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Invisible water security: Moisture recycling and water resilience

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ABSTRACT

Water security is key to planetary resilience for human society to flourish in the face of global change. Atmospheric moisture recycling – the process of water evaporating from land, flowing through the atmosphere, and falling out again as precipitation over land – is the invisible mechanism by which water influences resilience, that is the capacity to persist, adapt, and transform. Through land-use change, mainly by agricultural expansion, humans are destabilizing and modifying moisture recycling and precipitation patterns across the world. Here, we provide an overview of how moisture recycling changes may threaten tropical forests, dryland ecosystems, agriculture production, river flows, and water supplies in megacities, and review the budding literature that explores possibilities to more consciously manage and govern moisture recycling. Novel concepts such as the precipitationshed allows for the source region of precipitation to be understood, addressed and incorporated in existing water resources tools and sustainability frameworks. We conclude that achieving water security and resilience requires that we understand the implications of human influence on moisture recycling, and that new research is paving the way for future possibilities to manage and mitigate potentially catastrophic effects of land use and water system change.

1. Introduction

The movement and availability of water – through surface, soil, and atmosphere – is an important biophysical basis for water security and is crucial for the resilience of human society. Resilience includes the ability to persist in the face of a perturbation; to adapt to change; and to transform, leading to new system configurations of functions and interactions [1]. Water resilience can be defined as the role of water in enhancing this persistence, adaptability, and transformability of a desired system state [2,3]. Today, in a new era of social-hydro-ecological dynamics [4–6], significant anthropogenic impacts to the water cycle are re-wiring human-water dynamics and compromising the capacity of the biosphere to support the human endeavor.

While much of the focus in water management is on the visible water flows in rivers, and the use and pollution of this water by humans, most global freshwater flows are largely invisible. Each year 70,000 to 100,000 km^3 of water evaporates from land into the atmosphere where it combines with oceanic evaporation. Then, 100,000 to 130,000 km^3 yr^{-1} of atmospheric water falls as precipitation on land, providing the water that eventually flows off the land into the rivers, and back to the ocean [7]. These atmospheric water flows vastly surpass the 45,000 km^3 yr^{-1} of global river flows [8].

Ocean-to-land moisture transport, notably through atmospheric rivers [9,10] and monsoon systems [11–13], provides about 60% of precipitation on land. Conversely, land-to-land moisture transport driven by terrestrial evaporation, accounts for 40% of precipitation over land [14]. This process of evaporation from land, traveling through the atmosphere as vapor, and returning to the land surface as precipitation is often referred to as terrestrial moisture recycling (Fig. 1a), which is the focus of this paper. For brevity we will simply refer to terrestrial moisture recycling as 'moisture recycling' in this article. Broadly speaking, precipitation occurs under specific circumstances, including the availability of water vapor, proximity to saturation, and a dynamic or thermodynamic process that can drive precipitation [15]. The intensity and pattern of moisture recycling also depends on evaporation and transpiration patterns [17], geographic location [18], and spatial scale [19].

Vegetation plays a particularly important role as it can alter the evaporative flow from land to atmosphere and thus regulates not only regional water availability, but also precipitation elsewhere. The relative role of vegetation varies strongly on a regional basis (Fig. 1,bc) and with seasons [20]. The flow of evaporation can be in the form of

