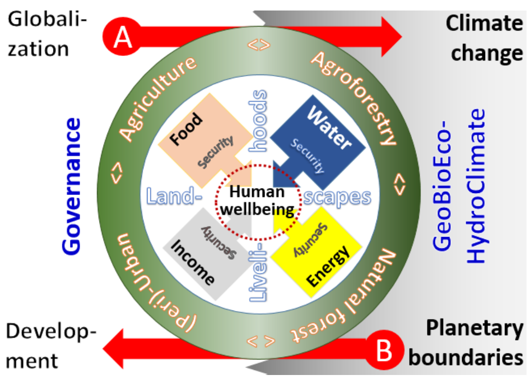
 10.1016/j.cosust.2016.10.00

Metrics of Water Security, Adaptive Capacity, and Agroforestry in Indonesia

Visual abstract:



Highlights

- Land use for Sustainable Development Goals links water, food, energy and income
- Ten prototype mechanisms allow co-investment in environmental stewardship
- Metrics relate hydroclimate to plant water use, plot- and watershed level buffering
- Agroforestry offers flexible space to resolve the forest versus agriculture conflict
- Co-investment requires shared learning and joint evaluation of metrics

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Abstract

Mixed agroforestry systems offer opportunities to simultaneously meet the water, food, energy and income needs of densely populated rural and peri-urban areas in Indonesia. Water flows out of upland areas provide multiple ecosystem services to downstream areas that can be part of performance-based rewards, payments or co-investment in environmental stewardship. Metrics for measuring performance and negotiating accountability need to cover river (blue), soil+vegetation (green), recycled (grey) and atmospheric (rainbow) water in relation to specific stages in the water cycle and associated services. A typology of services and prototype payment mechanisms was derived from action research in Indonesia and elsewhere in Asia by the Rewarding Upland Poor for Environmental Services (RUPES) project. The ecological metrics of landscape performance can be combined with measures of human capacity to assess and support the resilience of social-ecological systems under climate change.

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1. Introduction of the water, food, energy, and income nexus

Greater demand and more uncertain and irregular supply, due to climate change, define the challenge of water [1] in the Anthropocene [2**]. Rising demand is due to a growing human population increasingly living in urban and peri-urban areas, and with life styles based on greater material consumption. Due to these direct connections, key aspects of human well-being are discussed as part of a water, food, and energy nexus [3*]. Rural income security is closely connected to issues of water, food [4] and energy security and may be an integral part of this nexus. Each of these securities can be considered as having at least four dimensions: 1) excess of supply over demand, 2) access by vulnerable groups to adequate supply, 3) absence of factors hindering the utilization of the resource for human benefits, and 4) sovereignty and control over decisions. We propose these four securities as part of a water, food, energy, and income (WFEI) nexus. The United Nations' Sustainable Development Goals (SDGs) provides a politically legitimate framing for efforts to jointly attain these goals by managing their interactions [5]. Five of the 17 goals are primarily about equity and distributional issues; two deal with planetary boundaries and associated tipping points; the other ten goals deal with the WFEI nexus (Fig. 1). Progress towards the SDG's is most likely to come from adaptive learning loops in which monitoring of current conditions and change provides evidence for identification of issues with a common understanding across stakeholders, so that there is space and impetus for innovation, integration of new options and ways of linking knowledge with action, influencing decisions at the various scale that matter from households to national governments and private sector entities.

