Working Paper

The rooted pedon in a dynamic multifunctional landscape: Soil science at the World Agroforestry Centre

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

World Agroforestry Centre

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Abstract

Soil research has been a prominent part of the agroforestry research agenda from the start of the current World Agroforestry Centre as ICRAF in 1978 with a focus on new answers to land degradation problems. Early hopes that, in order to be widely adopted, agroforestry primarily lacked policy support and effective extension rather than research, proved to be too simple. While policy attention was drawn to the need for soil replenishment in Africa and for alternatives to slash-and-burn throughout the humid tropics, the specific ways to achieve these goals in the local context were under investigation. A research agenda was framed that saw trees on farms and in agricultural landscapes as ways to conserve and improve soil carbon (C) stocks, add nitrogen (N) by use of N_2-fixing trees, mobilize poorly available phosphorous (P) sources and capture deep soil nutrient stocks and mobile nutrients on the way out by leaching. Simultaneously the trees should be a source of valuable products (such as firewood, timber, fodder, fruits, medicinal bark and roots), a regulator of (micro)climate and watershed functions, and a provider of supportive functions for crops and animals. In doing so the experience with bottom-up approaches showed that local ecological knowledge of soils included classifications and functional insights complementary to what formal science had as yet explored. A phase of research on hypotheses at process level, analyzing the various tree-soil-crop interactions one by one, was followed by the construction of synthetic simulation models. Meanwhile, the early use of plot level experimentation, inherited from agronomic traditions, proved to be a challenge as lateral tree roots were difficult to control unless plot sizes were large and replicated trials huge. Beyond plot-level experiments, research shifted from characterizing to managing lateral resource flows and filter functions, reinterpreting the earlier erosion control emphasis at hill-slope and landscape scales. Dynamics of soil water led to quantification of soil structure and its dependence on root-based carbon inputs, old tree root channels and earthworms. Further soil biological work was focused on mycorrhiza, rhizobia, nematodes and other soil biota. The more fundamental understanding of soil biology, led to early work on soil carbon dynamics and greenhouse gas emissions from tropical land use, especially in humid tropical forest margins. Reducing and avoiding below- and aboveground emissions were combined in the search for alternatives to slash and burn. Understanding the underlying principles required for sustainable and profitable land use, with or without trees, contributed to a general trend where promises of packaged technology evolved into supporting farmer knowledge and decisions. Agroforestry practices aimed at soil fertility improvement were extensively tested on farms, which led to a better understanding of the risks and benefits under different conditions. A focus on the diverse realities on farm meant that laboratory methods for soil characterization had to be scaled up and simplified. The use of soil spectral properties proved to be efficient in dealing with the spatial diversity of soils in both landscape and farm level applications. However, at the end of the day, our funders and investors want to see and be assured of pathways to development impact, and demonstrating that through changes in soil quality over the long-term and over large extents requires wider application of these methods. The concepts of soil function in multifunctional landscapes, the interdisciplinary integration of tools and approaches, and the direct linkage of growing knowledge and increased action will continue to evolve, but can be rooted in a rich tradition and are on solid ground.

Keywords: agroforestry; carbon; ecosystem services; spectroscopy; soil fertility; soil health; tree-soil-crop models

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Introduction

The World Agroforestry Centre (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 temporarily and institutionally, as the example of long-rotation shifting cultivation may show. Agroforestry itself ranges from croplands with a few trees added, 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, and yield 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 tradeoffs at the scales of farmers, the landscape, (sub) national governments and global policy arena. Soils have a key function 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 (Fig. 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 1990's and flourished after 2000. Intermediate time patterns (steady progression in time) are found for agroforestry systems in social, policy and economic context, and for tree domestication.

