

# Chapter 2

## Climate-Forest-Water-People Relations: Seven System Delineations

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## 2.1 Introduction

In this chapter, we review current scientific understanding and hypotheses at seven system delineations that build up from the level of a ‘tree’ interacting with water, to that of a social-ecological system at the scale of landscapes. A system delineation separates internal entities that interact dynamically from external entities that may have a one-way influence but are not significantly influenced by feedback from within the system boundaries. Each system level has its characteristic outcomes or results. The seven (nested) system delineations (Figure 2.1) are:

1. Trees and water: Structure and function of leaves, stem and roots, *which are part of:*
2. Forests, soil and climate: Sponge effects; *part of:*
3. Atmosphere, oceans and terrestrial vegetation: Global water fluxes; *part of:*
4. Precipitation, evapotranspiration and discharge: Water balance and buffering; *part of:*
5. Dynamic landscape mosaics: Streamflow; *part of:*
6. Land and water use rights, local knowledge and forest institutions: Landscapes; *part of:*
7. Social-hydrological systems: Ecosystem services as valued human benefits.

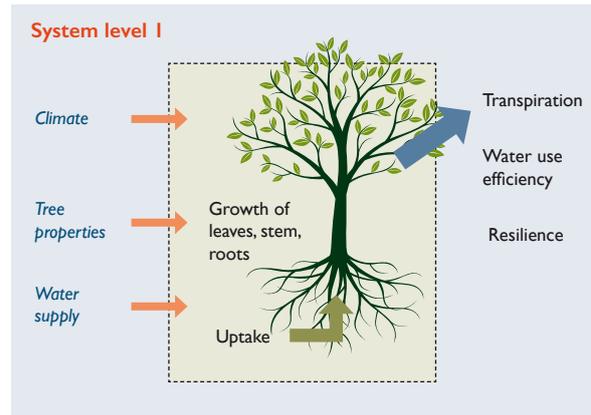
Elsewhere in this report, three additional system concepts are used that build on system delineation 7 (and include it as a subsystem) and explore governance of a society dealing with issues of coherence between the sustainable development goals:

8. Contested and evolving forest-water paradigms in public discourse, legislation and underpinning existing policies (as covered in Chapter 1);

9. Climate change policy in its relation to forest and water interactions (as covered in Chapter 7); and
10. SDG coherence in an interlinked, multiscale and polycentric governance perspective (as covered in Chapter 7).

## 2.2 Forests, Soils and Water

### 2.2.1 Trees and Water: Structure and Function of Leaves, Stems and Roots

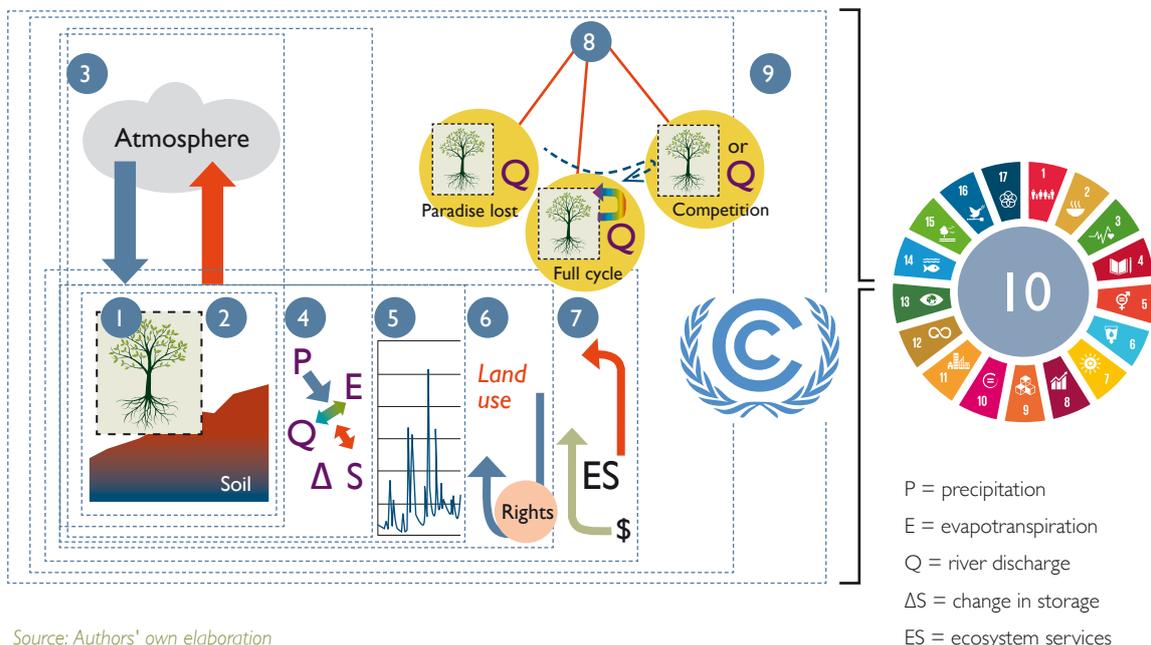


### Whole-plant physiology

Ecophysiology at the whole-plant level as a field of scientific study has a long history and rich toolbox of methods (Reynolds and Thornley, 1982; Kramer and Boyer, 1995; Lambers et al., 2008). Interactions between trees

Nesting of ten systems describing the relation between forest, water and Sustainable Development Goals (SDGs)

Figure 2.1



Source: Authors' own elaboration

and water are shaped by their leaves, stems and roots. The leaves and their stomata lose water in the process of transpiration, cooling leaves while allowing carbon dioxide (CO<sub>2</sub>) to be captured in photosynthesis.

Green leaves are essential for photosynthesis, but without stems, the leaves would stay close to the ground and be shaded by others. Trees, found in over 100 of the 620 plant families (often alongside other life forms), invest in perennial stems as a generic solution for these challenges. The stems transport water in their xylem (plant tissue), where the need to avoid getting clogged by air bubbles ('embolism') in wide vessels under dry conditions (Domec et al., 2006) is balanced against enhanced transport capacity in such vessels under wet conditions. Wood density is negatively related to vessel size, with high growth rates generally associated with low wood density, early successional status, low drought and fire tolerance and short life-spans (Larjavaara and Muller-Landau, 2010).

The roots are the primary organs for water uptake, and their amount and distribution in the soil determine options for water and nutrient uptake and structural stability (with increased demands in trees). Yet, every unit of dry

matter can be used for supporting only one of the three essential organs (i.e. leaves, stems and roots) and the allocation can be considered a strategic as well as an adaptive choice (van Noordwijk et al., 1998b, 2015a). The ability of trees to persist in dry or seasonally dry climates thus depends on a variety of eco-physiological adaptations to water scarcity (Breshears et al., 2009). Root patterns of trees present in natural vegetation differ in predictable ways based on climate and groundwater table depth (Fan et al., 2017).

### Diversity of contexts and ecoregions

Different tree species have different water needs depending on their phenology (timing of green leaf presence, flowering and fruit production) and crown architecture, and have different access to soil water based on their root development, making them adjusted to one or more of the ranges of climates (Box 2.1). Competition for the same water resources is minimised through mixtures of species with canopies that do not overlap, that develop their leaves at different times of the year, or that have different

#### Box 2.1

### Diversity of contexts for forests and trees

As is evident from the Holdridge (1967) climate and vegetation classification, a wide range of forest types occur in many hydro-climatic conditions. Based on the ratio of annual precipitation to potential evapotranspiration we can expect shrub (<0.5), dry forest (0.5-1), moist forest (1-2), wet forest (2-4) or rain forest (>4). This ratio reflects rainfall, ranging from superhumid (> 8000 mm/year) to superarid (< 125 mm/year), and latitudinal zones (tropical, subtropical, warm temperate, cool temperate, boreal, subpolar and polar) interacting with altitudinal belts (lowland to montane and alpine) in determining temperature and potential evapotranspiration. The latitudinal zones also determine the pattern of seasonality (Dewi et al., 2017). A global hydro-climate map shows a wide range of  $P/E_{pot}$  ratios ( $P$  = precipitation;  $E_{pot}$  = potential evapotranspiration, both at annual time scales) (Figure 2.2A). For the 33.6% of the global land area with a  $P/E_{pot}$  ratio < 0.5 there is only sufficient water for episodic rivers; for the 35.3% with a  $P/E_{pot}$  ratio between 0.5 and 1, water supply is limited part of the year, and rivers often are strongly seasonal. For the 31.2% with a  $P/E_{pot}$  ratio > 1 there usually is sufficient water to support permanent rivers.

The main climatically determined forest categories are:

**Hot and wet.** Consistently warm, never freezing. Includes tropical rainforest, tropical peat swamps (Gumbricht et al., 2017), tropical montane cloud forests (Bruijnzeel and Veneklaas, 1998), and lowland moist forests. Source of the world's largest rivers.

**Hot and dry.** Consistently hot leading to water stress and temporary river flow only after occasional storms that exceed the infiltration capacity of the soil.

**Subtropical.** Warm, with wet (monsoon) and dry season and associated seasonal rivers. Growth limited by seasonal moisture availability (D'Odorico et al., 2010; D'Odorico and Porporato, 2006; Newman et al., 2006). In the subtropical dry forest/Guinea savannah/ Sudan savannah/Sahel gradient wet and warm seasons may coincide, while in the Mediterranean zone, winter rains determine a relatively cool growing season (Llorens et al., 2011). In either, forest vegetation may depend on deep water storage (Bastin et al., 2017).

**Moist temperate.** Hot and cold seasons are clearly differentiated and precipitation can be seasonal or evenly distributed throughout the year, supporting deciduous, evergreen, or mixed forests with modest year-round river flow.

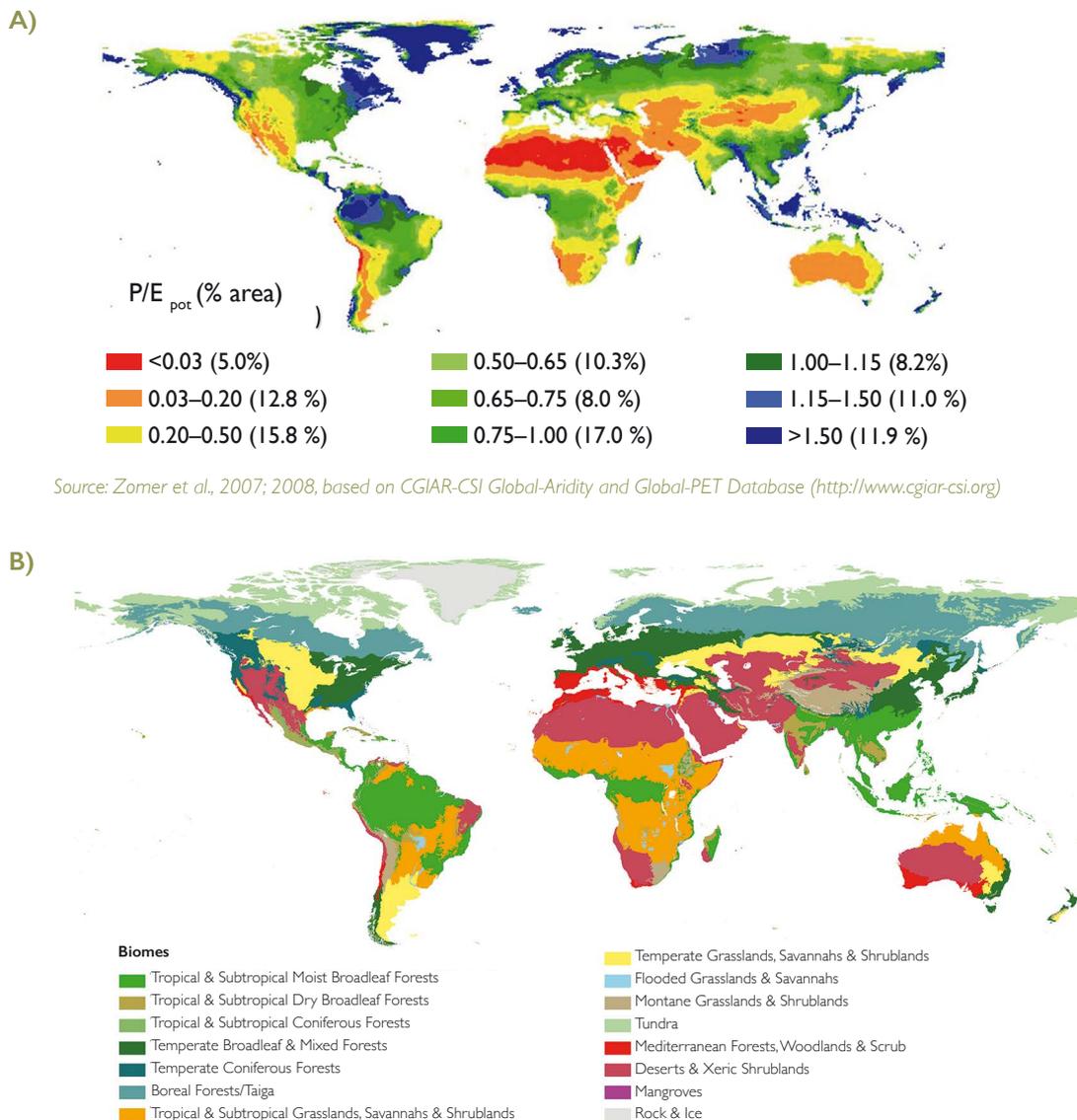
**Cold and wet.** Precipitation is much higher than potential evaporation, generating abundant river flow. Includes mountain climates with snow and ice.

