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DOI
10.1029/2020WR029234

Publication date
2021

Document Version
Final published version

Published in
Water Resources Research

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Water Resources Research

REVIEW ARTICLE

10.1029/2020WR029234

Key Points:

- Advanced understanding of the effects of land-use change on moisture recycling patterns demands an overarching review on this issue
- Spatial and temporal patterns 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

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

te Wierik, S. A., Cammeraat, E. L. H., Gupta, J., & Artzy-Randrup, Y. A. (2021). Reviewing the impact of land use and land-use change on moisture recycling and precipitation patterns. *Water Resources Research*, *57*, e2020WR029234. https://doi.org/10.1029/2020WR029234

Received 2 DEC 2020
Accepted 21 JUN 2021

Reviewing the Impact of Land Use and Land-Use Change on Moisture Recycling and Precipitation Patterns

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Abstract Green water, or plant-available soil moisture, is a substantial subset of terrestrial fresh water. Land-use change (LUC) alters green water dynamics through interactions on the micro-level (i.e., between the soil and vegetation) and on the macro-level (i.e., between the land surface and atmosphere). Ongoing global deforestation, and growing interest in reforestation projects, begs the question whether such large-scale LUCs have major eco-hydrological impacts via the process of terrestrial moisture recycling. This requires a systematic, mechanistic understanding of green water dynamics in relation to LUC. 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 LUC from different parts of the world. The results show that some regions are more vulnerable to LUC than others and can affect local as well as distant hydrology of landscapes. Furthermore, we find that many studies focus on the global level or on tropical rainforests, through which we identify a knowledge gap for temperate regions and drylands. We derive analytical tools and directions for further research that can improve understanding of the effects of LUC on moisture recycling patterns to minimize unexpected hydrological impacts for nature and society.

1. Introduction

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; Tuinenburg et al., 2020), of which 70% rains back again over land (Tuinenburg et al., 2020). Subsequently, terrestrial evaporation and transpiration comprise 40% of the total rainfall falling over land globally (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 patterns. Some studies suggest that deforestation and vegetation reduction can disturb TMR and affect local to regional rainfall patterns (Keune & Miralles, 2019; Savenije, 1995; Zemp et al., 2014; Zemp, Schleussner, Barbosa, & Rammig, 2017; Zemp, Schleussner, Barbosa, Hirota, et al., 2017). Deforestation and land degradation lead to the loss of natural ecosystems and could further reduce the resilience of remaining forests by affecting TMR patterns (Zemp, Schleussner, Barbosa, & Rammig, 2017; Zemp, Schleussner, Barbosa, Hirota, et al., 2017). Simultaneously, there is a growing interest in afforestation for biological capture-biological storage (BCSC) of carbon for climate mitigation (UN, 2015), and restoring ecosystems in general for various other Nature's Contributions to People (NCP) (Ellis et al., 2019). Bastin et al. (2019) estimate the global tree restoration potential to cover 0.9 billion ha of canopy cover, which can store 205 Gt of carbon. Between 2000 and 2012, 80 million hectares were reforested or afforested (Bentley & Coomes, 2020). Forest plantations can change regional (Branch & Wulfmeyer, 2019) to global (Swann et al., 2012) climate via land-atmosphere interactions, but also run the risk of distorting basin hydrology and

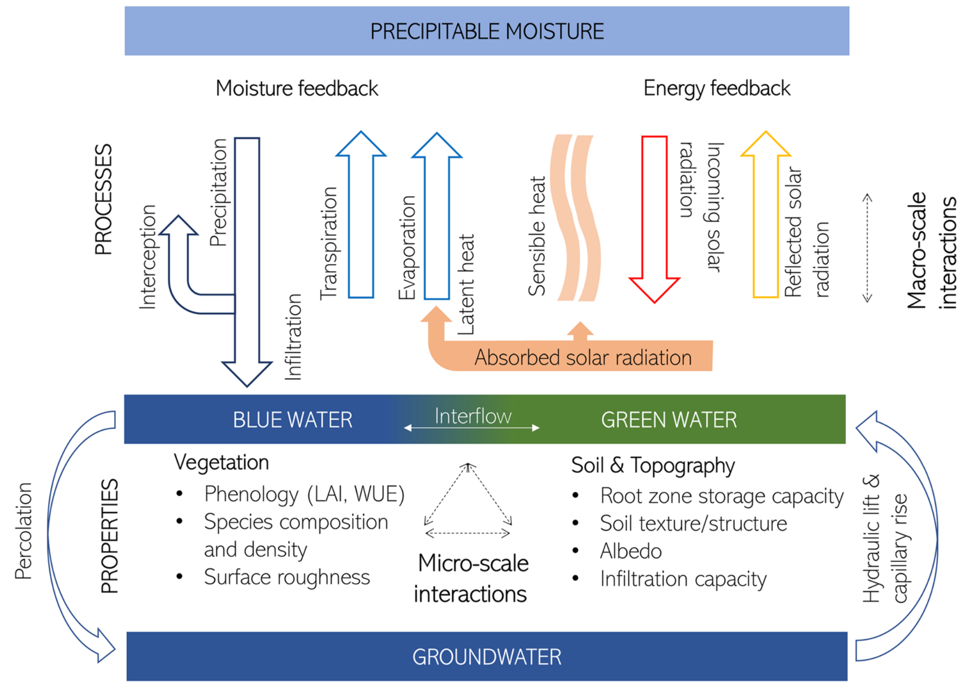

Figure 1. An overview of relevant properties and processes of moisture recycling dynamics. (LAI = Leaf Area Index; WUE = Water Use Efficiency). Microscale interactions occur at the land surface between the vegetation-soil-water system. Macroscale interactions occur between the land surface and the regional climate and are represented by exchanges of moisture, energy, and momentum. Interactions with groundwater also affect blue and green water (Lo & Famiglietti, 2010).

