Nature-based water management

Nature-based solutions for stabilizing the banks of an irrigation channel in Bali (Indonesia)

Photo: Brawijaya University/Eka Purnamasari

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CHAPTER SEVENTEEN

Trees as part of nature-based water management

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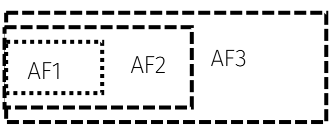
Highlights

- 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].

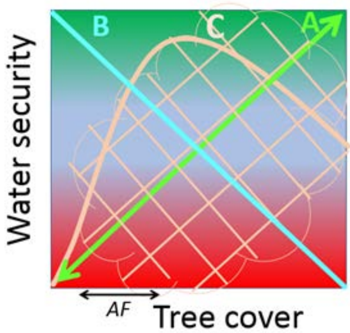


Figure 17.1 Contrasting perceptions of the relationship between tree cover and human water security: A. All loss of forest implies loss of security, B. Focus on maximizing blue water yield by minimizing green water use, C. Full hydrological cycle, with optimal tree cover concepts depending on context, 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].

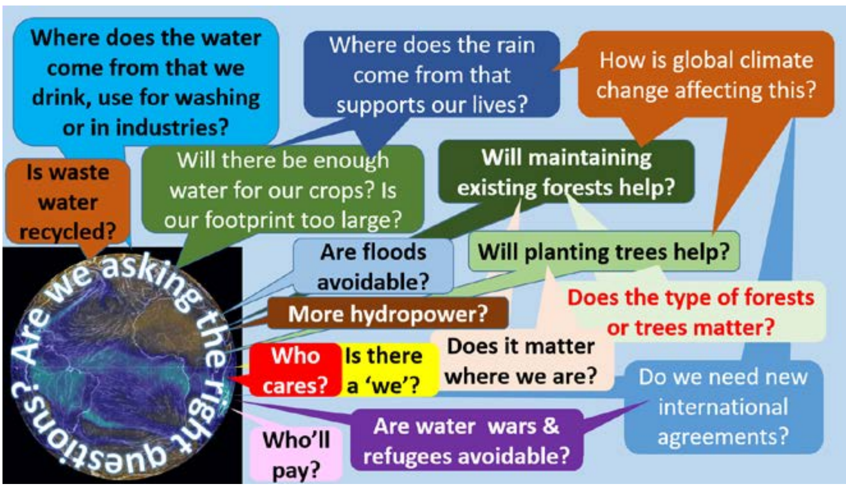


Figure 17.2 Questions related to forests, trees, water, people and climate (change)

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).

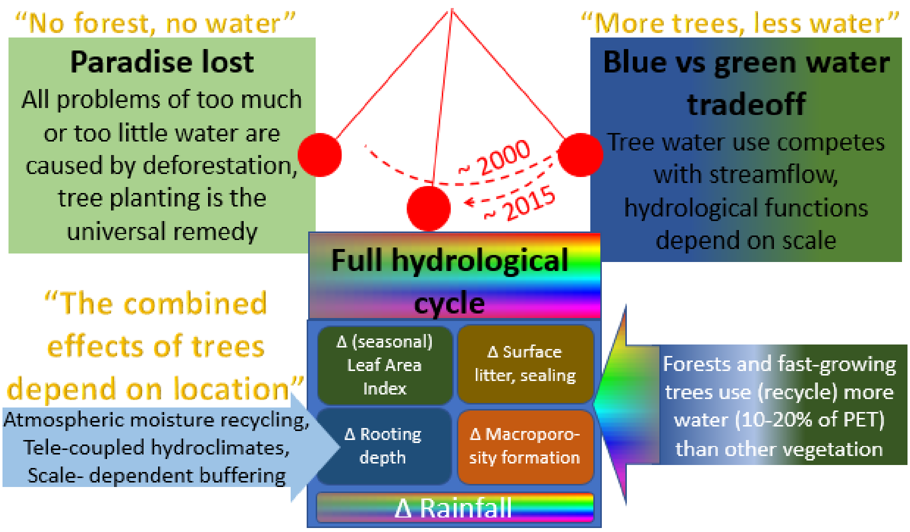


Figure 17.3 Shift between three 'forest-water' paradigms and examples of the scientific analysis and practical experience that contributed to paradigm shifts[1]

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.