**Cold and dry.** Snow and ice-dominated. Permafrost may limit rooting depth, accelerating runoff. The shallow thaw zone may be subject to drought and prone to wildfire (de Groot et al., 2013).

More differentiated schemes exist. In defining ecoregions, Olson et al. (2001) identified 867 unique terrestrial areas that are relatively large units of land containing a distinct assemblage of natural communities and species with boundaries that approximate the original extent of natural communities prior to major land-use change. These ecoregions are contained within 15 biomes, as reflected in Figure 2.2B. The trees in these various vegetation types differ both above- and below-ground in key properties affecting their hydrological functions.

Global maps of A. Hydroclimate (precipitation (P) relative to annual potential evapotranspiration ( $E_{pot}$ )) and B. Fifteen terrestrial biomes derived from 867 ecoregions

Figure  
2.2



Source: Zomer et al., 2007; 2008, based on CGIAR-CSI Global-Aridity and Global-PET Database (<http://www.cgiar-csi.org>)

Source: Adapted from Olson et al., 2001

rooting depths (González de Andrés et al., 2017). As a result, compared to single-species stands of trees, natural mixed forests can use water more efficiently (González de Andrés et al., 2018) and, on aggregate, respond less strongly to climate variability (Creed et al., 2014; Blanco, 2017; Laskurain et al., 2018; Kotlarz et al., 2018). Such ecological diversity effects can be mimicked in mixed tree-crop (agroforestry) systems in dry zones that can use more water compared to trees or crops alone (Bayala and Wallace, 2015; van Noordwijk et al., 2015a).

Tree rooting depth may also affect phenology, even in wet tropical climates with low seasonal variation, as it allows trees to benefit from dry (sunny) periods (Broedel et al., 2017). Tree phenology effects on hydrologic processes may be more pronounced under

single-species, even-aged forests, where phenology is synchronised, compared to mixed-species, multi-aged forests, with diverse phenology (Wright et al., 2017). Forest stands dominated by evergreen species tend to impact dry season low flows to a greater extent (in terms of proportional reductions in streamflow) than annual streamflow totals (Scott and Smith, 1997). Actively growing conifer forest plantations are associated with up to 50% reductions in summer streamflow relative to old-growth conifer forests (Perry and Jones, 2017). Naranjo et al. (2011) documented for forested watersheds of western North America that trends in the observed water balance can be associated to land cover disturbances well before the start of hydro-climatic observations, a century ago.

### Leaf Area Index (LAI)

The LAI of a forest or collection of trees is the total (one-sided) leaf area per unit two-dimensional ground surface area. If leaves were evenly spread out, an LAI of 1 would represent full coverage of soil and complete light interception. Given the architecture of plants, an LAI of 2-3 is typically needed for capturing 95% of radiation. An LAI of 5-6 is common in closed-canopy forests and allows only a small fraction of incoming radiation to reach the forest floor. Similarly, the leaf area also intercepts a large share of precipitation before it reaches the ground, but most of this drips off the leaves and continues its downward journey. The LAI of a forest or trees is influenced by a range of factors that impact the physical attributes of the canopy (i.e., canopy leaf density):

- inherent characteristics of forest/trees (e.g., species composition, age class distribution, tree size, tree density, canopy architecture, and canopy phenology);
- availability of, and competition for, light, water, and nutrients, which influences the spatial arrangement of the forest/trees (e.g., riparian, upland, forest margin effects); and
- anthropogenic effects and management practices (e.g., genetic modification, landscape alteration, weed control, harvesting, fertilisation, pruning, thinning and irrigation); and any disturbance that alter the area of leaves on trees (e.g., drought, wind, pests and diseases, pollution and temperature extremes).

Because transpiration takes place through stomata present on plant leaves, leaf area and water use are correlated (Gebhardt et al., 2014). In general, the higher the LAI, the greater the transpiration potential of the vegetation. However, increases in LAI are not directly correlated with rates of transpiration, but are moderated by water and energy availability, vapour pressure deficit (moisture demand of the air), and resultant variation in stomatal conductance (water and CO<sub>2</sub> fluxes) within the canopy. The LAI of a forest, such as a monoculture plantation, or mixed species/mixed age forest, consequently has significant effects on forest hydrology. As LAI, and the resultant transpiration potential, increase (usually with increasing tree age) so does the potential for extraction of water from the soil profile, through the trees' stems and leaves, into the atmosphere. Resultant changes in soil water at different depths in the soil profile subsequently affect infiltration, groundwater recharge and ultimately, streamflow. LAI also affects other hydrologic processes such as throughfall, stemflow, evaporation of leaf-intercepted rainfall and air turbulence (Hall, 2003).

Seasonal variation influences forest hydrology through the timing of leafing and associated interception and transpiration. Forest phenology includes leaf flush, senescence, flowering and fruiting, and can be understood as balancing the photosynthetic opportunities of a low cloud cover, high-radiation season, with water availability in the wet season. It is modulated by the presence of pollinators, seed dispersers and predators, pests and diseases. In deciduous forests, phenology strongly influences seasonal patterns of evapotranspiration,

groundwater recharge and streamflow, but phenology of evergreen trees also produces noticeable seasonal variations in streamflow and streamflow response to forest change (Jones and Post, 2004).

### Rooting depth

Forests and trees obtain most of their water through their roots, extracting it from soil pores. Root length density (length per unit volume of soil) determines the degree to which roots have access to all soil water; it varies with species, age, stand density, and soil characteristics. Woody vegetation usually has deeper roots than grasses, allowing it to take up water from deeper groundwater as well as soil moisture in the unsaturated zone (Moore and Heilman, 2011). While short-lived annual species in desert biomes have shallow roots, perennial species (including trees) in seasonally dry regions generally have deeper root systems than in those in permanently wet regions. Also, root systems in coarse-textured soils with rapid infiltration and limited water storage are generally deeper than those in fine-textured soils (Collins and Bras, 2007). These differences can be found as adaptive responses within any plant species ('functional equilibrium' theory; van Noordwijk et al., 2015a), but also between species most commonly found in these various environments. Rooting depth is not static and may change dynamically through the year. Water below the deepest roots can still be accessible to plants through capillary transport.



Shallow root system in moist but nutrient poor tropical peatland forests in Kalimantan, Indonesia

Photo © Daniel Murdiyarso

Plant roots move water from wetter to drier layers. Such equilibration usually consists of hydraulic lift, the process of bringing water to the soil surface from deeper rooted layers, or downward siphoning, the process of bringing fresh precipitation to deeper layers (Bayala et al., 2008; D'Odorico et al., 2010). Hydraulic

equilibration by forests and trees is most effective at night when stomata are closed and transpiration has stopped (Bayala et al., 2008; Prieto et al., 2012). In this way, water can rehydrate drier zones connected by a single root system (Manoli et al., 2014), but can also leak out of roots in dry soils and be captured by roots of other species, as has been demonstrated with isotopic tracer experiments (Caldwell et al., 1998). Estimates of the extent of hydraulic redistribution of water by trees vary by nearly two orders of magnitude and depend on the combination of root architecture, soil physical properties, and gradients in water potential in the rooted part of the soil profile (Neumann et al., 2012). In temperate and semi-arid environments, hydraulic redistribution can contribute 17-81% of water transpired (Sardans et al., 2014) and may account for up to 30% of transpired water on dry late summer days in seasonally dry and wet forests. It may also enhance seedling survival and maintain overstory transpiration during summer droughts (Brooks et al., 2002; Domec et al., 2010). Hydraulic redistribution has been documented in Amazonian rainforests (Oliveira et al., 2005), neotropical savannahs (Scholz et al., 2002), semi-arid shrublands (Ryel et al., 2002), desert shrubs (Hultine et al., 2004), seasonally dry conifer forests (Domec et al., 2004), semi-arid savannahs (Barron-Gafford et al., 2017) and Sahelian agroecosystems (Bayala et al., 2008; Kizito et al., 2012).

Variation in root length density and rooting depth between tree species has direct relevance for soil moisture dynamics (Wilcox et al., 2011). As different species have different capabilities to explore soil layers, water out of reach for some species could still be available for others (Hardanto et al., 2017). Through different root system architecture, different tree species sharing the same stand can avoid competition and complement each other, using water from different soil layers or at different times of the year (Xu et al., 2011; Forrester and Bauhus, 2016; González de Andrés et al., 2018).

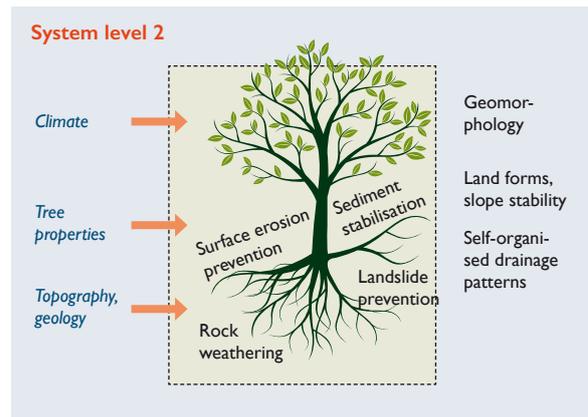
Water excess may be a problem for trees in some settings. Trees in mangroves and peat swamps have adapted roots to enable them to maintain adequate supplies of oxygen and remove gases such as ethylene and methane. Stilt roots, pneumatophores and aerenchym are common adaptations in mangrove (Pi et al., 2009) and peat swamp forests (Farmer et al., 2011; Pangala et al., 2013).

### 2.2.2 Forests, Soils and Climate: Sponge Effects

#### Forests and soils: a two-way relationship

Forests depend on soil, but also play a major role in soil formation by bedrock weathering, maintaining soil on-site (reducing landslides and erosion), and capturing it in sedimentation sites. Globally there is major variation in the depth and nature of soils, even when the forests look similar, causing variation in hydrologic responses.

The depth of a soil profile, together with its texture and soil organic matter content, determine the ‘sponge’



effect (and its spatial variation) of buffering water availability within the reach of root systems. Forests influence soil formation and soil retention in the landscape (Brantley et al., 2017). Soils, in turn, impact forest hydrology through retention of water, infiltration, percolation, soil moisture storage, release, erosion, sediment deposition, landslides, and as a medium for roots. Deforestation effects on streamflow depend on soil type, soil depth and terrain features that are often ignored when seeking generic patterns. Spatial information on subsurface hydrology, added to remote sensing that has so far focussed on land cover, is currently filling a major research gap (McDonnell et al., 2018).

#### Soil water storage capacity

Part of the literature and much of the modelling done to date rely on a ‘rooting depth’ concept that assumes all water above a certain depth is available and all water below is unavailable to vegetation. This simplified approach assumes that water below rooting depth will either exit the ecosystem as subsurface flow or recharge the groundwater stocks. Using this approach, it is possible to estimate the water storage capacity of the root zone (Wang-Erlandsson et al., 2016). In a recent drought in California, specific forests where trees were found to have access to deep weathered bedrock were found to remain green (Rempe and Dietrich, 2018). Using data from 300 diverse catchments in Thailand and the USA, Gao et al. (2014) estimated the effective soil moisture storage to vary from around 50 to 500 mm, representing 25 to 250 days in which evapotranspiration rates of 2 mm/day can be sustained in the absence of precipitation or lateral inflows. Root-zone water storage capacity was reduced by logging in catchments with long-term monitoring data, and took a decade or more after forest regrowth to recover (Nijzink et al., 2016).