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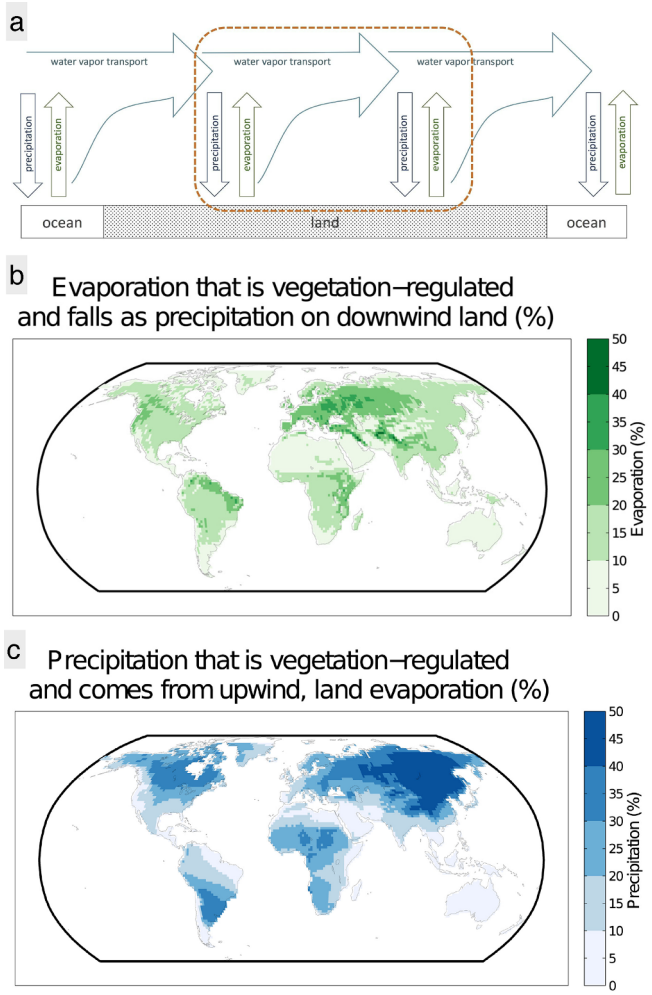

Fig. 1. Moisture recycling: (a) the flow of water that has evaporated from the Earth's surface and falls back as precipitation; while the ocean provides 60% of the precipitation falling globally on land, the orange box denotes the focus of this article, i.e. the land-to-land component, which provides 40% of terrestrial precipitation; (b) the percent of total evaporation that is regulated by vegetation for precipitation on land elsewhere; and (c) the percent of precipitation that is dependent on upwind vegetation regulation [22].

'fast' fluxes of water vapor (water that evaporates quickly after being intercepted by the land and vegetation surfaces, such as the forest floor and canopy) or 'slow' fluxes (water that evaporates after infiltrating into soil moisture and used for biomass production in plants as transpiration, or that evaporates from open water). While 'fast' fluxes are most important for maintaining a quick turnover of moisture recycling locally, 'slow' fluxes occur long into the dry period and help support more distant precipitation during dry seasons [21].

Moisture recycling offers a mechanism through which processes and management of land can affect both the quantity and spatio-temporal distribution of invisible atmospheric flows of water and, consequently, the resilience of the ecological and social-ecological systems that depend on it. Anthropogenic influences on terrestrial evaporation include climate change-induced modification of temperature and water availability [23,24], carbon dioxide fertilization [25], and land-use changes such as deforestation, irrigated croplands, and reservoirs [26–28]. Land-use change further has the ability to modify circulation patterns, such as through the influence of irrigation on monsoon onset in the Indian sub-continent [17] and afforestation impacts to wind directions in the Amazon [29]. Because rainfall is a key determinant of the local hydroclimate that ecosystems and societies have adapted to, substantial and abrupt changes in moisture recycling can lead to a reduction of local resilience and increase the risk for irreversible regime shifts. Based on a review of water related regime shifts, Falkenmark et al. (2019) proposed "moisture feedback" as one of eight core resilience functions of water [3].

In this paper, we summarise the current state of knowledge on human influences to moisture recycling and on the contribution of atmospheric moisture recycling to water security and the resilience of different ecological and social-ecological systems both locally and at a distance. We then consider implications for governance and the importance of a planetary perspective on building a water resilient future.

1.1. Regime shifts and resilience

A regime shift refers to a large and abrupt system-wide re-configuration of interactions and/or functions, often triggered by an external perturbation or change in internal dynamics [30–33]. Regime shifts can be non-linear, with gradual changes leading to abrupt responses in the system. They occur when system thresholds are passed. For some systems they are easily reversible. However, in most regime shifts, internal feedbacks among system drivers change, resulting in hysteresis effects where the external drivers need to be restored beyond the point when the regime shift happened. This may be both very costly and difficult to reverse, or even irreversible. In the context of moisture recycling, the key dimensions are precipitation and vegetative cover. In some cases the transition from low to high vegetation cover is continuous (Fig. 2a), while in other systems, especially tropical forest systems, a hysteresis may exist between a lower vegetation savanna state and a higher vegetation forest cover state (Fig. 2b).