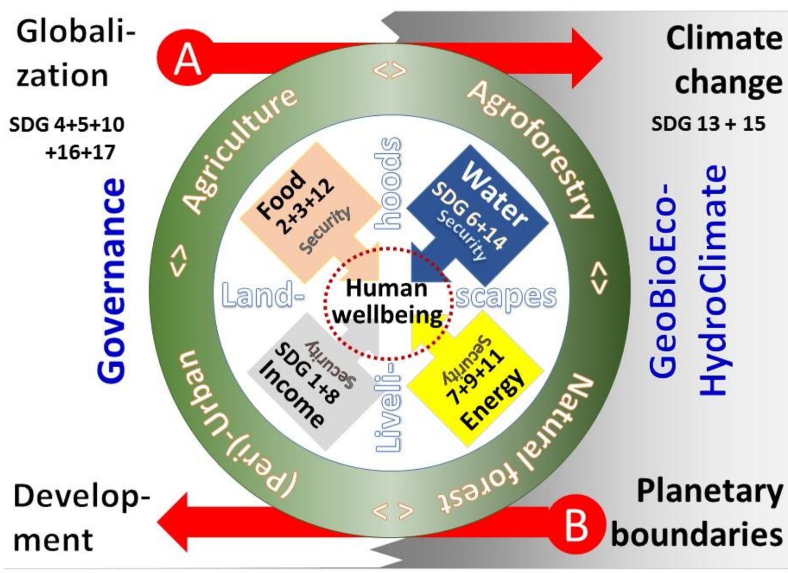

Figure 1. Water security as part of the Water+Food+Energy+Income (WFEI) nexus, in landscapes of (peri)urban, agricultural, agroforestry and natural forest land uses in a world of globalization, climate change and Sustainable Development Goals (SDGs) (A: human influence affecting the rate of climate change; B: human influence affecting ecosystem responses to climate change)

Key to the securities concept is how people and ecosystems can adapt to climate change. To increase adaptive capacity, especially in developing countries, it is necessary to synergize efforts to address the WFEI nexus and ecosystem conservation, as the need for 'supply' of ecosystem services is likely to increase over time [6]. For reasons that are partially explained by current science [7], but that may also require further discoveries of the way rainfall depends on vegetation [8**], there is an intuitive association between forests, tree planting and all aspects of the water cycle [9]. Given the WFEI nexus, we focus here on adaptive capacity and opportunities to increase water security, in its broadest sense, by land uses with partial tree cover. While there are multiple definitions of agroforestry in current use [10], the intersection of tree cover and agricultural lands as operational definition is most readily quantified at global scale [11*].

Agroforestry links directly with traditional bio-energy (fuelwood, charcoal) [12] as well as modern hydro-energy through regularity of river flow. Agroforestry systems also contribute to food production and income, and provide flexible options for managing the associated trade-offs between production for household use and for markets [13].

Mixed agroforestry systems, intermediate in properties between open-field agriculture and natural forest, allow for diversity-based climate adaptation through increasing farmer portfolios at the farm level [14], and increasing multi-functionality of land uses in the landscape [15*]. International forest definitions use 10% tree cover as lower threshold for forests. More than 43% of all agricultural land globally, an area where 900 million people live, has more than 10% tree cover [11*]. The percentage of agricultural land with at least 10% tree cover has been increasing globally and in Southeast Asia [11*]. Efforts to reduce the rate of deforestation, such as REDD+, (reducing emissions from deforestation and forest degradation in the global climate convention) are unlikely to succeed without addressing the WFEI nexus [16]. Although the potential conservation values of agroforestry systems have been recognized, ecological benefits may vary depending on practices and location [17]. However, land use and tree cover alone can be poor indicators of water services.

The limited freshwater buffer on many tropical islands adds a specific context to these issues in Indonesia. As an archipelago of more than 3,000 inhabited islands, Indonesia has many parts that are susceptible to drought, flood and sea level rise [18]. Rainfall variability is highest in eastern Indonesia, with strong effects of the El Nino/La Nina cycle [18]. Low values of the Human Development Index (http://hdr.undp.org/en/content/human-development-index-hdi), rural poverty, and dependence on climate-sensitive agriculture and fisheries coincide with seasonal shortages of dependable water supplies. The increase of tourism in islands such as Bali and Lombok implies demand in sectors with higher ability to pay for water than agriculture, and increased competition for a scarce resource.

Here, we first explain why metrics for water security should be defined within the context of social-ecological systems and the WFEI security issues. Then we provide a synthesis of our current understanding of the way reliable metrics of water security can be used in the broader context of co-investment by stakeholders of landscape multi-functionality. The metrics are organized by micro-, meso-, and macro-climatic scales for understanding beneficial and problematic roles of tree cover and agroforestry in reducing climate vulnerability. The main typology was derived from an analysis of the RUPES program ('Rewarding Upland Poor for Environmental Services they provide'), which encouraged local site teams in the adoption of improved forest, land, and watershed management practices by rural poor through rewards for environmental services (the RUPES program includes 16 action research sites in 9 countries throughout southeast Asia) [19**].