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 deforestation and reforestation on the hydrological cycle should be addressed given scarce water resources (Sterling et al., 2013). There is lack of clarity concerning the effects of LUC on TMR patterns (Spracklen et al., 2018) and whether they can be distorted or intensified through deforestation or reforestation, respectively. Therefore, this research aims to synthesize our current understanding on the role of vegetation by addressing the question: How does land use and LUC affect precipitation patterns via the process of TMR? Drawing from observation-based and simulation-based studies from across the globe, we answer this question through a scoping literature review 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 LUC 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 et al., 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 1970s (Bosch & 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 et al. (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 & Barton, 2018). Observations during the European colonization 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 & 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 1970s, rainfall reductions in the Sahel were linked to reduced vegetation cover resulting from overgrazing and landscape degradation (Charney & Stone, 1975). 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 (Brubaker et al., 1993), questioning the extent to which the earth surface, and particularly vegetation, contributes to rainfall patterns via the exchange of mass, energy, and momentum (Bennett & Barton, 2018; Bonan, 2008; Eltahir & Bras, 1996). The biotic pump theory (Makarieva & Gorshkov, 2007) suggests that continental forests are crucial to transport atmospheric moisture of oceanic origin over the continents. These new insights gave rise to the idea that forests influence the climate and *generate* rainfall. As such, deforestation would result in rainfall reductions via interacting feedbacks at the microscale and macroscale (Figure 2). However, many references show that deforestation produces more complex local to regional effects on the climate and atmosphere (Boers et al., 2017; Chen et al., 2019; Ruiz-Vásquez et al., 2020; Silva et al., 2016; Zemp, Schleussner, Barbosa, & Rammig, 2017; Zemp, Schleussner, Barbosa, Hirota, et al., 2017), which makes predictions on rainfall patterns difficult.

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 (Gimeno et al., 2012). Computational methods use coupled land surface and vegetation models to climate models as 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 (e.g., see Foley et al., 1998). Furthermore, mechanistic models that partition the observed upward moisture flux into different fluxes can induce the relative contribution of vegetation-regulated fluxes (Wang-Erlandsson et al., 2014), or use the vertically integrated atmospheric moisture budget to understand the impact throughout the atmospheric layers (Chen

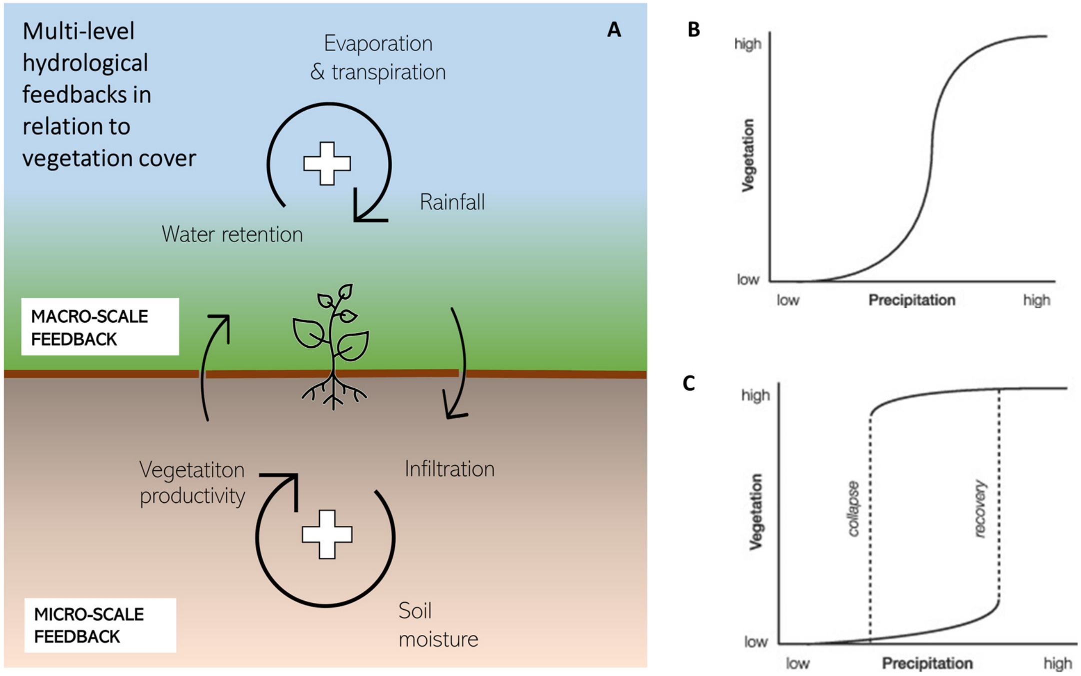

Figure 2. Conceptual diagram of the multi-level hydrological feedbacks in relation to vegetation cover. (A) On the microlevel, vegetation cover enhances the infiltration capacity due to changes in the soil (e.g., rooting structure). This enhances soil moisture availability and subsequently increases vegetation productivity. On the macro-level, increased water retention of the landscape increases evaporation and transpiration, which could subsequently lead to increased rainfall. The positive feedback cycle on the micro-level is linked to the macro-level as both cycles positively reinforce each other. Deforestation may affect these positive feedback cycles and lead to reduced rainfall patterns. Through climate change, these feedbacks can also be distorted as rainfall intensification may change infiltration and water retention in the landscape (Huang et al., 2014). (B, C) Panel B shows the nonlinear relation (and sometimes discontinuous relation, Panel C) between precipitation and vegetation (Panels B and C from Keys et al. [2019]).