#### Macroporosity and water infiltration

The soil’s infiltration capacity below the surface is influenced by soil porosity. Porosity defines the spaces between soil particles and aggregates, and thus the two primary biotic influences, are soil aggregation (related to organic matter and fungal hyphae) and the balance between disappearance and generation of macropores by roots and

soil macrofauna ('engineers') (Bünemann et al., 2018). In some regions, with porous soils and relatively low precipitation or snowmelt rates, almost all water infiltrates. In these regions, overland flow is generally not a consideration, except where water has accumulated in the soil (e.g., at the base of hillslopes with shallow soils). In these places, soil saturation means that there is no room for more water to infiltrate, so all incoming water remains at the surface, creating saturation excess overland flow (potentially leading to flooding). In other regions, a combination of low infiltration capacity and/or high rates of precipitation can lead to infiltration excess overland flow which will contribute to flooding, with the risk of erosion. Overland flow at the soil surface – whether created by infiltration excess or saturation excess – does not contribute to subsurface water storage, which can sustain both streamflows and plant growth during drier periods. It can, elsewhere, lead to excess soil moisture, waterlogging and vegetation dieback.

Soil moisture storage depends on the pore size distribution of the soil. Very large pores (macropores) associated with roots, animal burrows, arthropods and earthworms are specifically sensitive to soil compaction but where present enable rapid infiltration and limit overland flow (Beven and Germann, 2013; Vereecken et al., 2016; Barrios et al., 2018); intermediate size pores (mesopores) associated with sand- to silt-size particles contribute to soil water holding capacity against gravitational drainage, and tiny pores (micropores) within organo-mineral aggregates or clay particles hold water very tightly. Dominance of vertical (infiltration) or horizontal (interflow) processes can depend on pore distribution, but also on precipitation and season (Grayson et al., 1997). Tightly bound micropore water can be differentiated from mobile water that tends to enter the stream via 'interflow' and is taken up most readily after a rainfall event (Brooks et al., 2010; Berry et al., 2017; Evaristo and McDonnell, 2017).

Coarse-textured (sandy) soils have low water storage capacity, but often high infiltration capacity, except where they develop water repellency and induce overland flows (Doerr et al., 2002). Fine-textured (clay and silt) soils have high storage capacity, but low infiltration capacity, except where cracks and biogenic macropores develop. A soil with a wide range of pore sizes has both high infiltration and high water storage capacity. In many landscapes the most agriculturally suitable soils have been converted and forests are left on the less favourable sites.

Loss of forest cover and forest disturbance generally reduce the capacity of soils to absorb and retain moisture. In the short term, forest harvest or forest removal can lead to macropore enlargement as roots decompose, facilitating infiltration (van Noordwijk et al., 1991; Noguchi et al., 1999), but subsequent collapse of macropores without new ones being generated reduces infiltration rates and increases overland flow. High runoff from bare patches combined with high interception and infiltration by shrubs or trees effectively partitions scarce soil moisture among plants in patchy dryland vegetation (Crockford and Richardson, 2000; Llorens et al., 2011; Li, 2011; Maestre et al., 2016), creating 'resource islands' (Roberts and Jones, 2000). Positive tree influences on soil macroporosity and

infiltration can last years or decades after the tree has died (Ilstedt et al., 2007; 2016).

### Litter layer and overland flow

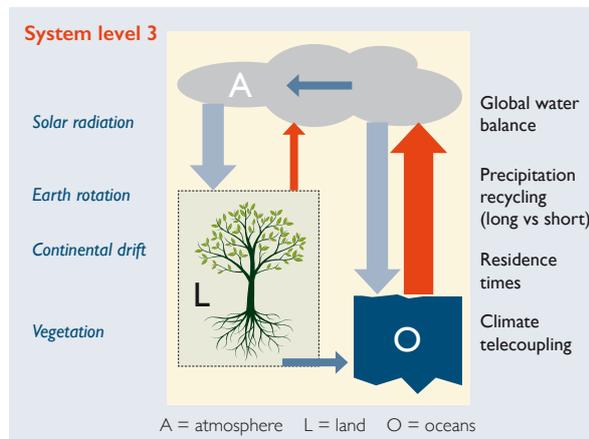
Once precipitation water passes through the tree canopy it encounters a critical interface at the litter/soil layers. Here, partitioning occurs between that water which infiltrates further downward into the soil, and that which does not. The ratio between the rate at which water reaches the soil surface (throughfall or snowmelt) and the rate at which the soil allows water to infiltrate determines this partitioning. Litter is composed of decaying leaves and needles, but also fungi (including mycorrhizal hyphae), soil arthropods, and earthworms, whose activities produce organo-mineral aggregates. Roots, animal burrows, arthropods, and earthworms create macropores, which in turn promote rapid water infiltration and limit overland flow (Barrios et al., 2018). In the short term, the presence of a litter layer is a store of water, and it also protects soil surfaces from the erosive capacity of direct rain droplet impacts (Hairiah et al., 2006). Where litter layers are dependent on trees, reduction of soil evaporation will partially offset increased transpiration (Wallace et al., 1999). In the longer term, the contribution of litter to soil organic matter will influence both infiltration capacity and porosity. Litter removal and grazing reduce infiltration rates and increase overland flow (Ghimire et al., 2014a). Forest and tree presence is a pre-requisite for the existence of litter, but the tree characteristics (e.g., species composition, age class distribution, tree density and deciduousness) as well as management activities (e.g., timber harvesting and under-canopy burning) also influence the properties of the litter layer in relation to how much accumulates, hydrophobicity and carbon pools (Paul et al., 2002; Bargaés Tobella et al., 2014).

Soil litter layers and associated surface infiltration rates can be restored quicker than the organo-mineral aggregates, root channels and soil biota of the upper soil layers that are needed in larger rainfall events. Recovery of interflow will depend on soil macroporosity rather than surface characteristics and will take longer (Bruijnzeel, 2004; Ghimire et al., 2014b). The time frame (e.g., years, decades) at which forestation (used here to refer to an increase in tree cover, regardless of previous landuse, methods or species used) can restore soil infiltration capacity remains an active research frontier (Ghimire et al., 2014b), with a range of site-specific results (Marín-Castro et al., 2017; Qazi et al., 2017; Zwartendijk et al., 2017).

### Groundwater

Near-surface water – also called water table – is dynamic and is affected by biotic (e.g., vegetation type, leaf area, rooting pattern) and abiotic factors (e.g., precipitation timing, intensity, and amount; air and soil temperature). It can be an important contributor to the water supply at all temporal and spatial scales (Issar and Simmers, 1990; Lerner et al., 1990). Aquifer water, beyond the reach of current vegetation, on the other hand is typically considered to be reflecting a much longer history ('fossil');

decades to millennia) of recharge, having a composition that is often isotopically different to near-surface water. Near-surface water can be indirectly affected by aquifer water if there is hydrological contact between the two. If aquifer water is used for human activities, the water enters the dynamic hydrologic cycle while the aquifer from which the water originates may be permanently reduced or depleted (Custodio, 2002; Konikow, 2013). Lateral groundwater flow, which is generally simplified or excluded in Earth system models, is important in many landscapes and may provide a missing link for reconciling observations on stable isotope patterns and global models of terrestrial water fluxes (Maxwell and Condon, 2016).



### 2.2.3 Atmosphere, Oceans and Terrestrial Vegetation: Global Water Fluxes

#### Global water cycle

The hydrologic cycle has been described as such for hundreds of years (Box 2.2), but most of hydrology has been based on the perspective that incoming precipitation is seen as an external variable rather than a variable that both influences and is influenced by vegetation.

Two and a half percent of the world's water is freshwater, with the largest proportion of freshwater existing in glaciers and permanent snow (Shiklomanov, 1999). Water available in streams, rivers, lakes, (surface and sub-surface beyond reach of root systems) and reservoirs is considered blue water and has been the historical starting point of hydrology. However, on average, only about 35% of precipitation becomes blue water, with the other 65% used on-site by vegetation as green water (Falkenmark and Rockström, 2004; 2006). Blue water can be used for irrigation, drinking water or industry, while green water is used by plants for production of biomass (Sood et al., 2014). Recently the term 'rainbow water' has been suggested as atmospheric moisture, which is the source of all blue and green water, and the direct destination of all evapotranspiration (van Noordwijk et al., 2014a).

Partitioning of precipitation over streamflow ('blue water' – integrating overland, interflow and groundwater-based pathways) versus evapotranspiration by vegetation

#### Box 2.2

### Water cycle, forest-climate relationships and desiccation theory

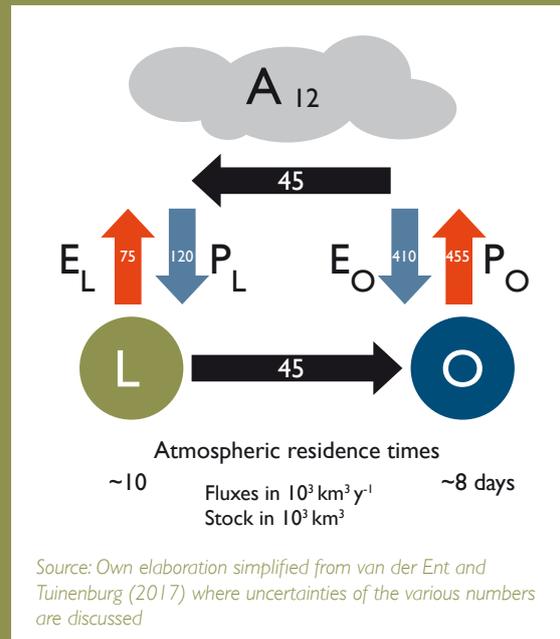
Around the time William Harvey clarified blood circulation in the human body (1628), the study of plants found water to move mostly from the roots in the soil to the leaves where it evaporated. It was clear that water in the soil derived from rainfall, but where did the rain originate? The physics of evaporation and condensation made clear that water vapour, although invisible, was the 'missing link' in the hydrologic cycle, but how far and how long did it travel as water vapour before returning as rainfall? The idea of a hydrologic cycle composed of a 'short cycle' (over land) and a 'long cycle' (involving oceans) was born (Perrault, 1674; Nace, 1975). Around 1693, the astronomer Edmond Halley asserted that evaporation from the oceans was sufficient to explain all rainfall, strengthening the case for the 'long cycle'. Stephen Hales ('Vegetable Staticks' 1727) quantified transpiration, leaf areas and root lengths, and consolidated the understanding of plants as part of the hydrologic cycle. Around the same time, John Woodward started to link vegetation and climate through the hydrologic cycle. This became the basis of the 'desiccation' theory (Grove, 1996). In the 18<sup>th</sup> century, the effects of deforestation on small islands (St Helens, Mauritius, Tobago) used as stop-overs in the Asian-Europe trade became clear: rainfall was affected. A speech by Pierre Poivre in 1763 in Lyon may well have been the start of widespread climatic concerns over human impact on (tropical) forests. While widespread forest clearance by European settlers in temperate North America was seen by them as climate improvement, replacing damp air by healthier drier air, similar effects in the tropics were seen as negative and forest protection policies started in Mauritius found their way in the French and English colonial expansion in the tropics (Grove, 1994). The desiccation theory became part of the discourse in Africa, undergoing drastic changes after its incorporation in the colonial world, as documented by Endfield and Nash (2002). A specific form of the desiccation theory became the basis of explanations for the historical decline of land productivity in the Middle East, cradle of cereal-based agriculture (Kubat, 2011).

('green water'), and the subsequent use of blue water downstream were the primary concern for science as well as practitioners. While it is hard to imagine how a national economy would be managed if it considered only monetary flow rather than a monetary cycle, the full hydrologic perspective has been slow to emerge in quantitative studies. The last two decades have seen major progress, however, facilitated by global data sets that reconcile measured atmospheric moisture flows, precipitation and evapotranspiration, supported by models to fill gaps (Trenberth et al., 2011). These datasets themselves are subject to improvement and refinement (van der Ent and Tuinenburg, 2017), but allow direct comparisons of atmospheric moisture concentrations, air movement (wind), precipitation and evapotranspiration, over oceans as well as land.

