural-urban interfaces of land use thus gives space for new discourses on how land use as an integral concept can be managed, in line with societal priorities. This is especially relevant in developing countries before and around their demographic and economic transition where more than half of the population and economy is urban. With current projections Africa is the only continent where rural populations are expected to still show absolute increases[c], elsewhere rural population densities are expected to be stable or on the decline[59]. This transition has consequences for an increasing space for forests, but tree densities in densely populated (peri- or sub- urban) sub-catchments of the tropics, are higher than those for purely agricultural ones[60]. Evidence for a global increase in trees outside forest[61] can be seen in this light.

Recent debate[62,63] has focussed on the relevance of a diversity of conceptual frameworks[64], beyond what the Millennium Ecosystems Assessment[65] promoted, especially in connection

[c]https://data.worldbank.org/indicator/SP.RUR.TOTL.ZG

with the 'payments' concept[66,67]. The new language promoted by the IPBES assessment[68] of 'nature's contributions to people' expresses the same degree of anthropocentricity as the 'ecosystem services' it tries to replace, assuming a 'free and prior informed consent' on the other side of human resource appropriation[d]. While the terminology debate may have relevance for part of the audience, a more empirical approach may see that many of the functions, services or contributions of 'wild' nature are taken over by more 'domesticated' land uses and/or non-land-based technology (Figure 21.4). A further quantification of these relations will undoubtedly lead to a refinement of the options and context-specificity of the various substitution processes, but a first mental step is to see land uses as a continuum open to empirical exploration, rather than as forest-agriculture dichotomy.

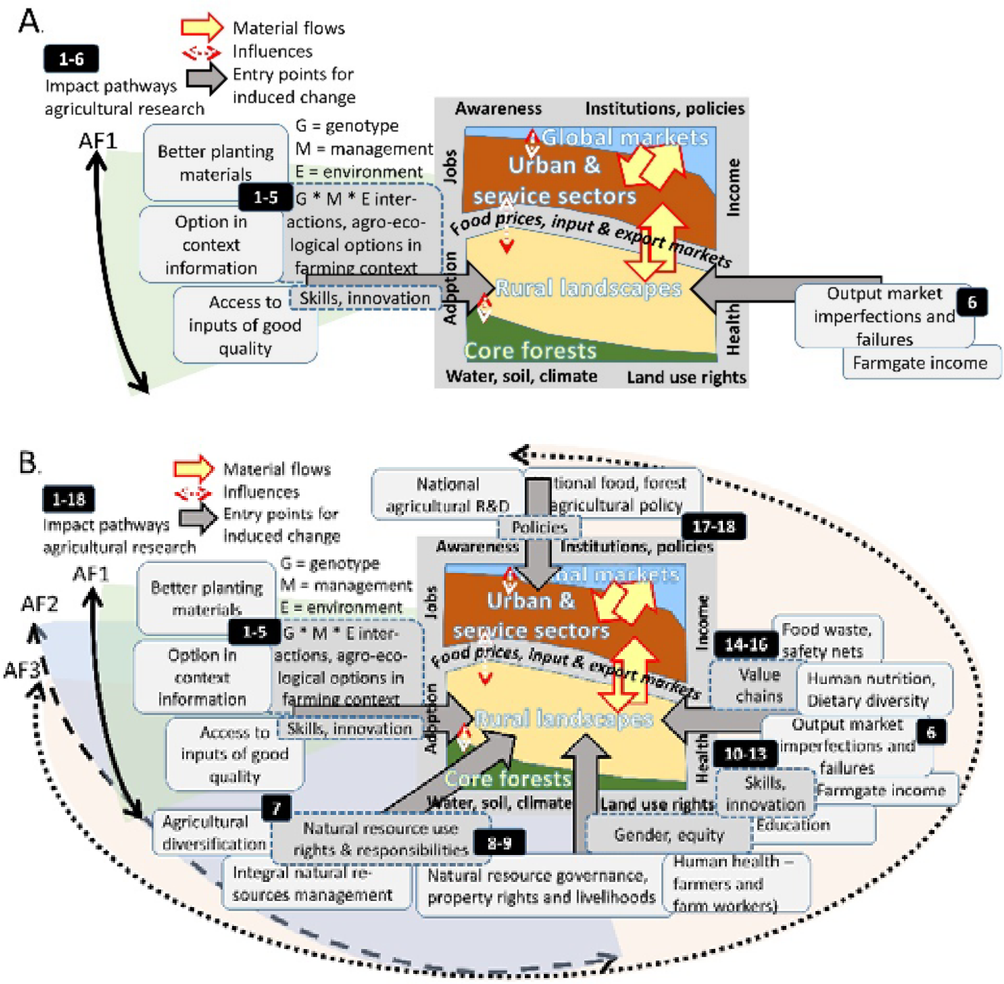

Figure 21.3 Systems perspective on aspects of agriculture, rural development and national economies, with multiple impact pathways for agricultural research; A. Focused on the initial strength of international agricultural research; B. With the current agenda[59]; three interpretations of agroforestry are indicated as AF1, AF2 and AF3