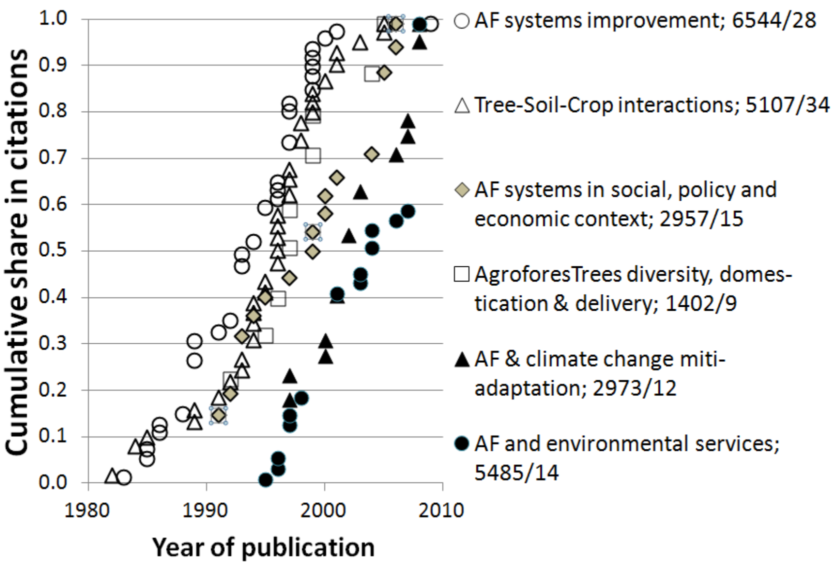

Figure 1. Citations to ICRAF publications classified by topic and year of publication (total / #of papers with more than 100 citations); based on Scholar.Google (May 2013); AF = agroforestry

We will here review progress in agroforestry soil science in the past two decades under seven headings and provide key references for each that point to more detailed reviews and syntheses.

1. 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 (Sanchez, 1987) 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, as the issue interacts with international terms of trade, value chains for inputs and outputs in the local, national and international economy, 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 (Sanchez et al., 1997), but they were not backed up 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 (Soule and Shepherd, 2007; Shepherd et al., 1996a). 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 shelf in Africa. The call for new initiatives to save Africa’s soils remains urgent (Swift and Shepherd, 2007).

The 1992 Rio Conference where the primary global environmental conventions were shaped marked the start of a new interest in how local and (inter)national 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 (Sanchez, 1995). The Alternatives to Slash and Burn (ASB) program was initiated to identify and support sustainable land use intensification in tropical forest margins, alongside protection of remaining forests. While declining soil fertility under reduced fallow length is one of the classical storylines that can be quantified in simple models (van Noordwijk, 2002), the focus of ASB was not on traditional shifting cultivation for subsistence livelihoods (van Noordwijk et al., 2008), but on its modern market-related versions. Almost from the start, the researchers recognized that slash-and-burn as a method of land clearing is used by large-scale operators as a cheap way of establishing plantations, as 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 context, 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 (van Noordwijk et al., 1998a; 1998b). This led to analysis of tradeoffs and interest in the way drivers of business-as-usual change can be leveraged to nudge systems into a more desirable direction (Murdiyarso et al., 2002).

An important part of the ASB research agenda along the forest transition curve was the rehabilitation of abandoned land, as 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 use (Minang et al., 2014). The extent and dynamics of Imperata grasslands in Southeast Asia were reviewed (Garrity et al., 1997), with specific attention to soil conditions. The latter were found to not be a real constraint to subsequent intensification (Santoso et al., 1997; van Noordwijk et al., 1996).

Agricultural systems can greatly benefit from integrative approaches that combine formal and informal knowledge to address current sustainability problems associated with global change (Joshi et al., 2004a,b). 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 (Barrios and Trejo, 2003). 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 (Barrios et al., 2006; Sileshi et al., 2007). 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 (Barrios et al., 2012a). It was designed to facilitate bottom up approaches that integrate local knowledge into the 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 farmer community 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 the land management decision making to promote and protect multifunctional land uses (Sinclair and Joshi, 2000; Sileshi et al., 2009; Pauli et al., 2012). 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 (Tittonell et al., 2010).