**Global water balance**

Based on global data averaged over at least ten years, Figure 2.3 suggests a net ocean-to-land transfer of around 45,000 km<sup>3</sup>/year balanced by a similar return flow of rivers and groundwater into oceans. As the annual precipitation over land is around 120,000 km<sup>3</sup>/year, the net contribution of terrestrial evapotranspiration to terrestrial precipitation is, on average  $(120 - 45)/120 = 75/120 = 63\%$ . If one would be able to 'tag' the water molecules from the two sources (land and ocean) of evapotranspiration (which isotope analysis allows only to a very approximate degree) one may find that the fraction of precipitation most recently derived from land rather than oceans varies between 13% (if atmosphere is fully mixed) and 63% (if there would be no land to ocean transfer of atmospheric moisture). The relevant point is that an average water molecule crossing the ocean-to-land boundary in the atmosphere may fall 2.7 (120/45) times as precipitation over land, once as original ('long cycle') rainfall plus 1.7 (2.7-1) times as terrestrially recycled ('short cycle') rain, before flowing back to the ocean in a river. There is no compelling reason why this is not either more (which would imply more rainfall) or less (less rainfall), even if the conditions of the oceans do not change. This is the core of the 'hydrologic space' argument posed by Ellison et al. (2012).

A first estimate of the global mean residence time is obtained by dividing the time-averaged stock of precipitable water (i.e. 12,000 km<sup>3</sup>) by the mean daily average precipitation (530,000/365 km<sup>3</sup>/day), yielding 8.2 days. Spatial variation around this average has been mapped (van der Ent and Tuinenburg, 2017), with a more accurate global mean of 8.9 days as current estimate. There is how-



Summary of current understanding of global water cycle involving atmosphere (A), land (L), oceans (O), precipitation (P) and evapotranspiration (E) as key exchange processes

ever some uncertainty in this conceptual model and its numerical results, linked to assumptions about the degree of layering of atmospheric transport.

**Short and long cycle rain**

The short cycle only involves terrestrial systems and the atmosphere (Figure 2.3). In contrast, the long cycle includes atmospheric moisture that is derived from both terrestrial and ocean sources. Current understanding of the global cycling of water between atmosphere, oceans, and land areas is based on a combination of data on evapotranspiration, precipitation, air movement, and the presence of 'precipitable water' (Bosilovich et al., 2002; 2011; Trenberth et al., 2003; Dirmeyer et al., 2009; Gimeno et al., 2012). Uncertainty around the long-term average values for the global balance is within a few percent of the estimates provided, as a number of different models used in combination with empirical data provide similar results (van der Ent and Tuinenburg, 2017).

The higher the rate of evapotranspiration, the more a land area contributes atmospheric moisture to the short cycle. Land covers that excel in this function include open water, wetlands, irrigation agriculture, and forests (Ong et al., 2015). On average, forests on sufficiently deep soils can be expected to match the potential evapotranspiration of a site to the degree that precipitation allows, with little loss to rivers until this potential is reached. In other vegetation, part of rainfall comes in amounts that cannot be immediately absorbed by the soil and flow into the

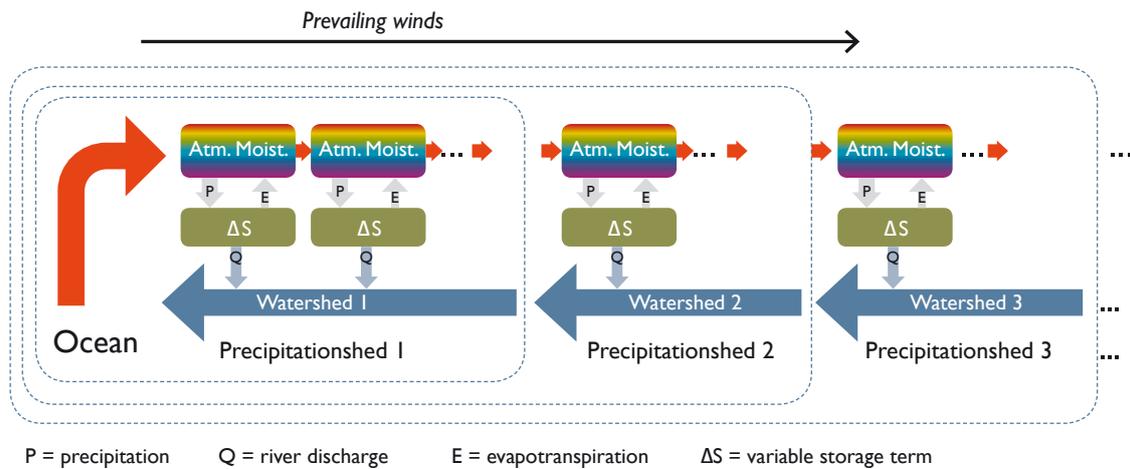
river, while vegetation may not be present throughout the year and shallower roots cannot fully use the soil reserve (Black et al., 2015; Bayala and Wallace, 2015). On average, the difference between forests versus other vegetation was estimated by Zhang et al. (2001) to be around 200 mm/yr. Spracklen et al. (2012) showed that rainfall is statistically associated with passage of air masses over forest in the days preceding a rainfall event, with the specific mechanisms still subject to debate (Spracklen and Garcia-Carreras, 2015).

**Precipitationsheds**

Watersheds are the land areas that contribute water to a given river, considering precipitation as the start of a flow (rather than cycle). Starting one step earlier in the cycle, precipitationsheds are the upwind surfaces of the Earth (whether oceans or land areas) that provide evaporation that later falls as precipitation in a given location (for example, a watershed). The source of atmospheric moisture responsible for, say 95%, of precipitation in a specified location (a point, a catchment, a nation or a region) provides an operational definition of these precipitationsheds (Keys et al., 2012), with recent specifications provided for countries and regions (Keys et al., 2017; Wang-Erlandsson, 2017). The precipitationshed of a watershed is considerably

Conceptual model of the water balance along a series of spatial units following the prevailing winds from an ocean-land interface

Figure 2.4



Source: Authors' own elaboration based on Keys et al., 2012

larger than that watershed itself, and typically contains some part of the global oceans plus parts of one or more terrestrial watersheds (Figure 2.4). For example, watershed 3 in Figure 2.4 can contribute water to watershed 2, but its precipitationshed can include the ocean plus watersheds 1, 2 and 3. Thus, shifting the question from “what happens to the precipitation that a watershed receives?” to “where does this precipitation originate?”, and hence “what factors might influence variability and trends?”, implies a much stronger regional and global dependence and influence of forest-water relations.

The size of precipitationsheds depends on wind speeds and residence times of atmospheric moisture. As shown by van der Ent et al. (2010), depending on the location relative to global circulation patterns and the shape and size of continents, terrestrially evapotranspired water has a probability of returning as rainfall over land that varies between 0 and 100%. For any given location the uncertainty in this estimate is relatively small (van der Ent, 2010). Similarly, the percentage of rainfall in any location derived from terrestrial rather than oceanic sources varies from 0 to 100% with location, but uncertainty of the location-specific estimate is small.

Prevailing winds together with atmospheric residence time determine moisture recycling (van der Ent, 2014; van Noordwijk et al., 2014a; Ellison et al., 2017). The net transport distances of atmospheric moisture during a mean residence time of around eight days vary from less than 100 to several thousand kilometres. Strong short cycle precipitation in the Amazon and Congo basins and on the large island of Borneo is associated with low wind speeds<sup>1</sup>.

The telecoupling (or spatial dependency of processes) that is quantified in a precipitationshed has geopolitical

implications that only recently have been explored from a policy perspective (van der Ent et al., 2010; van Noordwijk et al., 2014a, 2016; Ellison et al., 2017; Keys et al., 2017). These are discussed further in Chapter 7.

### Vegetation effects on precipitation

Satellite observations and atmospheric trajectory modelling increasingly permit research to disentangle the origin and immediate drivers of growing-season precipitation, and the extent to which ecoregions themselves contribute to their own supply of rainfall (van der Ent et al., 2010). While the amount of water recycled varies between wet and dry years, the recycling ratio increases in dry years (e.g., Miralles et al., 2016). For example, as much as 25% of basin-evapotranspired moisture may be recycled within the Congo basin (Dyer et al., 2017), with further rainfall occurring elsewhere. Recent analysis of rainfall records for Borneo (McAlpine et al., 2014) showed that watersheds with >15% forest loss had a >15% reduction in rainfall, as maritime influences are limited and measured wind speeds low. Weng et al. (2018) identified parts of the Peruvian Amazon and western Bolivia as the atmospheric moisture sink areas most sensitive to land use change in the Amazon. Water tagging studies indicate that continental recycling of water explains more intraseasonal variations in moisture in inland areas than in coastal areas (Risi et al., 2013). In the Amazon, rainforest transpiration enables an increase of shallow convection that moistens and destabilises the atmosphere during the initial stages of the dry-to-wet season transition, which drives moisture convergence and wet season onset 2-3 months before the arrival

<sup>1</sup> This can be verified for any part of the world at any day on a website such as [www.windy.com](http://www.windy.com) for wind speeds at a standard height of 80m above the land surface.

of the Intertropical Convergence Zone (ITCZ) (Wright et al., 2017).

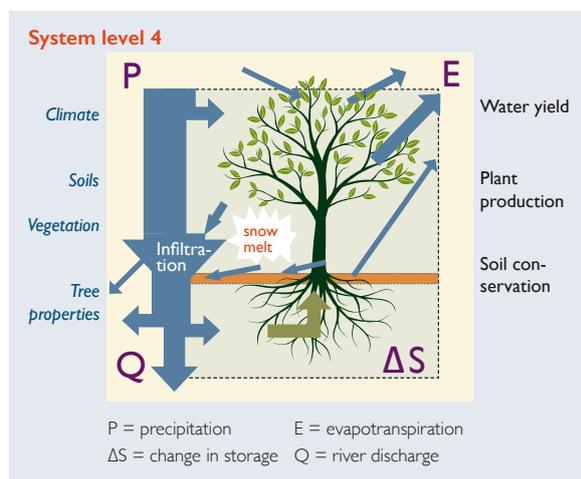
Variation in precipitation and the frequency of extreme events is likely to be as important as the annual mean precipitation. Degu et al. (2011) described cases where the construction of manmade reservoirs induced local extreme rainfall with negative effects. Such extreme events may be related to a relative scarcity of rainfall triggering agents – as the presence of these would induce more frequent and moderate precipitation rather than cloudbursts. This, however, represents the frontier of current science, as it requires atmospheric physics, chemistry, biology, and particle transport to be reconciled with global circulation models.

### Human modification of the global water cycle

Humans modify the hydrologic cycle through the withdrawal of blue water for agricultural (92%), domestic (4%), and industrial (4%) uses from lakes and rivers (Hoekstra and Mekonnen, 2012). Partly to support these abstractions, humans affect the flow of water in the landscape through the construction of reservoirs for hydro-power, flood control and irrigation. In addition, humans modify the hydrologic cycle through land use/land cover change. Human use of river flow in many cases (most directly in case of water abstractions for agriculture) leads to further evapotranspiration, making the blue versus green water partitioning (Falkenmark and Rockström, 2006) highly scale dependent.

Many human activities based on water use do not lead to evaporation but to impaired water quality, as described in the grey water footprint (Hoekstra and Mekonnen, 2012). This involves both point sources of pollution (e.g., industry or residential wastewaters) and diffuse sources of pollution (e.g., agricultural chemical and erosion loads to water). New insights on human influence on precipitation through land cover change, have yet to be incorporated in such footprint estimates.

### 2.2.4 Precipitation, Evapotranspiration and Discharge: Water Balance and Buffering



### Water balance equation

Box  
2.4

The water balance equation is:

$$Q = P - E - \Delta S$$

where  $Q$  = streamflow,  $P$  = precipitation (including rain, snow, cloud water interception),  $E$  = evapotranspiration, and  $\Delta S$  = change in water storage.  $P$ ,  $E$  and  $Q$  are expressed as depth (mm) per unit of time (day or year).  $\Delta S$  can, depending on context, be split into  $\Delta SS$  (change in soil water),  $\Delta SN$  (change in snow and ice water storage, where snowfall is part of  $P$ ), and  $\Delta GWS$  (change in groundwater stores). The change in water storage in plants ( $\Delta SP$ ) may be non-negligible (Dietrich et al., 2018).

