Reviewing moisture recycling dynamics: implications of land use change on green and atmospheric water

Sofie A. te Wierik[1], Erik Cammeraat[1], Yael A. Artzy-Randrup[1], and Joyeeta Gupta[2]

[1]University of Amsterdam
[2]Unesco IHE

November 23, 2022

Abstract

Green water, or plant-available soil moisture, is a substantial subset of terrestrial fresh water. Land use change alters green water dynamics directly, by changing soil and vegetation properties, and indirectly, via feedbacks in the soil-vegetation-climate system. Ongoing global deforestation, and growing interest in reforestation projects, begs the question: Do such large-scale land use changes have major eco-hydrological impacts via the process of terrestrial moisture recycling (TMR)? This requires a systematic, mechanistic understanding of green water dynamics in relation to land use change, and the interactions with the soil-vegetation-climate system in which it is embedded. Hence, this literature review addresses the above question via a scoping review that draws from papers covering empirical observations and simulated approximations on the hydrological effects of land use change from different parts of the world. The results show that some regions are more vulnerable to land use change than others and can affect local as well as distant hydrology of landscapes. Furthermore, we derive analytical tools and directions for further research that can improve understanding of the effects of land use change on moisture recycling dynamics in order to minimize unexpected hydrological impacts for nature and society.

Title: Reviewing moisture recycling dynamics: implications of land use change on green and atmospheric water

Authors names and affiliations:

1. Sofie A. te Wierik [1,2], https://orcid.org/0000-0003-1921-0588, University of Amsterdam, s.a.tewierik@uva.nl *
2. Erik L.H. Cammeraat [1], https://orcid.org/0000-0003-4398-206X, University of Amsterdam, l.h.cammeraat@uva.nl
3. Joyeeta Gupta[2], https://orcid.org/0000-0003-1424-2660, University of Amsterdam, j.gupta@uva.nl
4. Yael A. Artzy-Randrup [1], https://orcid.org/0000-0003-3958-7892, University of Amsterdam, yael.artzy@uva.nl

[1] Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam
Sciencepark 904, 1098 XH Amsterdam, The Netherlands

[2] Geography, Planning and International Development Studies, University of Amsterdam
Nieuwe Achtergracht 166, 1018 WV Amsterdam, The Netherlands'

Corresponding author: Sofie A. te Wierik (s.a.tewierik@uva.nl)

Declaration of interest: None of the authors have any conflicts of interest to declare.

Key words: moisture recycling; land use change; deforestation; reforestation, green water; atmospheric water

Key Points:

- Advances in hydrological modeling increasingly broaden our understanding of land use change effects on moisture recycling dynamics, although there was no overarching review on the issue yet.

- Spatial and temporal dynamics of moisture recycling are highly variable, but the hydroclimatic effects of land use changes on these patterns remain – although sensible considering the processes of scale and uncertainties due to water's active role in the atmosphere– under-researched.
- There is a need to increase our understanding of context-specific land use change effects on moisture recycling dynamics via case study research to evaluate potential hydroclimatic effects and prevent unintended consequences on water resources.

Grant: This work was supported via funding provided by the Interdisciplinary Doctorate Agreement, University of Amsterdam

Abstract

Green water, or plant-available soil moisture, is a substantial subset of terrestrial fresh water. Land use change alters green water dynamics directly, by changing soil and vegetation properties, and indirectly, via feedbacks in the soil-vegetation-climate system. Ongoing global deforestation, and growing interest in reforestation projects, begs the question: Do such large-scale land use changes have major eco-hydrological impacts via the process of terrestrial moisture recycling (TMR)? This requires a systematic, mechanistic understanding of green water dynamics in relation to land use change, and the interactions with the soil-vegetation-climate system in which it is embedded. Hence, this literature review addresses the above question via a scoping review that draws from papers covering empirical observations and simulated approximations on the hydrological effects of land use change from different parts of the world. The results show that some regions are more vulnerable to land use change than others and can affect local as well as distant hydrology of landscapes. Furthermore, we derive analytical tools and directions for further research that can improve understanding of the effects of land use change on moisture recycling dynamics in order to minimize unexpected hydrological impacts for nature and society.

1. Introduction

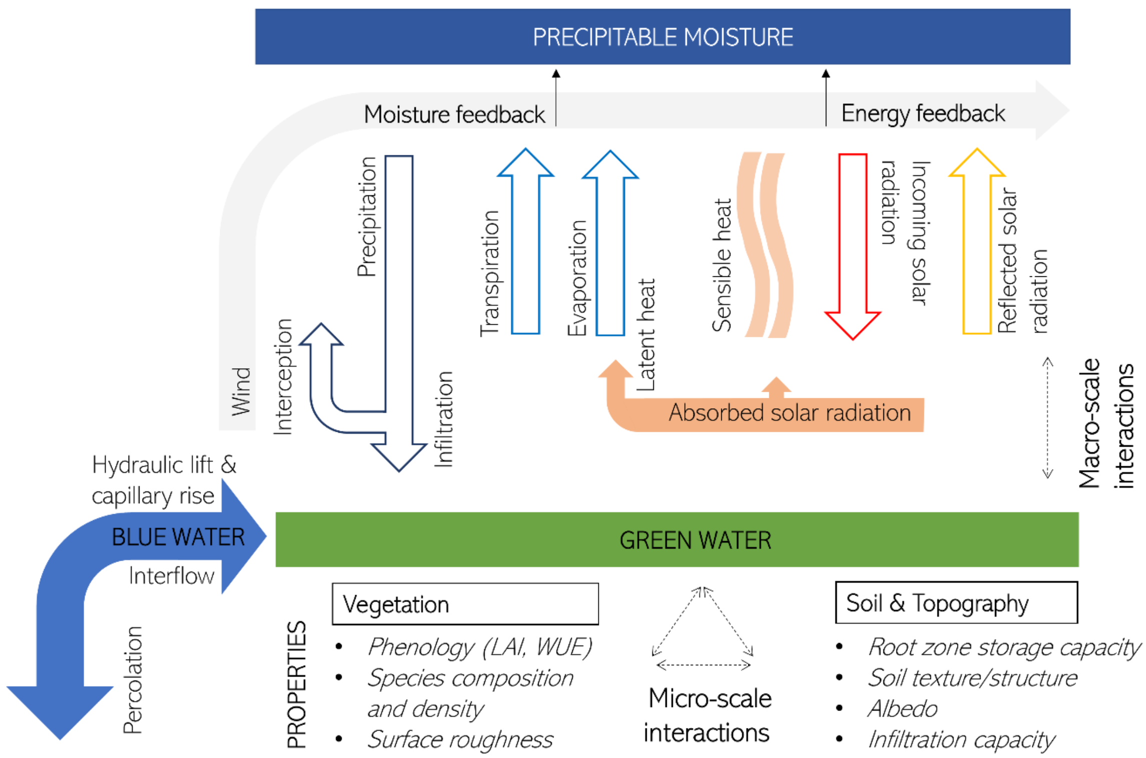


Figure 1 Relevant properties and processes in the green water system. Properties of the land surface are described in italic (LAI = Leaf Area Index; WUE = Water Use Efficiency). Micro-scale interactions occur at the land surface between vegetation-soil-water system. Macro-scale interactions occur between the land surface and the regional climate and are represented by exchanges of moisture, energy and momentum.

A significant part of the global terrestrial freshwater is stored in the soil. Green water, or plant-available soil moisture, enables vegetation growth and determines vegetation form and functioning (Eagleson, 2002). In turn, vegetation cover governs many green water processes, such as infiltration capacity, evaporation, and percolation (Figure 1). Vegetation changes can affect green water dynamics that subsequently affect moisture recycling patterns by altering the magnitude and timing of evaporation and transpiration (Wang-Erlandsson et al., 2014). *Terrestrial moisture recycling* (TMR) is referred to as the "process of terrestrial evaporation entering the atmosphere, traveling with the prevailing winds, and eventually falling out as rain" (Keys et al. 2017: 15). Globally, 57% of the rainfall over land returns to the atmosphere via evaporation or transpiration (Eagleson 2003). Subsequently, this upward moisture flux contributes to 40% of the rainfall over land (Van Der Ent et al., 2010). TMR thus represents a significant hydrological pathway for the global distribution of water.

Anthropogenic land use change (LUC) following increasing demand for food, fuel, fiber and timber (Schyns et al. 2019) might affect TMR. Some studies suggest that deforestation and vegetation reduction can disturb TMR and affect local to regional rainfall patterns (Keune and Miralles 2019; Savenije 1995; Zemp et al. 2014; Zemp et al. 2017). Deforestation and land degradation leads to loss of natural ecosystems and carries the risk of crossing ecological boundaries that affect green water dynamics and TMR patterns (Zemp et al. 2017). Simultaneously, there is a growing interest in afforestation for *biological capture-biological storage* (BCSC) of carbon and restoring ecosystems in general for various other Nature's Contributions to People (NCP). Between 2000-2012, 80 million hectares were re- or afforested (Bentley & Coomes, 2020), mainly temperate forests (Fagan et al. 2020). Reforestation is promoted by the UN declaring 2020-2030 as the decade of ecosystem restoration (UN, 2019); world leaders in Davos committing to planting 1 billion trees (i.e. the One Trillion Tree Initiative); afforestation is increasingly interesting for commercial carbon sequestration approaches for climate change mitigation in line with the Paris Agreement (UN, 2015). Bastin et al. (2019) estimates the global tree restoration potential to cover 0.9 billion ha of canopy cover, which can store 205 Gt of carbon. Furthermore, deliberate bio-geoengineering with forest plantation can change regional climate and rainfall via land-atmosphere interactions (Branch & Wulfmeyer, 2019). However, tree planting runs the risk of distorting basin hydrology and sediment dynamics (Farley et al. 2005), as has occurred in many forestry projects worldwide (e.g. introduction of exotic Eucalyptus in South Africa) (Albaugh et al., 2013). Accordingly, the impact of both de- and reforestation on the hydrological cycle should be addressed given scarce water resources (Sterling et al., 2013). There is lack of clarity concerning the conditions under which TMR patterns can be distorted or intensified via LUC (e.g. Spracklen et al. 2018). This research therefore addresses the question: Do large-scale land use changes have major eco-hydrological impacts via the process of terrestrial moisture recycling (TMR)? We answer this question through a scoping literature review addressing both empirical observations and simulated predictions from across the globe in order to provide a state-of-the-art synthesis on the effect of LUC on TMR.

We first provide a historical and theoretical background, describe the methodology for the review, and present the results, including global and regional assessments of the empirical effects of LUC and implications for governance.

2. Historical and theoretical background

Historically, human-induced patterns of vegetation change have altered large areas of the earth's surface and hydrology. The debate on the effect of forests on hydrology centers around the question whether trees are net *water users* or net *water producers* (Andréassian 2004; Ellison, Futter, and Bishop 2012). Forests use water via transpiration and evaporation (reducing local water availability), but they also enhance infiltration and the water retention capacity of the soil (increasing local water availability). The trade-offs between these processes in specific contexts determine whether vegetation is a water user or producer (Peña-Arancibia et al., 2019). To address the effect of forests on a catchment level, many hydrological studies using *paired-catchment approaches* have been performed since the 1970's (Bosch and Hewlett 1982). Forest removal generally shows increases in streamflow, whereas forest establishment reduces streamflow (on average 23% over 5 years and 38% over 25 years) (Farley et al., 2005; Filoso et al., 2017). Yet, forest increase also reduces peak flows and damaging floods as it increases infiltration capacity, and in some cases, streamflow has partially recovered (Bentley & Coomes, 2020). The hydrological effects of forest removal and restoration on catchment hydrology remain variable due to many different landscape variables at work (Andréassian, 2004; Filoso et al., 2017).

On a planetary scale, the biophysical properties of vegetation regulate the hydrological cycle and climate. Interactions between the biosphere and atmosphere include exchanges of water, energy, momentum (biophysical interaction), and gases (biogeochemical interaction), which co-produce observed climate patterns. Exploring these interactions with computational models has increased our understanding of land cover effects on the global climate. The illustrative model Daisyworld (Watson & Lovelock, 1983) shows the self-regulating properties of vegetation (daisy flowers) that stabilize atmospheric temperature via radiative feedbacks. A similar computational thought-experiment by

Kleidon, Fraedrich, and Heimann (2000) investigates the effect of vegetation on the climate system by conceptualizing two contradicting worlds: a 'desert world' and a 'green planet', accounting for both radiative and hydrological feedbacks. The simulation shows that a green planet produces three times more continental evaporation and transpiration, two times more precipitation and results in a decrease in surface temperature. TMR increases due to the higher energy availability through absorbed radiation and due to increased soil moisture retention capacity associated with tree cover. Although such extreme models are unrealistic, they illustrate the significant climatic effect of interactions within the biosphere-atmosphere system.

