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Atmospheric water recycling an essential feature of critical natural asset stewardship

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Abstract

Non-technical summary. In this paper, we explore how critically important ecosystems on the land provide evaporation to the atmosphere, which will later fall as precipitation elsewhere. Using a model-based analysis that tracks water flowing through the atmosphere, we find that more than two-thirds of the precipitation over critically important ecosystem areas is supplied by evaporation from other land. Likewise, more than 40% of the evaporation from critically important ecosystems falls as precipitation on other land. We conclude our work by discussing the policy implications for how these critically important ecosystems connect spatially distant wild and working lands via the atmospheric water cycle.

Technical summary. Global ecosystems are interconnected via atmospheric water vapor flows. Land use change can modify evaporation from land, altering atmospheric moisture recycling and potentially leading to significant changes in downwind precipitation and associated ecological impacts. We combine insights on global ecosystem-regulated moisture recycling with an analysis of critical natural assets (CNA, the 30% of global land providing most of nature's contributions to people) to reveal the sources and sinks of atmospheric water cycle regulation. We find that 65% of the precipitation over CNA is supplied by evaporation from other land areas. Likewise, CNA regions supply critical moisture as precipitation to terrestrial natural ecosystems and production systems worldwide, with 44% of CNA evaporation falling on terrestrial surfaces. Specifically, the Congo River basin emerges as a hotspot of overlap between local atmospheric water cycle maintenance and concentration of nature's contributions to people. Our results suggest global priority areas for conservation efforts beyond and in support of CNA, emphasizing the importance of sparsely populated managed forests and rangelands, along with wild forests, for fostering moisture recycling to and within CNA. This work also underlines the manifold benefits associated with achieving United Nations Sustainable Development Goal #15, to sustainably manage terrestrial life and conserve biodiversity.

Social media summary. Critically important ecosystems are essential for connecting distant landscapes via the atmospheric water cycle.

1. Introduction

Nature's contributions to people (NCP), the benefits or detriments of living nature to people's quality of life (Díaz et al., 2018), are increasingly recognized as an important concept in conservation research and sustainability governance (Brauman et al., 2020; Global Biodiversity Framework, 2021; IPBES, 2019; Millennium Ecosystem Assessment, 2005; Wood et al., 2018). Well-recognized local benefits from NCP include water security, food security, hazard risk reduction, material well-being, cultural values, and climate security.

Vegetation-regulated moisture recycling (VMR), that is, the role of vegetation in generating evaporation and maintaining precipitation, is one crucial way that nature contributes to people via supporting global food security and economic prosperity (Keys et al., 2016). Around a fifth of precipitation falling on global land areas is supplied by vegetation through VMR, and regionally, up to half of precipitation can originate from VMR (Keys et al., 2016). Thus, through VMR, reductions in evaporation associated with land cover and land use change in upwind areas can lead to decreased downwind precipitation (see Box 1). An improved quantitative understanding is needed of the spatially explicit regions that are most essential for generating, and benefitting from, VMR.

Recent work has identified critical natural assets (CNA), the most important natural and semi-natural ecosystems for providing beneficial NCP, comprising 30–44% of the total global land area (Chaplin-Kramer et al., 2022). While this work included VMR among the 14 NCP considered, it only considered the benefits of VMR to rainfed working lands, rather than to the

Box 1. What is moisture recycling?

The global hydrological cycle over land includes surface, subterranean, and atmospheric flows of water (Oki & Kanae, 2006), of which the latter are the largest (at 115,000 $km^3 yr^{-1}$ of terrestrial precipitation and 65,000 $km^3 yr^{-1}$ of terrestrial evaporation). In this work, we focus on the atmospheric flows of water, specifically tracking the contribution of evaporation from the land surfaces into the atmosphere, following the moisture flows across the planet, and locating its fate as precipitation elsewhere (van der Ent et al., 2010; Figure 1). Moisture tracking has been studied for decades (Koster et al., 1986; Trenberth, 1999), including tracking the atmospheric flows of water associated with terrestrial surfaces (Dirmeyer et al., 2006; Dirmeyer & Brubaker, 2007).

The important role of vegetation in supplying evaporation flows to the atmosphere and downwind precipitation has been demonstrated globally (Keys et al., 2016; Wei et al., 2012), as well as regionally, including in the Amazon (Spracklen & Garcia-Carreras, 2015; Staal et al., 2020b), the Indo-Gangetic plain (Tuinenburg et al., 2014), Eastern China (Guo et al., 2019), the North American great plains (DeAngelis et al., 2010), and across Siberia (Oshima et al., 2015). Forests typically generate more evaporation than short vegetation types such as grasslands, as they are able to intercept more rainfall on the canopy, forest floor, stems, and epiphytes, as well as store and access more water from soil moisture, bedrock moisture, and groundwater. However, even short vegetation can generate substantial evaporation, particularly over large areas. Where soil moisture is not a constraining factor, grassland evaporation can during its active biomass growing season exceed forest evaporation (Teuling et al., 2010). A desert planet is estimated to have a substantially less active water cycle with substantially less rainfall (Kleidon et al., 2000), and human deforestation is already estimated to have reduced precipitation substantially (Wang-Erlandsson et al., 2018). Vegetation's role in remote precipitation is especially important since transpiration, the water flows that vegetation use for photosynthesis and biomass growth is typically more important in supporting precipitation over longer distances and during dry periods (O'Connor et al., 2021; Staal et al., 2018; van der Ent et al., 2014; Wang-Erlandsson et al., 2014).

Recent work emphasizes the outsized importance of densely vegetated areas, such as tropical forests, in both providing moisture for other downwind areas as well as for recycling water internally (Spracklen et al., 2018). For example, in the interior Amazon basin, there is evidence that the moisture recycled by the tropical forest contributes to the resilience of the forest itself, stabilizing rainfall to avoid falling below critical thresholds that could lead to (potentially irreversible) savannization (O'Connor et al., 2021; Staal et al., 2018). In East Africa, the forested Kenyan highlands provide important moisture recycling both internally within the highlands themselves as well as for adjacent regions including the cross-border regions in Uganda and Rwanda (Keys et al., 2022). Globally, tropical forests may buffer themselves against climate shocks, though this may change as global climate change proceeds into the 21st century (Staal et al., 2020a).

CNA themselves; the remote functional connections between downwind CNA areas and the upwind source areas whose moisture they rely on have yet to be mapped.

A CNA area is fundamentally an ecosystem that provides a critical benefit to people, and to the extent that all ecosystems depend on precipitation, or more precisely the maintenance of their current precipitation regime, disturbing that precipitation regime could result in alterations to the ecosystem that could diminish its capacity to provide benefits to people. From a policy standpoint, such interdependencies can be important to understand, because if CNA regions are maintained but the ecosystems they depend on for precipitation are not, land use in those source regions could lead to reductions in (or potential collapse of) NCP in dependent ecosystems (Staal et al., 2020a). Likewise, if CNA for moisture regulation are not maintained, this could lead to reductions in precipitation in downwind areas, with implications, for example, river flows, water supply availability (Keys et al., 2018), crop production (Bagley et al., 2012; Oliveira et al., 2013), and self-amplified forest loss (Zemp et al., 2017).

In this work, we explore for the first time the importance of sources of precipitation for local CNA regions globally, as well as the global areas that are reliant on CNA evaporation, specifically how global or continental-scale moisture recycling supports the ecosystems that provide more landscape-scale benefits. We further aim to explore the types and spatial distribution of anthropogenically modified landscapes, in an effort to understand the demographic and land management challenges that may be associated with sources and sinks of CNA moisture. This study will help identify regions to be prioritized for protection, restoration, and improved management, in ways that are synergistic with other conservation objectives (Keys et al., 2017; te Wierik et al., 2020).