et al., 2019). Subsequently, atmospheric moisture tracking models that are forced with meteorological data can identify source and sinks of these upward moisture fluxes, 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. However, the effect of LUC on moisture recycling patterns remains difficult to predict due to uncertainties regarding processes of scale operating in the atmosphere: both moisture tracking models (Keune & Miralles, 2019; Keys et al., 2012; Tuinenburg et al., 2020; Van Der Ent et al., 2010) and static partitioning models (Wang-Erlandsson et al., 2014) address mostly "first-order" hydrological processes (e.g., evaporation fluxes, source-sink relationships). "Second-order" effects may occur when first-order processes affect atmospheric properties and processes, such as on the moist static energy of the boundary layer (Eltahir, 1998), gross moist stability and convection (Kooperman et al., 2018), and continental to global circulation patterns (Makarieva et al., 2009, 2014). Furthermore, model assumptions regarding vertical mixing of the atmosphere pose the most prominent uncertainty of moisture tracking models (Tuinenburg et al., 2020).

Statistical approaches use LUC measurements to observed changes in rainfall (Sterling et al., 2013). Changes in total evaporation and transpiration (TET) can also be measured using flux towers or satellite imagery and climate data (Shivers et al., 2019). Yet, causality between LUC and changes in rainfall patterns is difficult to prove due to the influence of many other biophysical and climatic factors which may explain precipitation changes (e.g., mesoscale atmospheric circulations) (Spracklen et al., 2018). Furthermore, statistical methods fall short in providing estimations of precipitation or evaporation recycling metrics.

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-dependent and scale-dependent: the evaporation of an infinitely small area has negligible contribution to precipitation while the whole earth has a moisture recycling ratio of 1 (Trenberth, 1999). The relation between scale and recycling follows a nonlinear relationship due to the spatial heterogeneity encountered with scaling up or down (Dominguez et al., 2006). Besides shape and scale, the specific location on the Earth's surface also strongly affects the magnitude of precipitation and evaporation ratios (Ma et al., 2019; Tuinenburg et al., 2020). 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), similar to the hydrological connections represented in upstream and downstream regions of a watershed. Thus, 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* (Van der Ent et al., 2013) identifies the sink area of evaporation from a given area. Contrary to watersheds, precipitationsheds are statistically defined 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* establishes atmospheric moisture connections on a watershed level, to identify how evaporation from one watershed contributes to precipitation in another (Keune & Miralles, 2019). 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 patterns in relation to LUC 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" (1,106 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 microscale and macroscale dynamics and (2) empirical observations and modeling simulations of quantitative hydrological change in relation to LUC. We distinguished observation-based and simulation-based studies based on whether the presented outcomes are ex-post or ex-ante: empirical studies are data-driven and reconstruct past or current observations; model simulations test future scenarios. Studies that used observation data to feed mechanistic models to understand past or current processes were classified as "mixed." Furthermore, empirical studies were classified based on the biomes of the area of interest. In case study regions were transcontinental (e.g., de Vrese et al., 2016), the sink region was selected as the main biome; if the case study region crossed biomes (e.g., Syktus & McAlpine, 2016), the largest surface area was selected as the main biome. Predominantly theoretical or review studies were not included in this frequency analysis (Figure 3).