2.1 Theory of moisture recycling and land use change

The theory of forest-rainfall connections dates back to the 15th century (see Bennett and Barton 2018). Observations during the European exploration of the Americas have led naturalists to argue that rainfall over dense continental forests derived from forest evaporation itself. Furthermore, deforestation on colonized islands, such as the Azores, led to observations of reduced rainfall, but without tools to quantify such dynamics, these theories remained unverified (Bennett and Barton 2018). Biogeographers generally assumed that observed vegetation patterns were a consequence of assuming more-or-less stable weather patterns (e.g. rainfall is an external variable that is not influenced by the vegetation itself) (van Noordwijk & Ellison, 2019). In the 1970's, rainfall reductions in the Sahel were linked to reduced vegetation cover resulting from overgrazing and landscape degradation. Savenije (1995) developed a moisture recycling theory based on hydrological processes, confirming the mechanistic role of vegetation reductions on drought spells. More recent TMR studies show a strong dependency on recycled rainfall in wet tropical regions (i.e. the Amazon and Congo basin) (Wang-Erlandsson et al., 2018). Advances in computer models and the availability of global climate data reinforced a revival of the inquiry into TMR, questioning the extent to which the earth surface, and particularly vegetation, contributes to rainfall patterns via the exchange of mass, energy and momentum (Eltahir and Bras 1996; Bennett and Barton 2018). This gave rise to the idea that forests *generate* rainfall. As such, deforestation would result in rainfall reductions via interacting feedbacks at the micro- and macroscale (Figure 2)

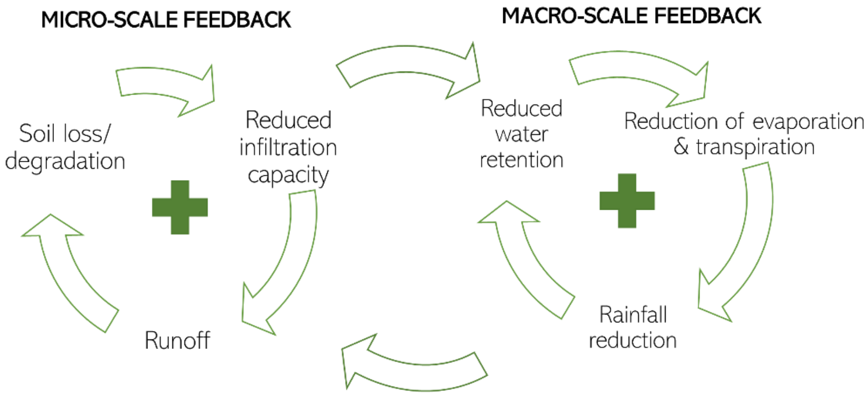


Figure 2 Interaction between micro- and macroscale hydrological feedbacks in the soil-vegetation-climate system following reduction of vegetation cover. On the microlevel, the loss of vegetation cover reduces the infiltration capacity due to changes in the soil (i.e. rooting structure, desiccation). This increases runoff and results in soil degradation, further reducing soil infiltration capacity. On the macro-scale, the reduction in infiltration capacity reduces soil water retention, which results in lower evaporation and transpiration rates. Subsequently, this would reduce the amount of precipitable water in the atmosphere and leads to lower rainfall.

2.2 Approaches, tools and methods to address moisture recycling

The hydrological toolbox to assess the effect of LUC on rainfall comprises of computational, statistical and chemical methods. Computational methods use coupled land surface and vegetation models to climate models to represent relevant interactions between the biosphere and atmosphere. On global scales, General Circulation Models (GCMs) and dynamic vegetation models have been coupled to simulate interactions between climate and vegetation (Foley et al., 1998). Atmospheric moisture tracking models that are forced with meteorological data (i.e. ERA-Interim data) can identify source and sinks of atmospheric moisture, which allows tracking of moisture forward and backward in time (Keune & Miralles, 2019; van der Ent et al., 2014; Zemp et al., 2014). Subsequently, such simulations can be summarized into metrics representing regional dependency on recycled moisture. The *precipitation recycling ratio* ρ, for example, is defined as the fraction of precipitation that derives from land surface evaporation (P_E) over the fraction deriving from oceanic sources (P_O) (van der Ent et al., 2014):

$$\rho = \frac{P_E}{P_O}$$

Vice versa, the *evaporation recycling ratio* describes the fraction of regional evaporation which returns as precipitation over land. Statistical approaches use remote sensing measurements that link

LUC to changes in rainfall. Changes in total evaporation and transpiration (TET) over forests are measured using flux towers or satellite imagery and climate data (Shivers et al., 2019). Yet, causality is difficult to prove due to the influence of many other biophysical and climatic factors (e.g. meso-scale atmospheric circulations) (Spracklen et al., 2018). Chemical approaches use isotope measurements that allow backtracking of different moisture sources and their contribution to local rainfall (Zhao et al. 2019). Stable isotope ratios of hydrogen and oxygen (i.e. the isotopic compositions) vary between different sources of moisture (e.g. advection, evaporation or transpiration) hence reflect information about the source of atmospheric moisture (Gat, 1996).

Precipitation and evaporation recycling ratios are measures of strength of hydrological land surface-atmosphere coupling and are used to identify local, regional or distant rainfall responses of surface evaporation and transpiration (Goessling & Reick, 2011). They are shape- and scale-dependent: the evaporation of an infinitely small area would have negligible contribution to precipitation while the whole earth would have a moisture recycling ratio of 1 (Trenberth 1999). The relation between scale and recycling follows a non-linear relationship due to the spatial heterogeneity encountered with scaling up or down (Dominguez et al., 2006). The *precipitationshed* (Keys et al. 2012) captures the spatial dependence between source and sink regions of atmospheric moisture. It is “the upwind atmosphere and upwind terrestrial land surface that contributes evaporation to a specific location’s precipitation (e.g. rainfall)” (Keys et al. 2012: 734). It represents an analytical framework to identify the source area of precipitation in a region of interest (i.e. sink region). Vice versa, the *evaporationshed* identifies the sink area of evaporation from a given area. The frameworks build on the concept of an *atmospheric river,* a feature in the hydroclimate that transports large amounts of water vapour from the ocean inland. Contrary to watersheds, precipitationsheds are probabilistic, in the sense that they do not have fixed borders, and are subjected to inter and intra-annual variation (Keys et al. 2012). Similarly, the concept of a *watershed precipitation recycling network* (Keune & Miralles, 2019) establishes atmospheric moisture connections on a watershed level, to identify how evaporation from one watershed contributes to precipitation in another (Keys, Wang-Erlandsson, and Gordon 2016). Finally, the concept of *moisture cascades* describes ‘*moisture transport between two* *locations on the continent that involves re-evaporation cycles along the way'* (Zemp et al. 2017, 2014) and addresses the *hydrological connectivity* of regions (Schaefli et al., 2012; Van Der Ent et al., 2010; Van Der Ent & Savenije, 2011). Although TMR estimates are limited predictors of the effect of changes in evaporation to precipitation due to a sequence of processes occurring in the atmosphere (Goessling & Reick, 2011) – they are useful to examine a region's vulnerability to changes in evaporation within the precipitationshed.

3. Methodology

As there was no existing systematic review paper, a scoping review of the literature on moisture recycling dynamics was carried out with the following search criteria on Scopus: "Terrestrial moisture recycling" OR "Moisture Recycling" AND "Atmospheric" OR "Land-Atmosphere" OR "Land-atmosphere dynamics" OR Land-use change" AND "moisture recycling" (1106 search results on 5-10-2020). Relevant literature was selected and subsequently, using backtracking and hand searching, additional literature was added. The references were analyzed for 1) relevant mechanistic relations and feedbacks in the soil-vegetation-climate system, specifically micro- and macro-scale dynamics and 2) empirical observations and modelling simulations of quantitative hydrological change in relation to LUC. Evidence from different continents and climate regions using Köppen-Geiger classification is included to account for regional variation (Table 1).

Table 1 Reviewed literature and their covered bioclimatic zone and region/countries.

	BIOCLIMATIC ZONE (KÖPPEN)	REGION/ COUNTRY	# PAPERS	REFERENCES
NORTH AMERICA	Bsk; Dfb	US; Canada	3	(Dominguez et al., 2006); (Meng & Quiring, 2010); (Raddatz, 2005)
SOUTH AMERICA	Af/Am/ Aw	Amazon; Brazil; Bolivia	9	(Bagley et al., 2014); (Boers et al., 2017); (Butt et al., 2011); (Makarieva et al., 2014); (Staal et al., 2018); (Weng et al., 2019); (D.C. Zemp et al., 2014);(D.C. Zemp et al., 2017) (Delphine Clara Zemp et al., 2017)
EUROPE	Dfb; Ds; Cfb; Csa;	Central Europe; Iberian Peninsula; United Kingdom; Eastern Mediterranean	7	(Bisselink & Dolman, 2009); (Kelemen et al., 2016); (Rios-Entenza et al., 2014);(Robinson et al., 2016); (Zangvil et al., 2010); (Cammeraat et al., 2010); (Nadal-Romero et al., 2016)
AFRICA	BWh;	Sahel; Zimbabwe;	10	(Yu et al., 2017) (Savenije, 2004)

	BSh; Aw/As; BShs; Aw; Af	Ethiopia; South Africa; Nile basin; Cameroon; Congo Basin; North-Africa		(Castelli et al., 2019); (van Luijk et al., 2013); (Mohamed et al., 2005); (Njitchoua et al., 1999); (Saeed et al., 2013); (Savenije, 1995); (Yu et al., 2018) (Bamba et al., 2019)
ASIA	BWk; BSk; BSk/ET; BSk; Dfc; Cfa; BSk;	Northern-China; Tibetan Plateau; Arid eastern-central Asia; Central Siberian Plateau; South China; Tianshan Mountains; Russia; Ganges basin; East China	12	(Zhao et al., 2019); (Bai et al., 2019); (An et al., 2017); (Dong et al., 2018); (Ford & Frauenfeld, 2016); (Guo et al., 2019); (Huang et al., 2018); (Kong & Pang, 2016);(Kurita & Yamada, 2008); (Notaro & Liu, 2008); (Tuinenburg et al., 2012); (Z. Yang et al., 2019)
AUSTRALIA /PACIFIC	BWh/ BSh	Australia; New Zealand	3	(Syktus & McAlpine, 2016); (Szeto, 2002); (Vervoort et al., 2009)
GLOBAL	-	-	16	(Green et al., 2017); (Wang-Erlandsson et al., 2014); (van der Ent et al. 2014); (Duveiller et al., 2018); (Gerten et al., 2004); (Van Der Ent et al., 2010); (Sterling et al., 2013); (Peña-Arancibia et al., 2019); (Wang-Erlandsson et al., 2018); (Keys, Wang-Erlandsson, and Gordon 2016); (Trenberth 1998) (K.E. Trenberth, 1999) (Keys et al. 2012); (Keys et al. 2014); (D.G. Miralles et al., 2016); (Spracklen et al., 2012) (Spracklen et al., 2018)

4. Results

This chapter represents the findings from the literature review and is divided into a framework describing the general dynamics of moisture recycling (see 4.1), and an empirical framework addressing simulated and observed evidence of the impact of LUC on precipitation patterns (see 4.2) and implications for governance (see 4.3).

4.1 Dynamics of moisture recycling

The literature on TMR shows that there is a large spatial and temporal variation in the regional dependence on recycled moisture (Table 2). Some regions receive the majority of precipitation from oceanic sources (e.g. western Europe), while others depend on moisture from continental origin (e.g. inland regions such as the East African savanna and Mongolian steppe) (Miralles et al., 2016). There are 'hotspots' of regionally strong precipitation feedbacks in transitional zones (grasslands and savannas), such as semi-arid and monsoonal regions (Green et al. 2017) and of moisture recycling in regions where orographic lift drives precipitation events (Van Der Ent et al. 2010), in sub-tropical highlands with high evaporation and small advective moisture fluxes, and in convergence zones (Trenberth, 1999). Gradients of increased moisture recycling dependency moving further away from the coast have been observed in Cameroon (Njitchoua et al., 1999) and the Iberian Peninsula (Rios-Entenza et al., 2014).

Table 2 Three examples of water basin's internal recycling (i.e. amount of rainfall deriving from the basin itself) dependency regimes.

	PRECIPITATION RECYCLING	RECYCLING DEPENDENCY	REFERENCE
Nile basin	8-14%	Low	(Mohamed et al., 2005).
Amazon basin	32% (60% from transpiration)	High	(Staal et al., 2018).
Ganges basin	5-60%	Seasonal variable	(Tuinenburg et al., 2012).