2. Agroforestry as 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 (Young, 1997), 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 (van Noordwijk and Garrity, 1995). 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 (Cannell et al., 1996; Sanchez, 1995). Those circumstances potentially include, beyond sloping lands, the seriously nutrient-depleted landscapes of Africa on geologically old soils (Buresh et al., 1996, 1998; Shepherd et al., 1995).

In the 1980's major hope became vested in alley cropping or hedgerow intercropping. Inspired by farmer-developed technology on sloping lands in Flores (Indonesia), it was popularized in Africa by an Indonesian soil scientist working at IITA (Nigeria). There are many versions of the history of the hope-hype-crash dynamics of public expectations of what this technology can deliver, and how lessons could be learned from this experience (Coe et al., 2014). It was to be largely repeated, however, on the improved fallow and fertilizer tree story that replaced it as ‘silver bullet’ solution. While not ultimately leading to widespread success, the research done on hedgerow intercropping and improved fallows helped identifying underlying principles on the technical, social and economic side (Shepherd et al., 1997; Swinkels et al., 1997; Shepherd and Soule, 1998; Ndufa et al., 1999; Sjögren et al., 2010). 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 (Bayala et al., 2007). The attribution of this pattern to aboveground litter fall and belowground root turnover depends on local context (van Noordwijk et al., 2004). 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 (Barrios et al., 1996a). 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 of densities below 1.1 g cm^{-3} (Meijboom et al., 1995), can be used as a sensitive measure of differences in SOM among cropping systems (Barrios et al., 1996a) as it correlates with whole soil N mineralization (Barrios et al., 1996b). Planted tree fallows significantly modified light fraction SOM when compared to a continuous unfertilized maize control; total SOM, however, was not affected (Barrios et al., 1997). 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 (Barrios et al., 1998). 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 (Barrios et al., 1997). 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 (Phiri et al., 2001). 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 (Kwesiga et al., 1999; Barrios et al., 2005).

With trees as the primary point of differentiation between agroforestry and agriculture and range management, the specific aspects of perenniality imply a different sampling in space and time of soil functions (Nair et al., 1999; van Noordwijk et al., 2004). Trees tend to be deeper rooted (with many noticeable exceptions; van Noordwijk et al., 1996) 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 depend 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):

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

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(van Noordwijk et al., 2004). 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 modeling can be compared with farmer 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 (van Noordwijk, 1999), especially in Africa (Stoorvogel and Smaling, 1990; Cobo et al., 2010), considerable effort has been directed in the use of trees as 1) sources of biologically fixed nitrogen (Hairiah et al., 2000; Mafongoya et al., 2006), 2) recyclers and safety-nets of nutrients from deeper layers (van Noordwijk and Cadisch, 2002), and 3) converters of less-processed nutrient sources, such as rock phosphate. However, farm level nutrient budgets (Shepherd et al., 1996a; Shepherd and Soule, 1998) cautioned that agroforestry can result in large nutrient extractions in product removals while pointing to opportunities for nutrient imports through livestock feeds. The potential for tree fallows to re-capture leached nitrate held in the subsoil on anion exchange surfaces was demonstrated (Jama et al., 1998; Shepherd et al., 2000; 2001), and also the ability to reallocate some of the soil P into more labile P-pools (Hoang Fagerström et al., 2002; Schroth et al. 2003; Rao et al. 2004)). While a number of technical solutions have emerged that still are worth further testing (Akinnifesi et al., 2007), no silver bullets have emerged that 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 modeling 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 (UNEP, 2012a; www.aricasoils.net). 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 (Hoang et al., 2013). There are some examples of tightly controlled designs for assessing changes in soil conditions in landscapes for forest transitions (Awiti et al., 2008) and exclosures (Vagen et al., 2008).