4. Results

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

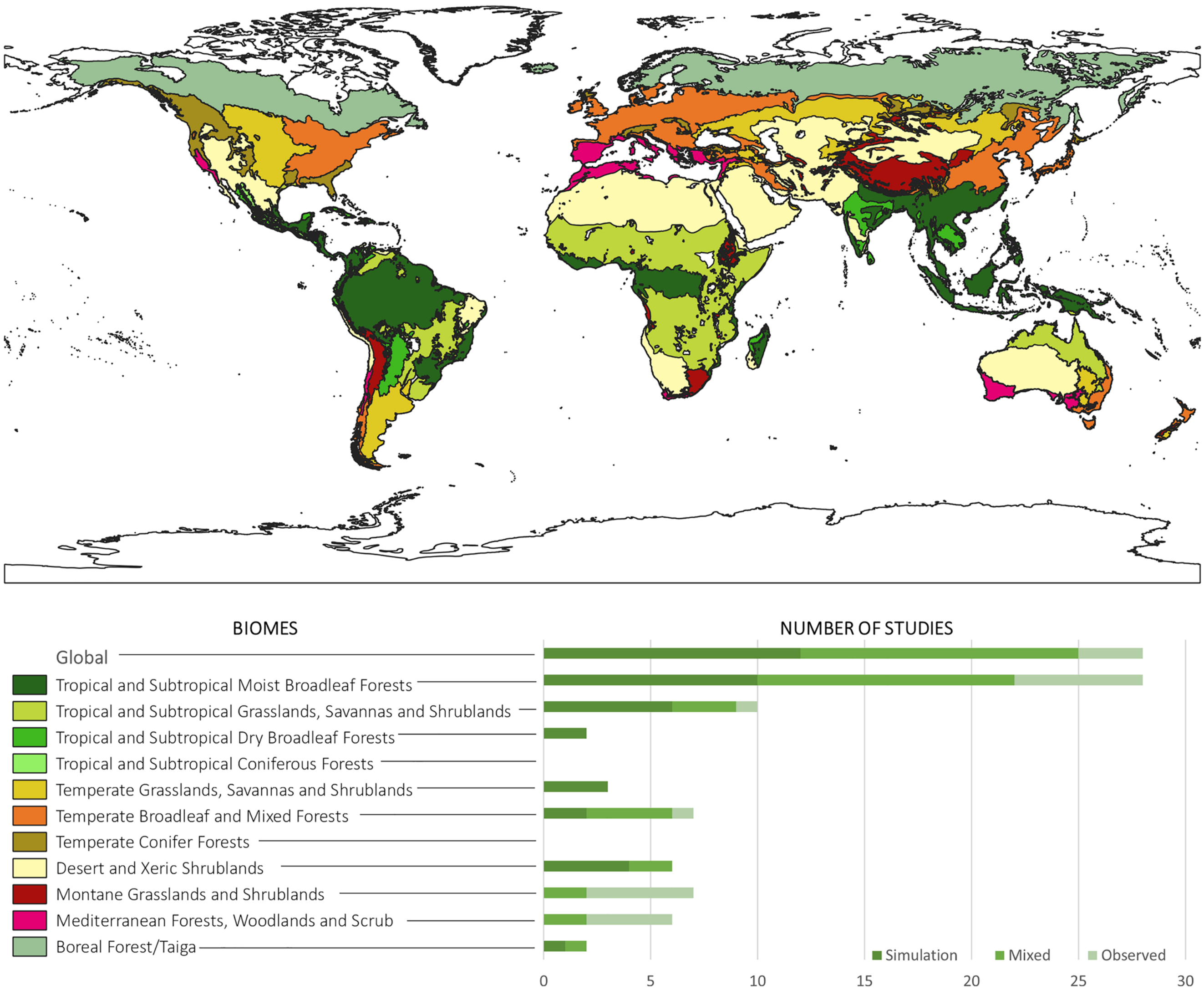

Figure 3. Overview of the number and type of studies executed for each biome. In total, 99 studies were included. Biomes such as the "rock and ice" and "inland waters" are excluded from the figure. Biomes are derived from Olson et al. (2001).

4.1. Patterns of Moisture Recycling

The literature on TMR shows that there is a large spatial and temporal variation in the regional dependence on recycled moisture. Gimeno et al. (2012) already reviewed the variation of moisture sources (i.e., oceanic and terrestrial) between regions around the globe. 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). Some regions depend largely on recycled moisture from the own water basin (i.e., 32% of rainfall over the Amazon derives from the basin itself) (Staal et al., 2018), whereas others are dependent on evaporation from other water basins (i.e., 89% of rainfall over the Nile Basin comes from sources outside of the basin) (Mohamed et al., 2005). "Hotspots" of regionally strong precipitation feedbacks are observed in transitional zones (grasslands and savannas), such as semi-arid and monsoonal regions (Green et al., 2017) and 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 also been observed (Njitchoua et al., 1999; Rios-Entenza et al., 2014).

Seasonal variation in TMR (Tuinenburg et al., 2012) 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 derives from evaporated moisture supplied by other watersheds (Keune & Miralles, 2019). Some regions depend highly on recycled moisture to produce peak spring precipitation (Holgate et al., 2020; Rios-Entenza et al., 2014).

Interannual variation in moisture recycling patterns can be caused by weather cycles, such as El Niño Southern Oscillation (Z.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). In the Congo Basin, extreme rainfall events were linked to moisture recycling *reductions* due to relative lower soil moisture availability and higher surface runoff (Saeed et al., 2013). In response to climate change, such extreme rainfall events and increasing precipitation intensity are expected to become more frequent (Emori & Brown, 2005; Seager et al., 2010; Sun et al., 2007; Trenberth et al., 2003), subsequently increasing the relative amount of runoff and reducing soil moisture infiltration (Lan et al., 2016) and propagate along atmospheric teleconnections (Boers et al., 2019).

As precipitation length scales vary between 500 and 7,000 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). 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 in turn 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 (Dominguez et al., 2006; Kong & Pang, 2016). Around the Tibetan plateau, 50%–80% of the precipitation derives from locally evaporated water (An et al., 2017; Kurita & Yamada, 2008). 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 (500–2,000 km). Precipitation events are strongly driven by diurnal (Giles et al., 2021) and monsoonal dynamics (Tuinenburg et al., 2012) characterized by strong soil moisture feedbacks (i.e., local evapotranspiration produces afternoon rainfall) 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 maintain 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% and 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 traveled is generally shorter which may be caused by convection triggering local precipitation.