[d]http://science.sciencemag.org/content/359/6373/270/tab-e-letters

Figure 21.4 Conceptualization of the degree to which a range of 'forest functions' are provided by natural forests, plantation forestry, agroforestry, open-field agriculture or industry, with an indication of the technical alternatives that can substitute for 'contributions from nature' to match human agendas

Agroforestry landscape including a tea plantation, Vietnam. Photo: World Agroforestry/Ingrid Öborn

Box 21.1 Land equivalent ratio for multifunctionality

The continuum can be described by a single metric: the degree to which land use in its current form achieves the goals set, relative to other ways of achieving these. The Land Equivalence Ratio concept, so far focussed on productivity, can be expanded to do so. The conventional Land equivalence ratio (LER) concept (Eq. 1) that is central to AF1, can for AF2 be expanded to a multi-functionality land equivalence ratio (LERM, Eq.2).

$$LER = \sum_i P_i / P_{i,ref} \qquad 1$$

$$LERM = \gamma_{P,S} \sum_i P_i / P_{i,ref} + \gamma_{R,S} \sum_j R_j / R_{j,ref} + \gamma_{C,S} \sum_k C_k / C_{k,ref} \qquad 2$$

Where P_i, R_j and C_k represent the attainment (in any metric of choice, per unit area) of a range of provisioning (P), regulating (R) and Cultural (C) services provided by a landscape, $P_{i,ref}$, $R_{j,ref}$ and $C_{k,ref}$ the attainment (in the same metric) of such services in a landscape optimized for that specific service (often a 'monoculture') and $\gamma_{P,S}$, $\gamma_{R,S}$ and $\gamma_{C,S}$ the weighting functions for the importance of the three groups of ecosystem services from perspective S. Full representation of all weighting factors γ_S may in fact represent the AF3 concept (Figure 21.3). A comprehensive analysis of properties of alternative cropping systems was recently completed for cacao, quantifying various trade-offs.

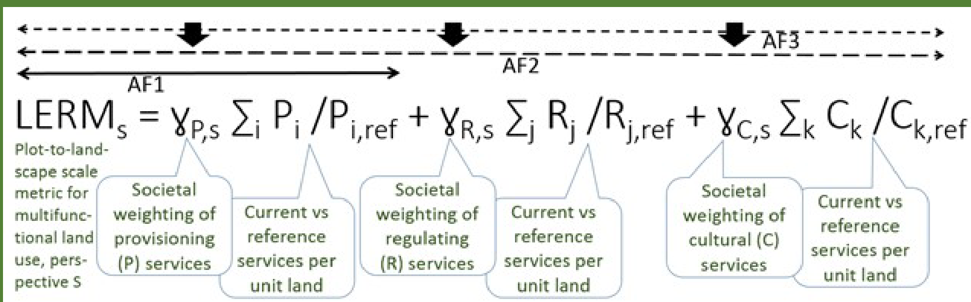

Figure 21.5 Land Equivalent Ratio for Multifunctionality (LERM) as landscape (AF2) extension of the plot-level (AF1) productivity LER; if LERMs > 1 the mixed system, from perspective s and its weighting parameters ɣ, spares land relative to a segregated mosaic of monofunctional reference land uses

The big questions of the Anthropocene about the ecological footprint of humanity, already transgressing the planetary boundaries of 'safe operating space', require that the full spectrum of SDGs is taken seriously (Box 21.2). 'Land use' (with or without 'agroforestry') is the starting point for supply chains (and their current waste that can be recycled), life-style consumption choices (with greater awareness of consequences for personal and planetary health) and continued efforts to ensure that '*nobody is left behind*'.

Box 21.2 Anthropocene equation

Human impact on the planet has since the 1970's been summarized in the IPAT equation[69], stating that impact (I) is the product of population (P), affluence (A), and technology (T). In current discussions, the affluence is replaced by 'well-being' (in a SDG sense) and the life-style choices that support is, while the technology needs to at least distinguish between the efficiency of value chains between production and consumption, and the land-based 'primary' production that is at its base. In impact the concept of resilience and human adaptive capacity to support it need to be part of the analysis. A more elaborate and up-to-date form is presented in Figure 21.6 as '***Anthropocene equation***'. Agroforestry has conventionally been conceived as a form of land use, to be evaluated primarily on the basis of its productivity. In the fifth decade of agroforestry a wider perspective is needed on balancing human ambitions with the various planetary boundaries that have already been crossed.