2. Data and methods

This study first maps the moisture recycling associated with different CNA regions, and secondly, examines the composition of the CNA regions globally with regard to VMR (Keys et al., 2016) and the anthropogenic biomes known as anthromes (Ellis & Ramankutty, 2008).

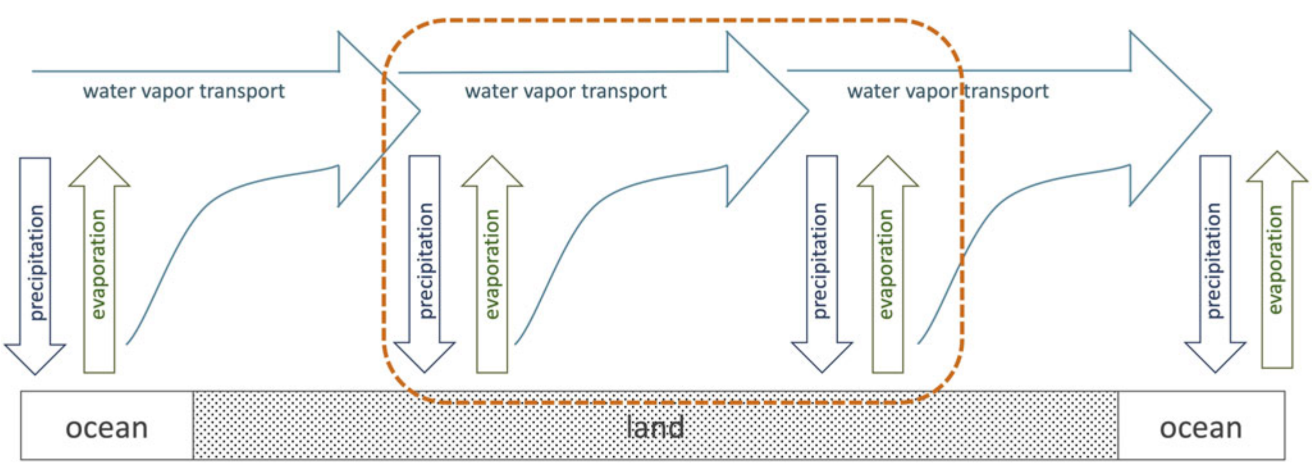

Figure 1. Schematic representation of atmospheric branch of water cycle, emphasizing moisture recycling that occurs over land. Within the orange dashed box, precipitation that is primarily of oceanic origin falls onto land, and the water that evaporates is from the land surface. This water is transported through the atmosphere, falls out as precipitation again, and is then re-evaporated on land again. Used with permission from Keys (2016).

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2.1 Identifying the 90% CNA regions

To recognize the multitude of contributions that ecosystems provide to human societies, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has underlined the importance of quantifying NCP (Díaz et al., 2018). CNA were mapped by Chaplin-Kramer et al. (2022) for 12 of nature's local contributions to people (including crop pollination, fodder for livestock, riverine fish harvest, marine fish harvest, nitrogen retention, sediment retention, flood mitigation, coastal protection, timber, fuelwood, access to nature, and marine recreation), identified through multi-objective optimization. While VMR was included in a separate prioritization to identify CNA for 'global NCP' (which included just VMR and carbon storage) and then overlapped with the CNA for these 12 local NCP, we focus here only on the local NCP to avoid circularity in the use of the VMR layer. Global maps of each of the 12 NCP mapped onto natural and semi-natural habitats at 300 m resolution (ESA-CCI land cover) were used to select 2 km planning units that achieve different target levels (ranging from 5 to 100%) of each NCP within each country in the minimum area. The NCP–area relationship asymptotes at around 90% of the total current value of all NCP in 30% of global land area, after which point much more area is required for each additional increment of NCP value; for this reason the 90% target was defined as 'critical'. This analysis uses only the local CNA (optimized at the country level) rather than the global CNA (optimized globally), because the latter includes only two NCP that are relevant at only larger scales, carbon storage, and moisture recycling (from the same model used here). The local CNA regions at the original resolution of 2 km were resampled to 1.5 degrees to match the resolution of the VMR layer, using 'near' to produce a 0–1 mask and using 'average' to produce a proportional area raster for the amount of CNA area within the 1.5 degree grid cell. For this analysis, we focus on areas in which CNA (providing 90% of NCP at 2 kpm) occupy 90% of a VMR grid cell (at 1.5 degree), hereafter CNA regions. We note that we do not disaggregate the 90% CNA areas into constituent NCPs. We use the aggregated 90% CNA areas, to specifically understand the role of CNA hotspots in the broader atmospheric water cycle.

We also note that we use the lens of NCP, which is an inherently anthropocentric view of nature. These methods to delineate the functional interdependencies between ecosystems could be applied to other conservation priority maps, such as biodiversity hotspots or key biodiversity areas.

2.2 Moisture tracking with WAM-2layers

The Water Accounting Model 2-layers (WAM-2layers) is a Eulerian atmospheric moisture tracking model, which permits tracking evaporation arising from the surface of the Earth, the water vapor flowing through the atmosphere, and the eventual fate of precipitation elsewhere. We track the moisture budget in the ERA-Interim reanalysis, using six types of input data, including two-dimensional surface pressure, precipitation, and evaporation, and three-dimensional zonal and meridional winds, and specific humidity (Dee et al., 2011). These data were downloaded at the 1.5 degree by 1.5 degree grid resolution. The two-dimensional data were downloaded at the three-hourly increment, and the three-dimensional data were downloaded at the six-hourly increment. We provide an overview of the WAM-2layers below, but other dimensions of model performance are explored and evaluated elsewhere, including the original implementation (van der Ent et al., 2010), modification for two atmospheric layers (Wang-Erlandsson et al., 2014), evaluation of variability (Keys et al., 2014), and comparison with results from regional climate models (van der Ent et al., 2013).

There are several procedures for the WAM-2layers analysis. First, the three-dimensional moisture data are integrated into two layers, representing an upper and lower level of the atmosphere. The boundary between the upper and lower layers generally corresponds to the approximate 800 hectopascal level, which can assist in separating upper and lower-level wind shear (Keys et al., 2014). Second, the fluxes of moisture entering upward (evaporation), horizontally (water vapor transport along prevailing winds), and downward (precipitation) are calculated at the 15-minute timestep. This procedure is calculated for numerical stability (van der Ent et al., 2010). Third, we use the 90% CNA data calculated above as a mask whereby we can track moisture forward in time (i.e. tracking evaporation from CNA origins through the atmosphere to its fate as precipitation elsewhere on Earth), and backward in time (i.e. tracking precipitation falling on CNA regions backward through the atmosphere to its origin as evaporation elsewhere on Earth).

The results of this analysis yield 15 years of moisture tracking information, from 2000 to 2014, aggregated at the monthly timestep. CNA moisture tracking information was calculated first for all 'local' CNA regions globally, and then separately for CNA regions within individual continents, including Africa, Australia, Eurasia, North America, and South America.