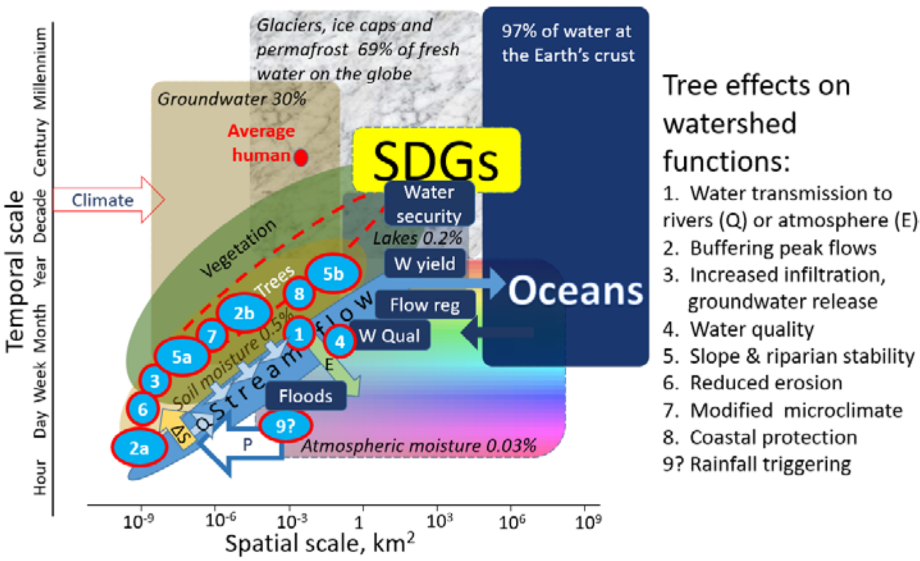


Figure 17.4 Water (as gas, fluid or solid phase) at a range of spatial and temporal scales with the associated tree effects on 'watershed functions' (modified from[1])

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

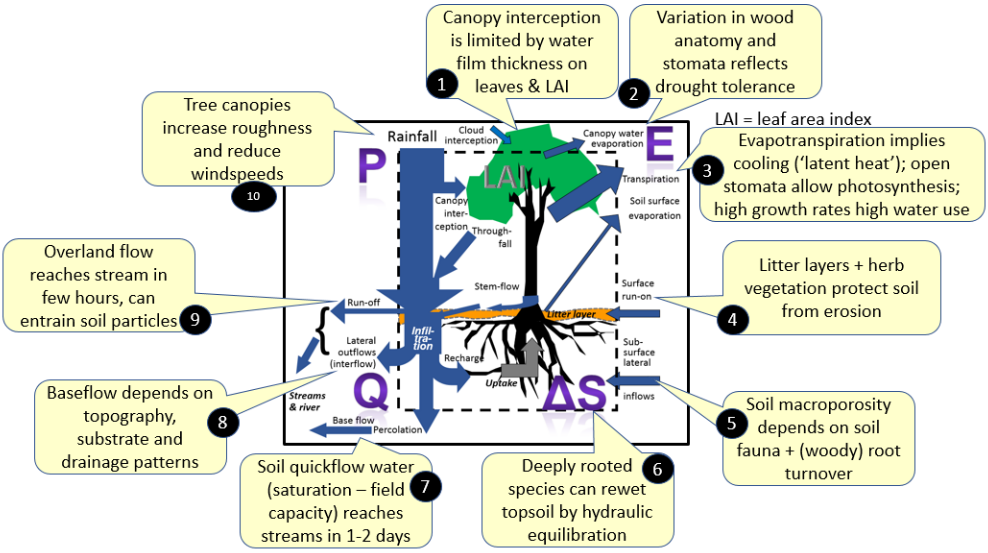


Figure 17.5 Examples of plot-level understanding of the way trees and soils interact with the terms of the water balance (P = rainfall, E = evapotranspiration, Q = streamflow or discharge, S = changes in stored water)

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

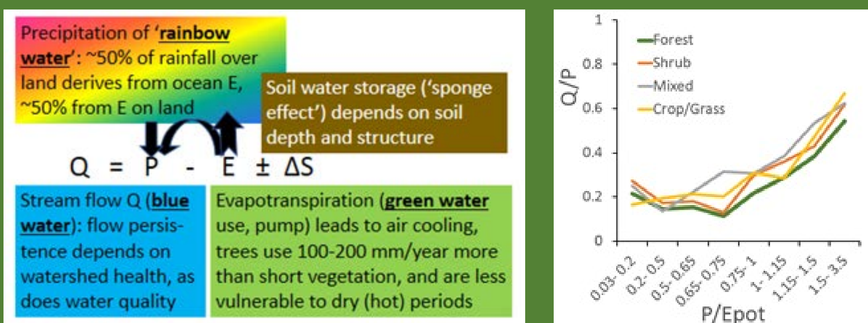


Figure 17.6 A. The 'colours of water' linked to the terms of the water balance; B. Relationship between water yield (Q/P ratio) as function of climate (P/E_{pot}) for four land cover categories in a comprehensive global case study compilation[a]

The plot-level water balance is commonly defined as ΔS = 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.