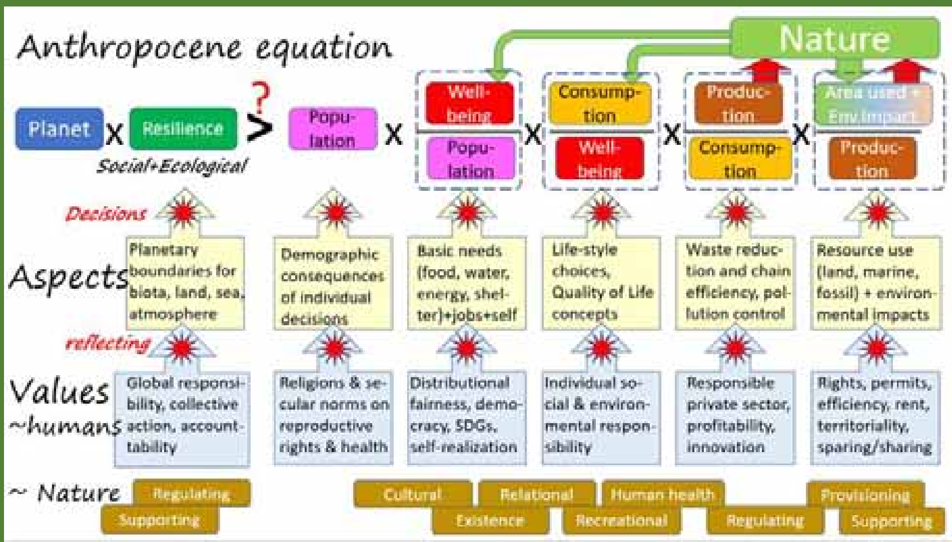

Figure 21.6 Updated version of the IPAT (Impact = Population * Affluence * Technology) equation incorporating life-style choices, waste reduction and contributions of Nature to quality of human life based on a range of ecosystem services; agroforestry discussions can no longer be restricted to the land use box without connecting to the chains of value (or waste), consumption and wellbeing that link 'Nature' to 'People'

21.4 Willingness to act on ambitious goals

Research on land use, especially that on tropical forest margins, has quantified trade-offs between production (local income) and conservation (global wellbeing) goals[11,70,71]and clarified the need for policy instruments to align land use choices across scales by internalizing externalities. Such trade-offs have in the past been portrayed as 'development' versus 'environment', or short- versus medium- and longer-term goals. The 'future we want' agenda of 17 SDGs has stressed the coherence between these goals and has refrained from a hierarchy among the 17 goals to ensure that national policy can adopt them according to each country's contexts and needs. Yet, domestic policy platforms for the various goals have not (yet) converged as much as the international agreements suggest. Within countries and governments, a strong preference for 'development' over 'sustainability' dimensions can still be observed. The same may be true where international organizations, and parts thereof, that have so far focussed on single goals, now face new challenges to achieve a higher level of coordination and integration[72],[73]. Although accepted as goal by all countries, the effective integration of the gender agenda on land use and natural resource management remains a challenge[74,75]. Complementarity between international, national and local policies needs to be met in raising the 'ability to act'.

Box 21.3 Global trade and consumer responsibility: shifting blame or resolving issues?

Figure 21.7 Four-component system view (governance, private sector value chains, producers and consumers) on global trade, with 5 emerging issues discussed in the text

Public-private partnerships connect consumers, producers, value chains and governance as four subsystems in the global Social-Ecological System (Figure 21.7). Nature plays a role in both the producer and consumer side, but in different ways, and partly in a trade-off. Outsourcing the production of commodities such as timber, animal feed or staple crops has facilitated local nature conservation and reforestation[76], but at unaccounted costs for global nature. Despite all social differentiation in both consumer and producer settings (indicated by the red circles in Fig. 21.7), the complexity of human can for the current analysis be reduced to three layers of the Maslow pyramid: securities or basic needs of shelter, water, food and energy, a middle layer of jobs and income, and an upper part of identity and self-realization. The governance connection needs to reconcile a democratic streak, in which consensus among 192 UN countries counts, and a power-reality one, in which three economic blocks (China, EU and USA) control 50% of the global economy[e] and 3 countries dominate two-thirds of globally traded commodities in the case of tropical timber, palm oil, coffee, cacao, coffee and tea (Chapter 6). Global trade developed as the margin between willingness of consumers to pay for (low-cost in their view) products still left an entrepreneurial profit margin after farmgate commodity prices were paid, and costs