Seasonal variation in terrestrial moisture recycling is caused by the warmer land surface compared to the ocean during summer, resulting in higher continental precipitation recycling ratios (Dominguez et al., 2006 Szeto, 2002). Higher moisture availability at the land surface in the wet season increases the relative importance of surface evaporation to precipitation (Van Der Ent et al. 2010). In summer, 74% of precipitation over watersheds in Europe derive from evaporated moisture supplied by other watersheds (Keune & Miralles, 2019). Some regions depend highly on recycled moisture to produce peak spring precipitation (Rios-Entenza et al. 2014). Intra-annual variation in moisture recycling patterns can be caused by weather cycles, such as El Niño Southern Oscillation (Yang et al. 2018), the North Atlantic Oscillation and monsoonal cycles (Guo et al., 2019). Weather anomalies, such as extreme precipitation or drought events can be traced back to high continental evaporation (Kelemen et al., 2016) or low advection (Bisselink & Dolman, 2009) respectively, the latter showing increasing importance of local evaporation to sustain precipitation. Extreme rainfall events in the Congo basin were linked to moisture recycling *reductions* due to relative lower soil moisture availability and higher surface runoff (Saeed et al., 2013).

As precipitation length scales vary between 500-7000 km (Van Der Ent & Savenije, 2011), evaporated water is likely to precipitate *outside* the water basin it originates from. In northern China, 15-50% of the precipitation is derived from local (i.e. within the water basin) terrestrial moisture (Zhao et al., 2019). China is for 80% dependent on continental evaporated moisture (Figure 3), although regional variation is large. Rainfall in forests in the southwest of the Amazon basin derives largely from transpiration and evaporation in other parts of the basin (Staal et al., 2018). The Congo basin depends largely on evaporated moisture from East-Africa, and supplies rainfall to the Sahel region. *Moisture recycling cascades* in this region appear established due to dominant continental wind patterns (Zemp et al. 2014). Moisture recycling cascades over South America contribute around 10% of the total precipitation over the continent. In the La Plata basin, 17-18% of the rainfall derives from such cascades, generally deriving from the Amazon due to the topography of the Andes mountains guiding the moist air from the Amazon downward to the La Plata basin. Local moisture recycling in mountainous regions (e.g. Tibetan Plateau, the Andes) is dominant due to orographic lift (Kong & Pang, 2016). Moisture recycling estimates from the Rocky Mountains in the US show a higher ratio around the mountain range (Dominguez et al., 2006). Around the Tibetan plateau, estimates show that 50-80% of the precipitation derives from locally evaporated water (Kurita & Yamada, 2008) (An et al., 2017). An observed increase in moisture recycling may be caused by climate change, which increases both evaporation and precipitation rates in the region (An et al., 2017).

In tropical regions, precipitation length scales are generally shorter (500-2000 km) and driven by monsoonal dynamics with intense feedbacks and short atmospheric lifetimes. In the Amazon, roughly one-third of the rainfall derives from the basin itself, of which 60% comes from plant transpiration (Staal et al., 2018). The ability of these plants to access deeper soil moisture can be important to remain transpiration flows in the dry season (Wang-Erlandsson et al., 2014) and sustain precipitation even when advection from the ocean is low (Staal et al., 2018). On average, 46% of the transpiration falls back as precipitation in the basin itself, while in the dry-season this can amount up to 70% (Staal et al., 2018). In the Ganges basin, moisture recycling varies between 5-60% and is low in winter and high in summer during the monsoon. Spatial variation in the atmospheric water budget (70% inter-basin difference) is most likely caused by irrigation schemes, increasing evaporation locally, even during the dry season (Tuinenburg et al., 2012). TET from Indian irrigation schemes alone may support 40% of the rainfall in regions in East Africa (de Vrese et al., 2016). When evaporation is high, the distance of moisture travelled is generally shorter. This might be caused by convection subsequently triggering local precipitation.

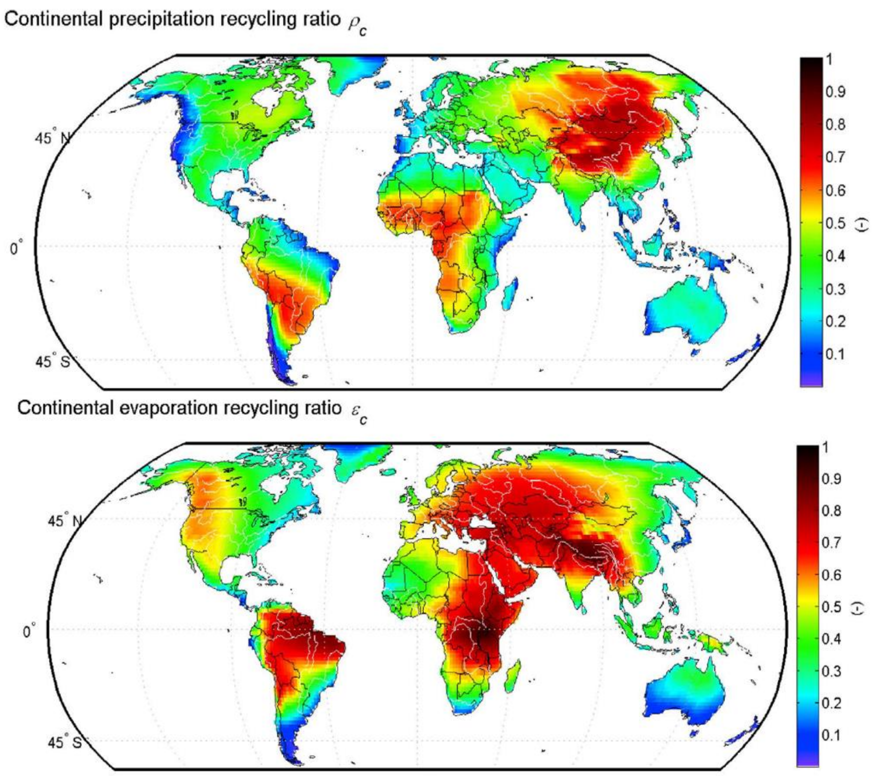


Figure 3 Global continental precipitation recycling ratio (ρ_c) and evaporation recycling ratio (ε_c). Figure copied with the author's permission from Van der Ent et al (2010).

In water limited regions, temporal variation in the fraction of terrestrial moisture recycling between the wet and dry season is small. In the Nile basin, the inter-annual moisture recycling variation is low (between 8-14%). Annually, more than 89% of the water resources originate from outside the basin itself (Mohamed et al., 2005). Comparing wet season recycling ratios of water limited regions shows that in the South American Pampas, recycling is only 3%, whereas in the Kalahari, it is 28%. In the dry season, recycling in the Kalahari reaches up to 34% (Miralles et al., 2016). In the Sahel, local moisture recycling appears strong in the post-monsoon period due to wet soils and high vegetation growth (Yu et al., 2017). Observations of high vegetation productivity in seasonally dry regions correlate with increases in evaporation and transpiration and lead to increasing precipitation (Green et al., 2017). This implies that in dry regions, retaining water locally (i.e. preventing quick run-off), might result in an intensification of local precipitation in the wet season and post-monsoon period (Figure 4). Many semi-arid regions are depending on recycled moisture for agricultural production during the growing season which also makes them social-economically vulnerable to changes in precipitation (Dominguez et al., 2006). Vice versa, dry spells in these regions can facilitate positive land-atmosphere feedbacks that can amplify drought (Miralles et al., 2016). Thus, patterns of TMR in time and space appear highly variable and influenced by local geography, climate, topography and vegetation properties.

Figure 4 Constructing half-moon pits to capture runoff in degraded landscapes in the Baviaanskloof Hartland, South Africa (Source: Living Lands, 2020).

4.2 Effects of land use change on precipitation patterns

This section addresses simulated and observed evidence of the impact of LUC on TMR. Moisture recycling metrics (e.g. evaporation recycling ratio) cannot be used directly to estimate the impact of LUC on precipitation, due to uncertainties in the effect of changes to the atmospheric moisture budget (Goessling and Reick, 2011) and water's active role in the climate system. Although temporal reductions in evaporation have shown significant precipitation effects (Keys et al. 2014), studies that specifically address the impact of LUC on precipitation are scarce. This is not surprising, as the processes of scale, data-availability, and lack of clear causalities in complex systems present difficulties to find clear evidence (Spracklen et al., 2018). For the Amazon and Sahel, rainfall patterns have changed following vegetation cover reduction, but the processes are caused by different mechanisms and with different effects. Hence it is crucial to understand how LUC affect precipitation patterns and the scale at which they become significant. First, we describe the role of vegetation in moisture recycling more generally. Subsequently, we specifically address the effects of de- and reforestation.

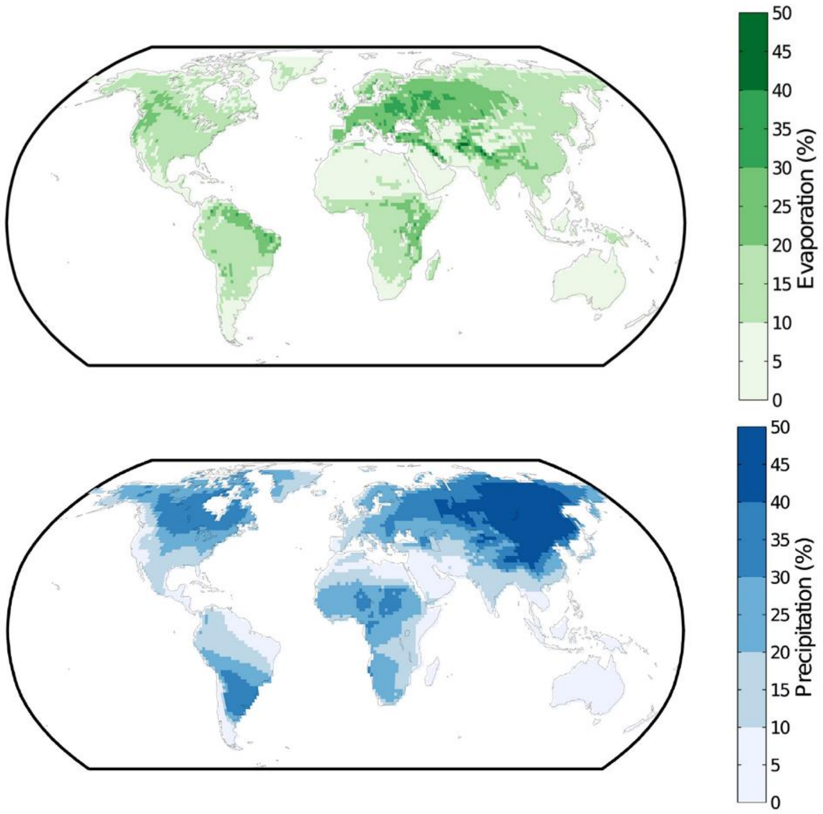


Figure 5 **Source regions** (left) percentage of vegetation-regulated evaporation that falls as precipitation on land Source: figure copied from (Keys, Wang-Erlandsson, and Gordon 2016) and **sink regions** (right) percentage of precipitation that derives from vegetation-regulated evaporation. Source: figure copied with the author's permission from Keys, Wang-Erlandsson, and Gordon (2016)

4.2.1 The effect of vegetation on upward moisture fluxes

Vegetation regulates fluxes of transpiration and evaporation with various dynamics, i.e. magnitudes, sources and time scales (Wang-Erlandsson et al. 2014). A global analysis shows that 22% of terrestrial rainfall is *vegetation-regulated,* although spatial variation is large (Figure 5) (Keys et al., 2016). In Mato Grosso, Brazil, a vast region with different land uses and high rates of LUC, 30-45%

of the evaporation is vegetation-regulated. Furthermore, 6% of the precipitation in the region itself derives from vegetation-regulated moisture recycling. A hypothetical transformation of this region to a desert state, shows less interannual variability in rainfall and a strong reduction (-45%) in rainfall in the dry season. This implies that vegetation-regulated moisture recycling in this area is important to produce rainfall during the dry season (Keys, Wang-Erlandsson, and Gordon, 2016).