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

Research on soil-tree-crop interactions in agroforestry have focused on growth resources sharing between trees and crops mediated by soil with the hypotheses of trees creating favorable microclimate and soil modifications for the associated 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 ground water recharge, and (3) soil regeneration, carbon sequestration and nutrient cycling (ICRAF, 2013). However, the potential benefits depend on complex spatial and temporal interactions between the biological, physical, hydrological and climatic components of the system (Rao et al., 1998; Ong et al., 2013). Such interactions change with time as trees are getting larger together with the processes that affect the soil which are governed by the root systems to a larger extent (Lott et al., 2000a,b), but also by the tree phenology (Broadhead et al., 2003a,b; Muthuri et al., 2005). Finally, management practices also affect these interactions like the tree density and vegetation cover, the use of fires to clear the land (Ketterings et al., 2002; Rodenburg et al., 2003; van Noordwijk et al., 2008), the pruning of tree crown or root (Bayala et al., 2008b, 2013; Coulibaly et al., 2014), and the maintenance of pruned biomass, crop residue and litter as mulching (Rodenburg et al., 2003; Agus et al., 2004; Fonte at al., 2010; Malmer et al., 2004; Coulibaly et al., 2014).

While tree species vary in rooting architecture and root biomass, tree roots can extend to deeper soil layers compared to those occupied by the crop roots. They may therefore take up water from the groundwater even though there is evidence of trees taking up water from the top soil layers as well depending on the species and its root systems (Ong et al., 2014). Nevertheless, it is good to mention that there is no direct relationship between tree water extraction and fine root density as decreasing water potential also play a role (Radersma and Ong, 2004). The effects of the increase of CO_2 and temperature as a result of climate change on change of soil carbon storage were reported to be contradictory, calling for more investigations to separate the effect of increase C and that of possible changes in root and rhizosphere (van Noordwijk et al., 1998). 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 the annuals (Jonsson, 1995; Bayala et al., 2006; 2014). As the tree root can go down deep, they can also lift up water and together 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 (Rowe et al., 1999; Buresh et al., 2004). Such mechanism was reported to improve N use efficiency (Rowe et al., 2001). In addition, the estimates of water volume lifted/redistributed can represent up to 30% of the daily evapotranspiration (Burgess et al., 1999; Bayala et al., 2008a). According to these authors, this has a number of eco-physiological implications, e.g. maintaining fine root viability and avoidance of drought, while affecting some of the soil processes such as increase soil water and soil biota activity.

Some synthetic analyses of published data using meta-analysis have also helped understanding in which circumstances soil improvement translates into better crop production (Sileshi et al., 2010a; Bayala et al., 2012). Another review and meta-analysis by Sileshi et al. (2010b) showed that spatial heterogeneity in savannah vegetation was a result of termite mounds being fertility spots in the landscape enriched in clay, carbon, nitrogen, calcium, magnesium and potassium.

The field investigations have helped generating a wealth of information on the processes in isolation but failed to reveal which one was the most prominent. A solution to this problem has been the development of a modeling phase which tried to synthesize the generated information to reveal the most limiting factors and processes for the production of the associated crops. For instance, simulations using WaNuLCAS revealed that the decrease in *Zea mays* growth near *Grevillea robusta* water due to lower soil water content that resulted in a decreased P diffusion (Radersma et al., 2008).

Similarly, water was found to be the most limiting nutrient under *Vitellaria paradoxa* while it was P under *Parkia biglobosa* (Bayala et al., 2008b). For planning adaptation, WaNuLCAS was also used by Coulibaly et al. (2014) 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 is a certain number of other models (APSIM, HiSafe, HyPAR, SCUAF, etc.) but they all have their limitations, which are inherent to models (over-simplification), or due to our poor understanding of the processes involved in soil-tree-crop interactions or to both (Matthews et al., 2004). If combining field investigations and modeling 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 tradeoffs and synergies between and among goods and services, and how to boost the provisioning of ecosystems services Boffa et al., 2000).