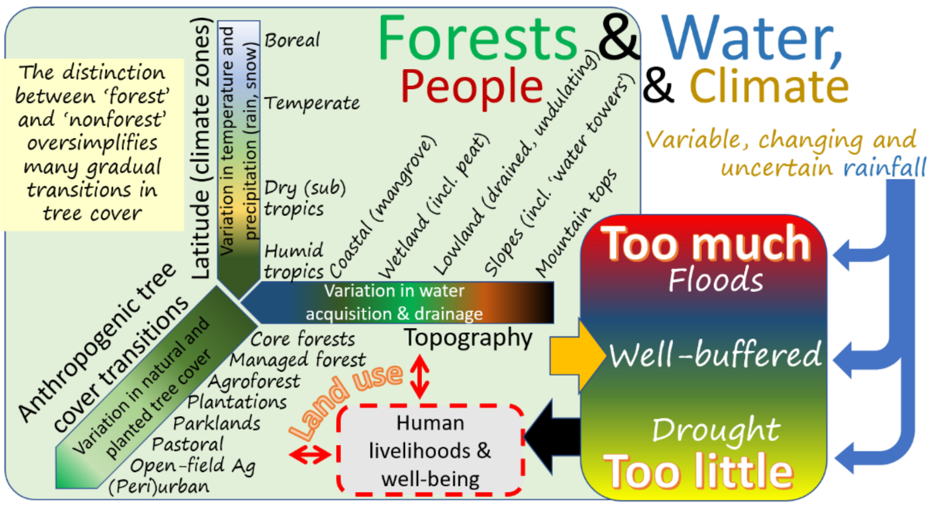


Figure 17.7 Three main axes of variation that influence biophysical tree-water relations: latitude (climate zone), topography and anthropogenic tree cover transitions, combining to the degree to which variable rainfall is buffered from a human perspective avoiding both situations of 'too much' and 'too 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

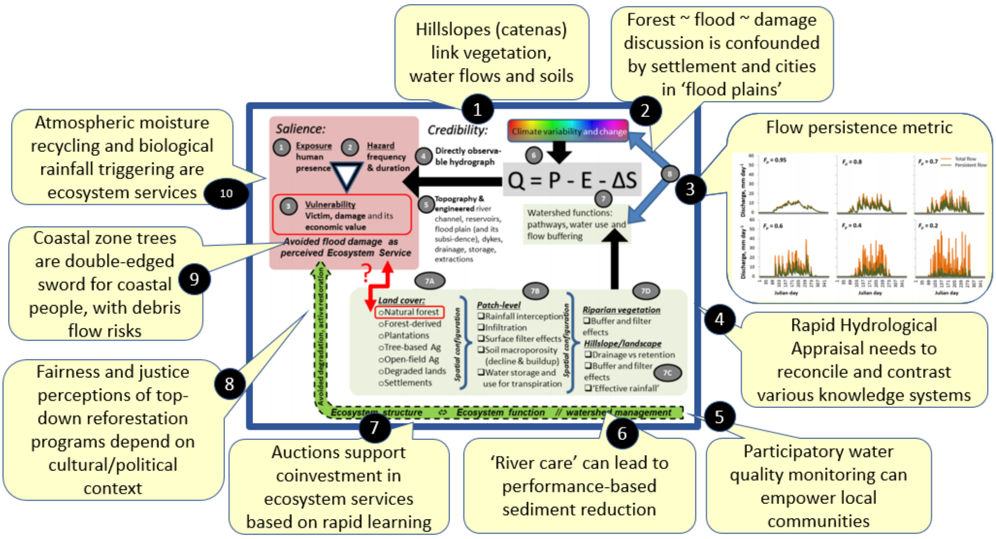


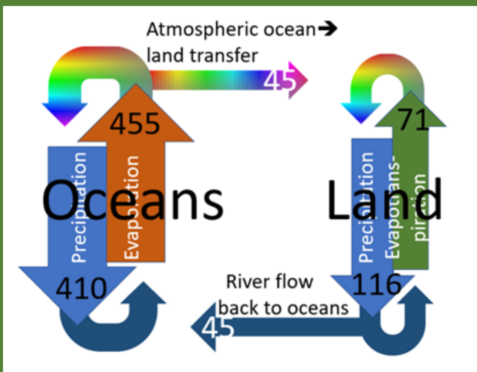
Figure 17.8 Landscape level progress in understanding how agroforestry relates to stream flow

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].