2.3 Vegetation-regulated moisture recycling

To distinguish the importance of vegetation for fostering current moisture recycling relationships, we employ previously calculated data on the role of vegetation in global moisture recycling (Keys et al., 2016). These data provide an estimate of the fractional evaporation that arises globally and that can be attributed to the present composition and configuration of vegetation on terrestrial land surfaces. The data were generated, in part, by the Simple Terrestrial Evaporation to Atmosphere Model (STEAM) (Wang-Erlandsson et al., 2014), and the WAM-2layers. The data are available at the monthly timestep and employ the same ERA-Interim atmospheric water cycle data as that used in the present study, except for the evaporation data which are simulated by STEAM.

We note that the source of the three-dimensional atmospheric data (ERA-Interim) and the time period of analysis (2000–2014) for the moisture tracking data used in this analysis is the same as that used for the VMR analysis (Keys et al., 2016). Thus, we can be confident that the three-dimensional moisture tracking (particularly the wind patterns) is identical between the two analyses.

2.4 Synthesizing source and sink data with anthropogenic biomes

Global data on anthropogenic biomes (i.e. anthromes) were originally downloaded at the 5 arc minute resolution. We perform a nearest neighbor spatial interpolation to upscale the anthrome data to the resolution of the ERA-Interim analysis, which is considerably coarser. However, because our analysis is inherently continental and global in nature, this coarsening of the data is considered acceptable. Future work that aims to explore country- or smaller-scale relationships would likely require a different approach. The global map of these anthromes is available in the supplementary information.

3. Results

Our results are broadly divided into two sections. First, we examine the results of moisture recycling associated with different CNA regions. Second, we examine the composition of the CNA regions by employing two additional datasets, VMR (Keys et al., 2016) and the anthropogenic biomes known as anthromes (Ellis & Ramankutty, 2008).

3.1 Substantial global moisture regulation occurs on land for both sources and sinks for CNA

Globally, CNA regions are spread across all populated continents (Figure 2, black outlines). The largest cluster of CNA regions in this analysis is located in Sub-Saharan Africa, in and around the Congo River basin. We find that source regions providing evaporation to precipitation within CNA regions (Figure 2a) are spread across all continents, and that taken collectively, land is responsible for 65% of the moisture falling as precipitation in CNA regions. Likewise, 44% of evaporation arising from CNA regions falls as precipitation on land elsewhere in the world.

3.2 CNA regions are associated with substantial internal moisture recycling

Moisture recycling dynamics reveal that CNA regions send and receive a substantial amount of moisture from and to one another (Figure 3). In this case, we find that CNA regions receive about 27% of average annual precipitation from other CNA regions. When restricted to specific continents, African and South American CNA have very high internal recycling from regional CNA, with 27 and 24%, respectively, of precipitation coming from intracontinental CNA regions. This demonstrates the outsize importance of CNA regions, particularly in those parts of the world, for providing supporting ecosystem services in the form of moisture recycling regulation.

3.3 Interpreting importance of contiguous ecosystems for moisture recycling

We explore the importance of current vegetation globally by using the VMR metric (Keys et al., 2016). Using this, we identify the parts of the world that are sending (or receiving) a substantial amount of moisture to (or from) CNA regions. We define these source areas by the 10 mm yr^{-1} boundary of contribution, meaning that each year, regions enclosed in the pink boundaries contribute 10 mm yr^{-1} or more of evaporation to CNA

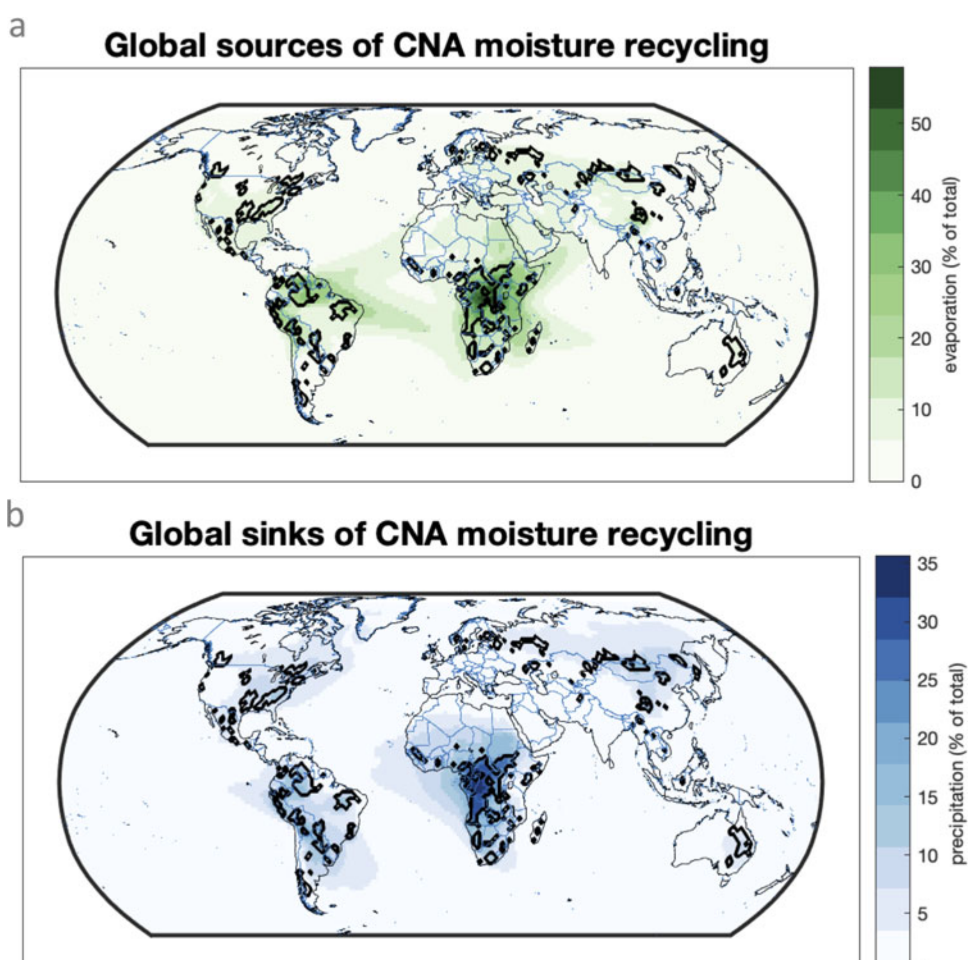

Figure 2. Global moisture recycling ratios for the evaporative origins of moisture that will fall as CNA precipitation (a), and the precipitation sinks from CNA evaporation (b). Black outlines enclose the CNA regions.

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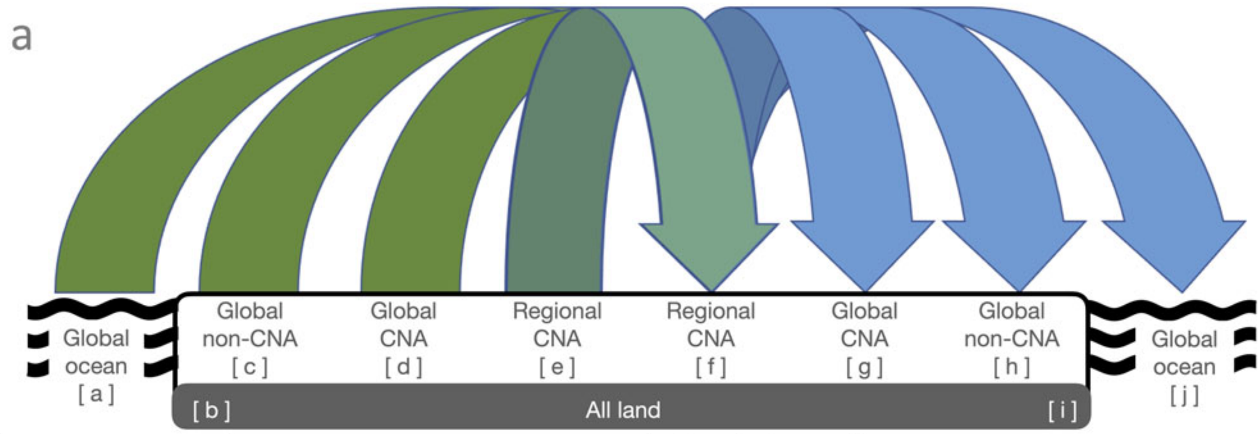