[e]https://en.wikipedia.org/wiki/World_economy

of transport, processing and taxes covered. Gaps between living standards of producers and consumers increased opportunity for the private sector controlling value chains, with 'intellectual property rights' on intermediate steps in the value chains delaying a race to the bottom. Globalization, however, also brought increased flows of information about the social and environmental consequences of commodity production, and an increasing sense of guilt. Boycotts (or threats thereof) sparked a response that started with 'denial' and moved to 'shifting blame', when 'worst case' examples were confirmed in public scrutiny. Shifting blame requires the articulation and acceptance of 'standards', and forms of 'certification' of compliance to such standards by trusted third parties. As a range of social and environmental issues, each initially triggering separate standards, coalesce, overarching standards and labels emerge. Globally established companies try to gain trust in their brands, but to do so have to be seen as front-runners in 'voluntary standards' and declarations on 'deforestation-free', 'fair-trade', 'organic' or whatever is the term with most traction in public discourse. As a response of last resort, the social responsibility for poor primary producers and the 'sovereignty' of producer countries faced with demands of ill-informed affluent consumers is brought into the debate, polarizing and politicizing the issues. Analysis of such 'issue cycle' responses for a number of tropical commodities[77,78] (from heavily contested palm oil[79] and tropical timber[80], via fair-trade focussed coffee[81] and cacao[82], to agnostic rubber[83]) has focussed on the 'shifting blame' and 'resolving issues' aspects. Five trends have been noted for further analysis:

1. Optimal intensification: where the land-sparing benefits of intensification and the local-impacts minimizing aspects of land sharing have been contrasted as an a priori choice, the analysis of footprints per unit product show[84] that there is a middle-ground of 'socially optimal intensification' from an environmental perspective, that may or may not coincide with 'privately optimal intensification'.
2. Chain responsibility drives towards the monopsonies of vertical integration and exclusion of smallholder producers, unless the gap between end-consumers and primary producers is so wide that the chain functions better if links are partially independent.
3. The concept of indirect land use change (ILUC) has come on top of the responsibility on the producer side to meet emerging standards; ILUC is arbitrary in its level of aggregation (e.g. 'palm oil' versus 'vegetable oils') and in its current application feeds conspiracy theories in exporting countries.
4. There may well be a trend from a product-based to a territorial 'jurisdictional' approach, looking for integrated solutions. Products can be protected by 'geographic indication' with local compliance checking and joint responsibility for brands. Transfer of accountability for net greenhouse gas emissions along the value chain may require a globally coordinated 'carbon tax' (e.g. similar to the 'value added tax' concept)
5. Limits to public responsibility and government involvement support a 'consenting adults' perspective, where Free and Prior Informed Consent (FPIC) on the producer side is accompanied by absence of child labour and compliance with producer-country regulations (e.g. ISPO), with fully informed customers who are free to express their preferences, responsibility and choices. The norms, values and procedures of the World Trade Organization (WTO) that aim to protect 'free trade', need to be reconciled with the 'responsible production and consumption' intent of Sustainable Development Goals 12.

21.5 Ability to act across goals with common programs, funding and institutions

The historical institutional divides between 'mitigation' and adaptation', as well as between 'forestry' and 'agriculture' remain a barrier for effective SDG attainment, as project proposals have to target one of the two as goal, as basis for eligibility for international or national funding[85]. An analysis of 201 project design documents from adaptation funds, mitigation instruments, and project standards found that 37% of the documents explicitly mentioned a contribution to the other objective[86], though often as unsubstantiated co-benefit. The drive to integrate climate change mitigation and adaptation includes urban areas[87] and 'climate smart' landscapes[88].

Despite challenges in its operationalization, an integrated landscape approach[89,90,91] still appears to be the best way of coherently targeting the Sustainable Development Goals (SDGs) through new forms of collaboration between stakeholders (which can include scientists) based on long-term commitments[92]. It requires a perspective on land use that integrates beyond what has currently been mainstreamed in 'green economy' policies, both at the national and sub-national level. Local governance systems, linked with existing jurisdictions, have to reconcile compliance with national rules, especially where forests are concerned, and local interests that more directly align with agriculture. Beyond land use planning, clear performance metrics for landscape functions and systems for monitoring and evaluation of achievements are essential to a culture of innovation.

David Kenduywo at his farm in Kembu, Bomet County in Kenya. He grows fodder trees, shrubs and grass for his dairy cattle. Photo: World Agroforestry/ Sherry Odeyo

Box 21.4 Rural Resource Centres

While the essential role played by rural advisory systems in reducing poverty and hungeris increasingly recognised, agricultural extension in many developing countries continues to offer single size interventions that do not consider the increasingly complex nature of farming systems in the face of global challenges, such as poverty, food insecurity, climate change and degradation of natural resources. A shift to more user-driven research and co-production of solutions is needed[93, 94].

The participatory tree domestication efforts (Chapter 3) started filling such a gap in Cameroon about 15 years ago[95,96, 97]and since then found following in diverse socio-economic and cultural settings, e.g. in Chad, Burkina Faso, Democratic Republic of Congo, Ethiopia, Indonesia, Kenya, Mali, and Rwanda. In a bid to tackle land degradation and social deprivation, farmers are being enabled to implement agroforestry techniques using a novel community-based extension approach, providing a multitude of services and products tailored to farmers' livelihood needs and capacities. Rural Resource Centres (RRC) are training, experimentation and demonstration hubs that are managed by grassroots organisations[98]. Emphasis is put on access to knowledge, interactive learning, and networking among farmers, and between farmers and other actors. In Cameroon, 10 RRCs were opened, hosting 150 nurseries and serving over 10,000 households, planting over 1.6 million trees. The average income of participating communities rose to over USD 26,000. More recently in Mali, 14 RRCs were established, 4 million trees of 25 species planted and 80,000 farmers in 183 villages engaged. The Regreening Africa project, led by ICRAF, supports the Governments of Kenya, Rwanda and Ethiopia for land restoration through the establishment of rural resource centres and community nurseries to improve access to high-quality tree germplasm.