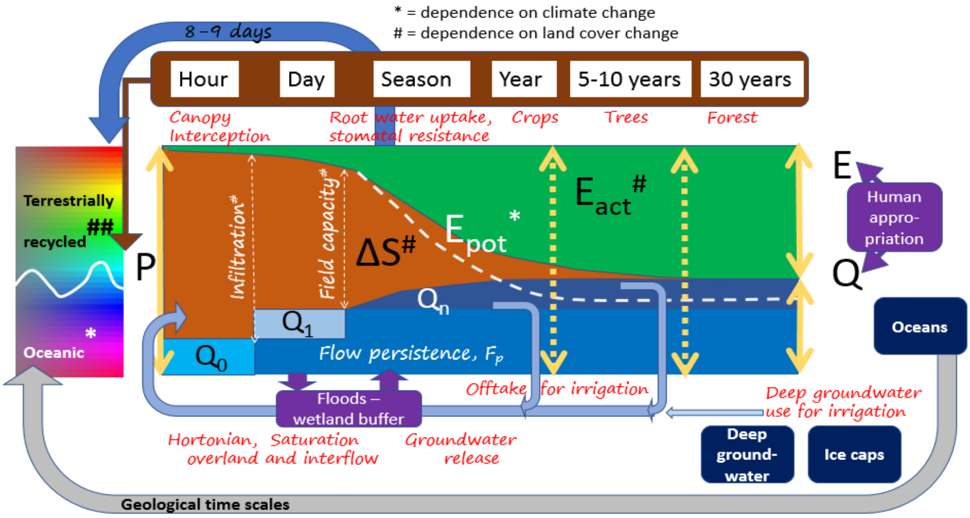


Figure 17.10 Connection between water balance processes across multiple time scales (logarithmically represented)

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].

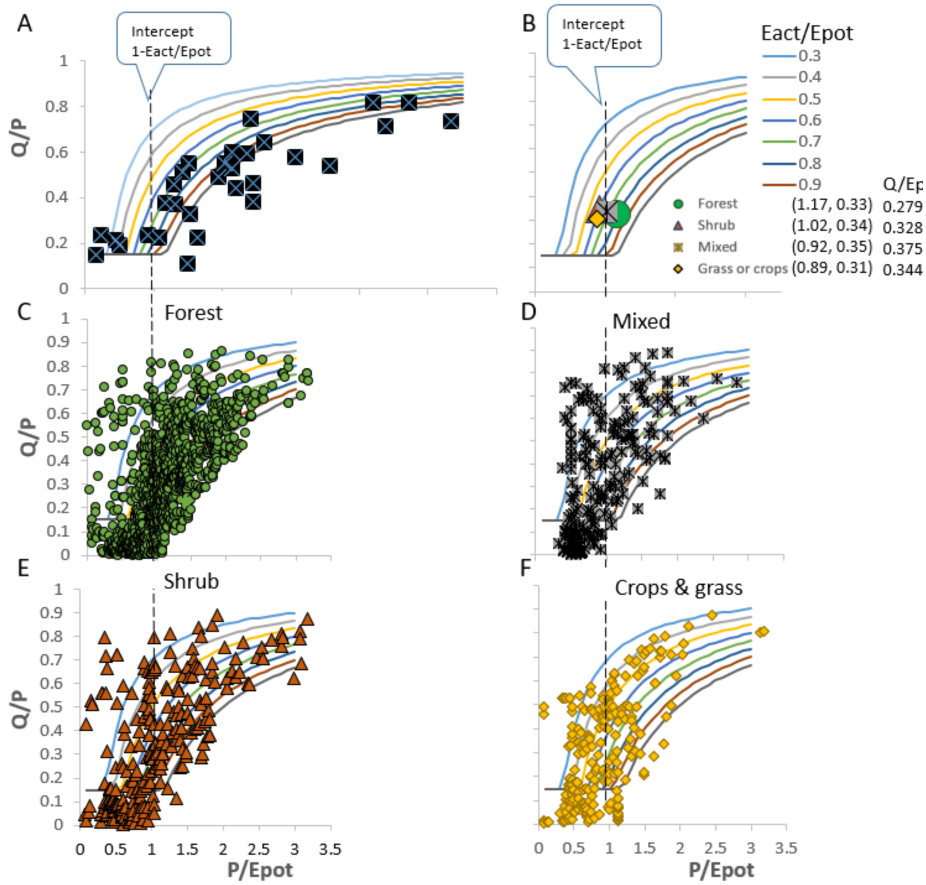


Figure 17.11 Modified Budyko plots (compare Box 17.2) for a large data set of comprehensively monitored subwatersheds characterized by dominant land cover[1]; A. North American long-term ecological research data set[87]; B...F global dataset[88]

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 ^{o}C 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.