### Paired watershed experimental studies as gold standard of forest hydrology

Box  
2.5

Paired watershed experimental studies became key to the development of forest hydrology as a science, a century ago. Typically, data collection on at least two similarly-sized watersheds starts a few years before a major intervention is applied to one of the watersheds (i.e., the calibration period) with the other serving as a control. The response is monitored for as long as it takes until the difference in hydrologic response between the sub-catchments has disappeared. Data from paired watershed experiments have been mostly obtained in temperate moist climate zones (e.g., Hibbert, 1967; Bosch and Hewlett, 1982; Andreassian, 2004; Jackson et al., 2005). Where sets of paired watershed experiments have been compared over time with various treatment intensities, short-, medium- and longer-term effects of forest change on water yield have been attributed to changes in the  $E$  and  $\Delta S$  terms of the water balance equation (Scott et al., 2000; Webb et al., 2012). Critiques of existing paired watershed studies often refer to the absence of 'mosaic' effects, where treatments are applied uniformly while in the real world many intermediate degrees of tree cover or mosaics are expected. The results from paired watershed experiments cannot be directly applied in large watersheds (> 1,000 km<sup>2</sup>), as several scale-dependent processes need to be factored in.

### Linking ecosystem structure and function

At the scale of a patch of land, the hydrologic cycle is reflected by three long-distance, one-way fluxes (precipitation, evapotranspiration and contributions to streamflow) and local two-way exchanges with water stored in soils, plants and/or snowpack. Four key ecosystem structure attributes (leaf area index, rooting depth, litter layer and soil macroporosity) determine vegetation effects on flow pathways, buffering and flow regime via the basic water balance equation (Box 2.4).

### Scale and scaling

Paired-watershed experiments (Box 2.5), which test the effect of forest conditions on hydrology, are typically conducted in small watersheds, usually less than 100 km<sup>2</sup>.

Recent advances in ecohydrology include scaling water fluxes from the leaf to the watershed and landscape, the effects of plant-soil interactions on soil moisture, and the influence of plant water use on streamflow regimes (Asbjørnsen et al., 2011). Conceptually, studies of forests and water connect spatial scales from the leaf to the globe, and temporal scales from hours to multiple decades. Spatial scales of interest range from hillslopes and forest stands (0.001-0.1 km<sup>2</sup>), to forest management units and small watersheds (0.1 to 10 km<sup>2</sup>), meso watersheds (10 to 1,000 km<sup>2</sup>), large watersheds (1,000 to 10,000 km<sup>2</sup>), regions (10,000 to 1,000,000 km<sup>2</sup>), and to continents and the globe. Reaching numerical agreement across scales is challenging (van Noordwijk et al., 2004, 2015d).

Annual means of precipitation, evapotranspiration, and streamflow may scale with area, but peak flows (defined as the “maximum instantaneous discharge of a given stream”) have been found to scale with area to the power 0.7 (Rodríguez-Iturbe and Rinaldo, 2001) or 0.8 (Lin and Wei, 2008). Peak flows relative to mean flows decline with area: for an area that is 10 times larger, the mean flow will be 10 times larger, but the peak flow is expected to be five (equal to 10 to the power 0.7) times larger, so the peak-to-mean ratio halves. The scaling parameter (and its variation across landscapes) reflects both flow buffering in larger watersheds (with greater likelihood of riparian wetlands beyond head catchments) and spatial correlation of peak rainfall events (high for frontal rains, low for thunderstorms). Flood risks and its determinants strongly depend on scale of consideration (van Noordwijk et al., 2017a).

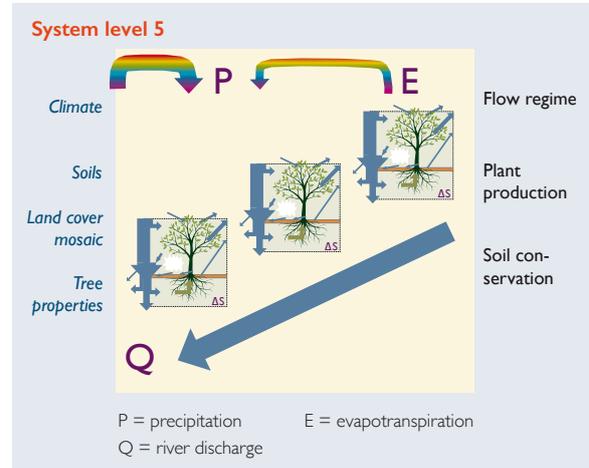
There have been many attempts to develop scale transfer functions, clarifying scaling rules for hydrologic variables and hydrologic effects across different sized watersheds (Blöschl and Sivapalan, 1995; Hrachowitz et al., 2013). Gupta and Waymire (1990) introduced the concepts of simple scaling (e.g., area-based or scale-independent fractal rules) and multi-scaling (more complex scale-dependent rules) to describe spatial structures of rainfall and floods (Blöschl and Sivapalan, 1995). Gupta and Dawdy (1995) showed that floods exhibit simple scaling in snow-dominated watersheds and multi-scaling in rain-dominated watersheds.

### Evaporation versus transpiration

In the absence of a litter layer, soil evaporation can be a significant part of total evaporation in some forest types (Raz-Yaseef et al., 2010). At the forest stand and watershed scales it is difficult to distinguish evaporation from soils or intercepted canopy moisture from transpiration, but at the global scale this has been recently accomplished by combining water balance and isotope data. Globally, across all vegetation types, transpiration has been estimated to be  $64 \pm 13\%$  of evapotranspiration (Good et al., 2015). Stand- and watershed-scale studies of water isotopes imply different cycling and terrestrial retention times of water involved in transpiration compared to streamflow (e.g., Evaristo et al., 2015), but such studies have not yet been paired with water quantity measurements to close the water balance. Only  $38 \pm 28\%$  of surface water is derived from

the plant-accessed soil water pool (Good et al., 2015), with the remainder reaching streams by overland flow, but these numbers are likely differentiated by land cover type.

### 2.2.5 Dynamic Landscape Mosaics: Streamflow



### Flow regimes as landscape signature

Most forest hydrologic studies focus on understanding the response of homogeneous forest patches to specific treatments, but the reality is that land cover dynamics involve complex space-time patterns of roads, forest conversion, partial recovery of secondary forests, intensified agriculture, plantations and urbanisation.

The spatial pattern in land cover also matters for surface and subsurface lateral flows, modifying streamflow regimes (water quantity, quality, regularity of flow). The black-and-white language of ‘deforestation’ and ‘re-forestation’ does not do justice to the many intermediate situations that influence streamflow in complex ways. Land cover transitions (e.g., the loss of natural forest and the subsequent return of trees – planted, spontaneously established and not removed, or spared during land clearing) matter for the four ecosystem structure attributes (LAI, roots, litter, soil porosity), with different response times for above-and belowground changes.

### Forest (tree cover) transitions

Forests and tree cover are part of a three-dimensional space, where climatic zones and topography interact with an anthropogenic forest transition (Dewi et al., 2017). Many natural forests are converted, frequently to more open agricultural land cover types, but trees can come back (Meyfroidt and Lambin, 2011), either under pressures of ‘push’ (increased value of trees used in plantations or as part of agricultural and urban land use mosaics) or ‘pull’ (urbanisation, land abandonment). Under a ‘push’ scenario, most of the new trees may be planted, whereas under the ‘pull’ scenario, most of the trees will be secondary forests with spontaneously established trees (among which invasive exotic species may compete with native pioneer trees) (Ordóñez et al., 2014).



The swidden-fallow mosaic landscape in Xishuangbanna of China has been replaced by monoculture rubber plantation  
Photo © Xiaobao Han

The usual binary classification of land cover into forest versus non-forest, which is used in many studies of forest effects on water, obscures both the effects of forest quality and the effects of spatial arrangement of forest within a watershed, especially in landscapes where swidden/fallow (or secondary forest) cycles are subject to segregation of ‘forest’ and ‘agriculture’ (Malmer et al., 2005; van Noordwijk et al., 2012a, 2015b). For example, any possible flood-mitigating effects of forest expansion and growth in the headwaters of a large watershed were overwhelmed by agricultural intensification from the traditional swidden-fallow system in the lower reaches of the Huong basin in Vietnam over the period 1989 to 2008 (Figure 2.5), which experienced a statistically significant increase in the highest yearly flood peak in the lowland. Hence, the spatial distribution and character of forest and tree cover influence hydrologic behaviour in large watersheds, with conditions of the land outside the forest at least as important as that inside remaining forest. Concepts, as specified in the Indonesian spatial planning law, that 30% of forest is needed to guarantee watershed functions, regardless of what happens in the other 70% of land, have little empirical basis, even when occasional studies seem to confirm the 30% estimate (Tarigan et al., 2018).

### Special forest niches

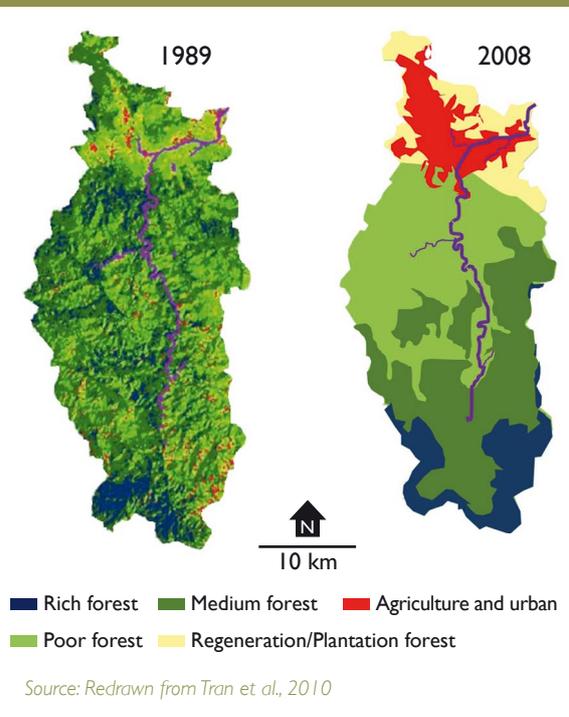
Beyond bioclimatic zones, topography is an important determinant of ecosystem structure and hydrologic function of forests and tree cover. Specific forests of interest include the following:

#### Water towers

Water towers are found at high altitudes and are areas where the ratio of precipitation to evapotranspiration is sufficiently high to generate streamflow. They are often the primary source of streams on which life in lower and drier zones depends (Viviroli et al., 2007). Tropical water

**Despite recovery of forests in the headwaters (lower part of map) of the Huong river basin in Vietnam from 1989 to 2008, expansion of agriculture in the lower portions of the basin (upper part of map) exacerbated flooding over the period**

Figure 2.5



towers tend to have relatively high human population densities and rates of forest conversion (Dewi et al., 2017); they thus are hotspots of conflict over water.

#### Cloud forests

Cloud forests – often the mountain tops of water towers – have a special place in forest hydrology as the vegetation plays an active role in trapping moisture from clouds, attaining higher precipitation than measured by standard rainfall gauges (Bruijnzeel et al., 2011). A recent study of cloud forests in Colombia, however, suggested that low evaporation due to foggy conditions is a key part of streamflow generation (Lawton et al., 2001; Ramírez-Correal et al., 2017a,b), making the continued functioning of such forests dependent on evapotranspiration of adjacent lowlands.

#### Wetland and riparian forests

For wetlands and riparian forests, factors that control the surface and subsurface flows of water may be at least as important as local precipitation in determining water availability to plants. This includes the large seasonal floodplains of the Amazon basin and smaller parts of many other river systems. Where wet conditions are permanent, peat forests may form based on trees with sufficient root adaptations to live in a permanently anaerobic environment. Wetlands and riparian forests can have

an important flow-regulating effect on downstream river behaviour, as long as their water table level is allowed to move up and down. With conversion to agriculture or urban areas, changing water table levels become problematic and engineering solutions externalise the variability, implying a loss of flow buffering functions.

**Vegetation around springs and wells**

Due to obvious relations with water quality and public health, the vegetation around springs and wells has been protected by locally-developed resource use rules in many parts of the world with national legislation usually formalizing such rules (Galleani et al., 2011; German et al., 2013).

**Mangroves**

Along marine coastal zones, a specially adapted tree flora forms mangroves (see Box 2.8), providing flood and storm surge protection of the hinterland (Bayas et al., 2011), mitigating sea level rise and coastal erosion, as well as being a spawning ground for coastal fisheries or protecting other important ecosystems, such as seagrass and coral reefs.

**Small island forests**

On small islands, limited fresh groundwater impacts water availability for forests, agriculture and people (White and Falkland, 2010), making them especially vulnerable to climatic variability. Small island states have been strong advocates of global climate change mitigation, and they also are at the forefront of adaptation discussions (Duguma et al., 2014). For example, the Tobago Main Ridge Forest Reserve (proposed as a UNESCO World Heritage Site)<sup>2</sup> is on record as the oldest legally-protected forest reserve established specifically for water conservation purposes. It was established on April 13th, 1776 by an ordinance which states, that the reserve is “for the purpose of attracting frequent showers of rain upon which the fertility of lands in these climates doth entirely depend.”