2. Water Security in Social-Ecological System

Water security is defined by what are considered to be acceptable levels of water-related risk, with its many aspects of 'too much' (flooding), 'too little' (drought) and inadequate quality. Water security requires the availability of sufficient quantity and quality of water on a consistent basis, sufficient resources and knowledge to have access to and utilize water, as well as sovereignty, in a social-political setting, over water supply and distribution. Under this definition, threats to water security can originate from natural (e.g., climate change hazards and ecosystem responses to climate change) and human (over-consumption, lack of infrastructure, and skewed allocation) systems. Human systems can directly influence the rate of climate change (Fig. 1, A) and also affect ecosystem capacity to respond to climate change (Fig. 1, B). Human systems can also modify the level of exposure by reducing or increasing people and assets in hazardous locations, and the level of vulnerability by adaptation and intervention [20].

Metrics for water security must start with a basic understanding of the hydrological cycle in relation to land use (*So what?),* then by identifying the likely political scale of the decision space (what are drivers of change? *Why* are patterns what they are*? Who Decides?* And *Who Decides for Whom?*), as well as the necessary biophysical scale of negotiation on allowable land use (*Where? What?*), highlighting the areas of the mismatched scales. The specific threats to the various aspects of water security can then be assessed (*So What?*) and its stakeholders identified (*Who cares?*). Where these threats can be linked to modifications of the hydrologic cycle by land use change, the drivers (*Why?*) of this land use change can become a target for efforts to address not just the symptoms, but the underlying causes [21]. However, specific issues and concerns vary widely, from supplying clean water to metropoles [22], to sustaining highly fragmented smallholder agriculture, as well as addressing increased demands due to tourism development [23] and international commodity trade [24]. Thus, we need a comprehensive 'theory of place' (*Who?, What?, Where?*) to analyse contextual aspects as the basis for a 'theory of change' (*So what?, Who cares?, Who decides?*) to find implementable and rational pathways for watershed management [25].

Broadening issues in 'watershed management' can enable a shift from command-and-control decision making to the use of economic incentives (Payments for ecosystem services, 'PES') [26*] and co-investment in public-private-people partnerships. Metrics are the interface between at least five steps in the generation and use of knowledge [27, 28]:

1) Succinct representation of current understanding of cause-effect networks and their social and ecological feedbacks,
2) Diagnostic tools to identify and prioritize 'issues' that are or should be of public concern and require a policy response,
3) Tools for boundary work, bridging local knowledge, science, and policy-making, and to aid negotiations among stakeholders,
4) Basis for 'performance-based' contracts to resolve 'issues',
5) Basis for wider monitoring and evaluation of conditions and trends, enhancing transparency of governance.

The challenges involving water are that there are many human (dis)benefits linked to its movement in the landscape (Fig. 2), and it is not easy to tease