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 (van Noordwijk et al., 1996), and much of the experimental evidence need to be interpreted with caution. It is possible that 'control' plots were effectively mined by tree roots from neighboring 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. Van Roode (2000) found in a well-designed, replicated field trial on various types of hedgerows as erosion control strategies, 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 on the field, rather than on controlled experiments. Cohen et al. (2005) found for a landscape in Kenya that after a substantial effort to spatially parameterize the Universal Soil Loss Equation (USLE), 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. Verbist et al. (2010) found little spatial agreement between prediction of different models (including modified USLE approaches), but also concluded that for the coffee dominated landscape in Lampung (Indonesia), in-field erosion was not the major determinant of river sediment transport. Overland sediment flows were partially filtered, while paths used for motorbike transport, 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 (van Noordwijk et al., 1998c; Ranieri et al., 2004) was found to have a parallel in the social organization of watershed management institutions (Swallow et al., 2002). There has been little accompanying work on the economic costs of soil erosion and benefits of agroforestry. Cohen et al. (2006) estimated ecological-economic costs of soil erosion in Kenya using emergy analysis at different scales and found costs at the national level to be equivalent to the value of agricultural exports or electricity production.

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 farmer decisions to plant, prune, manage, harvest and/or remove (van Noordwijk et al., 2004).

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 (van Noordwijk et al., 1991), the impact of deeply burrowing earthworms (Hairiah et al., 2006), 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 higher infiltration rates. The question of how such infiltration hot-spots at field scale operates during extreme rain events cannot be easily assessed from current measurement techniques, as 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 (Fonte et al., 2010) and by fungal hyphae associated with mycorrhiza (Kuyper et al., 2004). Attribution of biological activity associated to 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 (Velasquez et al., 2007).

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 additional safety net (Suprayogo et al., 2002). Later versions of the WaNuLCAS model (van Noordwijk et al., 2011) have included such processes and allow the dynamics of soil structure, bypass flow and root-based safetynets for leaching nutrients to be quantified.

In Burkina Faso, with yearly rainfall ranging from 570 to 1180 mm, groundwater recharge was simulated to be equivalent of 2-14% of the total gross water input. A combination of the measurement and modeling of drainage and transpiration in agroforestry parkland revealed that intermediate density of trees (5-25 trees ha^{-1} based on the assumption that 100 to 0% of transpired water is coming 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 (Ilstedt et al., 2014).

The soil environment may well host and interact with the most complex biological community once we account for scale (Susilo et al., 2004). Soil biota (e.g. microbes, invertebrates), mostly contained in the upper few decimeters 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 ecosystem (Barrios, 2007; Sileshi et al., 2007). New high-throughput DNA profiling techniques are supporting efforts to assess the global distribution of soil biota and the relationship of below-ground biodiversity to above-ground biodiversity (Wu et al., 2011). Soil biota directly influence soil fertility by mobilizing nutrients (Kuyper et al., 2004), and form soil structure (Fonte et al., 2010) 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 which is required for sustaining land health in agricultural ecosystems (Barrios et al., 2012b). Strategies for maintaining native biota of farm soils, such as mycorrhizal inoculum potential, are generally preferable to inoculation strategies (Shepherd et al., 2006b). 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 negative effects of climate change (Maestre et al., 2012). Slash and mulch agroforestry systems show greater abundance of soil macro fauna than the native forest suggesting that maintenance of soil cover with organic materials of different qualities promotes favorable conditions for soil biological activity (Pauli et al., 2011). Comparison of adjacent agricultural plots with and without trees show that tree presence increases abundance of several groups of soil biota (Barrios et al., 2012b). Further, greater soil biological activity occurs near trees but effect is greater for some tree species than for others (Pauli et al., 2010) and this is likely related to differences in plant functional traits (Ordonez et al., 2014). 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 these functions that underpin soil-mediated ecosystem services (Barrios et al., 2012b). Farmer perspectives and knowledge on soil biota together with scientific knowledge contribute to better understanding of tree-soil biota interactions in time and space that would allow designing diverse cropping systems that can sustain multiple functions required for the adequate provision of ecosystem services (Swift et al., 2004; Giller et al., 2005; Sileshi et al., 2008; Pauli et al., 2012).