**Trees outside forest**

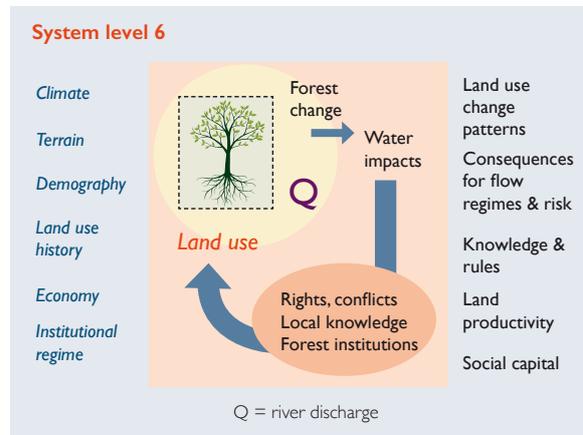
With 43% of the world’s agricultural lands having at least 10% tree cover<sup>3</sup> (Zomer et al., 2016), the roles that these trees play for the local economy, as well as for the water balance and local climate, deserve attention (Ong et al., 2015). Agroforestry has seen a growing recognition that land use at the interface of agriculture and forestry has much to offer to sustainable development concepts (Garrity, 2004; Prabhu et al., 2015).

**Urban trees**

Trees and other vegetation in urban areas are essential for rainfall infiltration and storm surge abatement. They function as air conditioners, cooling surrounding air by producing latent heat through transpiration. This ecosystem service per unit biomass may be as high as that of the sparse

trees in dry zones. The mechanical instability of urban trees (due to limitations to root development and functioning) is a problem, and the selection of suitable trees for urban environments is a specialised field of science (Pokorny et al., 2003). Perennial climbers on walls may combine the positive roles of a high leaf area index, with the absence of tree and branch fall risks (Alexandri and Jones, 2008); green walls as complements to urban trees have become popular, for example, in Singapore (Magliocco, 2018).

**2.2.6 Land and Water Use Rights, Local Knowledge and Forest Institutions: Landscapes**



**Local rights and forest institutions**

The forest (tree cover) transitions described and analysed as statistical phenomena with hydrologic consequences in the preceding system level are in fact a consequence of complex interactions between social and ecological aspects of a dynamic interaction that changes people as well as landscapes.

Rights, conflicts, multiple knowledge systems, the emergence of forest institutions of various types, all controlling what individual actors can or cannot do to forest and tree cover (Freeman et al., 2015), indirectly influence streamflow regimes (van Noordwijk et al., 2015e). In the history of land use change, evolving local institutions on forest and water use rights have restrained private benefit maximisation, often progressing from ‘first come, first served’ rules towards collective action, stewardship and shared responsibility. In many countries, state-based forest use rights (‘concessions’) have been applied without reference to local or traditional rights.

The historical evolution of forest institutions in relation to local rights has reflected issues of national security (including shipbuilding, navigable rivers, accessible ports), economic gain (logging), watershed protection (depending

<sup>2</sup> <https://whc.unesco.org/en/tentativelists/5646/>

<sup>3</sup> Within the global climate convention countries were asked to specify their tree cover threshold (between 10 and 30%) to be used in distinguishing forest from non-forest

on downstream interests), biodiversity protection and conservation, and recreation, with shifts in the public-private balance of power. Conflict resolution, more participatory forms of forest management and transparency of landscape resource monitoring have changed the forest-water relation over time and its role in national development strategies.

### Water and forest rights

Water is among the resources with the longest history of clarifying public, club, and collective rights and responsibilities. At the most basic level of rights, there is a concept of ‘settler rights’, where the first to claim establishes a long term right, and a ‘riparian right’ where all those with land bordering a stream or lake have collective rights and responsibilities to share and manage the resource. Given their military importance, navigable rivers have been claimed by states from the start of codified law. In the establishment of ‘forests’ as a state resource, the concept of ‘terra nullius’ (land without settler rights) provided the opportunity, while public concern over water flows became a justification (Williams, 2003; Galudra and Sirait, 2009). With many post-independence nations inheriting strong ‘state’ claims from indigenous peoples, conflicts have occurred over what are ‘club’ collective rights, versus ‘state’ prerogatives. In subsequent ‘privatisation’ of state claims of resources, e.g., through concessions for water use or drinking water distribution, a new arena for conflicts was opened (Boelens, 2009).

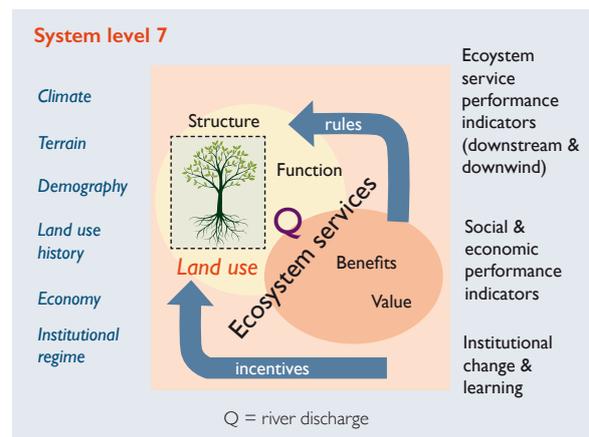
Schlager and Ostrom (1992) in their foundational analysis described five property rights with respect to natural resources: the right to access, the right of withdrawal, the right of management, the right of exclusion, and the right of alienation. Recent stocktaking (Galik and Jagger, 2015) of progress in the understanding of property rights added a sixth category (the right to alter) to those defined by Schlager and Ostrom. Regulating the right to alter land cover and land use is central to efforts to manage public functions of water, alongside private rights to ‘harvest’ and ‘manage’. A delicate balance exists in water resource management between plot-level issues that are better handled with private tenure security versus those that require collective action at the levels of streams and rivers (Swallow et al., 2001). This has become an important issue in South Africa, where the introduction of licences for ‘stream flow reduction activities’ were introduced to control large scale plantation activities and their downstream impacts (Gush et al., 2002). Climate change provides a new complication at the public/private interface where forest and water resources are involved.

### Local and traditional knowledge

Traditional knowledge is typically transferred between generations as part of local culture, whereas local knowledge can be accumulated by a person or community merely by experiencing local conditions for a period of

time. Both can involve component (ethnobotany, ethnozoology) and explanatory knowledge (Joshi et al., 2004). There is an inextricable link between traditional ecological knowledge systems and forest-water interactions that emerges from historic ties to cultural landscapes (Xu et al., 2009). For example, many ‘globally important agricultural heritage sites’ from the Andes and Asian highlands show the complex but coupled linkage between the forest-village-terraced-rice paddy and river systems (Camacho et al., 2010; Jiao et al., 2012) involving local world views, knowledge systems, norms and institutions, trials and innovations, teaching and learning. Various government policies and the expansion of regional and global markets play important roles in shaping the landscape and associated cultural influences (Xu and Grumbine, 2014a). More recently, there has been considerable discussion on ways to integrate local knowledge with government policies for managing forest-water interactions (Jeanes et al., 2006; Xu, 2011; Rahayu et al., 2013; Leimona et al., 2015b).

### 2.2.7 Social-Hydrological Systems: Ecosystem Services as Valued Human Benefits



### Typology of services

The Millennium Ecosystem Assessment (MEA, 2005) has popularised a classification scheme of ecosystem services that is based on the type of human benefits (provisioning, regulating, cultural, supporting) that are derived from functioning ecosystems (De Groot et al., 2002; see Chapter 5).

Both the anthropocentricity of the definition of ecosystem services and the association with economic representation of value and proposed alternative concepts used in the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services studies have become the subject of intensive debate<sup>4</sup> (Tomich et al., 2010; Pascual et al., 2017; Diaz et al., 2018; Braat, 2018; Peterson et al., 2018). Yet, the ecosystem services concept has sparked new ways of combining rule-based approaches with economic incentives. Such incentives may

<sup>4</sup> <http://science.sciencemag.org/content/359/6373/270/tab-e-letters>

**Water-related ecosystem functions provided by vegetation and potentially perceived as ‘ecosystem services’****Table 2.1**

	Functions	Metrics
<b>Generic</b>		
W1	Water transmission	Total water yield per unit rainfall
W2	Buffering peak river flows	Wet- and dry-season flow persistence (van Noordwijk et al., 2017a,b) or flashiness (Holko et al., 2011) River discharge per unit above-average rainfall
W3	Gradual release of stored water supporting dry-season flows	Dry-season flow persistence Aquifer recharge
W4	Maintaining water quality (relative to that of rainfall)	Pollutants per unit volume of water Biological water quality indicators
<b>Site-specific</b>		
W5	Stability of slopes, absence of land-slides	Woody roots for topsoil binding and anchorage Non-erosive pathways for overland flow
W6	Controlling soil loss by erosion	Surface runoff pathways Volume of trapped sediment in filter zones Infiltration of topsoil and subsoil (macro porosity due to worms and roots)
W7	Microclimate effects on air humidity, temperature and air quality	Wind speed; reduction in daily maximum temperature; land surface temperatures
W8	Coastal protection from storm surges, tsunamis	Retardation of waves, reduced maximum run up height
<b>Frontier of science</b>		
W9	Ecological rainfall infrastructure and biological rainfall generation	Recycling of atmospheric moisture; height above vegetation of rainfall generating events; ice-nucleating agents

Source: van Noordwijk et al., 2016; Lusiana et al., 2017

‘nudge’ (Thaler and Sunstein, 2008) land use decisions, rather than impose them. Wunder (2015) differentiated payments for ecosystem services from regulation-based (command-and-control) efforts to protect and enhance ecosystem services by emphasising that payments for ecosystem services are a realistic, voluntary, and conditional contracts between at least two parties. In practice, a balance between ‘efficiency’ and ‘fairness’ had to be found to make the concept operational (van Noordwijk et al., 2012b; Kerr et al., 2014; Leimona et al., 2015a; Lapinski et al., 2017).

A classification of water-related ecosystem services that is closer to hydrologic function (rather than the way people benefit, as in provisioning, regulating or cultural services) has been used in recent reviews (Table 2.1; van Noordwijk et al., 2016; Lusiana et al., 2017).

### 2.2.7.1 Generic Functions

#### Function W1: Water transmission

The commonly observed association of streamflow and forests is the combined effect of the high-precipitation places where forests tend to occur and the way water is partitioned over streams and recycled to the atmosphere (Box

2.6). When total water yield is the primary performance criterion for a watershed (e.g., where a large reservoir is to be filled and sediment loads are not an issue), less trees will lead to more blue water. Overall, studies in both small and large watersheds indicate that removal of forests reduces evapotranspiration (ET) and increases streamflow, while reforestation does the opposite (Moore and Wondzell, 2005; Andréassian, 2004; Li et al., 2017a).

In a summary of hydrological research in 30 long-term ecological research sites in the US and Canada (Jones et al., 2012; Figure 2.6 A and C), the  $E_{act}/E_{pot}$  ratio was close to the  $P/E_{pot}$  ratio when the  $P/E_{pot}$  ratio was less than 1, indicating water-limited ET and plant growth, and around 1 when the  $P/E_{pot}$  ratio was greater than 1, indicating energy-limited ET.  $E_{act}/E_{pot}$  ratios > 1 point to uncertainties in the calculation of  $E_{pot}$  (Lu et al., 2005), timescales where  $\Delta S$  is not negligible, or situations where groundwater flows support E that are not accounted for in P. These  $E_{act}/E_{pot}$  ratios for natural vegetation in the dataset of Jones et al. (2012) are higher than the average for ‘forest’ in the Zhou et al. (2015) data set, and may point to heterogeneity of what is included in forests when compared to non-forests.