In water-limited regions, temporal variation in the fraction of TMR between the wet and dry seasons is generally small. In the Nile basin, the inter-annual moisture recycling variation is low (between 8% and 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

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

the post-monsoon period due to wet soils and vegetation greening (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. Introducing water harvesting measures, such as half-moon pits (Figure 4), can enhance soil moisture retention in the landscape and affect meso-climate through surface temperature changes (Castelli et al., 2019). Many semi-arid regions are depending on recycled moisture for agricultural production during the growing season which also makes them socially economically vulnerable to changes in precipitation (Dominguez et al., 2006). 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. Gimeno et al. (2020) presents an in-depth review of atmospheric moisture transport and the establishment of source-sink relations, but do not explicitly address our understanding of how land cover changes affect source-sink relationships through vegetation-regulated moisture (Keys et al., 2016). Hence, the following paragraphs specifically review the existing knowledge on the impact of vegetation changes on atmospheric moisture transport and moisture recycling.

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 & 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). Here, we describe the role of vegetation in moisture recycling more generally. Subsequently, we specifically address the effects of deforestation and reforestation.

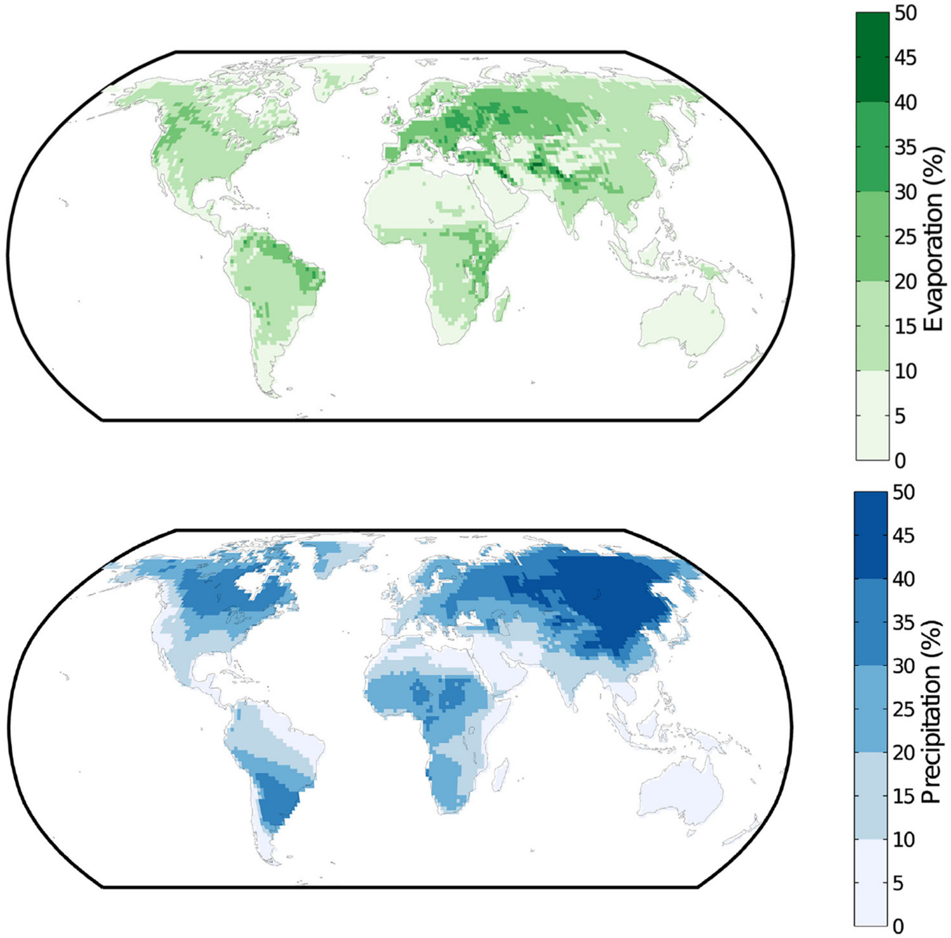

Figure 5. Source regions (left) percentage of vegetation-regulated evaporation that falls as precipitation on land Source: figure copied from Keys et al. (2016) and sink regions (right) percentage of precipitation that derives from vegetation-regulated evaporation. Data are generated using the Eulerian atmospheric moisture-tracking model Water Accounting Model-2 layers (WAM-2layers). Source: figure copied with the author's permission from Keys et al. (2016).

4.2.1. The Effect of Vegetation on Upward Moisture Fluxes

Vegetation regulates TET through various dynamics, that is, magnitudes, sources, and time scales (Wang-Erlandsson et al., 2014). A global analysis that compares the current vegetative state to a hypothetical nonvegetated scenario, shows that 22% of terrestrial rainfall on Earth's land surface is vegetation-regulated (Figure 5) (Keys et al., 2016). The spatial variation in the relative contribution is large. In some regions, such as Mato Grosso, Brazil, a vast region with different land uses and high rates of LUC, up to 45% of the evaporation is vegetation-regulated compared to a nonvegetated scenario characterized by less interannual rainfall variability and a strong reduction (−45%) in dry season rainfall. This implies that vegetation-regulated moisture recycling in this area is important to produce rainfall during the dry season (Keys et al., 2016). Other approaches present estimations of the relative contribution of vegetation-regulated fluxes such as transpiration and interception based on mechanistic partitioning models. For example, Wang-Erlandsson et al. (2014) apply a mechanistic approach to show that 59% of mean global TET composed of transpiration. Furthermore, different land-use conversions have been linked to specific effects on TET (Figure 6) (Sterling et al., 2013).