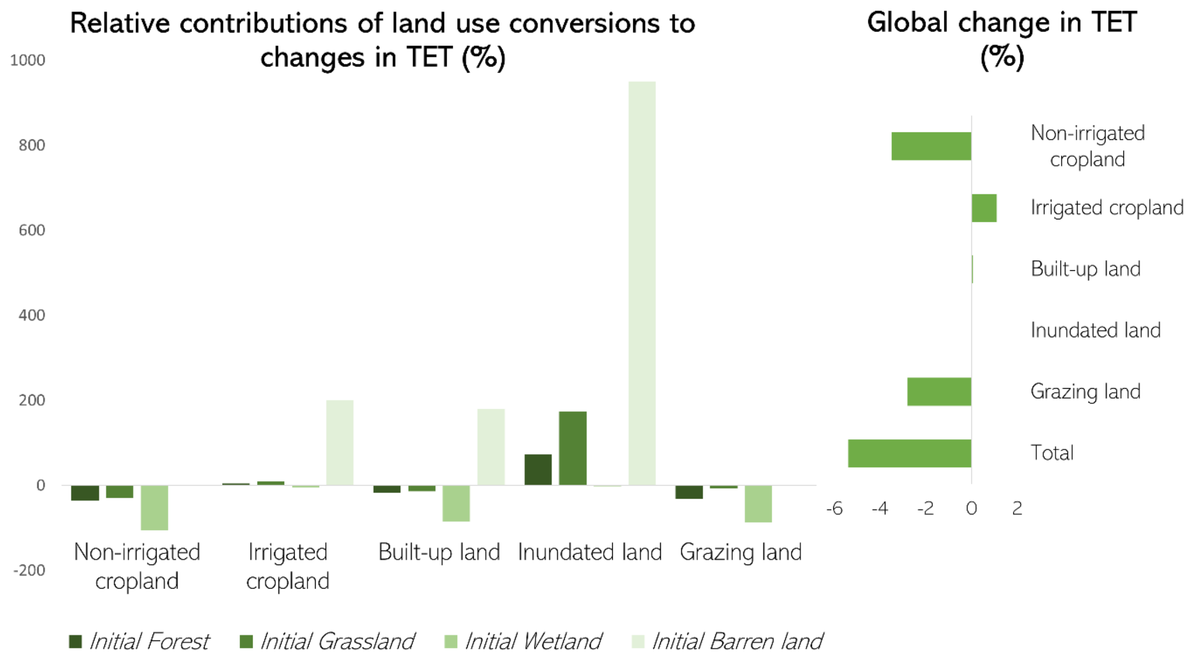


Figure 6 Contributions of various LUC to changes in TET. The horizontal graph on the left shows the relative contributions of land use conversions (from initial to anthropogenic land cover) to changes in global total evaporation and transpiration (TET). Converting barren land to inundated land increases TET over that area with >900%. The vertical graph on the right shows the normalized contributions of the different land use conversions to the global change in TET (%). It shows that conversion to non-irrigated croplands have reduced global TET with nearly 4% (data derived from Sterling et al. (2013).

Figure 6 shows the effects of different LUC on TET. On the left, it shows the relative changes in TET for specific conversions (e.g. converting barren land to inundated land increases TET with 900%). On the right, the contribution of land use conversions to the total change in global TET is shown. It shows that the global conversion to non-irrigated cropland has globally reduced TET with 3.5%. Hotspots of changes in TET following LUC are situated in Western Africa, South-East Asia and Eastern Europe. These are regions that have experienced large scale land use conversion of forest and grasslands to irrigated and non-irrigated croplands (Sterling et al., 2013).

LUC closer to the ocean might have a higher impact on precipitation patterns downwind due to the effect of moisture cascades moving inland (Schaefli et al., 2012). Precipitation and forest cover show a positive relationship along an atmospheric moisture transport trajectory in the tropics (Spracklen, Arnold, and Taylor 2012). Air moving over dense vegetation produces more than twice the amount of rain compared to air moving over sparse vegetation. The mechanisms behind the observation are disputed: one explanation postulates increasing TET over the forest canopy intensifies the hydrological cycle, assuming no change in atmospheric circulation (Spracklen, Arnold, and Taylor 2012), whereas another theory stipulates the ‘secondary’ effect of forest evapotranspiration, creating a low pressure system, subsequently drawing in atmospheric moisture from the oceans (Makarieva et al., 2014). Meteorological data gathered for the Amazon forest confirms changes in atmospheric pressure regime due to different atmospheric moisture contents. This implies that forest loss in tropical ecosystem can potentially change atmospheric circulation, yet the scales of forest loss at which this becomes significant remains unclear.

4.2.2 Deforestation

The effect of deforestation on moisture recycling patterns is influenced by 1) direct changes in the magnitude and timing of moisture fluxes, and 2) indirect changes in atmospheric circulation due to exchanges in energy, moisture, and momentum. Vegetation cover loss can severely affect infiltration, interception and moisture storage at the land surface (van Luijk et al., 2013), triggering a ‘soil erosion feedback’ that gradually result in the loss of ecosystem resilience (Flores et al., 2019) and reduces upward moisture fluxes which can produce self-propagating droughts and heatwaves via land feedbacks (Miralles et al., 2019). In many regions where TET reductions following agricultural expansion occurred, downwind reductions in precipitation were observed (Wang-Erlandsson et al., 2018). In most cases, changes in rainfall occurred outside of the river basin, which implies that LUC are less likely to produce local effects. In the Amazon basin however, local feedbacks are unusually strong - significant deforestation-rainfall relations were found on a scale of 30-50 km - anticipating stronger local effects of deforestation (Spracklen et al., 2018). In the dry-season and in drought years – when oceanic inflow is low - the relative importance of moisture recycling increases, which implies that reduced forest cover can result in a self-amplified forest loss during drought events (Bagley et al., 2014; Zemp et al., 2014) A ‘*deforestation-induced tipping point’* is proposed for the Amazon, referring to the westward moisture cascade in which some regions are depending on precipitation from evaporation elsewhere. Using observation-based moisture recycling networks, Zemp et al. (2017) show that Amazon deforestation can reduce rainfall in the La Plata basin in the dry season with up to 20%. Subsequent loss of forest resilience suggests that it can trigger further climatological effects resulting in permanent forest reduction along the moisture recycling cascade (Zemp et al. 2017). Deforestation along the cascade affects the monsoonal circulation that is initially driven by latent heat from the rainforest, which attracts moist air coming from the Atlantic Ocean. Deforestation reduces transpiration up to a moment in which atmospheric moisture is insufficient to release latent heat, which is a crucial mechanisms to draw in moist air (Boers et al., 2017). Furthermore, air moving over deforested land loses more moisture relatively, due to lower evapotranspiration rates (intact Amazonian forest on average adds 3-4 mm of transpiration to the air). The cascading effect (Zemp et al. 2017) might therefore result in lower downwind precipitation. Increasing scales of Amazonian deforestation trigger changes in thermal circulations and surface roughness. In deforested lands wider than 10 km, changes in surface roughness and sensible heat can already trigger mesoscale circulation changes resulting in redistribution of rainfall. On very large scales, 100-1000 km, deforestation can change atmospheric properties that result in macroscale hydroclimatic changes (Spracklen et al., 2018). Furthermore, long term rainfall trend data from Rondonia, Brazil, shows that regions with large deforestation rates, have experienced a delay in the onset of the rainy season of 11 days (Butt et al., 2011).

Some deforested areas show an *increase* in total precipitation. In the South-West of Brazil, satellite-derived evidence suggests an increase in dry-season cumulus and convective clouds over deforested area (Negri et al., 2004). This may be due to increased surface heating over deforested regions, producing an upward air motion which draws atmospheric moisture from neighbouring areas. Fragmented deforestation patterns may also lead to observations of increased rainfall: tropical forest edges produce more transpiration compared to its interior due to micro-climatic effects, which may result in increased rainfall. Deforestation increases energy transfers between the land surface and the atmosphere which drive thermal circulations, leading to an observed increase in precipitation patterns in parts of the Amazon (Chagnon & Bras, 2005). Based on long-term rain gauge observations, a seasonal shift in precipitation was also recorded. LUC appeared to have a more severe effect on dry-season precipitation in the Amazon (Bagley et al., 2014). In cold climates, the effect of snow cover is important. Increased albedo following forest cover reduction in Russia elongates the snow season, reduces air temperature and transpiration, and results in lower moisture recycling rates (Notaro & Liu, 2008). In arid climates, such as the Sahel, vegetation reductions resulting in an increased albedo and reduced evapotranspiration, might have exacerbated drought duration in the 20th century extreme droughts occurring in these regions (Charney & Stone, 1975; Savenije, 1995). Recycling of evaporated moisture in the Sahelian belt appeared to contribute significantly to rainfall patterns in the region during the wet season. By changing energy and moisture fluxes, this may have affected convection and circulation of the African Easterly Jet (Yu et al., 2018).

4.2.3 Reforestation and afforestation

Although in theory, increasing vegetation cover can positively affect local rainfall patterns, there is little known about the bioclimatic conditions and spatial and temporal scale of reforestation required to increase moisture recycling. The Loess Plateau in China has experienced a long period of severe degradation from intensive agriculture, followed by extensive reforestation since the year 2000's under the Grain for Green Project which has doubled vegetation coverage on the Plateau from 31% in 1999 to 59% in 2013 (Bai et al., 2019). Sub-basin evapotranspiration trends show a significant increase in (mainly summer) TET of 3.45 mm year^{-} (Bai et al., 2019). Vegetation productivity contributed 93% to this increasing TET trend (Bai et al., 2019). Soil moisture response of former farmlands to pine forest shows a 35% reduction in soil moisture content in deeper soil layers. No significant differences in soil moisture reductions were found for different vegetation types. Observed soil moisture deficits mostly related to plant density. Pine tree species are known to deplete soil moisture due to their ever greenness (Yang et al. 2012). Reforestation simulations using regional climate models for West Africa and the Sahel how that reforestation can enhance precipitation with+3.6 - 14.4% (Oguntunde et al., 2014) but the location of the reforestation experiment has a significant role on macro-scale climatic changes and the spatial distribution of predicted rainfall patterns (Bamba et al., 2019). Reforestation enhanced surface roughness, weakening the atmospheric temperature gradient, which results in a delay in the onset of the monsoon (Oguntunde et al., 2014). A modelling scenario of potential restoration of Australia's woodlands on current economically marginal lands shows an increase in evaporation, resulting in increased cloud formation and precipitation over the region. The ability of woodlands to access deeper soil moisture would be the mechanism behind increased evaporation (Syktus & McAlpine, 2016). Branch & Wulfmeyer, (2019) assess the possibilities for rainfall enhancement using bio-geoengineering approaches (i.e. forest plantations to deliberately enhance rainfall) in desert regions and conclude that agroforestry plantations enhance local wind convergence, increase cloud cover and precipitation. Regional studies that address the effects of reforestation and afforestation remain scarce. Although in some cases there is evidence that it enhances local precipitation through increased TET, there are many climatic and geographic variables that determine final effects on local and regional rainfall patterns (Keys et al. 2012).

Table 3 Summary of the evidence of LUC (deforestation and reforestation) on various processes governing moisture recycling patterns

	PROCESS	EVIDENCE FROM THE LITERATURE	CLIMATIC REGION	REFERENCES
DEFORESTATION	**Soil moisture/ infiltration**	○ Reduction of infiltration rates (mm h^{-1})	South Africa /succulent vegetation	(van Luijk et al., 2013)
	Green water flow	○ Correlates with rainfall intensity in post-monsoon period	Arid Sahel (Africa)	(Yu et al., 2017) (Zhao et al., 2019)
		○ Change in isotope ratio (evaporation/transpiration)	Arid Northern China	(Sterling et al., 2013)
		○ Reduction in total ET (-5.5%)	(Asia)	(Butt et al., 2011)
		○ Delay in rain season (11 days)	Global assessment	(Zemp et al. 2017)
		○ Reduced dry-season transpiration in comparison to other vegetation (1 mm day^{-1}) from roots accessing subsurface water	Brazil Amazon	
	Albedo	○ Increased local temperature (global average 0.23°C 2000-2015)	Global assessment, effect strongest in tropics	(Duveiller et al., 2018) Charney & Stone (1975)
		○ Cooling and sinking of air suppress convection and rainfall	Semi-arid Sahel	
	Streamflow	○ Global average 18-26% increase in water limited regions	Dry tropics	(Yang et al. 2012) (Peña-Arancibia et al., 2019)
		○ Increase in streamflow in regions with strong seasonality, high infiltration capacity, recharge of soil- and groundwater, high soil moisture storage, groundwater maintaining base flow	Dry tropics	
	Precipitation	○ *Increase* in local rainfall	Southwest Brazil	(Negri et al., 2004)
		○ Reduction in rainfall (more than 50%)	Pan-tropical	(Spracklen et al., 2012)
		○ *Simulated* 20% reduction in the dry season (deforestation scenario's)	Amazon-La Plata (South America)	Zemp et al (2017)
REFORESTATION	**Soil moisture/ infiltration**	○ Roots channeling water to deeper soil layers for natural vegetation development following land abandonment	Southern Spain	(Cammeraat et al., 2010)
		○ Reduction in deep soil moisture from pine plantation	Loess plateau, China	(Yang et al. 2012)
	Albedo	○ Reduction in short wave reflection, increase in latent heat	Global assessment	(Duveiller et al., 2018) (Castelli et al., 2019)
		○ Reduction in land surface temperature (1.74 °C)	Ethiopia	
	Streamflow	○ Decreases, although relatively less with temporal and spatial scales	Global assessment	(Filoso et al., 2017)
		○ Decreases the (seasonal) low flow	Global assessment	(Brown, 2005)
		○ Decreases of time, but in some cases shows partial recovery	Global assessment	(Bentley & Coomes, 2020)
	Precipitation	○ *Simulated* increase in precipitation (1.25%) and runoff in dry season (26%)	Bolivia	(Weng et al., 2019)

4.3 Implications for governance of land use change

Under certain conditions, LUC can affect local or regional rainfall and redistribute – either intentionally or unintentionally – water resources. To ensure equitable and sustainable water use, there is a need to address the governance aspects of land use-water interactions and prevent adverse local or regional effects. Keys et al. (2017) address the notion of transboundary moisture recycling governance as ‘the attempts for steering social and environmental processes among countries and their sometimes-conflicting objectives', evolving around the process of human interactions with moisture recycling patterns. From the literature, three themes of governance approaches emerge: spatial planning, impact assessments, and boundary setting.