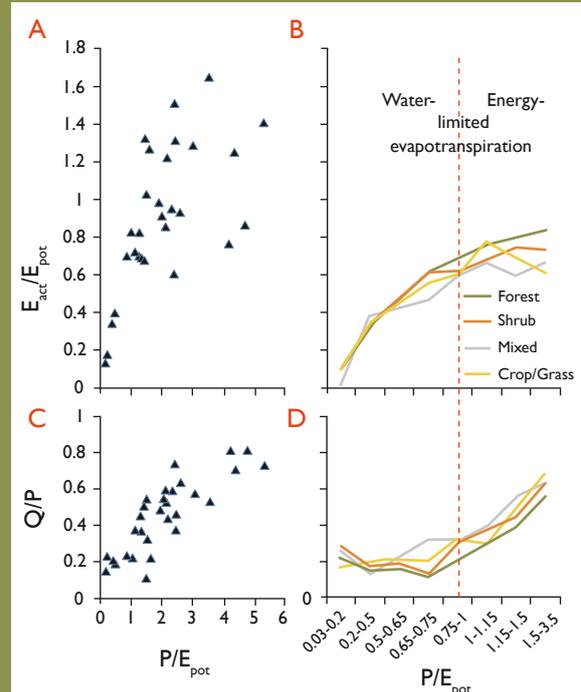
Canopy interception may contribute to higher  $E_{act}/E_{pot}$  ratios of forests compared to other vegetation. Water

### Blue water yield in relation to vegetation and precipitation

Forests occur mostly in places with relatively high precipitation. However, relative to most other vegetation, evapotranspiration for a given precipitation is higher in forests, implying less water transmission to streams (and more to 'rivers in the sky'). The net effect on streamflow of these two findings has been debated. In the most comprehensive global dataset of watershed studies, where  $P$ ,  $Q$ , and  $E$  have been assessed across the main continents at annual time scales for a range of land cover types (Zhou et al., 2015; Zhang et al., 2017), an approximately constant water transmission or  $Q/P$  ratios of 32.7%, 34.5%, 34.5% and 30.5% were obtained for forest, shrub, mixed land uses and crops/grass, respectively. The forests were associated with the highest precipitation, with  $P/E_{pot}$  ratios for the four land covers of 1.17, 1.07, 0.92 and 0.88, respectively. This compensated for the higher  $E_{act}/E_{pot}$  ratios of the four land covers: 71.8%, 59.2%, 53.3% and 55.2%, respectively. Both the  $Q/P$  and  $E_{act}/E_{pot}$  ratio depend on local climate (Figure 2.6). The weighted average based on the global distribution of  $P/E_{pot}$  ratios (Figure 2.2A) indicates a global mean water transmission fraction for forests and non-forests of 33.8 and 40.8%, respectively (and  $E_{act}/E_{pot}$  ratios of 70.4 and 60.9%, respectively). In the wettest part of the data range, the difference in  $E_{act}/E_{pot}$  ratio is up to 20%. The averages for the four land cover classes are midpoints of a rather wide statistical distribution, and the stated differences may not hold for specific land covers compared in a given location. The lower  $E_{act}/E_{pot}$  ratios for crops reflect annual assessments; within the growing season, closed crop canopies can operate at  $E_{act}/E_{pot}$  ratios of close to 1 if the soil is sufficiently moist.

Figure 2.6 D shows that the average  $Q/P$  ratio for all vegetation types at low rainfall does not drop below 15% and may actually increase when the lowest  $P/E_{pot}$  ratios are considered. This is likely due to peak rainfall events that exceed the instantaneous infiltration capacity of the soil.

Part of the variation in annual data analysis like this is that groundwater stocks carry over from wet to dry years, depending on substrate and topography (Condon and Maxwell,



Source: Authors' own elaboration based on datasets from Jones et al., 2012; Zhou et al., 2015

Relation between precipitation relative to potential evapotranspiration ( $P/E_{pot}$ ) and actual relative to potential evapotranspiration ( $E_{act}/E_{pot}$ ) (A, B), and relation between streamflow  $Q$  relative to  $P$  (C, D) for two datasets. A and C are from 30 long-term ecological research sites in the US and Canada (Jones et al., 2012) and B and D are from a global dataset (Zhou et al., 2015).

2017). Gudmundsson et al. (2017) challenged the continuous functions used in the analysis of these data by Zhang et al. (2017); the current analysis is based on means for  $P/E_{pot}$  class to avoid the assumptions of continuous functions.

intercepted by forest canopies may evaporate without being measured (Sahin and Hall, 1996; Carlyle-Moses, 2004; Brown et al., 2005; Wei et al., 2005, 2013). Leaf area index, thickness, and characteristics (i.e., waxiness, hairiness and drip tips) determine the absolute amount of water stored after any precipitation event (Gash, 1979), and thus water available for evaporation from the canopy.

Forest species composition and age influence the  $E_{act}/E_{pot}$  ratio of forests. Paired watershed experiments (Box 2.5) have shown larger effects on streamflow for changes in evergreen forest than for changes in broadleaf deciduous forest (Bosch and Hewlett, 1982; Brown et al., 2005), but age of the experimental stands may have influenced these results (Jones and Post, 2004). Changes in forest water yield over time have been attributed to shifts in forest species composition between low and high-water

using (mesophytic) tree species (Caldwell et al., 2016; Elliott et al., 2017).

In a review of forestation effects on streamflow by Filoso et al. (2017), most studies reported decreases in water yields following the intervention. However, most studies referred to plantation forestry rather than forest restoration with mostly slower growing native species. Furthermore, studies were especially limited for the humid tropics and subtropics. One of the challenges in interpreting such data is that actual precipitation over forests is not readily measured, as standard climate stations measure away from trees, while wind-corrections on rain gauges are not consistently applied across data sets (Chang, 2006). If regional vegetation influences precipitation, then its effects are implicit in the data and may not be explicitly considered in the data analysis and conclusions.

### Function W2: Buffering peak river flows

Unanticipated floods create major damage (Brauman et al., 2007; Bishop and Pagiola, 2012; Winsemius et al., 2013) and the human and economic costs of floods, particularly where cities are built on floodplains, can be huge (Farber et al., 2002; Turner and Daily, 2002). While floods may originate from factors exogenous to the landscape of interest (such as heavy precipitation, earthquakes inducing dam collapse, tsunamis or coastal storm surges (van Noordwijk et al., 2017a)), they may also be caused by land use patterns, such as low infiltration capacity, limited soil water storage, logging practices, forest roads (Wemple and Jones, 2003) or accelerated snow melt (Jones and Perkins, 2010; Schulte et al., 2015). Avoided flood damage may translate into high economic value, justifying an ‘insurance’ approach to maintaining or restoring forests, if effects can be sufficiently quantified.

Forests and their management can affect the peak flows that cause flooding downstream (Rogger et al., 2017; Jacobs et al., 2018), but the degree to which this function is achieved in any given context remains subject to debate and uncertainty. Most of what has been presented from correlational studies as direct evidence of a relation between forest loss and increased flood risk has alternative interpretations in relations with human demography and remains contested (van Dijk et al., 2009). However, the analysis of Malaysian data by Tan-Soo et al. (2014) with adequate controls of confounding factors showed increased flood risk after conversion from natural forest to plantation crops and urbanization. Elsewhere natural forest was shown to be more effective in reducing floods than plantations on former agricultural lands (Nadal-Romero et al., 2016).

Forestation may reduce flooding by rapidly increasing evapotranspiration and enhancing infiltration more slowly once soil macroporosity increases (Bresson and Valentin, 1993; Ilstedt et al., 2007). The relative importance of these two effects varies with context, and is a challenge for analysis of empirical data, as is the statistical distribution of peak precipitation events that are the direct cause of floods.

Efforts are needed to relate the more readily observable response to less-extreme events to what can be expected in extremes. An index of ‘flashiness’ of streams has been used in evaluating streamflow records (Baker et al., 2004; Holko et al., 2011); it quantifies the relative day-to-day changes in flow. A recently introduced method goes a step further, as it provides a direct link between the part of a peak rainfall event that comes directly into the stream and the ‘flow persistence’ (flow regularity) that can be observed in the day-to-day changes in flow (van Noordwijk et al., 2017a, b). Instantaneous peak flow, which is relevant for flood risk management, can be derived from the maximum mean daily flow in various ways (Jimeno-Sáez et al., 2017), connecting flood assessments to daily flow accounting schemes. New ways of estimating flow duration curves for ungauged catchments have been developed (Poncelet et al., 2017) using geographic similarity.

In the temperate zone, floods can be caused by snowmelt in spring as well as by peak rainfall events in summer, with different opportunities for forests to provide

function W2. The energy relations of forests also cause snow to accumulate and melt differently than in openings, so forest cover may mitigate snowmelt peaks (Bergström, 1995; Seibert, 1999; Varhola et al., 2010). The first quantitative studies that related forest cover to flooding risks were carried out in Switzerland in the 1920s (Mather and Fairbairn, 2000). By comparing flooding responses in the valleys with varying degrees of conversion of forests to alpine meadows and/or agricultural lands, a safe threshold of forest cover of 30% was derived. In valleys with more than 30%, forest snowmelt was more gradual and flooding risk was lower, than in valleys where all snow could melt simultaneously.

Although it is difficult to assess statistical significance for rare, extreme events, forest harvest was associated with significant increases in peak flows in both small and large (100–1,000 km<sup>2</sup>) basins (Jones and Grant, 1996; Jones, 2000). Partial forest harvest may produce smaller effects on peak flows (Troendle et al., 2001). Forest harvest also is associated with increases in peak flows in watersheds ranging from 1 to 1,000 km<sup>2</sup> (Jones and Grant, 1996). Engineering measures (dams, reservoirs, canals and dykes) can significantly alter the flow regime of streams (Poff et al., 1997). The life expectancy of such structures depends, however, on the sediment load of incoming streams and thus on upper watershed conditions (Graf et al., 2010).

### Function W3: Gradual release of stored water supporting dry-season flows

Gradual release of water stored in the ‘sponge’ of forest soils primarily depends on the geomorphological context (Section 2.2.2) rather than on the more visible part of the forest.

After Hamilton and King (1983) and Bruijnzeel (1990; 2004) drew attention to the soil, rather than the trees, as the most hydrologically relevant part of a forest, forestation research has tried to clarify the increase in infiltration that is needed to have a positive effect on dry-season flows, offsetting additional water use by fast-growing trees. While annual streamflow is likely reduced by forestation, effects on groundwater release are uncertain, as they depend on the balance of infiltration and (deep) water uptake by trees (Ma et al., 2009; 2010).

Forest soils typically have a litter layer that retains water on the surface and increases the time available for infiltration and protects soil surfaces from the erosive capacity of direct rain droplets (e.g., Hairiah et al., 2006). In peri-urban environments, leaf litter, root channels, and animal burrows can detain and absorb water, reducing erosion and turbidity (Seitz and Escobedo, 2011). Loss of forest cover is associated with loss of soil organic matter and associated aggregates that lead to reduced moisture holding capacity (Allen, 1985).

Intermediate tree densities provide a solution for the tradeoff between enhanced infiltration and increased water use due to trees (Ilstedt et al., 2016). When clearing land for crop production, farmers in the parkland agroforestry systems of the Mediterranean and the Sahel retain

### Riparian forests and water quality

Forests can have direct influence on water quality in streams, including temperature, sediments, nutrients, and biological oxygen demand (Stelzer et al., 2003; Moore et al., 2005). First, direct microclimate effects influence stream temperature, critical for ‘cold water’ fish (Groom et al., 2017). Secondly, riparian forests act as buffer zones that filter sediment, nutrients, and contaminants before they reach the water (van Noordwijk et al., 1998a; Ranieri et al., 2004). For example, riparian forests can retain soil and limit sediment erosion that would otherwise transport unwanted mineral soil particles to the water, consequently darkening and decreasing its quality (Neary et al., 2009). Nutrients (nitrogen and phosphorus) and contaminants (pesticides and pathogens) that could also be transported to the water can be adsorbed in the forest soils or taken up by plants and microbes (Gilliam et al., 2011). Thirdly, organic matter from forests gets washed into waterways (Para et al., 2010). It provides shade, which prevents excessive growth from aquatic plants and algae, and consequently regulates oxygen levels and water clarity (Thrane et al., 2017). Additionally, these terrestrial inputs to the food web are either directly ingested by zooplankton and fish or are decomposed by sediment microbes that release bioavailable carbon into the water (Berggren et al., 2009). Together, these processes support as much as 20% to 85% of secondary production in freshwater systems (Karlsson et al., 2012). In order to meet their energy requirements, biota in less productive waters are particularly dependent on these terrestrial subsidies that supplement within-lake primary production (Tanentzap et al., 2017). The surrounding species of trees, land-use, seasonality, and the communities present within the water regulate how strongly these terrestrial inputs will impact the aquatic ecosystem (Cole et al., 2006).

old trees, especially those of a number of species with valued products (fruits, edible young leaves; Bayala et al., 2015). The ratio of beneficial effects and water use is likely higher for old than it is for young trees (van Noordwijk and Ong, 1999). Actual tree densities may be close to what is optimal from a perspective of groundwater recharge: more trees would imply higher water use, less trees would affect infiltration (Ilstedt et al., 2016).