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, as synthesized by Palm et al. (2005). A review of the way soil carbon stocks vary with soil type, elevation (temperature) and land cover introduced the concept of C-reference values and associated soil carbon deficits (van Noordwijk et al., 1997), taking the natural forest soils with the same texture, mineralogy, pH and elevation as 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 (Sitompul et al., 2000). Analysis of carbon dynamics in aggregate fractions (Albrecht and Kandji, 2003) could not be directly linked to fully functional carbon balance models.

Carbon stocks are additive and allow area-based scaling, making it straightforward to scale from plot to landscape (van Noordwijk et al., 2002), 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 (van Noordwijk, 2014). 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 (van Noordwijk et al., 2014). 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 farmer resilience and climate change adaptation (Verchot et al., 2007).

The early measurements on 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 (Verchot et al., 2006). In terms of net greenhouse gas effects the jury is out to determine whether biological N_2 fixation by trees is friend or foe (Rosenstock et al., 2014); 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 (Shepherd and Walsh, 2000). 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 (Shepherd and Walsh, 2000). This was later demonstrated at landscape scale in land use change studies in Madagascar (Vagen et al., 2006) and along a tropical forest-cropland chrono-sequence in Kenya (Awiti et al., 2008). 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 (Shepherd and Walsh, 2002). 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 (Brown et al., 2006) and for available samples from the International Soil Reference and Information Centre global archives using mid-infrared spectroscopy (Terhoeven-Urselmans et al., 2010).

Infrared spectroscopy uses a different set of principles than conventional soil fertility tests and provides a single multiple-utility measure of soil production potential and response to management (Shepherd & Walsh, 2007; Nicota et al., 2014). 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 (Shepherd et al., 2007).

The ability to derive spectral indicators of soil fertility was demonstrated in several studies. Vagen et al., (2006) 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 Awiti et al. (2008) who were able to spectrally discriminate forest-cropland chronosequence classes. A similar approach was successfully used for spectral prediction and mapping of soil fertility classes in Mali (UNEP, 2012a), while Muhati et al. (2011) 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. Cohen et al. (2005) was able to spectrally discriminate ground visual observations of three ordinal erosion classes in the Kenya Nyando river basin with validation accuracies of 78%. De Graffenreid and Shepherd (2009) used a similar approach in the Kenya Saiwa river basin and obtained validation accuracies of 72%, with additional validation of the erosion classes using soil ^{137}Cs concentration data. Walsh and Shepherd (2006) developed an erosion-deposition index 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 (Janik et al., 2007). 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 (Mutuo et al., 2006). 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 (Verchot et al., 2011). Kamau-Rewe et al. (2011) found that 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.

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 (Shepherd et al., 2003, Vanlauwe et al., 2005). 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 (Shepherd et al., 2005; Tscherning et al., 2005; 2006). NIR for determination of crude protein content in cowpea (*Vigna unguiculata*) leaves was also demonstrated (Towett et al., 2013a).

The role of infrared spectroscopy enabling an evidence-based diagnostic surveillance approach to agricultural and environmental management in developing countries was articulated by Shepherd and Walsh (2007). This paper outlined a diagnostic surveillance approach to assessing agricultural and environmental problems in developing countries, based on the scientific principles used in public health surveillance, where surveillance is the main mechanism for determining public health policy and practice. 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 (Shepherd et al., 2008; 2015; UNEP, 2012a). 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; UNEP 2012a; Vagen et al., 2013a), so that inferences can be made back to the target area sampled. Georeferenced soil spectral estimates of soil properties are statistically modeled 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 (UNEP, 2012b) illustrate the land health surveillance concepts with a case study in the West Africa 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 the Africa Soil Information Service. 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 (Sanchez et al., 2009; www.africasoils.net). Spectral measurements were performed on all samples, while conventional reference measurements were done on a 10% random subsample (Vagen et al., 2010). A centralized Africa 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.