b	Origin of CNA moisture				Internal moisture recycling in focal CNA region		Fate of CNA moisture			
	Precip from all ocean (a)	Precip from all land (b)	Precip from all non-CNA land (c)	Precip from all CNA land (d)	Precip from internal CNA evap (e)	Evap to internal CNA precip (f)	Evap to all CNA land (g)	Evap to all non-CNA land (h)	Evap to all land (i)	Evap to all ocean (j)
Moisture flux region	total	total	total	total	total	total	total	total	total	total
African CNA	29%	71%	33%	38%	27%	19%	23%	28%	51%	49%
area (million km^2)	*359.6*	*143.2*	*128.1*	*15.1*	*5.5*	*5.5*	*15.1*	*128.1*	*143.2*	*359.6*
Eurasian CNA	32%	68%	55%	13%	13%	7%	7%	43%	51%	49%
area (million km^2)	*359.6*	*143.2*	*128.1*	*15.1*	*2.7*	*2.7*	*15.1*	*128.1*	*143.2*	*359.6*
Australian CNA	74%	26%	20%	6%	6%	4%	4%	15%	19%	81%
area (million km^2)	*359.6*	*143.2*	*128.1*	*15.1*	*0.9*	*0.9*	*15.1*	*128.1*	*143.2*	*359.6*
N American CNA	52%	48%	36%	12%	11%	8%	8%	23%	31%	69%
area (million km^2)	*359.6*	*143.2*	*128.1*	*15.1*	*2.3*	*2.3*	*15.1*	*128.1*	*143.2*	*359.6*
S American CNA	34%	66%	42%	24%	24%	12%	12%	25%	38%	62%
area (million km^2)	*359.6*	*143.2*	*128.1*	*15.1*	*3.7*	*3.7*	*15.1*	*128.1*	*143.2*	*359.6*
Global	**35%**	**65%**	**38%**	**27%**	**27%**	**15%**	**15%**	**28%**	**44%**	**56%**
area (million km^2)	*359.6*	*143.2*	*128.1*	*15.1*	*15.1*	*15.1*	*15.1*	*128.1*	*143.2*	*359.6*

Figure 3. The global and continental sources and sinks of atmospheric water. The top figure (a) shows a conceptual overview of the different flows of moisture, while the table (b) shows the fraction of moisture (with the corresponding areas) of different source and sink regions for CNA moisture.

precipitation (Figure 4). We see large, contiguous areas across much of the tropical world contributing both large fractions (Figure 4a) and absolute amounts (Figure 4b) of moisture to CNA precipitation.

The regions that are contributing 10 mm yr^{-1} or more of evaporation annually include substantial regions in tropical Central Africa and the Amazon. Also, the upper basin of the Congo River, the Sudd wetland in South Sudan, and the highlands around the Great Lakes of East Africa all provide substantial evaporation that is recycled as precipitation in CNA regions. Beyond the tropics, the key sources originate from the Himalayas, Eastern Europe, and western Russia, as well as the southeastern United States and the Pacific Northwest of North America.

A similar pattern is seen for moisture sinks as for moisture sources. Again, we see large, contiguous areas across much of the tropical world receiving both large fractions (Figure 5a) and absolute amounts (Figure 5b) of moisture from CNA evaporation. We define these as sink areas that receive 10 mm yr^{-1} or more of precipitation from CNA evaporation. The locations within the pink boundaries in Figure 5, that receive 10 mm yr^{-1} or more of precipitation from CNA evaporation, are more spatially extensive than the source regions displayed in Figure 4. Sinks extend beyond the tropics to include much of Sub-Saharan Africa, South America, substantial portions of Russia and China, and half of North America.

3.4 Anthropogenic biomes permit new perspective on CNA interconnections

Overlaying anthropogenic land uses (i.e. anthromes) with VMR, we find that as moisture sources, forests are generally above the average moisture recycling efficiency (Figure 6, top left; dashed line shows the area *vs.* volume relationship), meaning that they provide more moisture volume per unit area to CNA regions than do other evaporation sources, while rangelands and croplands tend to have equal or below average efficiency. For the VMR sinks (Figure 6, top right) we see a more heterogeneous result, with a mix of rangelands and forests above the average volume per area, and wild woodlands notably below average. Populated woodlands and rangelands are a dominant source of precipitation to CNA regions, and they also receive the greatest volume of CNA moisture (Figure 6). In contrast, wild woodlands are spatially the most frequent land use receiving moisture from CNA regions (Figure 6, top right: dark green dot at right side of sink graph).

In looking at the anthrome characteristics for the evaporative source regions of CNA, we see that there are substantial forested areas that provide evaporation to CNA. Tropical South America, northeastern Brazil, and the entire Guiana Shield provide substantial evaporation for CNA precipitation. Beyond the tropics, forested mountainous areas in central China and the Himalaya

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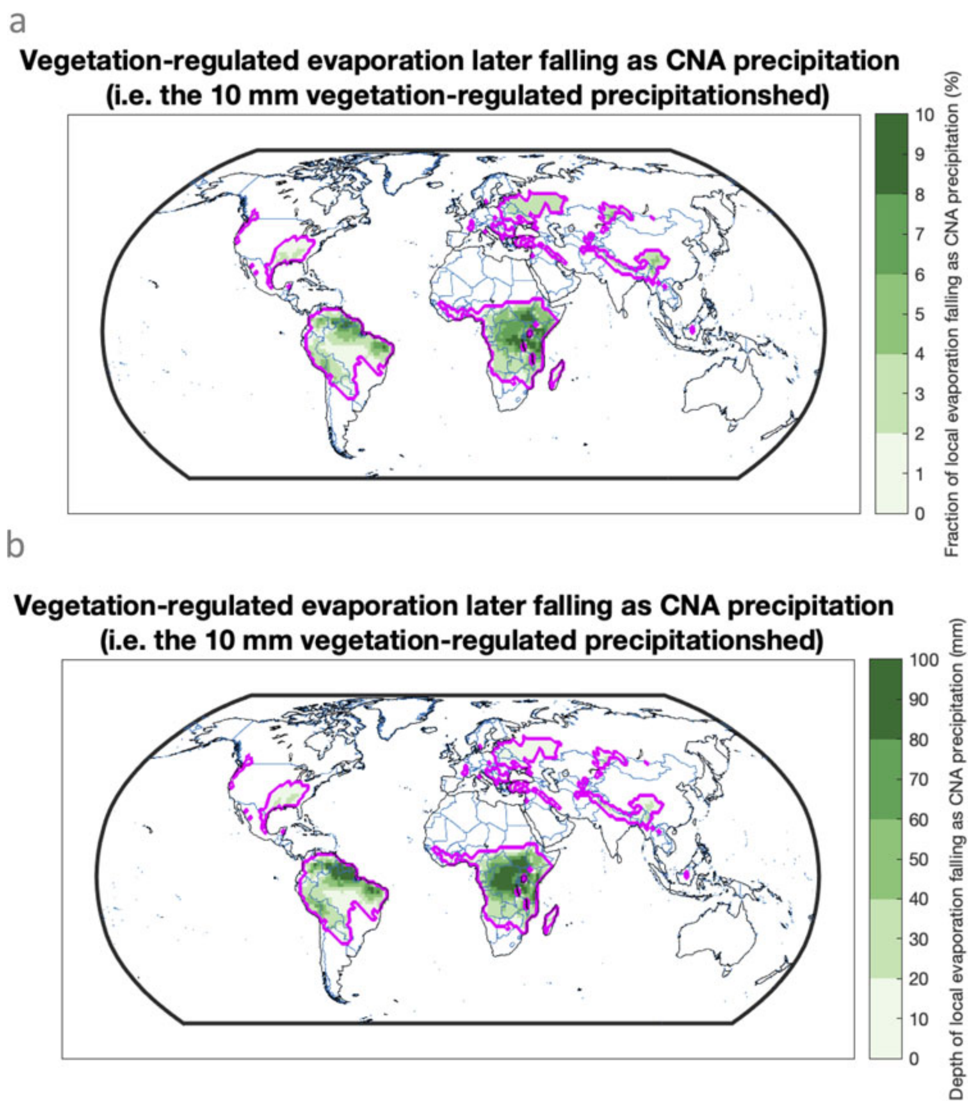