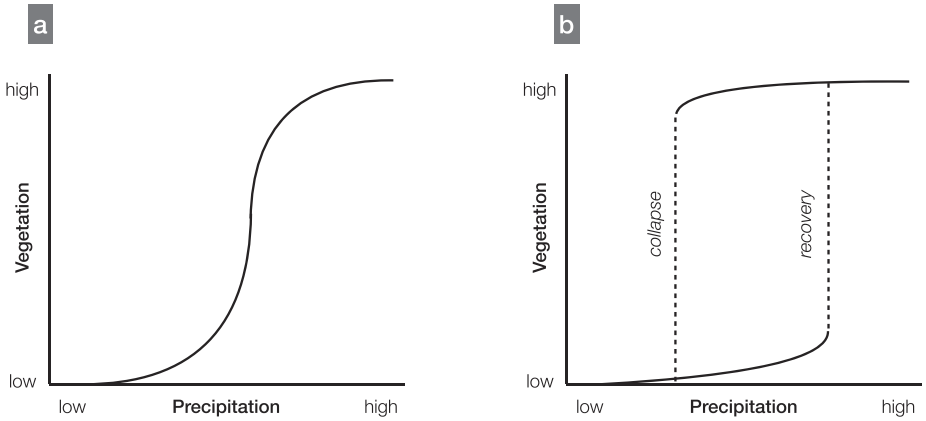

Fig. 2. A simple diagram showing how a linear change in precipitation (x-axis) may be associated with a nonlinear change in vegetation cover (y-axis). In some cases, (a) the change can be continuous and reversible, otherwise (b) changes can be discontinuous, leading to a hysteresis in the nonlinearity [34,35].

2. Evidence of moisture recycling influence on water resilience in various systems

2.1. Tropical rainforests

Forests are disproportionately important to the global water cycle owing to their high and persistent evaporation rates, e.g., tropical, evergreen broadleaf forests currently occupy about 10% of the Earth's land surface, but contribute 22% of land evaporation, and receive 29% of precipitation on land [20]. Forests in general, including tropical broadleaf forests, sustain transpiration long into rainless periods through their high soil moisture holding capacity and roots that reach deeper water in the soil, while also supplying high evaporation rates from interception of rainfall in the canopy, forest floor, as well as tree trunk vegetation and lichen [20,36–38]. Conversion of tropical forests to agricultural land or pasture generally decreases soil moisture and interception storage. Consequently, this decreases evaporation, the amount of moisture recycled, and precipitation available for downwind regions.

The average moisture recycling over the large, continuous tropical forests of Amazon and Congo is 25–45% depending on moisture tracking methods and study region selection [39,40]. In parts of the Amazon and Congo, up to 50% of the forest precipitation originates from the forest itself [41]. Internal moisture recycling in forests is especially important during drought years, when, in the Amazon and Congo for instance, recycling increases by 7–15% [41,42].

Decreasing amounts of precipitation (both annual and seasonal) over tropical forests is strongly connected to forest resilience, with a forest-savanna bistability range of 1000–2400 mm yr^{-1} of precipitation [34,43]. For a savanna to return to a forest requires higher precipitation rates than the rainfall level that caused forest collapse, due to hysteresis induced by moisture recycling and fire feedbacks (Fig. 2b). Moisture recycling feedbacks are further important in large continuous forest areas, as they allow deforestation-induced declines in evaporation to cascade, leading to self-amplified forest loss when precipitation decreases [21,35,44,45]. The fundamental importance of moisture recycling for both sustaining tropical forest structure, function, and for regulating the flow of moisture to downwind regions, suggests that forests will need to be a key point of consideration in understanding the relationship between water security and moisture recycling.

2.2. Drylands and savannas

Drylands and savannas typically experience water scarcity accompanied by high temperatures. Drylands are not necessarily characterized by low rainfall, but their high mean temperatures and strong seasonality with long drought periods mean that a high proportion of the precipitation is evaporated. Nonetheless, plant dryland ecosystems and biodiversity are extremely well adapted to this characteristic water scarcity and climatic variability. Dryland plant ecosystems show many specific adaptations to water stress, including the ability to limit transpiration by storing water within the plant, to develop deep roots that reach deep soil moisture or groundwater, or to become dormant through long dry spells [38,46].