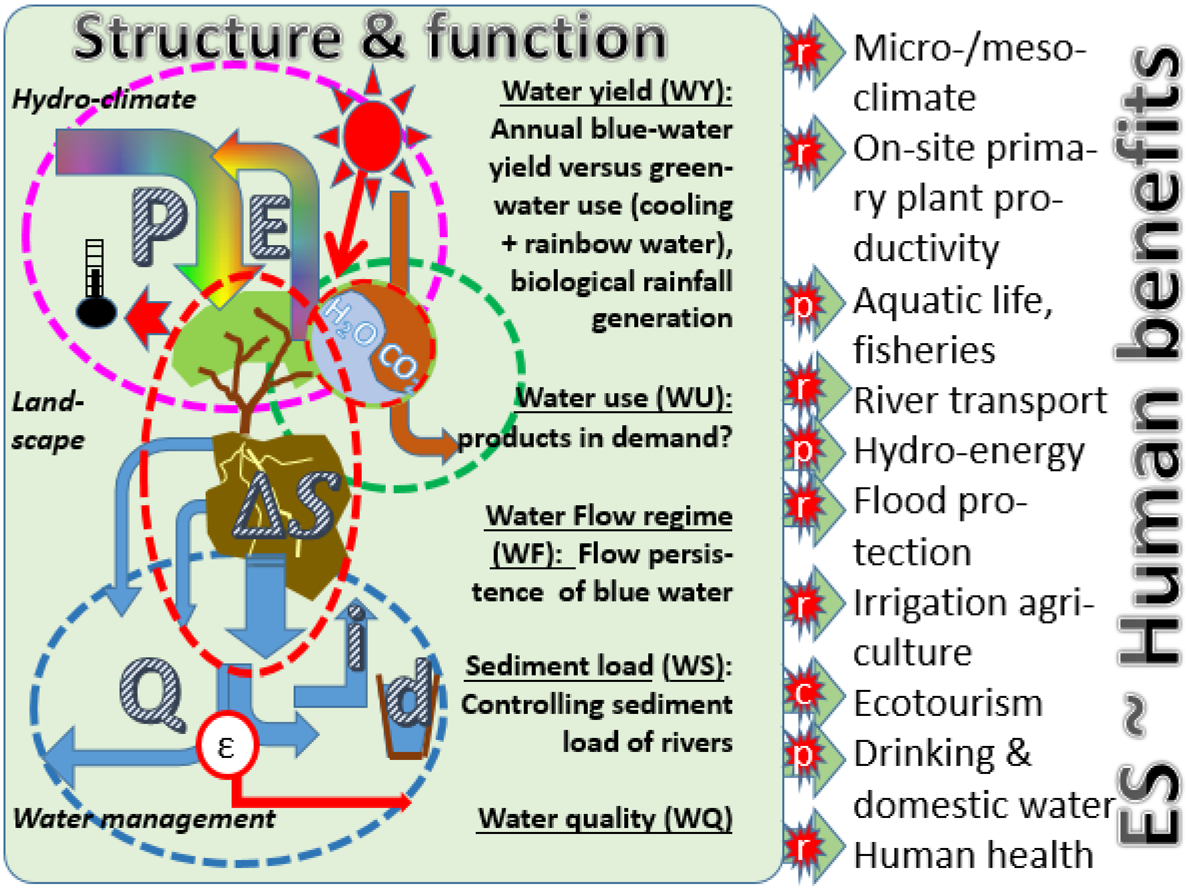

Figure 2. Aspects of the full hydrological cycle in which (agro)ecosystem functions at the nested scales of hydroclimate, plant, patch, and watershed (P = precipitation; E = evapotranspiration; ΔS = change in soil water storage; Q = river flow; ε = energy; I = irrigation; d = domestic water use), are related to human benefits, and thus to ecosystem services (p = provisioning; r = regulating; c = cultural)

apart the roles of climate variability, land use change, and engineering of water flows in influencing changing patterns of river flow [29], and water quality [30]. There are many misconceptions about the outcomes of watershed management [31], although recent evidence has documented increases in flooding risk due to forest conversion to oil palm and rubber plantations in Malaysia [32]. Water relations involve the hydroclimate at regional/subcontinental scale (rainbow water) [33], water use efficiency at the plant level (green water), plot/hillslope level interactions on overland and subsurface flows and buffered soil water supply (blue vs green water trade-off), and the watershed scale of linking blue water flows and water recycling (brown water). Across the micro-, meso-, and macro scales we will briefly review the metrics that can be used in a comprehensive approach to watershed management.

3. Metrics for Operationalizing Theory of Change within Theory of Place

3.1 Micro-Scale Metrics: Water Use Efficiency

Water Use Efficiency (WUE) relates net primary production at tree or crop, stand and canopy levels to water loss by transpiration. It is a useful metric in aiding farm-level decisions to evaluate expected outcomes at the expense of a certain amount of usable blue or green water supply. As one example, fast growing, rapidly transpiring *Eucalyptus* trees may have a higher water use efficiency than slower growing tree species, so replacing one with another does not achieve water saving if we evaluate options at a constant supply of wood products. WUE has been used to evaluate how different cultivation practices affect crop yields [34] and soil infiltration [35], as well as to predict physiological responses of woody plants under different climate conditions. Although trees and crops compete for water and nutrients, agroforestry systems can increase the overall WUE for producing food and biomass for energy [36] by improving microclimate for understory crops [37] and by capturing a larger proportion of the annual rainfall [38]. On the interface of micro- and meso-scales, the changes in soil organic matter content over the life cycle of a land use system [39] influence soil health, infiltration and water storage capacity [40]. However, opinions differ on the relevance of carbon markets in stimulating investment in healthy soils [41]. Peatland landscapes dominated by soil organic matter are a special case where water management dominates degradation and restoration phases [42].