Figure 4. Global distribution of regions that provide vegetation-regulated evaporation to downwind CNA regions, as a fraction of total evaporation that falls as precipitation (a) and in total mm yr^{-1} of water (b). The pink outlines enclose the regions that provide 10 mm yr^{-1} or more of annual evaporation to global CNA regions.

are critical sources of moisture for CNA regions. In Eurasia, the regions that provide substantial moisture recycling are dominated by heavily populated rainfed croplands, while sources in southeastern North America are predominantly residential woodlands and rainfed croplands (for more information see Supplementary Figure 1).

The locations that receive CNA precipitation include nearly all the tropical forests of Africa and South America, as well as tropical forests in Borneo and parts of southeast Asia. In extratropical South America and Africa, rangelands are the dominant landscape, while in North America and Eurasia, there is a heterogeneous cover of dense settlements, cultivated lands, rangelands, and woodlands.

4. Discussion

4.1 Managed lands play an integral role in CNA stewardship

This work enables the direct evaluation of the importance of different types of landscapes, and is unique in enabling the distinction between the performance of wildlands and managed lands. Wildlands, particularly tropical forests, often receive the majority of the attention with regard to climate and biodiversity concerns and are often prioritized in conservation conversations, yet wild tropical forests are not the only key sources of precipitation regulation for the ecosystems most important to people (i.e. containing CNA). We find that managed lands are also significant for modulating intra-CNA moisture recycling, serving as both sources of CNA precipitation and recipients of CNA evaporation. The importance of moisture recycling to managed lands such as populated woodlands and rangelands illustrates a key way that CNA regions support human well-being: providing moisture needed for rainfed livelihoods such as silviculture and pastoral production (Keys et al., 2012; Keys & Wang-Erlandsson, 2018). These lands require careful stewardship to ensure they are able to continue supporting CNA regions with VMR benefits. CNA regions internally recycle a large proportion of their moisture, but these areas still depend significantly on the lands beyond their boundaries for rainfall.

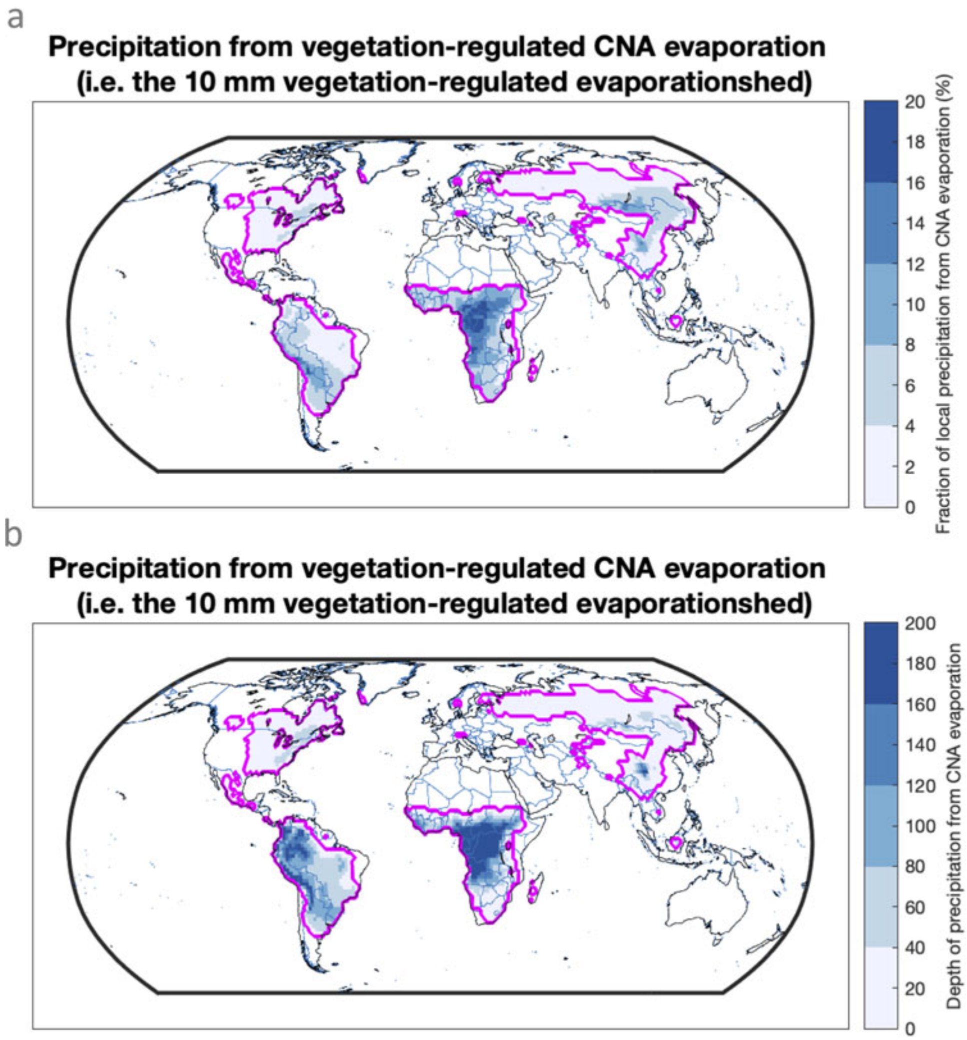

Figure 5. Global distribution of regions that receive vegetation-regulated evaporation from upwind CNA regions, shown in fractional (a) and absolute (b) amounts. The pink outlines enclose the regions that receive 10 mm yr^{-1} or more of annual precipitation from global CNA regions.

We find that managed woodlands are nearly as important as wild forests for consistently providing above-average volumes of water per unit area to CNA regions (Figure 6), despite natural forests' role in modulating and maintaining stable moisture recycling patterns globally (Meier et al., 2021; Molina et al., 2019; Mu et al., 2021; O'Connor et al., 2021; Pranindita et al., 2021; Staal et al., 2018; Wang-Erlandsson et al., 2018). The disproportionate importance of managed woodlands for CNA is likely a consequence of the spatial proximity of managed woodlands to CNA areas. Thus, both managed and wild forests are critical sources of resilience and stability to precipitation regimes for CNA regions globally, and both should be considered alongside CNA regions in conservation and management decision-making.