Moisture recycling fosters resilience in drylands through stabilizing vegetation-driven ecohydrological feedbacks [47,48] (Fig. 3). These feedbacks include maintenance of plant community structure and the associated plant water storage [49,50]. As aridity increases, the bistability between a vegetated and unvegetated state can become more abrupt [51], underlining the importance of the interplay among vegetation feedbacks and atmospheric moisture recycling feedbacks. In the extremely arid Kalahari, when woody vegetation with the associated (relatively) higher soil moisture flips to an absence of vegetation and soil moisture, this leads to increased system unpredictability [52]. Thus, the delicate ecohydrological balance of dryland vegetation suggests that the functional characteristics of this recycling can change abruptly. Evidence suggests that moderate tree cover in the dry tropics can be beneficial for water availability by maximising groundwater recharge [53]. Others show that grasslands can potentially better withstand extreme weather events than forests in semi-arid regions under climate change [54]. It remains to be studied how moisture recycling affects hydrologically 'optimal' tree cover in dryland regions under climate change.

2.3. Agriculture

2.3.1. Rainfed agriculture

Rainfed agriculture comprises between 60% and 80% of global food production [55–57]. Specifically, water productivity in dryland agricultural production systems tends to be extremely low [58]. Yet, dryland agriculture provides the primary livelihood for about 8% of the world population, many of whom live in extreme poverty [59]. Supplemental irrigation is often not possible due to the scarcity or inaccessibility of [58,60] surface water resources [58,60]. Moreover, possibilities to secure food supplies through international trade can be limited by a lack of either economic or physical access to imported food [61]. Even small declines in precipitation could therefore have disproportionately large impacts on agricultural yields and food security of dryland communities [58]. Also, rainfall seasonality (e.g. onset, length, and magnitude of growing season rainfall) has a significant impact on the functioning of dryland rainfed agriculture and ecosystems. Examples from the Sahel suggest that besides sufficient seasonal rainfall, length of the rainy season and steady rainfall after the first wet spells (when seeds tend to be sown) are crucial for successful harvest [62].

Recent studies have emphasised the importance of moisture recycling in the resilience of rainfed agricultural systems. Bagley et al. [63] found that land-use change in the evaporation sources of major global breadbaskets could reduce their moisture availability from between 8% and 17% with significant impacts on grain yields ranging from 1% to 17%, particularly in arid regions such as the Central Asian wheat belt. Keys et al. [16] studied the moisture recycling of seven locations where rainfed agriculture is particularly vulnerable to reductions in precipitation, and found that some regions, notably in East Asia, are more vulnerable to land-use change pressure in key evaporation source regions. Expansion of agriculture at the expense of the Amazon has also been shown to be a hydrologic no-win situation, due to decreased crop yields caused by reduction in rainfall supplied by forest evaporation [64].

Besides managing upwind moisture supply regions, rainfed agriculture can also do more to foster resilient and adaptable agricultural systems while maintaining its own moisture recycling self-regulation, and downwind provision of moisture. The primary method here is the "vapor shift", i.e. shifting soil moisture evaporation to agriculturally productive plant transpiration [58,65].

2.3.2. Irrigated agriculture

Irrigation-induced evaporation is known to have strong impacts on the hydrological cycle globally and regionally. For instance, De Vrese et al. [66] found that over a third of the annual mean precipitation in some of the arid regions of Eastern Africa can be attributed to moisture recycling from irrigated agriculture in Asia. Evaporation arising from irrigated agriculture contributes significantly to rainfall in Asia as well, comprising between 7 to 15% of Indian, Pakistani, Nepalese, and Tibetan precipitation, and over 20% in parts of northern Pakistan [67]. This pattern holds true in North America as well. In the Great Plains of the US, irrigation in Nebraska, Oklahoma, South Dakota, and Kansas has been associated with enhanced precipitation throughout the midwestern states [68]. Coupled regional climate modelling shows that irrigation in the California Central Valley can be linked to runoff increases of about 30% in the Colorado River [69].

Broadly, increased groundwater extraction to mitigate changes in moisture recycling provides a false sense of water security and instead