4.3.1 Spatial planning approaches

A recent study that investigates the potential to increase rainfall over a municipality in Bolivia with upwind 'smart reforestation' reveals that 7.1 million hectares of reforested land could increase precipitation over the city by 1.25% (5.8 10^8 m^3) annually (Weng et al., 2019). *Aerial river management* – the practice of redistributing flows of atmospheric water through strategic LUC intentionally, has the potential to cover between 22-59% of the additional water demand in 2030 (Weng et al., 2019). Furthermore, considering *moisture recycling trajectories*, generally starting from the coastal area and moving inland, reforestation efforts could consider to be 'build-up' incrementally along this trajectory to increase moisture recycling and also enhance the success rate of reforestation projects (Ellison & Ifejika Speranza, 2020) (Fagan et al., 2020). And finally, the identification of *hotspots* of moisture recycling sources (Zemp et al. 2017) can support delineation of areas for forest protection.

4.3.2. Impact assessments

NCP's associated with TMR are '*diffuse and spatially extensive'* and poses challenges to governance (Keys et al., 2016). *Precipitationshed analysis* (Keys et al. 2017) can identify and quantify the exchanges of atmospheric moisture between countries and provides a framework for impact assessments that addresses the effects of LUC on TMR, as well as the impact of various NCPs. Regional case studies are needed that address hydrological trade-off analyses that explicitly include land-atmosphere feedbacks and TMR patterns (Wang & D'Odorico, 2019; Ellison & Ifejika Speranza, 2020). For example, although bio-geoengineering can enhance rainfall in some regions, it should be balanced against the local effects on hydrology (Wang & D'Odorico, 2019) and cascading effects on social-ecological systems. There is a need for a robust impact assessment framework that can address the (transboundary) social and environmental trade-offs associated with interferences in TMR.

4.3.3. Boundary setting

Advances in earth observation technologies allow for detailed understanding of local to global water use. Measurements of TET and Net Plant Productivity (NPP) via satellite imagery allows for monitoring of green water use. For example, the FAO WaPOR project provides a monitoring platform using remote sensing data that tracks annual gross biomass productivity which shows the biomass production with respect to the actual evapotranspiration. The provided data facilitates water accounting and enables green water management via targeted interventions, for example when local vegetation growth is putting blue water resources at risk. In the Loess Plateau in China, a strong increase in NPP and TET following the Grain to Green reforestation programme has come at the costs of river runoff that is potentially societally unpropitious (Feng et al., 2016). Accordingly, a regional *NPP plafond* is proposed to prevent water shortages amongst the population (Feng et al., 2016). Alternatively, close monitoring of green water use and regional vulnerability also allows for measures restraining the use of high-water demanding species.

Governance of moisture recycling and land use-water interactions is in its infancy. Spatial planning approaches, impact assessments and boundary setting are governance approaches that are proposed in response to spatially extensive and diffuse nature of land-use water interactions via TMR. Furthermore, market-based and regulatory instruments, such as Payment for Ecosystem Services (PES) and transboundary agreements and collaboration, could facilitate the implementation of such approaches. Yet, little is known considering their practical implementation in the context of TMR. Hence, besides the need for tools to address trade-offs in TMR governance, research on the advantages, disadvantages and relation to inter- and transnational legal contexts (i.e. international water law and transboundary agreements) of market-based and regulatory approaches to moisture recycling is needed. Principles reflected in international water law refer to the obligation not to cause significant harm (Rahaman, 2009) which implies that countries may be held accountable when land use change appear to negatively affect rainfall patterns via international agreements. A 'one size fits all' approach to governance is likely to be undesirable due to 1) the spatial and temporal variance land-atmosphere interactions and associated water circulation and 2) the issue of scalability associated with non-linear responses of TMR to LUC.

5. Conclusion

Continuous global land use change, increasing understanding of biosphere-atmosphere interactions, and increasing water scarcity beg the question how LUC affects dynamics and feedback mechanisms with respect to water and rainfall in the soil-vegetation-climate system. This scoping review addressed the state-of-the-art knowledge on moisture recycling in relation to LUC and leads to five main conclusions:

- First, 22% of the global rainfall is vegetation-regulated, which implies that LUC can greatly affect rainfall patterns. In the last decades, LUC have reduced global TET by 5%.
- Second, deforestation in general has reduced local precipitation, distorted moisture recycling cascades (reduce downwind precipitation), intensified drought, delayed the onset of the rain season, and in some cases increased local rainfall due to microclimatic effects. In general, effects on precipitation are more likely to be non-local and occur outside the basin.
- Thirdly, dominant feedback mechanisms and effects differ strongly between regions. In tropical wet regions, stronger local effects of LUC on moisture recycling are expected which implies vegetation is more sensitive to drought and disturbance feedback mechanisms. In water-limited regions like the Sahel, the effects of the energy-feedback are more prominent.
- Fourth, hotspots of moisture recycling may occur along gradients between ocean and land surface, mountainous regions, and transitional zones. These hotspots might require protection to prevent disruption of moisture recycling patterns.
- Finally, the effects of reforestation on moisture recycling patterns appear sensitive to the scale and the spatial location of the reforestation project. Overall, the effects remain largely unexplored. Although this is sensible due to the complex nature of the question, there is a need to further explore the potential hydrological trade-offs of reforestation.

Coupled land surface and climate models have the potential to explore specific LUC scenarios to identify the change in rainfall patterns following different spatial locations and scales of LUC. Analytical tools that allow for atmospheric water network analysis such as moisture recycling cascades (Schaefli et al., 2012), watershed analysis (Keune & Miralles, 2019) and precipitation- and evaporationsheds (Keys et al., 2014) can support water accounting measures and environmental and social impact assessments (Bagley et al., 2012) to govern TMR. The notion of green and atmospheric water governance (Wierik et al., 2020) implies that – amongst others - trade-offs associated with vegetation's ability to redistribute water flows are addressed. This implies, for example, that climate mitigation policies for carbon sequestration explicitly consider the hydro-climatic effects at the precipitationshed level to prevent unexpected hydrological consequences for people and nature.

Acknowledgements

The authors like to acknowledge the Institute for Advanced Study (IAS) and Institute for Interdisciplinary Studies (IIS) from the University of Amsterdam, for providing the opportunity and support to carry out interdisciplinary research of this kind via the Interdisciplinary Doctorate Agreement (IDA).

For the writing of the review manuscript 'Reviewing moisture recycling dynamics: implications of land use change on green and atmospheric water', we did not create new data sets. We build on findings from previously published papers. The data represented in Figure 6 is available through Sterling et al., (2013).

References

Albaugh, J. M., Dye, P. J., & King, J. S. (2013, March 26). *Eucalyptus and Water Use in South Africa* [Review Article]. International Journal of Forestry Research; Hindawi. https://doi.org/10.1155/2013/852540

An, W., Hou, S., Zhang, Q., Zhang, W., Wu, S., Xu, H., Pang, H., Wang, Y., & Liu, Y. (2017). Enhanced recent local moisture recycling on the northwestern Tibetan Plateau deduced from ice core deuterium excess records. *Journal of Geophysical Research: Atmospheres*, *122*(23), 12,541-12,556. Scopus. https://doi.org/10.1002/2017JD027235

Andréassian, V. (2004). Waters and forests: From historical controversyto scientific debate. *Journal of Hydrology*, *291*, 1–27.

Bagley, J. E., Desai, A. R., Dirmeyer, P. A., & Foley, J. A. (2012). Effects of land cover change on moisture availability and potential crop yield in the world's breadbaskets. *Environmental Research Letters*, *7*(1), 014009. https://doi.org/10.1088/1748-9326/7/1/014009

Bagley, J. E., Desai, A. R., Harding, K. J., Snyder, P. K., & Foley, J. A. (2014). Drought and Deforestation: Has Land Cover Change Influenced Recent Precipitation Extremes in the Amazon? *Journal of Climate*, *27*(1), 345–361. https://doi.org/10.1175/JCLI-D-12-00369.1

Bai, M., Mo, X., Liu, S., & Hu, S. (2019). Contributions of climate change and vegetation greening to evapotranspiration trend in a typical hilly-gully basin on the Loess Plateau, China. *Science of The Total Environment*, *657*, 325–339. https://doi.org/10.1016/j.scitotenv.2018.11.360

Bamba, A., Diallo, I., Touré, N. E., Kouadio, K., Konaré, A., Dramé, M. S., Diedhiou, A., Silué, S., Doumbia, M., & Tall, M. (2019). Effect of the African greenbelt position on West African summer climate: A regional climate modeling study. *Theoretical and Applied Climatology*, *137*(1), 309–322. https://doi.org/10.1007/s00704-018-2589-z

Bastin, J.-F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D., Zohner, C., & Crowther, T. (2019). *The global tree restoration potential*. *6448*(365), 76–79.

Bennett, B. M., & Barton, G. A. (2018). The enduring link between forest cover and rainfall: A historical perspective on science and policy discussions. *Forest Ecosystems*, *5*(1), 5. https://doi.org/10.1186/s40663-017-0124-9

Bentley, L., & Coomes, D. A. (2020). Partial river flow recovery with forest age is rare in the decades following establishment. *Global Change Biology*. https://doi.org/10.1111/gcb.14954

Bisselink, B., & Dolman, A. J. (2009). Recycling of moisture in Europe: Contribution of evaporation to variability in very wet and dry years. *Hydrology and Earth System Sciences*, *13*(9), 1685–1697. Scopus. https://doi.org/10.5194/hess-13-1685-2009

Boers, N., Marwan, N., Barbosa, H. M. J., & Kurths, J. (2017). A deforestation-induced tipping point for the South American monsoon system. *Scientific Reports*, *7*(1), 1–9. https://doi.org/10.1038/srep41489

Bosch, J. M., & Hewlett, J. D. (1982). A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*, *55*(1), 3–23. https://doi.org/10.1016/0022-1694(82)90117-2

Branch, O., & Wulfmeyer, V. (2019). Deliberate enhancement of rainfall using desert plantations. *Proceedings of the National Academy of Sciences*, *116*(38), 18841–18847. https://doi.org/10.1073/pnas.1904754116

Brown. (2005). A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology*, *310*(1–4), 28–61. https://doi.org/10.1016/j.jhydrol.2004.12.010

Butt, N., Oliveira, P. A. de, & Costa, M. H. (2011). Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil. *Journal of Geophysical Research: Atmospheres*, *116*(D11). https://doi.org/10.1029/2010JD015174

Cammeraat, E. L. H., Cerda, A., & Imeson, A. C. (2010). Ecohydrological adaptation of soils following land abandonment in a semi-arid environment. *Ecohydrology, 3*, 421–430.

Castelli, G., Castelli, F., & Bresci, E. (2019). Mesoclimate regulation induced by landscape restoration and water harvesting in agroecosystems of the horn of Africa. *Agriculture, Ecosystems & Environment*, *275*, 54–64. https://doi.org/10.1016/j.agee.2019.02.002

Chagnon, F. J. F., & Bras, R. L. (2005). Contemporary climate change in the Amazon. *Geophysical Research Letters*, *32*(13). https://doi.org/10.1029/2005GL022722

Charney, J., & Stone, P. H. (1975). Drought in the Sahara: A Biogeophyscial feedback mechanism. *Science*, *187*, 434–435.

de Vrese, P., Hagemann, S., & Claussen, M. (2016). Asian irrigation, African rain: Remote impacts of irrigation. *Geophysical Research Letters*, *43*(8), 3737–3745. https://doi.org/10.1002/2016GL068146

Dominguez, F., Kumar, P., Liang, X.-Z., & Ting, M. (2006). Impact of Atmospheric Moisture Storage on Precipitation Recycling. *Journal of Climate*, *19*(8), 1513–1530. https://doi.org/10.1175/JCLI3691.1

Dong, W., Lin, Y., Wright, J. S., Xie, Y., Ming, Y., Zhang, H., Chen, R., Chen, Y., Xu, F., Lin, N., Yu, C., Zhang, B., Jin, S., Yang, K., Li, Z., Guo, J., Wang, L., & Lin, G. (2018). Regional disparities in warm season rainfall changes over arid eastern–central Asia. *Scientific Reports*, *8*(1). Scopus. https://doi.org/10.1038/s41598-018-31246-3

Duveiller, G., Hooker, J., & Cescatti, A. (2018). The mark of vegetation change on Earth's surface energy balance. *Nature Communications*, *9*(1). https://doi.org/10.1038/s41467-017-02810-8

Eagleson, P. (2003). *Dynamic Hydrology*. The Maple Press Company.