The importance of rangelands as a source of moisture for CNA regions, as well as a recipient of CNA moisture, is less well-appreciated. Rangelands, which are predominantly located in global arid and semi-arid regions and may comprise varying combinations of grasslands, shrublands, and partial treecover, can be highly sensitive to changes in precipitation patterns, including seasonality (Sircely et al., 2019), interannual variability (Wilcox et al., 2011), long-term climatic changes (Boone et al., 2018; Foley et al., 2003), and interactions with human societies (Galvin et al., 2006). In addition to this sensitivity, dryland vegetation can play a complex role in responding to ecological disturbance, including fires, overgrazing or denuding of vegetation, soil compaction, woody encroachment, and introduction of invasive species (Miralles et al., 2016; Turnbull et al., 2012). Our findings highlight the need to further study the moisture recycling inter-relationships that rangelands can have, both with other systems (such as providing moisture to CNA regions) and in terms of their reliance on CNA regions, to better understand implications for management.

4.2 Transboundary moisture regulation requires transboundary governance

A key implication of our results is that moisture recycling connects CNA regions to other landscapes, including in adjacent and distant countries. This transboundary dimension invites a discussion about what forms of governance might be possible in the context of moisture recycling and the atmospheric water cycle, specifically in the context of forests themselves. Keys et al. (2017) suggest that transboundary moisture recycling governance exists along a continuum of increasing complexity, from simple bilateral relationships (e.g. proof of harm [Allum, 2006]) to

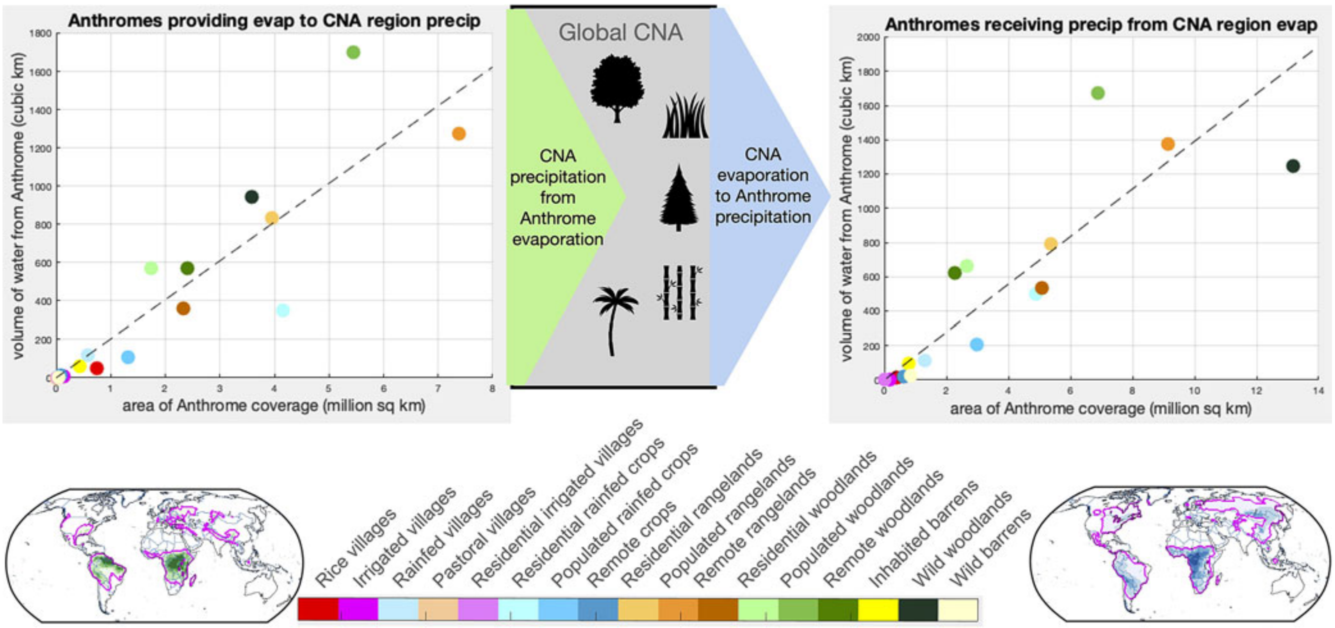

Figure 6. The role of different anthromes in modulating the sources of evaporation for critical natural assets (CNA) and the sinks of precipitation from CNA. The scatter plots show, for the 10 mm yr^{-1} boundaries (explained above), the relationship between the total area (*x*-axis) and total volume (*y*-axis) of a given anthrome. The dashed line on both scatter plots indicates the average moisture recycling efficiency across the 17 anthrome groups.

complex networks of overlapping and confounding connection, with less stringent but more flexible polycentric governance options (Galaz et al., 2008). Likewise, te Wierik et al. (2020) explore governance as it relates to both atmospheric water and green water (i.e. the water that exists in the soil column and vegetation but that does not form surface runoff). This opens different challenges than transboundary moisture recycling governance alone since this framing also considers how land use change can modulate green water, and correspondingly, evaporation flows. Despite this, such a framing is critical for understanding transboundary moisture recycling, particularly as it relates to interlinkages with the science of NCP which is the foundation for understanding CNA regions globally.

Other work has explored the importance of forests in fostering transboundary moisture recycling resilience. Ellison et al. (2018) explore the institutional scales at which forest–water relationships are governed, including the presence or absence of international agreements that can be meaningfully brought to bear in transboundary forest- and water-related topics. Likewise, other work has suggested that forest management should be explicitly linked to the maintenance of moisture recycling patterns, specifically given the fact that terrestrial landscapes recycle moisture many times as it cascades across the land surface (Food and Agriculture Organization of the United Nations, 2019). What our analysis adds to this body of evidence is that transboundary governance of moisture recycling is important not just for water management but for the variety of other ways that natural ecosystems support human well-being. The connections between forests and transboundary moisture recycling governance should be considered in the discourse around the global conservation of wilderness and semi-natural areas (Beyer et al., 2020; Riggio et al., 2020).

4.3 Uncertainties and research frontiers

This research connects several areas of study that have not traditionally been well-linked, specifically a largely academic research effort on moisture recycling dynamics, the conceptual and theoretical discussion of Earth system governance, and conservation planning. It also raises some key uncertainties that must be addressed to deepen understanding of how long-distance connections could be better integrated into conservation planning. We propose five new research frontiers based on our current work.

First, the scale dependence of moisture recycling phenomena is a key uncertainty. Our results demonstrate the average exchange of moisture among CNA regions for the period of time 2000–2014. This provides an important starting point for understanding the interannual patterns of the recent, observed past. However, while the data we use is suitable for global and regional analysis of patterns at the monthly or annual timestep, neither is sufficient for analyzing specific patterns, especially if being put to use for policy. Different moisture tracking models (Tuinenburg et al., 2020; van der Ent et al., 2010; Vázquez et al., 2021; Wei et al., 2012) and numerous types of climate data (Bosilovich et al., 2017; e.g. Dee et al., 2011) are available and appropriate for different scales. Global analyses may be similar at regional to global spatial scales and monthly to annual timescales (Keys et al., 2014; van der Ent et al., 2013), but different models and datasets will yield different results at finer spatial and temporal resolutions. Multiple simulations using multiple data sources (and possibly multiple moisture tracking models) will be required for specific policy relevance in particular contexts, to ensure robust results and better ability to explore uncertainties, both of which are essential to decision-making.