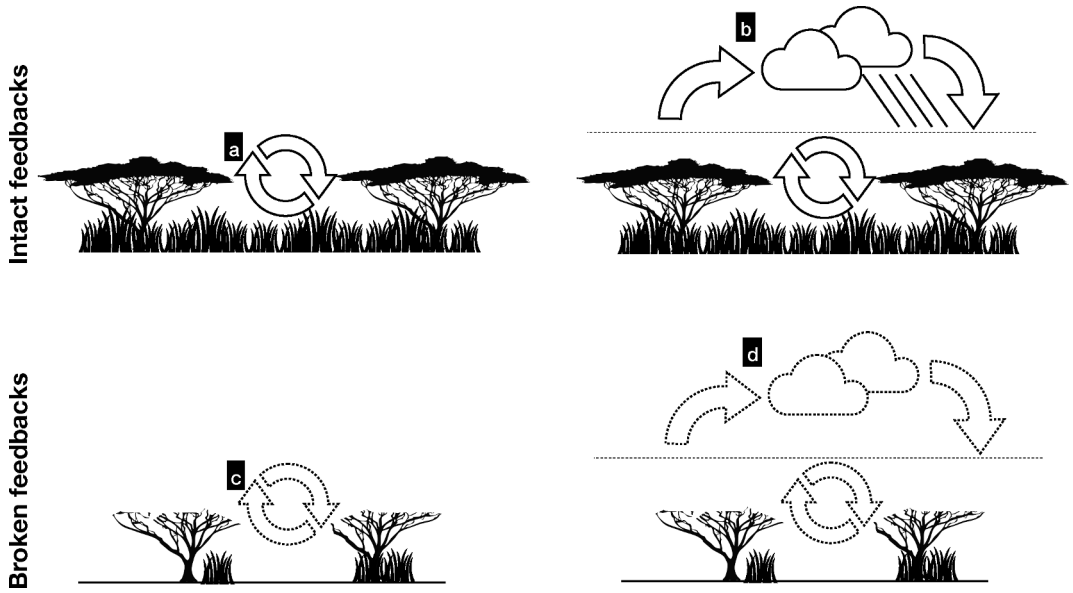

Fig. 3. Dynamics of dryland moisture recycling: (a) the primary importance of recycling of moisture among water in the root zone, transpiration from grasses, to interception by woody vegetation, to transpiration from the woody vegetation, which ultimately leads to (b) intact atmospheric water recycling feedback. The bottom row demonstrates (c) a broken vegetation feedback, which (d) interrupts the connection to the atmospheric moisture recycling feedback.

undermines resilience. A common limitation of current global hydrologic models is their limited capacity to account for decreases in river flow caused by groundwater withdrawal. Withdrawals from the US High Plains aquifer from 1940–1980 outweighed insignificant local precipitation increases, and caused moderate to severe river flow depletion through a decline in groundwater levels [70]. In arid European regions, there is a clear inverse relationship between a decrease in moisture recycling and increases in groundwater use [71]. As groundwater resources eventually disappear the agricultural systems adapted to this practice may struggle.

2.4. River flows

Moisture recycling studies have often used river basins as their study region to analyse internal basin recycling [39,72], the sources of precipitation over a basin [40,73], and the fate of evaporation from a basin [17]. Anthropogenic modifications of river flows, such as construction of reservoirs and water transfers, also greatly affect evaporation [74] and, presumably, moisture recycling.

Recently, coupled land-atmosphere modelling has more directly studied the effect of deforestation and irrigation on river flows through moisture recycling. Using a coupled land surface-moisture recycling framework, Wang-Erlandsson et al. [75] show that taking moisture recycling into account (i.e., allowing evaporation change to change precipitation) almost halves the estimate of human land-use change impacts on globally aggregated river flow (from $+1200\,km^3\ yr^{-1}$ to $+650\,km^3\ yr^{-1}$). Their results exhibit considerable spatial heterogeneity: in the Congo, Volga, and Ob basins, river flow increases are reduced by more than half; in the Amazon, river flow increases drop radically from $+1630$ to $+270\,m^3\,s^{-1}$; and in the Yenisei, the sign of river flow change is reversed from an increase ($+150\ m^3\,s^{-1}$) to a decrease ($-220\,m^3\,s^{-1}$). The ability of land–atmosphere feedbacks to reverse the sign of change in river flow has also been shown under a business-as-usual deforestation scenario in the Xingu River basin in the Amazon, where accounting for land-atmosphere feedbacks switched river flow change estimates from an increase of 10–12% to a decrease of 30–36% [76]. Weng et al. [77] further show that the heterogeneity of moisture recycling effects on Amazonian river flows extend to sub-basin levels, and identify sensitive sink and influential source regions.