Eagleson, P. S. (2002). *Ecohydrology: Darwinian expression of vegetation form and function*. https://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=112502

Ellison, D., & Ifejika Speranza, C. (2020). From blue to green water and back again: Promoting tree, shrub and forest-based landscape resilience in the Sahel. *Science of The Total Environment*, *739*, 140002. https://doi.org/10.1016/j.scitotenv.2020.140002

Ellison, D., N. Futter, M., & Bishop, K. (2012). On the forest cover-water yield debate: From demand- to supply-side thinking. *Global Change Biology*, *18*(3), 806–820. https://doi.org/10.1111/j.1365-2486.2011.02589.x

Eltahir, E. A. B., & Bras, R. L. (1996). Precipitation recycling. *Reviews of Geophysics*, *34*(3), 367–378. https://doi.org/10.1029/96RG01927

Fagan, M. E., Leighton Reid, J., Holland, M. B., Drew, J. G., & Zahawi, R. A. (n.d.). How feasible are global forest restoration commitments? *Conservation Letters*, *2020;e12700*.

Farley, K. A., Jobbagy, E. G., & Jackson, R. B. (2005). Effects of afforestation on water yield: A global synthesis with implications for policy. *Global Change Biology*, *11*(10), 1565–1576. https://doi.org/10.1111/j.1365-2486.2005.01011.x

Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., Lü, Y., Zeng, Y., Li, Y., Jiang, X., & Wu, B. (2016). Revegetation in China's Loess Plateau is approaching sustainable water resource limits. *Nature Climate Change*, *6*(11), 1019–1022. https://doi.org/10.1038/nclimate3092

Filoso, S., Bezerra, M. O., Weiss, K. C., & Palmer, M. A. (2017). Impacts of forest restoration on water yield: A systematic review. *PloS One*, *12*(8), e0183210.

Flores, B. M., Staal, A., Jakovac, C. C., Hirota, M., Holmgren, M., & Oliveira, R. S. (2019). Soil erosion as a resilience drain in disturbed tropical forests. *Plant and Soil*. https://doi.org/10.1007/s11104-019-04097-8

Foley, J. A., Levis, S., Prentice, I. C., Pollard, D., & Thompson, S. L. (1998). Coupling dynamic models of climate and vegetation. *Global Change Biology*, *4*(5), 561–579.

Ford, T. W., & Frauenfeld, O. W. (2016). Surface-Atmosphere Moisture Interactions in the Frozen Ground Regions of Eurasia. *Scientific Reports*, *6*. Scopus. https://doi.org/10.1038/srep19163

Gat, J. R. (1996). Oxygen and Hydrogen Isotopes in the Hydrologic Cycle. *Annual Review of Earth and Planetary Sciences*, *24*(1), 225–262. https://doi.org/10.1146/annurev.earth.24.1.225

Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W., & Sitch, S. (2004). Terrestrial vegetation and water balance—Hydrological evaluation of a dynamic global vegetation model. *Journal of Hydrology*, *286*(1–4), 249–270. https://doi.org/10.1016/j.jhydrol.2003.09.029

Goessling, H. F., & Reick, C. H. (2011). What do moisture recycling estimates tell us? Exploring the extreme case of non-evaporating continents. *Hydrology and Earth System Sciences*, *15*(10), 3217–3235. Scopus. https://doi.org/10.5194/hess-15-3217-2011

Green, J. K., Konings, A. G., Alemohammad, S. H., Berry, J., Entekhabi, D., Kolassa, J., Lee, J.-E., & Gentine, P. (2017). Regionally strong feedbacks between the atmosphere and terrestrial biosphere. *Nature Geoscience*, *10*(6), 410–414. https://doi.org/10.1038/ngeo2957

Guo, L., Van Der Ent, R. J., Klingaman, N. P., Demory, M.-E., Vidale, P. L., Turner, A. G., Stephan, C. C., & Chevuturi, A. (2019). Moisture sources for East Asian precipitation: Mean seasonal cycle and interannual variability. *Journal of Hydrometeorology*, *20*(4), 657–672. Scopus. https://doi.org/10.1175/JHM-D-18-0188.1

Huang, W., He, X., Yang, Z., Qiu, T., Wright, J. S., Wang, B., & Lin, D. (2018). Moisture Sources for Wintertime Extreme Precipitation Events Over South China During 1979–2013. *Journal of Geophysical Research: Atmospheres*, *123*(13), 6690–6712. Scopus. https://doi.org/10.1029/2018JD028485

Kelemen, F. D., Ludwig, P., Reyers, M., Ulbrich, S., & Pinto, J. G. (2016). Evaluation of moisture sources for the Central European summer flood of May/June 2013 based on regional climate model simulations. *Tellus, Series A: Dynamic Meteorology and Oceanography*, *68*. Scopus. https://doi.org/10.3402/tellusa.v68.29288

Keune, J., & Miralles, D. G. (2019). A Precipitation Recycling Network to Assess Freshwater Vulnerability: Challenging the Watershed Convention. *Water Resources Research*, *55*(11), 9947–9961. https://doi.org/10.1029/2019WR025310

Keys, P. W., van der Ent, R. J., Gordon, L. J., Hoff, H., Nikoli, R., & Savenije, H. H. G. (2012). Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions. *Biogeosciences*, *9*(2), 733–746. https://doi.org/10.5194/bg-9-733-2012

Keys, Patrick W., Wang-Erlandsson, L., & Gordon, L. J. (2016). Revealing Invisible Water: Moisture Recycling as an Ecosystem Service. *PLOS ONE*, *11*(3), e0151993. https://doi.org/10.1371/journal.pone.0151993

Keys, Patrick W., Wang-Erlandsson, L., Gordon, L. J., Galaz, V., & Ebbesson, J. (2017). Approaching moisture recycling governance. *Global Environmental Change*, *45*, 15–23. https://doi.org/10.1016/j.gloenvcha.2017.04.007

Keys, P.W., Barnes, E. A., Van Der Ent, R. J., & Gordon, L. J. (2014). Variability of moisture recycling using a precipitationshed framework. *Hydrology and Earth System Sciences*, *18*(10), 3937–3950. Scopus. https://doi.org/10.5194/hess-18-3937-2014

Kleidon, A., Fraedrich, K., & Heimann, M. (2000). A green planet versus a desert world: Estimating the maximum effect of vegetation on the land surface climate. *Climatic Change*, *44*(4), 471–493.

Kong, Y., & Pang, Z. (2016). A positive altitude gradient of isotopes in the precipitation over the Tianshan Mountains: Effects of moisture recycling and sub-cloud evaporation. *Journal of Hydrology*, *542*, 222–230. Scopus. https://doi.org/10.1016/j.jhydrol.2016.09.007

Kurita, N., & Yamada, H. (2008). The role of local moisture recycling evaluated using stable isotope data from over the middle of the Tibetan Plateau during the monsoon season. *Journal of Hydrometeorology*, *9*(4), 760–775. Scopus. https://doi.org/10.1175/2007JHM945.1

Makarieva, A. M., Gorshkov, V. G., Sheil, D., Nobre, A. D., Bunyard, P., & Li, B.-L. (2014). Why does air passage over forest yield more rain? Examining the coupling between rainfall, pressure, and atmospheric moisture content. *Journal of Hydrometeorology*, *15*(1), 411–426. Scopus. https://doi.org/10.1175/JHM-D-12-0190.1

Meng, L., & Quiring, S. M. (2010). Observational relationship of sea surface temperatures and precedent soil moisture with summer precipitation in the U.S. great plains. *International Journal of Climatology*, *30*(6), 884–893. Scopus. https://doi.org/10.1002/joc.1941

Miralles, D.G., Nieto, R., McDowell, N. G., Dorigo, W. A., Verhoest, N. E. C., Liu, Y. Y., Teuling, A. J., Dolman, A. J., Good, S. P., & Gimeno, L. (2016). Contribution of water-limited ecoregions to their own supply of rainfall. *Environmental Research Letters*, *11*(12). Scopus. https://doi.org/10.1088/1748-9326/11/12/124007

Miralles, Diego G., Gentine, P., Seneviratne, S. I., & Teuling, A. J. (2019). Land–atmospheric feedbacks during droughts and heatwaves: State of the science and current challenges. *Annals of the New York Academy of Sciences*, *1436*(1), 19–35. https://doi.org/10.1111/nyas.13912

Mohamed, Y. A., van den Hurk, B. J. J. M., Savenije, H. H. G., & Bastiaanssen, W. G. M. (2005). Hydroclimatology of the Nile: Results from a regional climate model. *Hydrology and Earth System Sciences*, *9*(3), 263–278. Scopus.

Nadal-Romero, E., Cammeraat, E., Serrano-Muela, M. P., Lana-Renault, N., & Regüés, D. (2016). Hydrological response of an afforested catchment in a Mediterranean humid mountain area: A comparative study with a natural forest: Hydrological Response of an Afforested Area in Mediterranean Mountain. *Hydrological Processes*, *30*(15), 2717–2733. https://doi.org/10.1002/hyp.10820

Negri, A. J., Adler, R. F., Xu, L., & Surratt, J. (2004). The impact of Amazonian deforestation on dry season rainfall. *Journal of Climate*, *17*(6), 1306–1319.

Njitchoua, R., Sigha-Nkamdjou, L., Dever, L., Marlin, C., Sighomnou, D., & Nia, P. (1999). Variations of the stable isotopic compositions of rainfall events from the Cameroon rain forest, Central Africa. *Journal of Hydrology*, *223*(1–2), 17–26. Scopus. https://doi.org/10.1016/S0022-1694(99)00087-6

Notaro, M., & Liu, Z. (2008). Statistical and dynamical assessment of vegetation feedbacks on climate over the boreal forest. *Climate Dynamics*, *31*(6), 691–712. Scopus. https://doi.org/10.1007/s00382-008-0368-8

Oguntunde, P. G., Abiodun, B. J., Lischeid, G., & Merz, C. (2014). Modelling the impacts of reforestation on the projected hydroclimatology of Niger River Basin, West Africa. *Ecohydrology*, *7*(1), 163–176. Scopus. https://doi.org/10.1002/eco.1343

Peña-Arancibia, J. L., Bruijnzeel, L. A., Mulligan, M., & van Dijk, A. I. J. M. (2019). Forests as 'sponges' and 'pumps': Assessing the impact of deforestation on dry-season flows across the tropics. *Journal of Hydrology*, *574*, 946–963. https://doi.org/10.1016/j.jhydrol.2019.04.064

Raddatz, R. L. (2005). Moisture recycling on the Canadian Prairies for summer droughts and pluvials from 1997 to 2003. *Agricultural and Forest Meteorology*, *131*(1–2), 13–26. Scopus. https://doi.org/10.1016/j.agrformet.2005.04.007

Rahaman, M. M. (2009). Principles of international water law: Creating effective transboundary water resources management. *International Journal of Sustainable Society*, *1*(3), 207. https://doi.org/10.1504/IJSSOC.2009.027620

Rios-Entenza, A., Soares, P. M. M., Trigo, R. M., Cardoso, R. M., & Miguez-Macho, G. (2014). Moisture recycling in the iberian peninsula from a regional climate simulation: Spatiotemporal analysis and impact on the precipitation regime. *Journal of Geophysical Research*, *119*(10), 5895–5912. Scopus. https://doi.org/10.1002/2013JD021274

Robinson, David. A., Jones, S. B., Lebron, I., Reinsch, S., Domínguez, M. T., Smith, A. R., Jones, D. L., Marshall, M. R., & Emmett, B. A. (2016). Experimental evidence for drought induced alternative stable states of soil moisture. *Scientific Reports*, *6*. https://doi.org/10.1038/srep20018

Saeed, F., Haensler, A., Weber, T., Hagemann, S., & Jacob, D. (2013). Representation of extreme precipitation events leading to opposite climate change signals over the Congo basin. *Atmosphere*, *4*(3), 254–271. Scopus. https://doi.org/10.3390/atmos4030254

Savenije, H. H. G. (1995). New definitions for moisture recycling and the relationship with land-use changes in the Sahel. *Journal of Hydrology*, *167*(1–4), 57–78. https://doi.org/10.1016/0022-1694(94)02632-L

Savenije, H. H. G. (2004). The importance of interception and why we should delete the term evapotranspiration from our vocabulary. *Hydrological Processes*, *18*(8), 1507–1511. https://doi.org/10.1002/hyp.5563

Schaefli, B., van der Ent, R. J., Woods, R., & Savenije, H. H. G. (2012). An analytical model for soil-atmosphere feedback. *Hydrology and Earth System Sciences*, *16*(7), 1863–1878. https://doi.org/10.5194/hess-16-1863-2012

Schyns, J. F., Hoekstra, A. Y., Booij, M. J., Hogeboom, R. J., & Mekonnen, M. M. (2019). Limits to the world's green water resources for food, feed, fiber, timber, and bioenergy. *Proceedings of the National Academy of Sciences*, *116*(11), 4893–4898. https://doi.org/10.1073/pnas.1817380116

Shivers, S. W., Roberts, D. A., McFadden, J. P., & Tague, C. (2019). An analysis of atmospheric water vapor variations over a complex agricultural region using airborne imaging spectrometry. *PLoS ONE*, *14*(12). https://doi.org/10.1371/journal.pone.0226014

Spracklen, D. V., Arnold, S. R., & Taylor, C. M. (2012). Observations of increased tropical rainfall preceded by air passage over forests. *Nature*, *489*(7415), 282–285. Scopus. https://doi.org/10.1038/nature11390

Spracklen, D. V., Baker, J. C. A., Garcia-Carreras, L., & Marsham, J. H. (2018). *The effects of tropical vegetation on rainfall* (Vol. 43). Annual Reviews Inc.; Scopus. https://doi.org/10.1146/annurev-environ-102017-030136

Staal, A., Tuinenburg, O. A., Bosmans, J. H. C., Holmgren, M., van Nes, E. H., Scheffer, M., Zemp, D. C., & Dekker, S. C. (2018). Forest-rainfall cascades buffer against drought across the Amazon. *Nature Climate Change*, *8*(6), 539–543. https://doi.org/10.1038/s41558-018-0177-y

Sterling, S. M., Ducharne, A., & Polcher, J. (2013). The impact of global land-cover change on the terrestrial water cycle. *Nature Climate Change*, *3*(4), 385–390. https://doi.org/10.1038/nclimate1690

Syktus, J. I., & McAlpine, C. A. (2016). More than carbon sequestration: Biophysical climate benefits of restored savanna woodlands. *Scientific Reports*, *6*(1). https://doi.org/10.1038/srep29194

Szeto, K. K. (2002). Moisture recycling over the Mackenzie basin. *Atmosphere - Ocean*, *40*(2), 181–197. Scopus. https://doi.org/10.3137/ao.400207

Trenberth, K.E. (1999). Atmospheric moisture recycling: Role of advection and local evaporation. *Journal of Climate*, *12*(5 II), 1368–1381. Scopus.