In Indonesia the number of extension agents is far short of the regulation that states each village should have one. Thus, ICRAF and partners are testing the effectiveness of Rural learning centres in scaling up the adoption of improved production practices of forestry and agroforestry commodities such as teak, coffee, candlenut, bamboo, honeyand fruits[99].

Rural Resource Centres can develop new, and mobilise existing, competencies to cultivate farmer-centred innovation suitable to rapidly changing biophysical and socio-economic conditions, including climate variability and change. The 'capacity to innovate' nurtured by the RRC approach is demonstrated in terms of their capacity to identify and prioritise problems and opportunities; their aptitude to test, evaluate and adapt different social and technical options; and their ability to network and enable learning and knowledge sharing[100].

21.6 Action, shared monitoring, evaluation, innovation

Once institutional constraints to synergy have been addressed, innovation and co-learning can take place. Non-state actors have played essential roles in moving forward debates where national governments are entrenched, such as in the debate on oil palm[101].

Multi-sectoral platforms are processes which often become institutionalized bodies drawing together multiple stakeholder representatives from different sectors to make decisions. They are convened to harness the benefits of collaboration in tackling planning problems that span more than one sectoral jurisdiction and therefore require a co-ordinated response in policy formulation and implementation. Examples include platforms to address planning issues around climate change, food security, biodiversity conservation, timber legality and so on – many of which have nested processes from international level right down to local level. A key question, however, is whether 'certification' can avoid prescribing 'solutions' and create space for goal-oriented innovation (Box 21.5).

Box 21.5 Green Growth and Restore⁺ planning

Green Growth as a concept fosters economic growth and development, while ensuring that natural assets continue to provide the resources and ecosystem services on which our well-being relies[102]. Mainstreaming Green Growth as a policy agenda comprises a menu of policy tools, strategies, principles and indicators that translate the concept into ways of solving trade-offs between economic growth and ecological problems. For green growth to matter in the world of policy and politics, two conditions have to be met[103]. First, strategies must exist for translating the framing concept into policy change. Second, those strategies must be adopted and implemented. For a number of provinces of Indonesia World Agroforestry (ICRAF)has used its experience in analysing land use and its trade-offs to gain commitments from the sub-national governments to apply the green growth concept at the practical level using evidence-based information. Development of a Green Growth Masterplan in South Sumatra led to its mainstreaming and a governor's decree in 2017. Similar efforts followed in Jambi, Papua, and Papua Barat provinces.

The South Sumatra plan for Green Growth is a homegrown initiative that emphasizes on distinct local characteristics. It is in line with the national initiative of the 'Nawa Cita' and partakes in the Nationally Determined Contribution (NDC) to the UNFCCC Paris Agreement, as well as Sustainable Development Goals (SDGs). South Sumatra is endowed with enormous capital to obtain green growth, namely: (i) leadership and commitment to global and national community; (ii) a favourable businessclimate – investment by and partnership withprivate sectors in palm industry and industrial plantation forest (HTI – Hutan Tanaman).

The Green Growth Plan of South Sumatra[104] resulted in 17 indicators at the provincial level comprising seven strategies. The strategies are: (1) Sustainable allocation and land-use planning that address the gap between land demand and supply; (2) Improve people's access to livelihood capital; (3) Increase productivity and diversification; (4) Improve value chain by ensuring fair distribution of benefits; (5) Improve connectivity and economic scale; (6) Restore degraded land and forests; and (7) Provide incentive for ecosystem services and innovative funding for sustainable commodities. Compared to the Business As Usual (BAU), the Masterplan of Green Growth South Sumatra will reduce greenhouse gas emissions by 22 percent. These calculations don't yet include likely reductions in the emission from forest and land fires as one of the pressing problems in this province. By applying the Green Growth scenario up to 2030, the emissions of the production forest, which is the largest land sector emitter, will be negative. Furthermore, the application of Masterplan of Green Growth will contribute to the protection and conservation of biodiversity at the landscape level by maintaining connectivity between dryland forest and mangrove through the landscape corridors. The LUMENS (Land Use Modelling for Environmental Services) projected that the regional GDP will increase by 6.4% by 2130 compared to BAU. The growth rate of regional GDP from land-based sectors will be 1.9% per annum.Follow-up activities have focussed on the way forest and peatland restoration can become part of such a wider Green growth scenario, under the heading Restore⁺.