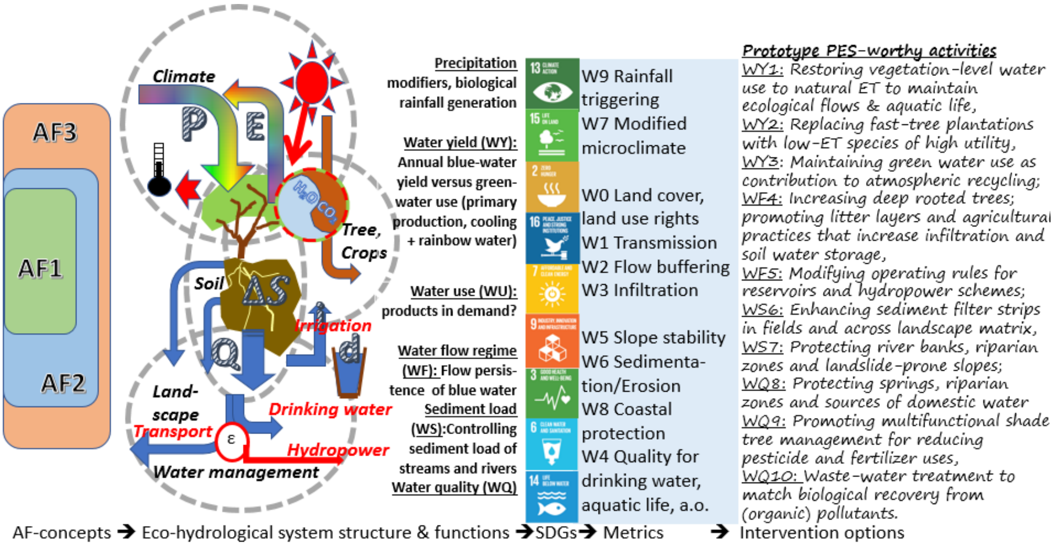


Figure 17.12 Eco-hydrological system structure and functions across subsystems (climate, plant and its stomata, rooted soil, river flow regimes and blue water management), as basis of human risks and food+water+energy+income security, and ten prototypes of interventions that can improve the key performance 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.

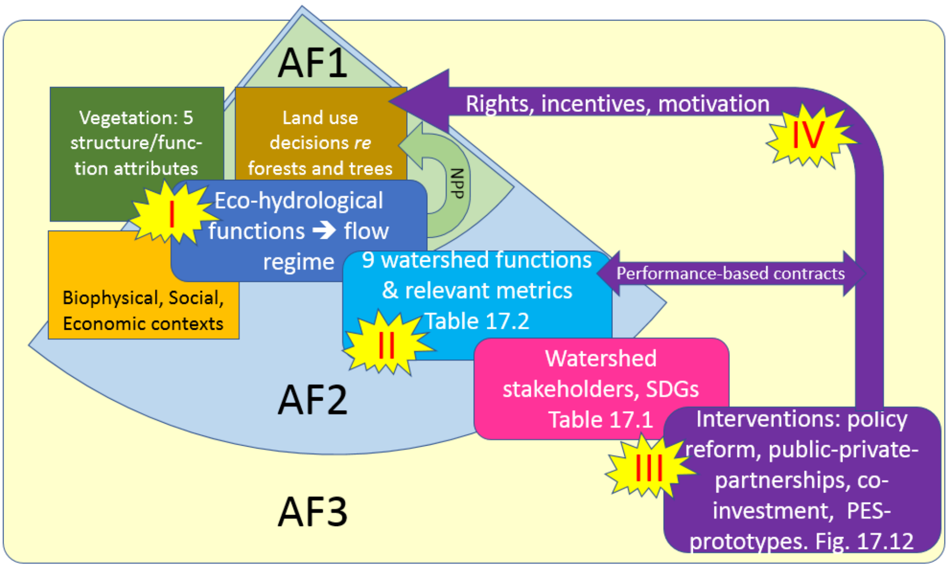


Figure 17.13 Ecosystem-services cascade as used to structure this chapter, with indications of the three AF paradigms and four types of boundary work (I = shared understanding, II = indicators and metrics, III = polycentric governance, IV = co-investment in ES)

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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