Trenberth, Kevin E. (1998). Atmospheric moisture residence times and cycling: Implications for rainfall rates and climate change. *Climatic Change*, *39*(4), 667–694.

Tuinenburg, O. A., Hutjes, R. W. A., & Kabat, P. (2012). The fate of evaporated water from the Ganges basin. *Journal of Geophysical Research Atmospheres*, *117*(1). Scopus. https://doi.org/10.1029/2011JD016221

UN. (2015). *Paris Agreement*. https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

UN. (2019). *United Nations Decade on Ecosystem Restoration (2021–2030)* (Seventy-third session; Agenda item 14). General Assembly.

Van Der Ent, R. J., & Savenije, H. H. G. (2011). Length and time scales of atmospheric moisture recycling. *Atmospheric Chemistry and Physics*, *11*(5), 1853–1863. Scopus. https://doi.org/10.5194/acp-11-1853-2011

Van Der Ent, R. J., Savenije, H. H. G., Schaefli, B., & Steele-Dunne, S. C. (2010). Origin and fate of atmospheric moisture over continents. *Water Resources Research*, *46*(9). Scopus. https://doi.org/10.1029/2010WR009127

van der Ent, R. J., Wang-Erlandsson, L., Keys, P. W., & Savenije, H. H. G. (2014). Contrasting roles of interception and transpiration in the hydrological cycle – Part 2: Moisture recycling. *Earth System Dynamics*, *5*(2), 471–489. https://doi.org/10.5194/esd-5-471-2014

van Luijk, G., Cowling, R. M., Riksen, M. J. P. M., & Glenday, J. (2013). Hydrological implications of desertification: Degradation of South African semi-arid subtropical thicket. *Journal of Arid Environments*, *91*, 14–21. https://doi.org/10.1016/j.jaridenv.2012.10.022

van Noordwijk, M., & Ellison, D. (2019). Rainfall recycling needs to be considered in defining limits to the world's green water resources. *Proceedings of the National Academy of Sciences*, *116*(17), 8102–8103. https://doi.org/10.1073/pnas.1903554116

Vervoort, R. W., Torfs, P. J. J. F., & Van Ogtrop, F. F. (2009). Irrigation increases moisture recycling and climate feedback. *Australian Journal of Water Resources*, *13*(2), 121–134. Scopus. https://doi.org/10.1080/13241583.2009.11465367

Wang, L., & D'Odorico, P. (2019). Water limitations to large-scale desert agroforestry projects for carbon sequestration. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(50), 24925–24926. https://doi.org/10.1073/pnas.1917692116

Wang-Erlandsson, L., Fetzer, I., Keys, P. W., Van Der Ent, R. J., Savenije, H. H. G., & Gordon, L. J. (2018). Remote land use impacts on river flows through atmospheric teleconnections. *Hydrology and Earth System Sciences*, *22*(8), 4311–4328. Scopus. https://doi.org/10.5194/hess-22-4311-2018

Wang-Erlandsson, L., van der Ent, R. J., Gordon, L. J., & Savenije, H. H. G. (2014). Contrasting roles of interception and transpiration in the hydrological cycle – Part 1: Temporal characteristics over land. *Earth System Dynamics*, *5*(2), 441–469. https://doi.org/10.5194/esd-5-441-2014

Watson, A. J., & Lovelock, J. E. (1983). Biological homeostasis of the global environment: The parable of Daisyworld. *Tellus B: Chemical and Physical Meteorology*, *35*(4), 284–289. https://doi.org/10.3402/tellusb.v35i4.14616

Weng, W., Costa, L., Lüdeke, M. K. B., & Zemp, D. C. (2019). Aerial river management by smart cross-border reforestation. *Land Use Policy*, *84*, 105–113. Scopus. https://doi.org/10.1016/j.landusepol.2019.03.010

Wierik, S. A. te, Gupta, J., Cammeraat, E. L. H., & Artzy-Randrup, Y. A. (2020). The need for green and atmospheric water governance. *Wiley Interdisciplinary Reviews: Water*, *7*(2). https://doi.org/10.1002/wat2.1406

Yang, L., Wei, W., Chen, L., & Mo, B. (2012). Response of deep soil moisture to land use and afforestation in the semi-arid Loess Plateau, China. *Journal of Hydrology*, *475*, 111–122. https://doi.org/10.1016/j.jhydrol.2012.09.041

Yang, Z., Huang, W., He, X., Wang, Y., Qiu, T., Wright, J. S., & Wang, B. (2019). Synoptic Conditions and Moisture Sources for Extreme Snowfall Events Over East China. *Journal of Geophysical Research: Atmospheres*, *124*(2), 601–623. Scopus. https://doi.org/10.1029/2018JD029280

Yang, Z., Huang, W., Qiu, T., He, X., Wright, J. S., & Wang, B. (2018). Interannual Variation and Regime Shift of the Evaporative Moisture Sources for Wintertime Precipitation Over Southern China. *Journal of Geophysical Research: Atmospheres*, *123*(23), 13,168-13,185. Scopus. https://doi.org/10.1029/2018JD029513

Yu, Y., Notaro, M., Wang, F., Mao, J., Shi, X., & Wei, Y. (2017). Observed positive vegetation-rainfall feedbacks in the Sahel dominated by a moisture recycling mechanism. *Nature Communications*, *8*(1). Scopus. https://doi.org/10.1038/s41467-017-02021-1

Yu, Y., Notaro, M., Wang, F., Mao, J., Shi, X., & Wei, Y. (2018). Validation of a statistical methodology for extracting vegetation feedbacks: Focus on North African ecosystems in the Community Earth System Model. *Journal of Climate*, *31*(4), 1565–1586. Scopus. https://doi.org/10.1175/JCLI-D-17-0220.1

Zangvil, A., Lamb, P. J., Portis, D. H., Jin, F., & Malka, S. (2010). Comparative study of atmospheric water vapor budget associated with precipitation in Central US and eastern Mediterranean. *Advances in Geosciences*, *23*, 3–9. Scopus. https://doi.org/10.5194/adgeo-23-3-2010

Zemp, D.C., Schleussner, C.-F., Barbosa, H. M. J., & Rammig, A. (2017). Deforestation effects on Amazon forest resilience. *Geophysical Research Letters*, *44*(12), 6182–6190. Scopus. https://doi.org/10.1002/2017GL072955

Zemp, D.C., Schleussner, C.-F., Barbosa, H. M. J., Van Der Ent, R. J., Donges, J. F., Heinke, J., Sampaio, G., & Rammig, A. (2014). On the importance of cascading moisture recycling in South America. *Atmospheric Chemistry and Physics*, *14*(23), 13337–13359. Scopus. https://doi.org/10.5194/acp-14-13337-2014

Zemp, Delphine Clara, Schleussner, C.-F., Barbosa, H. M. J., Hirota, M., Montade, V., Sampaio, G., Staal, A., Wang-Erlandsson, L., & Rammig, A. (2017). Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. *Nature Communications*, *8*(1), 14681. https://doi.org/10.1038/ncomms14681

Zhao, L., Liu, X., Wang, N., Kong, Y., Song, Y., He, Z., Liu, Q., & Wang, L. (2019). Contribution of recycled moisture to local precipitation in the inland Heihe River Basin. *Agricultural and Forest Meteorology*, *271*, 316–335. Scopus. https://doi.org/10.1016/j.agrformet.2019.03.014

Figure 1.

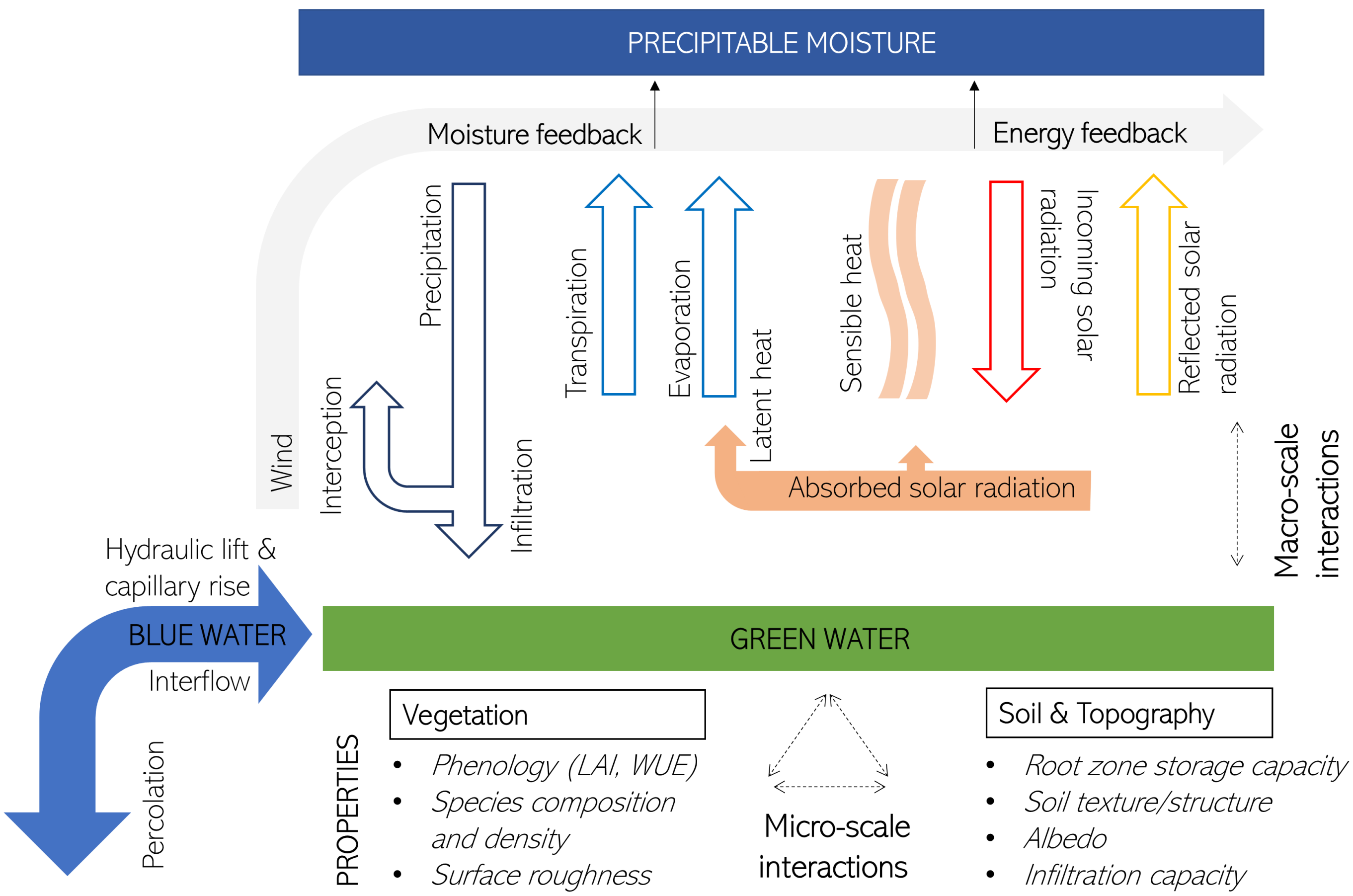

PRECIPITABLE MOISTURE
Moisture feedback
Energy feedback
Wind
Precipitation
Interception
Infiltration
Transpiration
Evaporation
Latent heat
Sensible heat
Incoming solar radiation
Reflected solar radiation
Absorbed solar radiation
Macro-scale interactions
Hydraulic lift & capillary rise
BLUE WATER
Interflow
Percolation
GREEN WATER
PROPERTIES
Vegetation
Phenology (LAI, WUE)
Species composition and density
Surface roughness
Micro-scale interactions
Soil & Topography
Root zone storage capacity
Soil texture/structure
Albedo
Infiltration capacity

Figure 2.