The combined effect of land-use change on river flows through changes in the water balance, depends on complex interactions among spatial and temporal dynamics among ground, surface, and atmospheric water flows. In addition to the need for saturation and dynamical drivers (e.g. cooling or lifting), it is also important to evaluate what configurations of internal versus external land-use changes lead to persistence in precipitation supply, facilitate adaptation in part of the river basin, or completely transform the function and structure of the river basin. The critical issue of how river resilience is affected by feedbacks between river flow change and moisture recycling remains to be investigated.

2.5. Megacities

Urban regions are rapidly expanding, increasing demands on scarce water resources. The water security of urban areas is a hotly studied topic [78], and the surface water that urban areas depend on is, in many cases, exposed to various moisture recycling pressures. Keys et al. [79] found that for 29 global megacities, municipal water was sourced from surface water supplies or actively recharged groundwater, which ultimately rely on precipitation falling within the watershed. Factors impacting moisture recycling such as the pace of land-use change, sensitivity to dry vs. wet year dynamics, and pre-existing water scarcity were particularly important. Understanding and managing moisture recycling (see Section 3) may need to be a part of designs to accommodate the needs of growing urban populations.

Urban water infrastructure is commonly designed for robustness to, and recovery from, water stresses and extreme events, with buffering capacity enabled by reservoirs, canals, pipes, treatment, and distribution networks [80]. These engineered approaches to water system resilience contribute to reliability, predictability, and to adaptability, but represent a more limited capacity to transform.

3. Management and governance of moisture recycling: tools and concepts

3.1. Basic spatial units of moisture recycling: precipitationshed and evaporationshed

Given the central role that terrestrial moisture recycling plays in water security, it would be useful to have an approach that (a) can assist

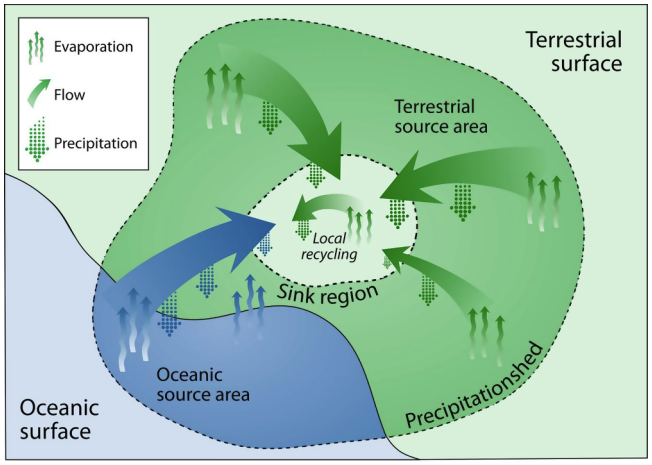

Fig. 4. Conceptual illustration of the precipitationshed. Originally published in [16], and reproduced here under Creative Commons Attribution 3.0 License.

in the identification of areas that provide rainfall to a given location, and (b) is flexible enough to incorporate multiple datasets, models, and spatial and temporal scales. The precipitationshed serves this purpose, and is defined as the upwind surface (both water and land) that contributes evaporation to a given location's precipitation (Fig. 4; also see Keys et al. [16]). As depicted, evaporation rises up from the surface, flows through the atmosphere, and falls as precipitation downwind.

3.2. Integrating scales and boundaries of moisture recycling, governance, and social-ecological systems

Managing moisture recycling for resilience requires a recognition of the complexity of moisture recycling systems. Keys and Wang-Erlandsson [4] describe this complexity in terms of 'moisture recycling social-ecological systems', that can range along a spectrum from 'isolated', 'regional', to 'telecoupled'. An example of a telecoupled moisture recycling system is the precipitationshed for the country of Bolivia. Moisture recycling provides a biogeophysical connection from the Brazilian and Peruvian Amazon to Bolivia's precipitation. However, socioeconomic infrastructure (e.g. roads, telecoms) and institutions (e.g. biological preserves, international treaties) create telecoupled connections and feedbacks, increasing both system complexity and making deterministic policies or management unsuitable.

In terms of the evidence presented earlier, management can mean a variety of different things. First, rainfed systems (such as forests, drylands, and rainfed agriculture) can be thought of as both providers of evaporation (i.e. sources) as well as beneficiaries (i.e. sinks). Moisture recycling management of these landscapes thus ought to reflect this duality, giving thought to both the key aspects of evaporation flow as well as precipitation. However, some other types of moisture recycling systems are one or the other, such as irrigation systems, which are primarily generators of evaporation to the atmosphere, or urban systems, which are primarily users of runoff that is generated by terrestrial moisture recycling. In these cases, the management might take a different form since it is focused on a specific part of the atmospheric water cycle.