3.2 Meso-scale metrics in ten PES prototypes

Addressing the WFEI nexus at the meso-scale of hillslope and landscape scale requires well-established metrics for measuring water yield, flow patterns [43*], and water quality [44]. These can inform the trade-offs and help in negotiating and monitoring stakeholder co-investment in stewardship, depending on the specific context.

In RUPES projects, agroforestry systems were studied in four major configurations of the forest-agriculture interface. These configurations are abstractions of a more complex diversity of situations, but cover the spectrum of parameter combinations. Operational definitions are provided in [45]. In configuration I, human population density is low and forest regeneration is well integrated with shifting cultivation; in configuration II, forest and agricultural land are segregated by exclusive institutional frames and competition for space; In configuration III, agroforestry systems exist within a forest-agroforestry-agriculture continuum as intermediate-intensity land uses at the interface. Finally, a combination of configurations II and III can exist where a productive agroforestry- agriculture gradient in landscapes interacts with a forest component that is segregated for non-provisioning services (configuration IV). The RUPES project locations across these configurations dealt with different priority issues within the concept of watershed services, and had to rely on partially differentiated meso-level indicators (Table 1).

3.3 Macro-scale metrics

A group of metrics used at the macro scale relates the crop (or tree) level water use efficiency to global trade, via ‘water footprints’ (WF) [46]. For water-scarce production areas, the export of ‘virtual water’ via the water footprint of exported commodities can help in understanding the trade-offs with other possible uses of that water in the WFEI nexus [47]. Indonesia is a major net exporter of virtual water through the cultivation and export of oil crops (72 $Gm^3\ y^{-1}$) [48]. Rice production consumes the largest amount of water due to a high production quantity and a high WF per unit production. Some major agroforestry crops, such as coffee and cacao, also have a high WF per unit product (about 22,900 m^3 ton^{-1} for coffee and 9,414 m^3 ton^{-1} for cacao), compared to other crops (e.g., 500 m^3 ton^{-1} for cassava). The primary question is whether or not this use of water for plant production is competing with other, potentially more rewarding uses of water.

Table 1. Metrics used in RUPES projects in Asia (incl. Indonesia) according to ten 'prototypes' of payments for watershed services

	Metrics for understanding water management at the landscape scale	Plausible actions through agroforestry, potentially supported by Payments for Ecosystem Services (PES)	Metrics used for monitoring
Theory of Place Where? ↓ What? ↓ Who? ↓ ↓	Water yield (WY): Annual blue-water yield versus green-water use	WY 1: Restoring vegetation-level water use to that of natural vegetation; WY2: Replacing fast-tree plantations with low-evapotranspiration species to maintain ecological flows to support aquatic life forms	• WUE of total vegetation cover and/or specified tree • River flow in specified locations • Native aquatic species diversity
	Water yield (WY): Rainbow Water	WY 3: Maintaining green water use as contribution to atmospheric recycling	• Location-specific vegetation type as ET predictor • Agency in biological rainfall generation
	Water Flow (WF): Flow pattern of blue Water [44]	WF4: Increasing presence of deep rooted trees; promoting litter layers and agricultural practices that increase infiltration and soil water content; WF5: Modifying operating rules for reservoirs and hydropower schemes	• River flow persistence (temporal autocorrelation) • Presence of vegetative cover and/or surface litter as influence on infiltration • Quantified seasonal flow buffering
Theory of Change Who Decides? ↓ Who Cares? ↓ So What?	Water Sediment (WS):Controlling sediment load of rivers	WS6: Enhancing sediment filter strips in fields and across landscape matrix; WS7: Protecting river banks, riparian zones and landslide-prone slopes	• Sediment load of streams and rivers • Sediment filter zones: vegetation plus litter layer • Vegetation in riparian zones
	Water quality (WQ) [29]	WQ8: Protecting springs and sources of domestic water use; WQ9: Promoting multifunctional shade tree management for reducing pesticide and fertilizer uses WQ10: Waste-water treatment to match biological recovery from (organic) pollutants.	• Biological water quality indicators • Biological oxygen demand • *Escherichia coli* counts • Agreed measures to control point sources and reduce nonpoint sources (e.g. agrochemicals)