Likewise, exploration of different time horizons and dynamic processes is needed to inform intra- and interannual variability and long-term change. Seasonality may drive more important changes in certain regions than mean annual characteristics. For example, the relatively larger importance of moisture recycling during dry seasons can be relevant for conservation policy in semi-arid and arid regions (Falkenmark et al., 2019; Staal et al., 2018; Wang-Erlandsson et al., n.d.). Dynamic climate simulations that can capture more detailed dynamic processes could also be used to better constrain and explore different types of uncertainty. While we do not consider climate change in this analysis, other work has begun examining how future changes in precipitation and rising temperatures could modulate moisture recycling (Findell et al., 2019). Accounting for climate change will be critical for robust long-term biodiversity conservation planning (Arneth et al., 2020; Hannah et al., 2020; Pecl et al., 2017). Future work should also consider interactions between climate trajectories and changing land use, for example, cascading impacts, surface water trade-offs, and geopolitical change. Additional questions related to longer-term sustainability and environmental justice, drawing on the increasing burden of climate change impacts, will also be important to consider (Menton et al., 2020).

Second, our results clearly identify ecologically critical, yet potentially fragile parts of the coupled Earth system including the tropical forests in both the Amazon and the Congo as key sources and sinks of moisture recycling. Recent advances in defining the specific interactions of the entire water cycle in terms of Earth system tipping points provide new frontiers of research and practice related to moisture recycling (Gleeson et al., 2020a, 2020b). Work by Zipper et al. (2020) highlights the social and ecological scales at which different aspects of the water cycle can be reasonably managed. We find that moisture recycling is simultaneously a transboundary phenomenon and that any management will likely need to be integrated with intersectoral resource governance. This is echoed by Ahlström et al. (2021), suggesting opportunities for engagement with resource management authorities, regional scientific organizations, and other forms of transboundary decision-making (Keys et al., 2017; te Wierik et al., 2020). The advent of computationally efficient simulations of Earth system dynamics (which include human societies) permits a new window into understanding the practical consequences of transgressing social and ecological tipping points (Wunderling et al., 2020, 2021). While this remains a theoretical aspect of Earth system science, the ability to link tipping point simulations to current policy discourse permits a realistic representation of Earth system surprises alongside conservation-related policies (particularly those related to tipping-prone systems like the Amazon rainforest). Such methods could enable forecasting of the ecological consequences of specific policy decisions (e.g. relaxed enforcement of protected Amazon forest, potential resulting savannization [Hirota et al., 2011; Nepstad et al., 2008; Staal et al., 2020a]), and consequences for downwind human systems via reductions in moisture recycling to Bolivia, Paraguay, and Uruguay (Keys & Wang-Erlandsson, 2018). These research questions can now be reasonably explored given recent conceptual, computational, and scientific advances.

Third, context-specific cases could be explored that enable higher-resolution modeling of coupled land use change and moisture recycling impacts, but with explicit inclusion of management criteria (e.g. different regulatory regimes in protected areas) alongside distinct political contexts (e.g. cooperative, antagonistic). Beyond addressing the resolution concerns addressed above, this sort of tailored case analysis would permit the production of management-relevant insights even more useful for addressing real-world problems. In particular, a blind spot in much of this work is the acute lack of moisture recycling analysis in the Congo basin (including both ground-based and modeling studies). Central Africa is among the most important CNA regions globally (Chaplin-Kramer et al., 2022), and it is clear from our analysis that it is also critical from a moisture recycling perspective. Thus, we need a much better, broader understanding of this region from an integrated land and moisture recycling perspective, as well as from a socio-economic perspective. This is particularly urgent given increased agricultural and ecological drought risks across Africa, as well as carbon sink-to-source conversion across the tropics due to tree mortality (Hubau et al., 2020).

Fourth, there is a fundamental need to consider systemic vulnerability and situated vulnerability, such that different socio-economic contexts make people more (or less) directly nature-dependent. Some work has attempted to explore moisture recycling vulnerability from a variety of perspectives (Keys & Wang-Erlandsson, 2018; Keys et al., 2012, 2018), yet very little work has explicitly focused on the nexus of moisture recycling, ecosystem conservation, and human well-being. Keys and Falkenmark (2018) highlight the importance of considering the ability to change moisture recycling (and detect such a change) in the context of Sustainable Development Goal (SDG) achievement, given that moisture recycling might drive surprising changes in ecosystem function but be delayed substantially in time. Weng (2020) suggests that thoughtful reforestation in the Amazon could lead to substantial improvements in the stability of the atmospheric water cycle for Bolivian farmers. Recent studies suggest that afforestation and forest restoration have substantial global potential to increase water availability both locally and regionally through moisture recycling (Cui et al., 2022; Hoek van Dijke et al., 2022).

Fifth, the results of our work should be updated regularly to reflect changes in underlying conservation efforts and to see whether those changes can be detected at national, regional, or global scales in the moisture recycling signature. This work points to several areas of future research that must be pursued to better inform national and international decision-making. Likewise, the entire analysis could be updated to reflect major policy changes, or even pre-emptively simulated to support more-informed decision-making. For example, policy implementing new targets set by the Convention on Biological Diversity (CBD) would benefit from multiple scenarios that consider moisture recycling changes to reflect the conservation-related consequences for the water cycle.

5. Conclusions

Conserving CNA regions in isolation is not sufficient to protect them and support their functioning; better conservation and management of the lands outside CNA regions is needed as well, especially in semi-populated managed rangelands and woodlands. A better understanding of the ways in which VMR connects spatially distant wild and working lands is an essential contribution to the global sustainability conversation. Transboundary water management in international river basins is already recognized as an important yet extremely difficult-to-achieve objective (Mason et al., 2020; Zeitoun et al., 2013). Similarly, carbon management for climate is a global challenge, and fighting biodiversity loss while sustaining NCP requires international cooperation to succeed (Schleicher et al., 2019; TWI2050-The World in, 2018). Like these objectives, VMR crosses the boundaries of watersheds and nations, yet it does not receive the same attention in international agreements such as the SDGs or the CBD.

We recommend VMR be considered as a crucial NCP and prioritized alongside biodiversity, climate change mitigation, and integrated watershed management in the international sustainable development conversation – not only among national governments, but within UN policy-setting contexts, international aid investment decision-making, and corporate business practice improvement. The best available science should underpin global action for achieving sustainable development, including the SDGs (Sachs et al., 2020a, 2020b) and the CBD's Global Biodiversity Framework (Global Biodiversity Framework, 2021). Better accounting for processes like VMR in land management decision-making would bring us one step closer to achieving such ambitious goals, particularly in regard to providing greater resilience in moderating local climate.

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References

Ahlström, H., Hileman, J., Wang-Erlandsson, L., García, M. M., Moore, M.-L., Jonas, K., Pranindita, A., Kuiper, J. J., Fetzer, I., Jaramillo, F., & Svedin, U. (2021). An Earth system law perspective on governing social-hydrological systems in the Anthropocene. *Earth System Governance*, *10*, 100120.

Allum, J. R. (2006). An outcrop of hell: History, environment, and the politics of the trail smelter dispute. In R. M. Bratspies, & R. A. Miller (Eds.), *Transboundary harm in international law: Lessons from the trail smelter arbitration* (pp. 13–26). Cambridge University Press.