#### Function W4: Maintaining water quality

The association between natural forests and good water quality is based on a number of aspects:

- lower sediment loads, as erosion is largely confined to shallow landslides and much of the soil involved can become incorporated in surrounding vegetation rather than reaching streams;
- tight nutrient cycling with little nutrients lost to streams (when compared to agricultural land with recurrent nutrient inputs); and
- scarcity of pollutant point sources, although bacteria such as *Escherichia coli* can be present whenever vertebrates are in close contact with streams.

However, the general association between forest conditions and good water quality needs to be contextualised. Retaining riparian zones of native forest can reduce some of the negative effects of plantation forestry on flow regimes and water quality (Little et al., 2015). Relatively small strips of riparian vegetation can act as sediment filters in overland flows from uphill agricultural plots and make a subwatershed behave ‘forest-like’ (van Noordwijk et al., 1998a; Ranieri et al., 2004) in terms of sediment load (Box 2.7).

#### 2.2.7.2 Topography-Dependent Functions

##### Function W5: Stability of slopes, absence of landslides

A large amount of literature links forestry to increased occurrence of landslides, debris slides, and debris flows in steep landscapes as a result of logging or forest roads (Swanson and Dyrness, 1975; Swanson and Swanson, 1976; Amaranthus et al., 1985; Wemple et al., 2001; Sidle et al., 2006). Landslides, however, are a natural part of landform evolution, but forest condition and soil type influence their occurrence (Verbist et al., 2010). Landslides are triggered by positive water pressures within soil pores, facilitated by macroporosity and high instantaneous infiltration rates (Sidle and Bogaard, 2016). Vegetation, especially undisturbed native forest, promotes cohesion of steep hillslopes through root systems (Hales et al., 2009), by decreasing peak rainfall intensities through canopy interception and by reducing soil water content through evapotranspiration, which promote slope stability (Turcotte and Malamud, 2004; Sidle and Bogaard, 2016); however, large trees can add weight and increase landslide risks when uprooted by strong winds. Increased land sliding is particularly likely within a window of a decade (or two decades in cold climates) after logging or forest conversion, depending on rates of root decay and root development by new vegetation (Dhakal and Sidle, 2003). Forest cover also modulates avalanche risk on mountains with snowpack; forest conditions that reduce likelihood of avalanche include a crown cover of >30%, the absence of gaps >25 m in length, and an increased terrain roughness associated with standing or downed trees that exceed snow depth (Bebi et al., 2009).

##### Function W6: Controlling soil loss by erosion

Forests with understory vegetation and intact litter layers have low rates of erosion, but forest harvest and roads increase erosion (Wemple et al., 2001; Sidle et al., 2006). Removal of the forest litter layer increases overland flow of water, and hence, surface erosion (as described for Nepal by Ghimire et al., 2014a). Forest plantations without understory can increase the kinetic energy of throughfall beyond that of rainfall and increase detachment of soil particles as a first stage of erosion (Wiersum, 1991). Riparian forests are particularly important to limit streambank erosion (Verbist et al., 2010). Reforestation has been associated with reduced erosion and sedimentation in major river basin systems in China (Miao et al., 2010; Ma et al., 2014; Yang et al., 2015).

### Function W7: Microclimate effects on air humidity, temperature and air quality

Many processes influence how forests and trees outside forest (in agricultural lands or urban environments) affect local air temperature, and effects depend on the climate zone. In boreal forests, a large amount of literature has debated the effects of forest and snow albedo (reflection of incoming radiation), forest change, and climate change on energy balances. Boreal forest albedo is very low both in summer and under snow (Betts and Ball, 1997; Manninen and Stenberg, 2009), contributing to warmer temperature under these forests in winter compared to other vegetation cover types, and these differences are not expected to be sensitive to anticipated climate change, including reduction in snow cover (Kuusinen et al., 2012). Furthermore, the effects of tree cover on reduced night-time cooling can offset day-time effects of increased evapotranspiration (Peng et al., 2014). Differences in albedo between forests and clearings in the tropics are relatively small (Pinker et al., 1980; Teixeira et al., 2015) and cooling associated with evapotranspiration may dominate the energy balance, making forest canopies cool relative to other cover types (Ellison et al., 2017). Cooling effects of trees and open water were first described for ‘urban heat islands’, but these effects are now recognized in agricultural landscapes with various degrees of tree cover (Bayala et al., 2015; Sida et al., 2018).

### Function W8: Coastal protection from storm surges and tsunamis

Coastal protection by mangroves and other forests may well represent the highest ecosystem services of trees per unit tree biomass, as coastal areas can have high human population densities (Box 2.8). Empirical evidence for the benefits of such protection during the December 2004 tsunami in Southeast Asia, however, has been mixed with trees blocking exit pathways for people living between the tree cover and the coast for example (Bayas et al., 2011). Nevertheless, interest in ecosystem-based coastal defence in the face of global change is increasing (Gedan et al., 2011; Temmerman et al., 2013), if only for financial reasons, as construction of alternative protective sea walls is expensive (Gunawardena and Rowan, 2005).

#### 2.2.7.3 Frontier of Science

### Function W9: Ecological rainfall infrastructure

Forests and trees outside forest may influence four factors required for precipitation at a given time and place: 1) the presence of atmospheric moisture; 2) phase shifts from vapour to water droplets (clouds); moist air has to get into cooler higher atmosphere layers for ice nucleation (and thus cloud formation) to happen, but just how cold (and thus how high) it has to be depends on ice nucleating agency (e.g., dust and bacteria that live on the leaves of plants) which can increase the temperature threshold (from minus 30°C in clean air to around minus 5°C); 3) local capture of atmospheric moisture (ending

the atmospheric residence of a specified unit of moisture) that might otherwise move elsewhere; and 4) mass flow of moist air during and between rainfall events that depends on modifications of prevailing winds (Makarieva et al., 2009, 2013).

Capturing atmospheric moisture in plant available form can occur at a number of scales. Water droplets in the air that are too small to fall can be captured by vegetation. For example, in cloud forests, epiphytic lichens, mosses, and hairy leaf structures strip ‘horizontal rain’ (Holwerda et al., 2006) from the atmosphere. The presence of cloud forests, often the highest parts of water towers (Viviroli et al., 2007; Dewi et al., 2017), can thus actively increase precipitation (Hamilton et al., 1995; Bruijnzeel, 2001; Ramirez et al., 2017; Domínguez et al., 2017; Regalado and Ritter, 2017). The loss of cloud forests can lead to reductions of water yield, opposite to the increases expected otherwise. Locally-generated moisture can also be captured as dew by hairy plants growing in dry environments with large diurnal temperature fluctuations that increase relative humidity at night (Stone, 1957; Zhuang and Zhao, 2017). Dew is a major source of green water rather than blue water (Ben-Asher et al., 2010), but can help in establishing ‘ecological rainfall infrastructure’ in dry environments (Zhuang and Zhao, 2017). Forest cover may affect cloud height and cloud cover (Millán et al., 2005), slow down winds, and therefore influence the likelihood of rainfall triggering (Fan et al., 2007; Poschl et al., 2010; Pöhlker et al., 2012; Morris et al., 2014, 2016; Bigg et al., 2015).

‘Rainfall triggering’ tends to have a physical component in cooling that follows the rise of air masses due to turbulence or orographic effects as well as a chemical and biological component. Forests, and especially forest edges, have been shown to influence turbulence and as

Box  
2.8

#### Mangroves and land building in the river deltas

Mangroves often dominate the estuaries of tropical river basins, providing significant services including trapping and accumulating sediments and eventually elevating surface and forming deltas. They are often considered land builders and in many places the accretion rate often exceeds sea level rise. Global estimates of the accretion rate are 4.0 + 3.5 mm/year (Breithaupt et al., 2012), while sea level rise under a high emission scenario ranges between 2.6 and 3.2 mm/year (Church et al., 2011). The rate and extent of accretion depend on the hydro-geomorphic settings of the coasts and estuaries. Tidal range, topography and geological formation of the watershed and coastal areas are important determining factors (Balke and Fries, 2016), as well as anthropogenic influences through coastal development (Alongi, 2008). The unique nature of mangrove root systems not only supports the trees to withstand sea currents and waves but also secures the stability of the coast itself. The ability of mangroves to successfully adapt to changes in sea-level depends on accretion rate relative to rate of sea-level change.

such can bring moist air to heights where it is sufficiently cold to form ice nuclei and raindrops (Degu et al., 2011; Pielke, 2013). Aerosols (e.g., dust or hygroscopic salts as used in ‘cloud seeding’) and volatile organic substances derived from vegetation (Stopelli et al., 2015; Fröhlich-Nowoisky et al., 2016) interact with biological cell wall material (e.g., ice-nucleating bacteria, pollen, fungal spores) that can act as catalysts for ice nucleation (van Noordwijk et al., 2015c; Morris et al., 2016).

Forests influence winds with their frictional resistance tending to reduce wind speeds. Wind speeds over the Amazon, Congo Basin and forested parts of insular Southeast Asia are remarkably low, allowing local evapotranspiration to be recycled as local rainfall before it is transported hundreds or thousands of kilometres.

The mechanism by which developing rainstorms can attract moisture from adjacent areas by creating low pressure systems (Makarieva et al., 2009, 2013) is not yet adequately represented in global circulation models and the debate over its significance continues (Sheil and Murdiyarso, 2009; Sheil, 2018).

The concept of tree planting in order to increase precipitation, such as in ‘Great Green Walls’ in China and the Sahel remains controversial, but recent advances in science make it open to further analysis.

## 2.3 Research Gaps and Conclusions

### 2.3.1 Research Gaps

For each of the seven system delineations there is a need for continuous refinement of the concepts, models, and methods as knowledge of the multiple relationships influencing forest-water relations grows. Research progress can especially be made at the interfaces between the various system delineations. These include: (1) estimates of evapotranspiration that can be scaled from tree-level sapflow, vegetation-level eddy-covariance and watershed-level water balances; (2) estimates of water storage and groundwater fluxes (including as it relates to soil type, soil depth and terrain features and may correlate with forest types); (3) estimates of atmospheric moisture recycling reconciling isotope-based and mass balance approaches; (4) estimates of both abiotic and biotic aspects of rainfall triggering; and (5) metrics that capture the effects of land cover change on flood (and drought) risk at various scales and in various contexts with confounding factors controlled.

### 2.3.2 Conclusions

A broader context that considers the interactions of climate, forests, water, and people is needed to assess current risks of not achieving the water quantity, quality and regularity of flow needed for the SDGs. At each of the seven system delineations of the climate-forest-water-people system, there are some globally valid conclusions, but also many statements that depend on the specific context:

- 1) At the watershed scale, four major determinants of ecosystem structure need to be considered – leaf area index, condition of the soil surface, infiltration patterns dependent on soil structure, and rooting depth – to understand hydrologic functions of forests and tree cover outside forests, and responses to ongoing and anticipated changes.
- 2) At the landscape scale, streamflow regulation through dams and reservoirs that tend not to occur evenly over larger watersheds and water abstractions can mask or strongly influence any positive effects forests in upper watersheds have on streamflow regimes. Unless one understands the physical basis of deviations from area-based scaling, it is risky to extrapolate beyond the scale range over which scaling rules were calibrated. This applies especially to peak flows, flooding risks and the degree of flood protection that intact natural forests and/or plantation forestry provides.
- 3) Tradeoffs between total water yield (expressed as fraction of precipitation) and the regularity of flow and water quality are to be expected for most contexts, as the rate of evapotranspiration in forests tends to be closer to the potential value than it is for most other vegetation, with the exception of wetlands and possibly irrigated agriculture.
- 4) Forest-derived atmospheric moisture mixes with ocean-derived moisture in spatially explicit patterns that have been well-documented on the basis of atmospheric measurements, and that lead to strong geographic variation in the percentage of precipitation derived from the long versus the short hydrologic cycle, as well as in the contribution a forest makes to short-cycle precipitation downwind. If confirmed by further scientific analysis, the idea that forests contribute to downwind rainfall could be of overriding importance for the prevention of water shortages, flood mitigation and design of forest restoration activities.
- 5) The hydrologic functioning of forests and landscapes with partial tree cover translates to a wide range of ‘ecosystem services’, with direct links between human benefits classified as provisioning, regulating, supporting and cultural services. The biophysical basis of the hydrologic functions and their variation in space and time may well be better understood than the social dimensions of associated rights, value concepts and regulations.

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