With the history of forests as part of the landscape that were to be protected from local, innovative resource use, it is particularly challenging to frame space for further agroforestry innovation in its polycentric governance context, avoiding the temptation to over-define and over-regulate at the highest level. Jurisdictional certification might address the above problems. The approach taken by the Common Agricultural Policy of the European Union[105], leaving specifics on what agroforestry is or can be to be further defined at country level is a step in the right direction. Similarly, the Indian agroforestry policy focussed on removing institutional hurdles between agriculture and forestry, rather than on creating agroforestry as a segregated policy domain[106].

21.7 Discussion

From our review of science-based understanding (chain 1) we found strong support for a 'continuum' understanding of 'land use, rather than a dichotomy of forests and agriculture as sectors. Trade-offs between functions are important for the SDG portfolio as a whole; the multifunctionality version of the Land Equivalent Ratio can guide a search for synergy and complementarity. Where willingness to act on ambitious goals (chain 2) is secured for the SDG portfolio at a high level, the ability to act across goals (chain 3) with common programs, funding and institutions is in many cases still a bottleneck. Shared monitoring, evaluation and support for innovation (chain 4) will be essential to allow the synergy options to become reality. The innovation and boundary work literature[107] suggests concrete steps to move to a higher level of integration:

1. **Resources**: It is important that there is an allocation of financial and human resources to encourage the integration of forestry and agriculture, potentially to re-emerge as 'agroforestry' (AF3). Donors could also give integration more space in their resources allocation processes and calls for proposals.
2. **Time**: Policy formulation and implementation issues are often slow processes which require deliberation at multiple scales in the form of consultation and learning. The growing quest for evidence in the policy spaces will require clarity on what difference integration can bring to the wider goal of achieving the SDGs in an effective and efficient way.
3. **Institutional space**: creating a space or a unit within the existing frameworks without complicating the management hierarchy can promote efforts to integration.
4. **Performance indicators**: existing key indicators across the SDG spectrum will be the direct test of integrated land use perspectives, but only if institutional agendas can be contained.
5. **Integrating scenarios** in local development planning for SDGs need to build on existing land use systems, regardless of their current 'agriculture' or 'forestry' labels. At national and global levels bottom-up and top-down models need to be reconciled in view of planetary boundaries and limits to adaptation.

In conclusion, the SDG portfolio can indeed trigger a major step towards more holistic land use perspectives at the agriculture-forestry interface and can, if used well, trigger institutional change to enhance dynamic sustainability. Agroforestry concepts, science and praxis can make major contributions to a comprehensive approach to land use.

In retrospect, agroforestry is the painful process of reinventing what was all part of agriculture previously, before the separation of crops and livestock from trees and forests. This segregation was artificial and driven more by the limits of imagination, the exigencies of mechanisation, power relations and the state of scientific knowledge than by any real needs to remove trees. It was both artificial and unnecessary in the extent to which it was practiced. It is the advance of knowledge and the (often forced - resilience, biodiversity, bioclimate, climate change, soil fertility, value for investment...) re-imagining of landscapes and land-use management along with a more nuanced development of mechanisation that is driving the changes we see and summarised in this book. While not seeing the forest for the trees is a well-known risk, agriculture for too long has not been able to see its future for the lack of trees.

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SOME EARLY REVIEWS

"The book is an overview of ICRAF research in agroforestry over the last four decades. This is structured with a broad definition of agroforestry at different levels, followed by a series of chapters on basic science in agroforestry, lessons from case studies in different regions and the contribution of agroforestry to sustainable development goals (SDGs). The last chapter provides an insight on agroforestry development in the coming years. It was great to see how agroforestry fits in the 17 SDGs and the linkage of global issues and the local changes. Agroforestry science with its tools and methods need to be refined based on the prioritized challenges. I believe this book is a very valuable contribution to the field of agroforestry. I found this to be a great resource to help me understand the state of the art of agroforestry science, the challenges and opportunities for agroforestry development in the future."

Mai Phuong Nguyen – researcher ICRAF Vietnam

"This publication reflects a unique combination of a sourcebook style describing the existing agroforestry systems and a benchmarking of practices providing elements of comparison across the tropics, including the important human dimension such as ethics, health and social connections to development. The book admirably describes how the scientific heritage helped elevate the narrative from agroforestry as an afterthought to a wider and stronger acceptation of agroforestry as a framing for solution-oriented strategies based on natural resources management. All chapters are building blocks that help understand how land management and production can rely on integrated systems to thrive. Because of these various merits, I believe that this book can serve as a set of guidelines for improvements and scaling up agroforestry in tropical areas."