On the left, Figure 6 shows the relative contributions of specific land-use conversions to changes in TET. On the right, the contribution of land-use conversions to the total change in global TET is shown. Globally, it appears that conversion to nonirrigated cropland has reduced global TET by 3.5%. Hotspots of changes in TET following LUC are situated in Western Africa, South-East Asia, and Eastern Europe. These are regions

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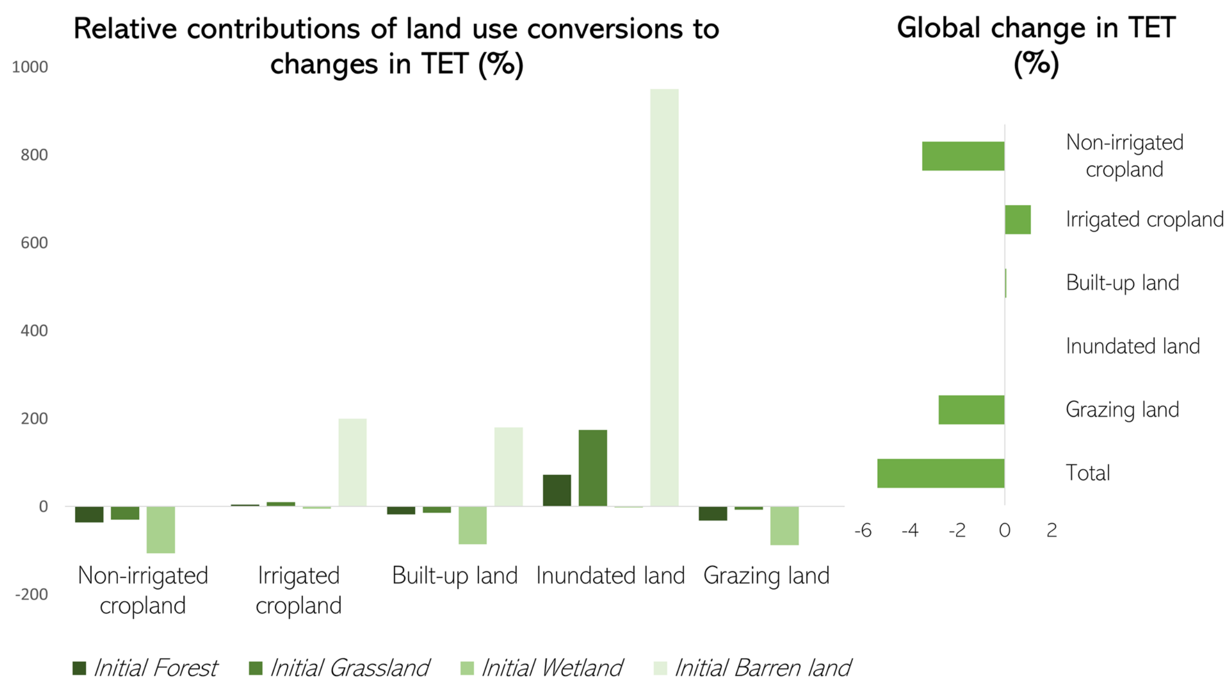

Figure 6. Contributions of various LUC to changes in TET. The horizontal graph on the left shows the relative contributions of land-use conversions (from initial to anthropogenic land cover) to changes in global total evaporation and transpiration (TET). For example, converting barren land to inundated land increases TET over that area by >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 nonirrigated croplands has reduced global TET by nearly 4% (data derived from Sterling et al. [2013]).

that have experienced large-scale land-use conversion of forest and grasslands to irrigated and nonirrigated croplands (Sterling et al., 2013). Furthermore, observations of the Earth "greening" (observed increases in leaf area index due to rising atmospheric carbon concentrations) has shown an increase in global TET (12 mm yr^{-1}) and precipitation (12.1 mm yr^{-1}), which is expected to significantly affect soil moisture in dry regions (Zeng et al., 2018).

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 et al., 2012). Air moving over dense vegetation produces more than two times the amount of rain compared to air moving over sparse vegetation. However, 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 et al., 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).

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, effects occurred outside the river basin, which implies that LUC is less likely to produce local effects. Such remote effects can propagate through shifts in the location of the ITCZ, affecting monsoonal precipitation patterns along this belt (Devaraju et al., 2015). However, in the Amazon basin, local feedbacks are unusually strong and expand