4 Adaptive capacity

Adaptive capacity rests in an institutional capacity for continuous learning and a willingness to face and respond to emerging issues [49,50]. Institutions governing the WFEI nexus must be participatory and inclusive and promote culture of social and institutional learning [51]. Societal commitment to social inclusion and greater gender equality [52, 53] is now anchored in the SDG portfolio. The concept of indigenous people needs to evolve beyond the current place-based concept [54]. Table 2 indicates that a shift from degradation to restoration requires a coordinated answer to the six leading questions of how landscapes function. It should be acknowledged that decision-making process, power structure as well as social and cultural contexts influence all six aspects and how they are perceived by actors in the social-ecological system. Thus collective knowledge gathering and sharing among all actors become an important factor for promoting change [55]. Integrative planning tools such as LUMENS [27], can help transform landscapes of conflict to places where there are opportunities for collective action and co-investment, with due consideration to cross-scale linkages [56].

Table 2. Six aspects of the change in a social-ecological system at landscape scale from an overriding degradation to a restoration phase

SES-feedback loop question	Degradation phase	Active restoration	Project language
Why?	Drivers of current/re-cent/past degradation?	Change of rules, incentives, motivation?	Approach
Who?	Who are actors and stakeholders of what led to degradation?	Free and Prior Informed Consent?	Actors, stakeholders
What?	What land uses, op-tions for change?	Δland use, value chains?	Means
Where?	Landscape configu-ration, lateral flows, buffers, filters?	Spatial zoning?	Targets
So what?	Ecosystem service change, based on structure and function interacting with external factors (e.g. climate)?		Objectives
Who cares?	Common but differentiated responsibility across scales		Co-investment shareholders

LUMENS (land use for multiple environmental services) is a scenario-planning tool that has grown out of efforts to support local governments in Indonesia to plan for low-carbon-emissions development pathways that seek economic growth opportunities while contributing to national targets for emission reduction. As a process, it involves integration across sectors and government entities, harmonizing spatial data, clarifying issues and -exploring options for innovation. As a tool it translates changes in trends of land use change to likely configurations of land cover, with consequences for environmental services that include water balance, expected changes in river flow, biodiversity and carbon stocks. A key feature of the way process and tool are combined is that indicators are fine-tuned to what is seen as relevant and salient in local context. The tool is being further developed in districts that represent the full spectrum of landscape configurations in Indonesia. Current efforts are to link "green growth" planning with restoration targets, using S Sumatra and Jambi as target provinces for urgent action, with issues ranging and interacting from the mountains to the coastal peat swamp zones.

A coherent approach to restoration has to be informed by the metrics described above, with monitoring systems that are salient, credible and legitimate. Whether the starting point is climate change, urbanization, renewable energy or food security, a deeper understanding of the way water cycles and flows function is crucial. Well-managed agroforestry systems are worthy of consideration as an intermediate-intensity land use system between forestry and agriculture. There are no valid blue-print designs, but rather adaptive learning loops that drive the further development of systems using available options in local context (Fig. 3). Adaptive leaning loops in social-ecological systems require capacity in at least six basic skills: 1) observation (monitoring), 2) interpretation of evidence and analysis of issues, 3) innovation through new options at any of the scales from trees to governance modalities, 4) scenarios of the ways innovations might interact in local context, 5) formation of platforms for change through effective communication, 6) agency and decisions ().The introduction of new concepts in the forest governance arena in the form of REDD+ has been a major challenge to human capacity development across the scales, with a considerable learning curve for all, as documented for Indonesia [56].