Dr. Cheikh Mbow -- Executive Director START International, Washington (DC, USA)

"If you can talk with crowds and keep your virtue,
Or walk with Kings—nor lose the common touch,
If neither foes nor loving friends can hurt you,
If all men count with you, but none too much;
If you can fill the unforgiving minute
With sixty seconds' worth of distance run,
Yours is the Earth and everything that's in it, ... [Rudyard Kipling]

That is my overwhelming impression reading this book edited by Meine van Noordwijk. Van Noordwijk is a compelling communicator- he provides the DK Eyewitness maps to complex systems. He creates a narrative that is a history of the evolution of agroforestry including the interdisciplinary silos, a tale of evolution over the last 40 years and concludes with finding common cause with farmers, scientists, and policy makers, by interpreting the multiple accords, agreements and frameworks which led to the SDG's. The potential contribution to the climate change debate is clear and contextualised.

This book comprises 368 pages. It weaves diagrams and flow charts into text that is linked to carefully referenced technical papers, but never loses its readability. The case studies are supported with relevant photographs.

The generalist would say it is a triumph of joined up thinking. It provides answers to those who are anxious about climate change but do not understand the impacts and do not know what to do. For the politician, it sets out a context for what can be achieved with an open mind and a participatory approach. It is required reading for those who are setting out on public private partnerships because it lays bare the folly of not factoring in the full costs of production in terms of natural resource use and depletion. For the policy maker, it showcases what agroforestry, forestry and land use can deliver-and when functioning in relevant multidisciplinary frameworks, the potential to leverage resources is persuasive.

The irony of our situation is that *"Agroforestry is the painful process of reinventing what was all part of agriculture previously before the separation of crops and livestock from trees and forest"*. This text will fill many an unforgiving minute.

M Claire O Connor -- Chair Board of Trustees of CIFOR-ICRAF

"This book is conceptualized, in the words of its editor (Preface), as a "travelogue from journeys of discovery" of agroforestry. The journey is portrayed to have discovered three levels of concept developments in agroforestry. Level 1 (Agroforestry 1) refers to understanding the foundations of agroforestry (trees, soils, and component interactions) at the "field and farm level." The extension and further development of the ideas to landscape level is perceived as the second level (Agroforestry 2) of "learning landscapes across tropical continents." The progression to Level 3 (Agroforestry 3) is described as "moving up the scales one step integrating the agenda of agriculture and forestry into a single land-use contribution to Sustainable Development Goals." The 21 chapters in the book are organized into three sections, each section roughly representing each of the three Levels.

The most noteworthy feature of the book is its impressive author line-up. An assemblage of essays by 80 authors, peppered by sprinklings of single-page "INTERMEZZOs" by current and former ICRAF leaders (DGs), makes it a who-is-who in ICRAF (and implicitly agroforestry?) today. Coming as they do from all too familiar names in AF, some readers might suspect the essays to be of the "same old" pattern; but a closer look shows that, overall, they do not represent "old wine in new bottle." Ranging in content from quantitatively biophysical pieces to science-supported policy formulations, the essays provide a real treat to agroforestry "elites" (meaning: the academic types) looking for new waves of initiatives loaded with enthusiasm and optimism. With the editor M. van Noordwijk being the main author or coauthor of 13 of the 21 chapters, his indelible footprint is all over the book. That being the case, it is only fair to call it a book authored (not just edited) by van Noordwijk. That by itself is its strength (and, possibly, weakness).

The basic premise of the book seems to be that agroforestry, over the 40+ years of its existence with some sort of “identity,” has all along been about concept building, and four decades of research in AF can be described in terms of three nested AF Concepts (or Levels) grouped as AF1, AF2, and AF3. No; that is neither true nor appropriate. In a way, all scientific activities involve a continuous flow or progression of concept building. Such conceptual evolutions are in a state of dynamic equilibrium; not static or compartmentalized as different Levels, especially in an application-oriented one such as AF. It Is not like “OK, this Level is done; let us now move on to the next.” This reviewer does not agree that the idea espoused in AF3 (“the governance and policy aspects of the way agriculture and forestry interact as a continuum with a full spectrum of sustainable development goals”) is something that has happened recently. The concept of sustainability was ingrained in the motivations and founding principles of ICRAF. Sustainability has all along been the cornerstone of the foundation of AF as ICRAF writings of the first decade show. When the Brundtland Commission Report (WCED 1987) brought sustainability to the forefront of global development agenda, land-use systems such as AF that had already incorporated sustainability as one of its basic attributes (along with productivity and adoptability) got a much-needed respectability and credibility. One of the first major conferences organized by ICRAF was on International Cooperation in Agroforestry, July 1979, in Nairobi (Chandler, T. and Spurgeon. D, ICRAF, 1979), attended by high-level policy officials from 31 countries; a major theme of that conference was policy development for agroforestry adoption. The fancied “SDGs: Sustainable Development Goals” were framed later (early 2000s). So, there is no justification for characterizing that a separate AF 3 Level of Concept Development happened after 2000 (except perhaps to project that as a background or justification for the recent merger between ICRAF and CIFOR!).