In support of this initiative, ICRAF established a globally unique, Soil-Plant Spectral Diagnostics Laboratory, which focuses on analyzing 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 in soils (Towett et al., 2013b), 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.

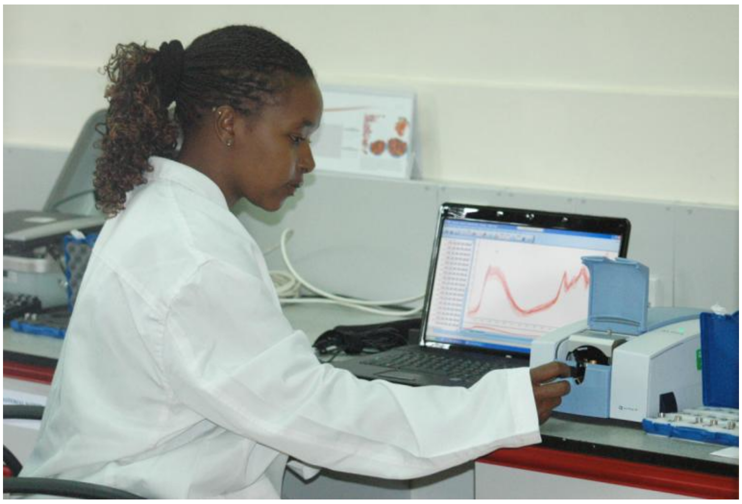

Figure 2. Portable mid-infrared spectrometer being used for rapid characterization of soil samples.

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 (Vagen et al., 2012), monitoring and degradation prevalence and soil functional properties in Ethiopia (Vagen et al., 2013b), and studying patterns in soil faunal and microbial activity in landscapes (Barrios et al., 2012). Soil spectroscopy has also been used to characterize patterns of variability in soil fertility in smallholder farming systems (Tittonell et al., 2005; 2008; 2010; 2013). 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 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 modeling 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 to demonstrating the economic value of soil ecosystem services and improved soil management practices, and to better integrating soil information into decision making processes (e.g. Herrick et al., 2013; Rosenstock et al., 2013; http://africasoils.net/labs/mapping/use-case-“make-agro-input-recommendations”-2/).

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 satisfying all and debating where the best position is along the curve described. 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 has often been seen as a problem, in that it does not allow simplistic perspective on scaling up to perform. As ‘homogeneity’ has often been used as a site-selection criterion for field experiments, as 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 (van Noordwijk and Wadman, 1992). 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 (Sanchez et al., 2001; Sanchez, 2002; Ajayi et al., 2007; Place et al., 2002). Having learnt from this experience, science and extension 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 (van Noordwijk et al., 1994).