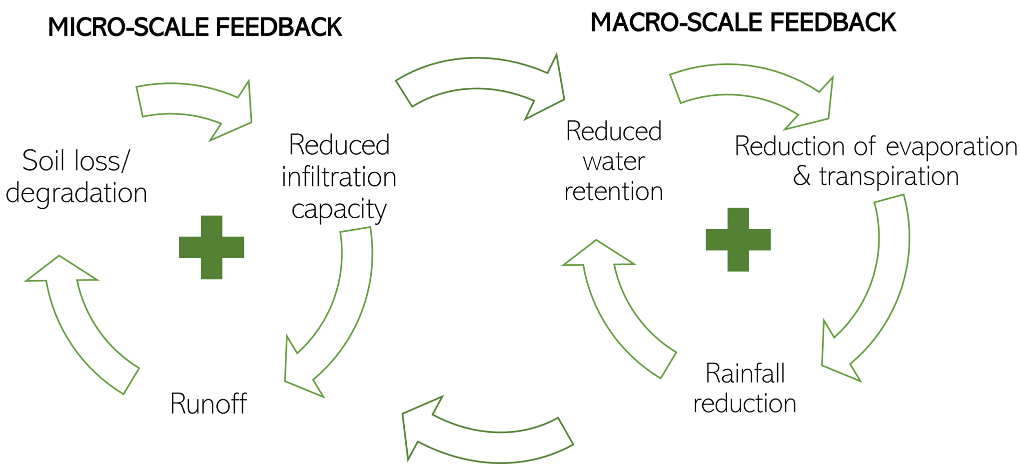
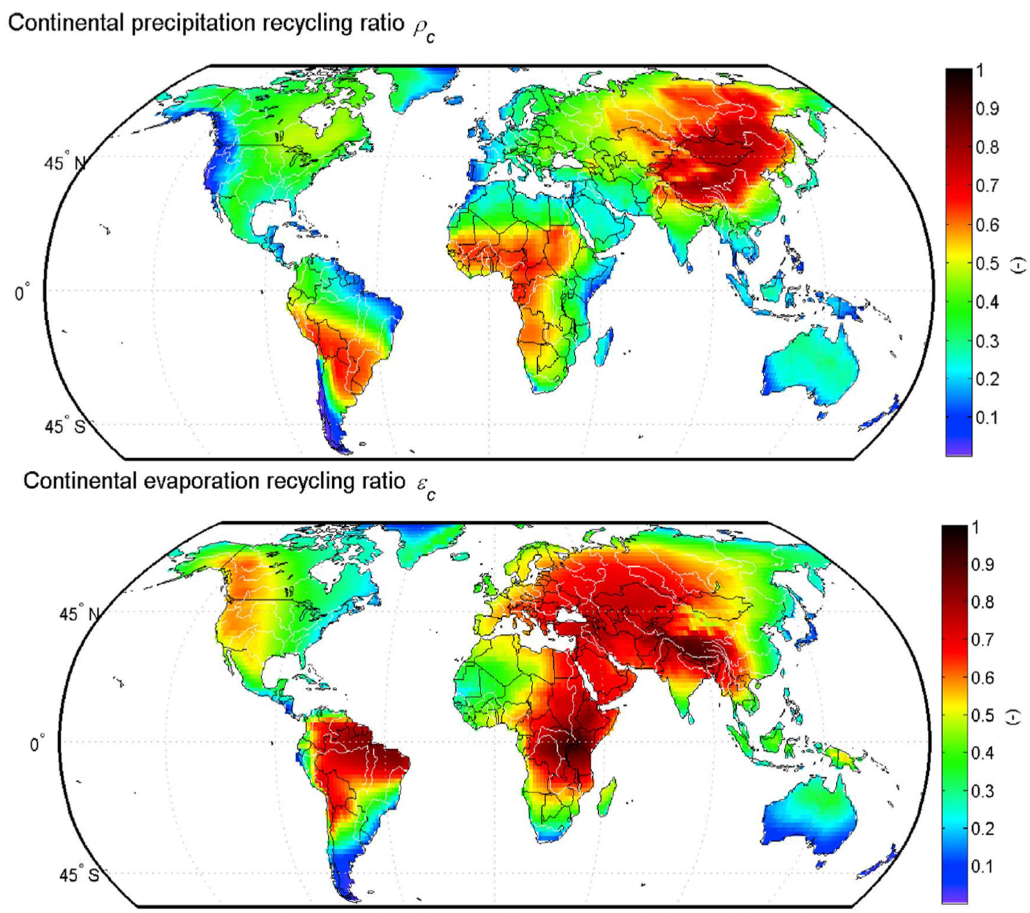

MICRO-SCALE FEEDBACK
MACRO-SCALE FEEDBACK
Soil loss/ degradation
Reduced infiltration capacity
Runoff
Reduced water retention
Reduction of evaporation & transpiration
Rainfall reduction

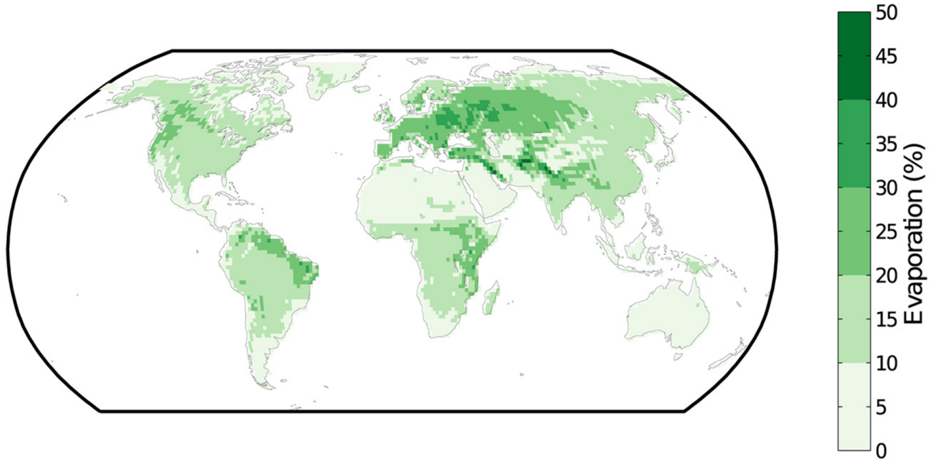
Figure 3.



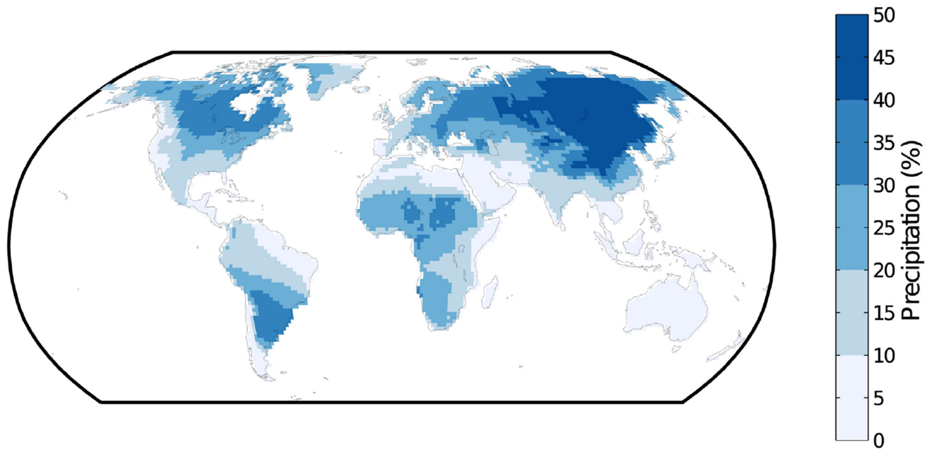
Continental precipitation recycling ratio ρ_c
45° N
0°
45° S
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
(-)
Continental evaporation recycling ratio ε_c
45° N
0°
45° S
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
(-)

Figure 4.

Figure 5.

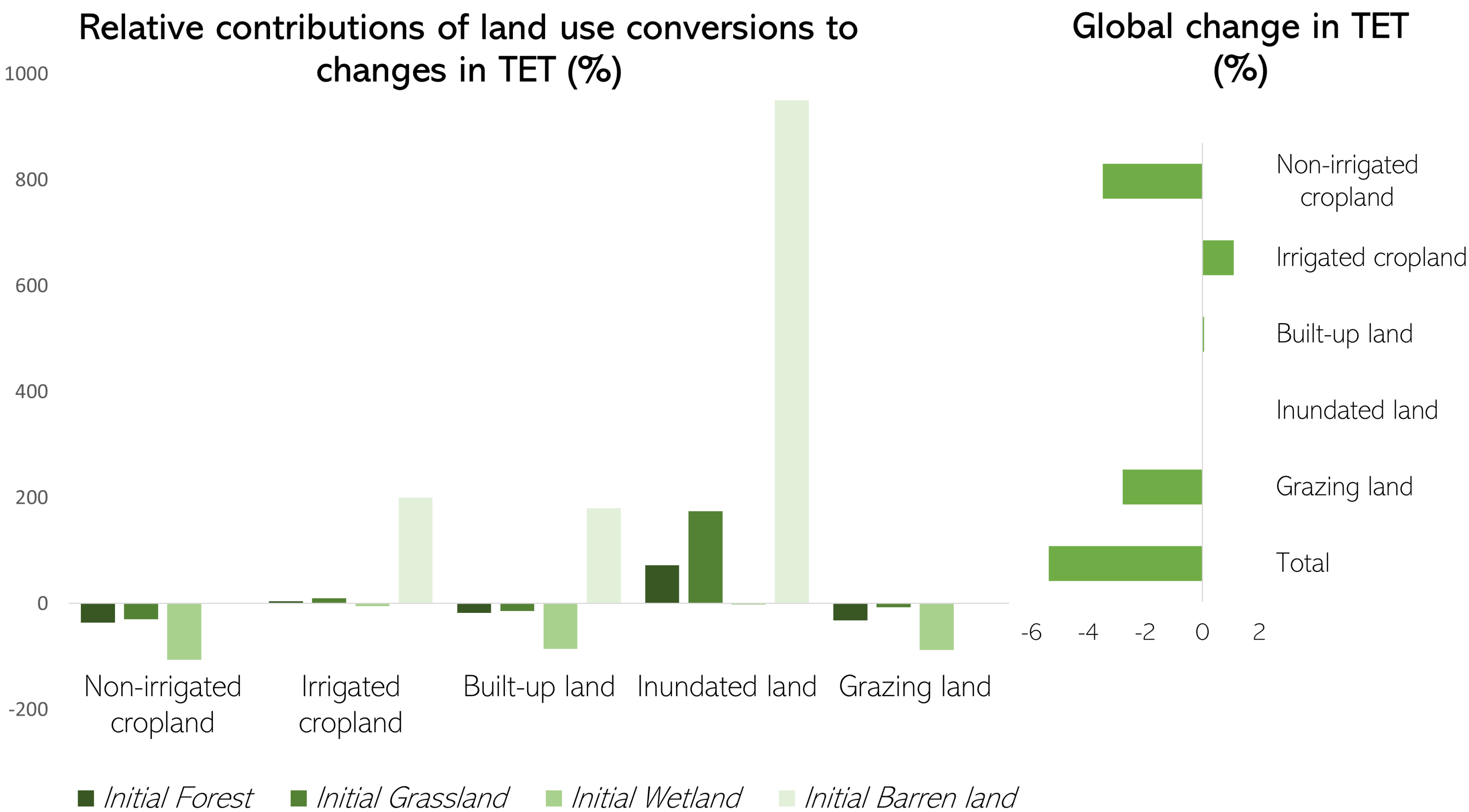


50
45
40
35
30
25
20
15
10
5
0
Evaporation (%)



50
45
40
35
30
25
20
15
10
5
0
Precipitation (%)

Figure 6.



Relative contributions of land use conversions to changes in TET (%)
1000
800
600
400
200
0
-200
Non-irrigated cropland
Irrigated cropland
Built-up land
Inundated land
Grazing land
Initial Forest
Initial Grassland
Initial Wetland
Initial Barren land
Global change in TET (%)
Non-irrigated cropland
Irrigated cropland
Built-up land
Inundated land
Grazing land
Total
-6
-4
-2
0
2