Meine van Noordwijk’s intellectual articulations and imaginative concepts are well known to his colleagues, not only within the scientifically narrow confines of agroforestry, but to the broader scientific community as well. He is a thinker par excellence. Most such thinkers live in a world of their own such that some of their thoughts expressed as caricatures and graphics full of all sorts of arrows and boxes flowing in all directions, interspersed with strange terms and phrases that appear to be from a different world, are incomprehensible to lesser mortals! Another observation is that almost all the 80-strong crowd of authors are intimately connected with ICRAF through its “permeable walls” (as the editor puts it), which strengthens the false impression prevailing in many circles that ICRAF is a synonym for agroforestry! Montpellier 2019 sent a clear signal that ICRAF cannot claim sole ownership of agroforestry (anymore). Indeed, agroforestry is now a global endeavor, not limited to the tropics and developing countries, and ICRAF should be proud of the emerging image of agroforestry. That said, it would have been appropriate to declare so on the title itself that this is not the whole story, but an ICRAF view. The title could also have been more accommodative to include all forms of agroforestry, not just “trees on farms.”

Despite some such drawbacks, the book is an outstanding contribution. Hats off to Professor van Noordwijk and colleagues for this exemplary accomplishment. The book will be a good addition to an AF collection; surely it will attract the attention of not only the “intellectual” type, but the “Average Joe” of the academic community as well. The comprehensive bibliography provided for each chapter makes the book an extremely valuable reference source for agroforestry researchers. “

Prof. PK Nair, Gainesville, Florida, USA

“2015 may have been the year of the intergovernmental Paris Agreement to address the climate crisis, but 2019 will be remembered as the year when the masses of real, average people, and the youth around the globe, truly woke up to the extreme seriousness of the climate emergency. It is the year when millions of people all over the earth first came out on the streets to demonstrate their passion about the future of the planet.

Scientists' warnings finally sunk into the global consciousness, and they are now prompting hundreds of millions of citizens to reflect deeply on what can be done to save the planet from ecological and economic disaster. It is also the year when serious new attention has focused on how important and urgent it is to ramp up the implementation of natural climate solutions as fast as possible, both to reduce greenhouse gases, and to adapt agricultural systems and transform them radically, to be capable of surviving and thriving in the future.

This awakening will turn the attention of many people to the existential imperative of perennializing agricultural systems, and to better restoring tree vegetation on degraded and misused landscapes throughout the world. And in doing so, they have here an amazingly comprehensive and elegantly constructed book to guide their inquiries about what to do.

Whether you are a farmer worried about your family's future livelihood, a generalist searching for answers and ways to get engaged, a scientist looking for more useful outlets for your research energy, an advocate dedicated to changing the world, or a policymaker trying to find innovative ways to cope with the political pressures of governing for the greater good — you have found a book that has an ample supply of knowledge gems that will help you shape your views. And it will spur you on to useful action. Don't miss the chance to do dive into it. You won't be disappointed.”

Dennis Garrity, Drylands Ambassador, UN Convention to Combat Desertification

Trees are invisible. At least agricultural statistics and policies don't usually mention them, while more than 40% of the worlds' farmland has at least 10% tree cover. Trees have been a footnote in agricultural science, representing the history, not the future, of farming. Farming a forest isn't done, or if farmers do, forest institutions will claim the results. Forests need to be restored under forestry rules. Forty years ago, this was the situation in many parts of the world – and now we can at least talk about this. Agroforestry as praxis is as old as agriculture. As science of the interface of agriculture and forestry it is entering its fifth decade. Time to reflect, take stock and look forward.

Agroforestry as a term, as a field of scientific enquiry and policy dialogues was created as the gap between two worldviews was too wide. In fact, a lot of life was found to thrive in this gap. Firstly, it exists. Secondly, it has challenges. Thirdly, something can be done. Fourthly, it can contribute even more to current global issues of focus than it already does. In a nutshell that's four decades worth of emancipation of agroforestry as it played out and is documented in this book, to be released at the 4th World Congress of Agroforestry in May 2019 in Montpellier (France).

In twenty-one chapters a total of 80 authors review the way agroforestry itself transformed, while studying and contributing to the transformation of rural livelihoods and landscapes. Initially, agroforestry was defined as a technology for using trees on farm. Then, it also came to be understood as landscapes with trees, inside and outside of forests. As a third step it represents a view that land use across the full spectrum of tree cover needs to be understood and managed as a continuum, harmonizing agricultural and forestry policies for progress on all 17 sustainable development goals. The first section of the book reviews the science of trees, soils and their interactions with crops. The second describes six landscapes around the world where the local transformations and learning contributed key lessons to the emerging agroforestry science. The third section starts from issues of current public and policy concern and discusses the prospects that a more integrated approach to land use policies can bring by connecting local action to global concerns.

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