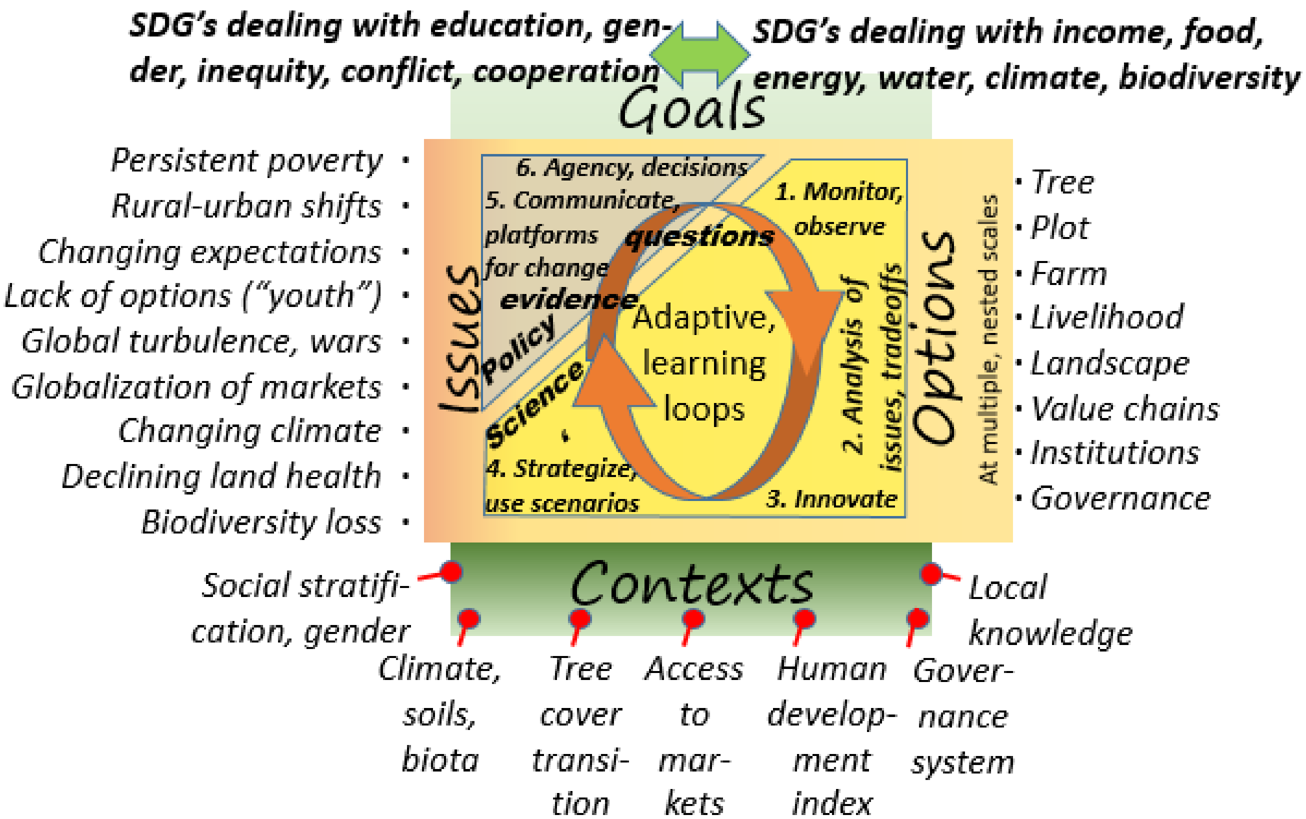

Figure 3. Adaptive leaning loops as central arena where issues, goals, options and contexts meet

The limiting step in adaptive capacity of societies to the combined challenges of water, food, energy and income may well be the high resilience and resistance to change of existing institutions that have been defined on and that maintain a divide between agriculture and forestry [57].

For the drier parts of Eastern Indonesia where water scarcity is a pressing issue, a recent analysis of regional-scale restoration of marginal agricultural lands to savanna woodlands in Australia points to options to reduce warming and drying [59]. Restoration triggers a positive feedback loop between the land surface and the atmosphere, characterised by increased evaporative fraction, eddy dissipation and turbulent mixing in the boundary-layer resulting in enhanced cloud formation and precipitation over the restored regions. Such effects are commonly perceived to be true in local knowledge, but have until recently been seen as beyond any evidence or credible mechanism by most scientists. Reconciling the evidence, concepts and interpretation as steps 1 and 2 of the adaptive learning loops of Fig. 3 will be essential to make progress at the science-policy interface.

Acknowledgements

This work was supported by the Forests, Trees and Agroforestry (FTA) research program of the CGIAR

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