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the geographical range of tropical forests (Staal, Fetzer, et al., 2020; Staal, Flores, et al., 2020). Significant deforestation-rainfall relations were found on a scale of 30–50 km—anticipating stronger local effects of deforestation (Spracklen et al., 2018). A meta-analysis of climate models shows a negative relation between rainfall and deforestation, which have led to a 12% mean annual rainfall reduction in the Amazon basin (Spracklen & Garcia-Carreras, 2015). In dry seasons and 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). This "reinforcing drought-deforestation feedback" is expected to increase in strength in the future with accumulating forest loss (Staal, Fetzer, et al., 2020; Staal, Flores, et al., 2020). For Amazonian deforestation, a tipping point is proposed (Boers et al., 2017), referring to the westward moisture cascade in which some regions are depending on precipitation from forest evaporation elsewhere. Crossing the tipping point would significantly reduce rainfall in regions downwind, thereby also putting agricultural production in the region at risk (Lawrence & Vandecar, 2015). Using observation-based moisture recycling networks, Zemp, Schleussner, Barbosa, and Rammig (2017) and Zemp, Schleussner, Barbosa, Hirota, et al. (2017) show that Amazon deforestation can reduce dry-season rainfall in the southward La Plata basin 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, Schleussner, Barbosa, & Rammig, 2017; Zemp, Schleussner, Barbosa, Hirota, et al., 2017). Deforestation along the cascade affects the monsoonal circulation that is initially driven by latent heat released from precipitation over the rainforest, which creates a pressure gradient between the ocean and continent that enhances the inflow of moist air from the Atlantic (Boers et al., 2017). Deforestation reduces transpiration up to a moment in which atmospheric moisture is insufficient to release latent heat and accordingly draws in atmospheric moisture from the ocean. 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, Schleussner, Barbosa, & Rammig, 2017; Zemp, Schleussner, Barbosa, Hirota, et al., 2017) might therefore result in lower downwind precipitation. Increasing scales of Amazonian deforestation trigger changes in surface roughness (Spracklen et al., 2018) and thermal circulations (Ruiz-Vásquez et al., 2020), on the boundary layer and the atmospheric stability (Bagley et al., 2014) and the upward motion intensity (Silva et al., 2016). 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, 100–1,000 km, deforestation can change atmospheric properties that result in macroscale hydroclimatic changes (Spracklen et al., 2018). Lawrence and Vandecar (2015) underline a nonlinear relation may exist between the scale of tropical deforestation and changes in rainfall, referring to a "critical patch size" of forests to sustain precipitation patterns. In regions that experienced large-scale deforestation, delays in the onset of the rainy season have been observed (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 areas (Negri et al., 2004). This may be due to increased surface heating over deforested regions, producing an upward air motion that draws atmospheric moisture from neighboring areas. Fragmented deforestation patterns may also lead to 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). A modeling study over the Maritime continent shows that deforestation increases atmospheric instability, leading to ascending air motions and increased moisture convergence, subsequently resulting in increased precipitation and surface temperatures (Chen et al., 2019).

Seasonal shifts in precipitation have also been recorded in response to deforestation. In the tropics, LUC has a more severe effect on dry-season precipitation (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. Changing energy and moisture fluxes 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 2000s 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^{-1} (Bai et al., 2019). Vegetation productivity contributed 93% to this increasing TET trend (Bai et al., 2019). Reforestation simulations using regional climate models for West Africa and the Sahel how that reforestation can enhance precipitation with +3.6% to 14.4% (Oguntunde et al., 2014) yet the location of the reforestation experiment has a significant role on macroscale climatic changes and the spatial distribution of predicted rainfall patterns (Bamba et al., 2019). Reforestation enhances surface roughness, weakening the atmospheric temperature gradient, which can result in a delay in the onset of the monsoon (Oguntunde et al., 2014). A modeling scenario of potential restoration of Australia's woodlands on marginal lands shows an increase in evaporation, resulting in increased cloud formation and precipitation over the region. The ability of these woodlands to access deeper soil moisture would be the mechanism behind increased evaporation (Syktus & McAlpine, 2016). Branch and 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. Yet, such conclusions should be interpreted with caution (see Section 4.3.2). 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). Swann et al. (2012) show how forest expansion in the Northern midlatitudinal zone would increase relative evaporation and absorb more energy, subsequently affecting atmospheric circulation and precipitation patterns over the Amazon, the Sahel, and the oceans.

4.3. Instruments for Moisture Recycling Governance

Under certain conditions, LUC can affect local or regional rainfall and redistribute—either intentionally or unintentionally—water resources (Figure 7). 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 governance instruments emerge: spatial planning, impact assessments, and boundary setting.

4.3.1. Spatial Planning Approaches

Through spatial planning, moisture recycling processes may be protected or intensified. The identification of hotspots of moisture recycling sources (Zemp, Schleussner, Barbosa, & Rammig, 2017; Zemp, Schleussner, Barbosa, Hirota, et al., 2017) can support the delineation of areas for forest protection. Furthermore, 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). The authors estimate that *aerial river management*—the practice of redistributing flows of atmospheric water through strategic LUC intentionally—has the potential to cover between 22% and 59% of the city's 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). However, issues of temporal and spatial scale remain: interventions to enhance moisture