Knowledge of moisture recycling system architecture does not on its own confer an ability to manage moisture recycling. An understanding of system lags and feedbacks is also critical to appreciate the appropriate temporal and spatial scales for measurement, monitoring, and determination of management efficacy. Keys and Falkenmark [65] suggest that different socio-hydrology systems operate at different timescales, often nested within one another. Additionally, the ability to detect an anthropogenic change in moisture recycling is complicated by internal climate variability [81].

Limited work examines the types of moisture recycling connections that may exist (particularly among nations), and the types of governance appropriate for each [82,83]. However, unlike surface water, atmospheric water does not channel into creeks, streams, and rivers, but rather flows continuously with wind currents around the planet. Despite hypothetical examples, intentional management and governance of moisture recycling remains highly theoretical. Yet, substantial evidence relates moisture recycling to the function and resilience of ecological and human systems alike. Consequently, we must understand how changes in land use, modification of surface and groundwater systems, agriculture and urbanization are not only changing terrestrial landscapes, but are altering vital planetary water flows.

3.3. Integration of moisture recycling in existing sustainability management tools and frameworks

Blending moisture recycling into existing sustainability efforts is essential to regional and planetary resilience. Moisture recycling has been scientifically described and evaluated as a key ecosystem service globally, and its inclusion in existing ecosystem service frameworks has been outlined [22]. Likewise, moisture recycling should be included in environmental and natural resource governance efforts, such as international conservation mechanisms and planning methods and potentially in trade and certification programs or other market and multilateral instruments [83]. Studies are further exploring the possibility to incorporate moisture recycling in water footprint assessments [84], which otherwise conventionally regard evaporation as a loss [85].

At the largest possible scale, the planetary boundary framework, which is used in sustainability policy and governance, proposes limits to water modifications for Earth to remain habitable for humanity [86]. Moisture recycling is currently only implicitly accounted for in the planetary boundary for freshwater use through the proxy variable 'total blue water consumption' [86,87] and in the land system change boundary [88].To explicitly account for human modifications of different components in the water cycle, a proposed revision of the water planetary boundary suggests six sub-boundaries, one of which concerns the role of moisture recycling for maintaining the stability of the atmospheric circulation system [89]. Ongoing work aims to determine the most important distributed hydrologic units for maintaining the stability of the atmospheric circulation system, such as keystone regions which are disproportionately important to the Earth system [90,91].

4. Conclusions. Understanding moisture recycling can nurture water resilience

Moisture recycling and human interactions are only beginning to be understood. Anthropogenic changes to the land surface in one location have significant potential to impact completely different, disconnected regions. Accordingly, we must develop a better scientific understanding and more suitable models for land-atmosphere interactions and regime shifts. This is particularly urgent, as moisture recycling, through its influence on precipitation, has profound implications for humanity – from agriculture, forestry, and urban water security to regional climatic stability and Earth system resilience.

Tropical forests serve as one of the most critical biomes for maintaining moisture recycling globally, and are thus critical to water resilience. Drylands and rainfed agriculture both exhibit a dependence on moisture recycling but also a complex self-regulatory role that is still not fully understood. Irrigated systems, especially those driven by groundwater, increase short term moisture recycling and perceived resilience, but threaten long-term resilience when societies overdraw groundwater to meet precipitation deficits. Finally, urban areas depend on their upwind hinterlands for stable and predictable sources of precipitation. In this way, moisture recycling further underscores water's role as a master variable for the resilience of human civilization.

Recent research points at multiple possibilities to address moisture

recycling in management and governance: introducing the management unit of precipitionshed, considering vegetation-regulated moisture recycling as an ecosystem service, as well as incorporation of moisture recycling in existing water resources tools and concepts. Existing efforts to consider moisture recycling in water footprinting, river basin management, and planetary boundaries are only at the exploration stage, and future work needs to both dive deeper into local-regional contexts and explore potential synergies with other sustainability management frameworks. Humanity has already unintentionally and substantially engineered precipitation patterns through land-use change, and conscious protection of the terrestrial water cycle is now urgently needed to achieve sustainability and build resilience.

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