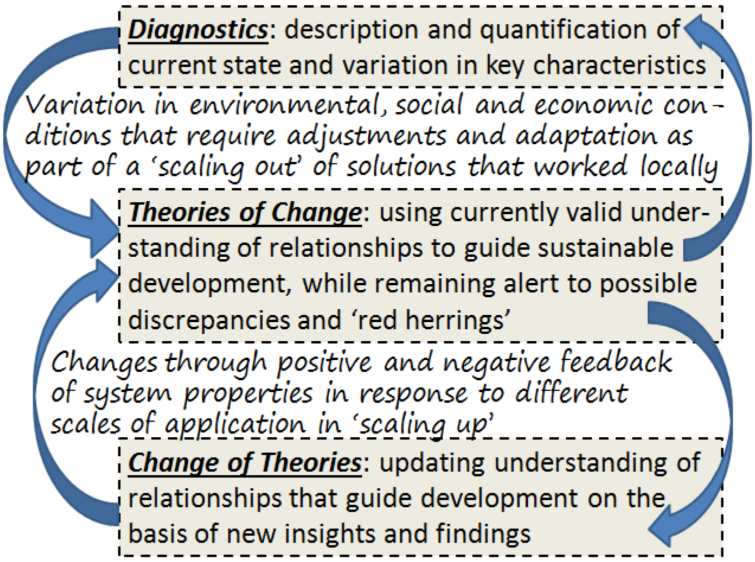

Figure 3. Key concepts of research in development, that require continued diagnostics as part of monitoring and evaluation and sentinel approaches, explicit theories of change that address both variation in circumstances encountered in ‘scaling out’ and changes in dynamic properties as a response of ‘scaling up’, and that may lead to change of theory.

Unfortunately, the funders of international agricultural research are fascinated by the numbers of farmers and the area of land that can be claimed to be 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’ (Coe et al., 2014), 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 before. 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 (Vanlauwe et al., 2005).

Change in soil properties tends to be slow compared to aboveground changes, and this ‘slow variable’ characteristics 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, the slow change, combined with high inherent spatial variability of soils, makes it difficult to obtain convincing evidence of any change. A simple spreadsheet model presented in Hoang et al. (2013) 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 on soil conditions informed land use patterns in the first place (Fig. 4).

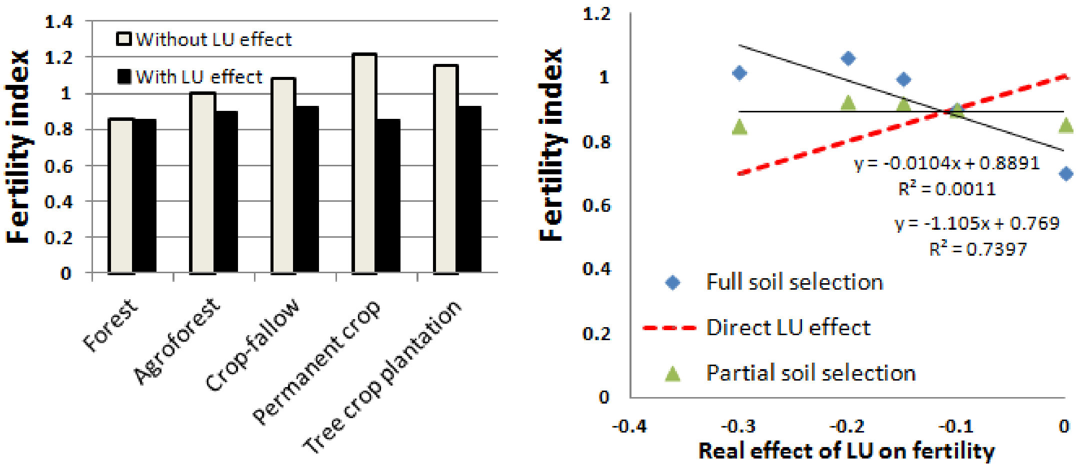

Figure 4. Illustration of the way land use (LU) effects on soil properties, together with the preferential positioning of land uses in specific parts of a landscape, influence survey results, with the possibility of apparent effects having opposite signs to real ones (Hoang et al., 2013)

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 interest may differ from those downstream (van Noordwijk et al., 2014b).

Conclusion: Soil as fundamental to a big issues agenda with attention to local knowledge

As stated in the introduction, a balance needs to be struck between research to gain a deeper scientific understanding of the complex systems that agroforestry deals with at pedon, farm, landscape and global scales, and efforts to share more effectively what we do know but what could be used more effectively.

Further progress in soil science at the World Agroforestry Centre 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 set (Mbow et al., 2014b), national green economy ambitions with land uses that minimizes damage or restores soils after phases of degradation (Mbow et al., 2014a), and local farmer preferences and choices. The complex involvement of multiple actors in what is perceived to be ‘sustainable’ (Bernard et al., 2014) suggests that a close linkage of technical and social expertise will remain important for impact-oriented fundamental soil science in agroforestry.

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