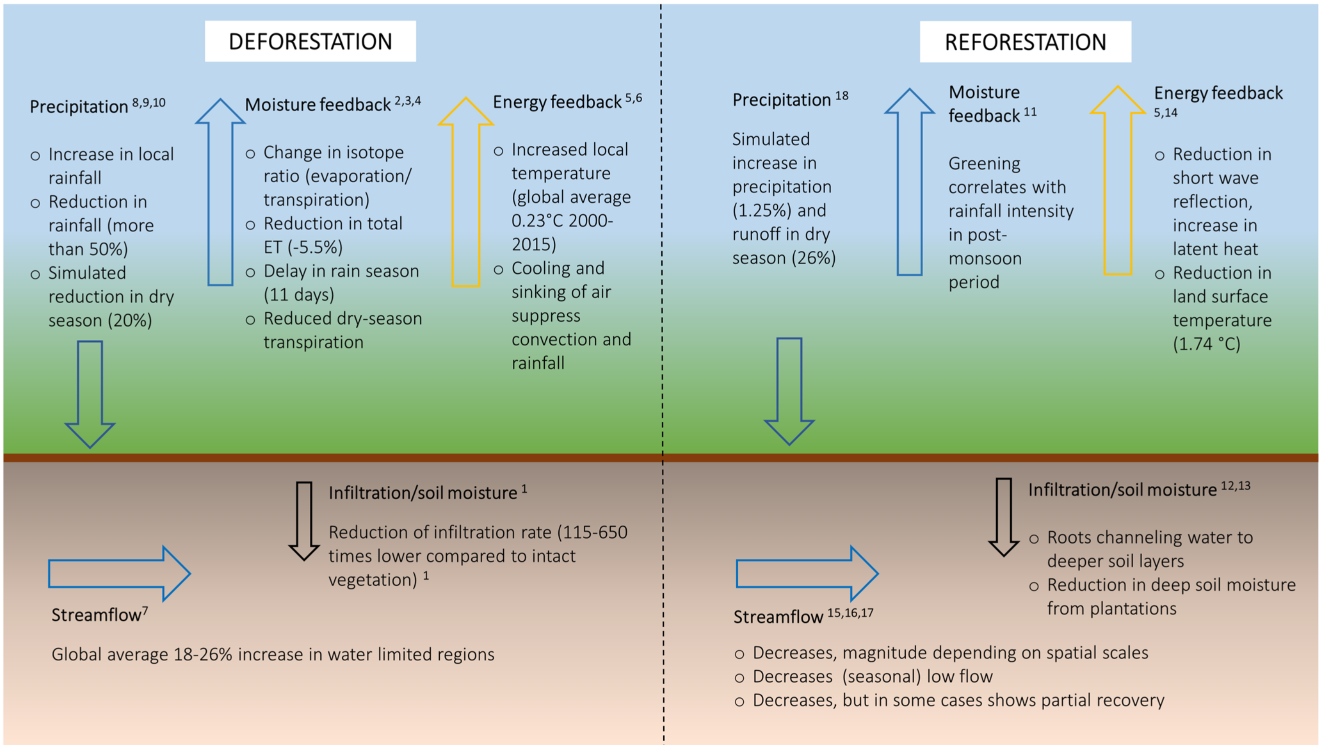

Figure 7. Schematic summary of the evidence of land-use changes (deforestation and reforestation) on various processes governing moisture recycling patterns. Note that although there is sparse evidence that reforestation or ecological restoration increases rainfall patterns; yet, observed positive relations between vegetation greening (Yu et al., 2017) suggest that the positive vegetation-rainfall feedback may be strengthened when vegetation productivity increases. References: (1) van Luijk et al. (2013), (2) Sterling et al. (2013), (3) Butt et al. (2011), (4) Zemp, Schleussner, Barbosa, and Rammig (2017), Zemp, Schleussner, Barbosa, Hirota, et al. (2017), (5) Duveiller et al. (2018), (6) Charney and Stone (1975), (7) Peña-Arancibia et al. (2019), (8) Negri et al. (2004), (9) Spracklen et al. (2012), (10) Zemp, Schleussner, Barbosa, and Rammig (2017), Zemp, Schleussner, Barbosa, Hirota, et al. (2017), (11) Yu et al. (2017), (12) Cammeraat et al. (2010), (13) L. Yang et al. (2012), (14) Castelli et al. (2019), (15) Filoso et al. (2017), (16) Brown (2005), (17) Bentley and Coomes (2020), and (18) Weng et al. (2019).

recycling would take decades to produce the significant effect (Keys & Falkenmark, 2018) and would require significant horizontal LUCs (although there is no research yet that addresses this scalar issue).

4.3.2. Impact Assessments

Nature's contribution to peoples (NCP) (Ellis et al., 2019) associated with TMR are "*diffuse and spatially extensive*" and pose 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 address the effects of LUC on TMR, as well as the impact on various NCPs. Regional case studies are needed that address hydrological trade-off analyses that explicitly include land-atmosphere feedbacks and TMR patterns (Ellison & Ifejika Speranza, 2020; Wang & D'Odorico, 2019). For example, although bio-geoengineering can enhance rainfall in some regions (Branch & Wulfmeyer, 2019), it needs to be balanced against the potential negative effects on soil and groundwater hydrology (Wang & D'Odorico, 2019; L. Yang et al., 2012) and cascading effects on social-ecological systems. Accordingly, 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 a detailed understanding of local to global water use. Measurements of TET and Net Plant Productivity (NPP) via satellite imagery allow 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 program has come at the costs of river runoff that is potentially societally undesirable (Feng et al., 2016). Accordingly, a regional *NPP plafond*—a limit to the mean NPP to control trade-offs between vegetation water use and river runoff—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 instruments that are proposed in response to the 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 international 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 LUC 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 of land-atmosphere interactions and associated water circulation and (2) the issue of scalability associated with nonlinear responses of TMR to LUC.

5. Conclusions

Continuous global LUC, increasing understanding of biosphere-atmosphere interactions, and increasing water scarcity beg the question of 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, a significant part of global terrestrial rainfall is vegetation-regulated, which implies that LUC can greatly affect rainfall patterns. In the last decades, LUC has significantly reduced global TET across the globe.
- Second, deforestation 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 nonlocal and occur outside the basin.
- Third, 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 may be more prominent. Yet, relatively little research is done in temperate and dry regions.
- Fourth, hotspots of moisture recycling may occur along gradients between the ocean and land surface, mountainous regions, and transitional zones. These hotspots might require protection to prevent disruption of continental 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 multi-scalar 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 (te 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.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

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 are available through Sterling et al. (2013).

Acknowledgments
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). This study was supported via funding provided by the Interdisciplinary Doctorate Agreement, University of Amsterdam.

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