Arneth, A., Shin, Y.-J., Leadley, P., Rondinini, C., Bukvareva, E., Kolb, M., Midgley, G. F., Oberdorff, T., Palomo, I., & Saito, O. (2020). Post-2020 biodiversity targets need to embrace climate change. *Proceedings of the National Academy of Sciences of the USA*, *117*(49), 30882–30891.

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: ERL [Web Site]*, *7*(1), 014009.

Beyer, H. L., Venter, O., Grantham, H. S., & Watson, J. E. M. (2020). Substantial losses in ecoregion intactness highlight urgency of globally coordinated action. *Conservation Letters*, *13*(2), 1.

Boone, R. B., Conant, R. T., Sircely, J., Thornton, P. K., & Herrero, M. (2018). Climate change impacts on selected global rangeland ecosystem services. *Global Change Biology*, *24*(3), 1382–1393.

Bosilovich, M. G., Robertson, F. R., Takacs, L., Molod, A., & Mocko, D. (2017). Atmospheric water balance and variability in the MERRA-2 reanalysis. *Journal of Climate*, *30*(4), 1177–1196.

Brauman, K. A., Garibaldi, L. A., Polasky, S., Aumeeruddy-Thomas, Y., Brancalion, P. H. S., DeClerck, F., Jacob, U., Mastrangelo, M. E., Nkongolo, N. V., Palang, H., Pérez-Méndez, N., Shannon, L. J., Shrestha, U. B., Strombom, E., & Verma, M. (2020). Global trends in nature's contributions to people. *Proceedings of the National Academy of Sciences of the USA*, *117*(51), 32799–32805.

Chaplin-Kramer, R., Neugarten, R. A., Sharp, R. P., Collins, P. M., Polasky, S., Hole, D., Schuster, R., Strimas-Mackey, M., Mulligan, M., Brandon, C., Diaz, S., Fluet-Chouinard, E., Gorenflo, L. J., Johnson, J. A., Kennedy, C. M., Keys, P. W., Longley-Wood, K., McIntyre, P. B., Noon, M., … Watson, R. A. (2022). Mapping the planet's critical natural assets. *Nature Ecology & Evolution*, *7*(1), 51–61. https://doi.org/10.1038/s41559-022-01934-5.

Cui, J., Lian, X., Huntingford, C., Gimeno, L., Wang, T., Ding, J., He, M., Xu, H., Chen, A., Gentine, P., & Piao, S. (2022). Global water availability boosted by vegetation-driven changes in atmospheric moisture transport. *Nature Geoscience*, *15*(12), 982–988.

DeAngelis, A., Dominguez, F., Fan, Y., Robock, A., Kustu, M. D., & Robinson, D. (2010). Evidence of enhanced precipitation due to irrigation over the Great Plains of the United States. *Journal of Geophysical Research*, *115* (D15), D15115.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., … Vitart, F. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597.

Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R. T., Molnár, Z., Hill, R., Chan, K. M. A., Baste, I. A., Brauman, K. A., Polasky, S., Church, A., Lonsdale, M., Larigauderie, A., Leadley, P. W., van Oudenhoven, A. P. E., van der Plaat, F., Schröter, M., Lavorel, S., … Shirayama, Y. (2018). Assessing nature's contributions to people. *Science*, *359*(6373), 270–272.

Dirmeyer, P. A., & Brubaker, K. L. (2007). Characterization of the global hydrologic cycle from a back-trajectory analysis of atmospheric water vapor. *Journal of Hydrometeorology*, *8*(1), 20–37.

Dirmeyer, P. A., Koster, R. D., & Guo, Z. (2006). Do global models properly represent the feedback between land and atmosphere? *Journal of Hydrometeorology*, *7*(6), 1177–1198.

Ellis, E. C., & Ramankutty, N. (2008). Putting people in the map: Anthropogenic biomes of the world. *Frontiers in Ecology and the Environment*, *6*(8), 439–447.

Ellison, D., Claassen, M., Van Noordwijk, M., Sullivan, C. A., Vira, B., Xu, J., Archer, E. R. M., & Haywood, L. K. (2018). *Governance options for addressing changing forest-water relations*. International Union of Forest Research Organizations (IUFRO).

Falkenmark, M., Wang-Erlandsson, L., & Rockström, J. (2019). Understanding of water resilience in the Anthropocene. *Journal of Hydrology X*, *2*, 100009.

Findell, K. L., Keys, P. W., van der Ent, R. J., Lintner, B. R., Berg, A., & Krasting, J. P. (2019). Rising temperatures increase importance of oceanic evaporation as a source for continental precipitation. *Journal of Climate*, *32*(22), 7713–7726.

Foley, J. A., Coe, M. T., Scheffer, M., & Wang, G. (2003). Regime shifts in the Sahara and Sahel: Interactions between ecological and climatic systems in Northern Africa. *Ecosystems*, *6*(6), 524–532.

Food and Agriculture Organization of the United Nations. (2019). *Unasylva 251: Forests: Nature-based solutions for water*. Food & Agriculture Org.

Galaz, V., Olsson, P., Hahn, T., Folke, C., & Svedin, U. (2008). *The problem of fit among biophysical systems, environmental and resource regimes, and broader governance systems: Insights and emerging challenges*, pp. 147–182.

Galvin, K. A., Thornton, P. K., de Pinho, J. R., Sunderland, J., & Boone, R. B. (2006). Integrated modeling and its potential for resolving conflicts between conservation and people in the rangelands of East Africa. *Human Ecology*, *34*(2), 155–183.

Gleeson, T., Wang-Erlandsson, L., Porkka, M., Zipper, S. C., Jaramillo, F., Gerten, D., Fetzer, I., Cornell, S. E., Piemontese, L., Gordon, L. J., Rockström, J., Oki, T., Sivapalan, M., Wada, Y., Brauman, K. A., Flörke, M., Bierkens, M. F. P., Lehner, B., Keys, P. W., … Famiglietti, J. S. (2020a). Illuminating water cycle modifications and Earth system resilience in the Anthropocene. *Water Resources Research*, *56*(4). https://doi.org/10.1029/2019wr024957

Gleeson, T., Wang-Erlandsson, L., Zipper, S. C., Porkka, M., Jaramillo, F., Gerten, D., Fetzer, I., Cornell, S. E., Piemontese, L., Gordon, L. J., Rockström, J., Oki, T., Sivapalan, M., Wada, Y., Brauman, K. A., Flörke, M., Bierkens, M. F. P., Lehner, B., Keys, P. W., … Famiglietti, J. S. (2020b). The water planetary boundary: Interrogation and revision. *One Earth*, *2*(3), 223–234.

Global Biodiversity Framework. (2021). *CBD/WG2020/3/3. First draft of the post-2020 global biodiversity framework*. United Nations.

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.

Hannah, L., Roehrdanz, P. R., Marquet, P. A., Enquist, B. J., Midgley, G., Foden, W., Lovett, J. C., Corlett, R. T., Corcoran, D., Butchart, S. H. M., Boyle, B., Feng, X., Maitner, B., Fajardo, J., McGill, B. J., Merow, C., Morueta-Holme, N., Newman, E. A., Park, D. S., … Svenning, J.-C. (2020). 30% Land conservation and climate action reduces tropical extinction risk by more than 50%. *Ecography*, *43*(7), 943–953.

Hirota, M., Holmgren, M., Van Nes, E. H., & Scheffer, M. (2011). Global resilience of tropical forest and savanna to critical transitions. *Science*, *334*(6053), 232–235.

Hoek van Dijke, A. J., Herold, M., Mallick, K., Benedict, I., Machwitz, M., Schlerf, M., Pranindita, A., Theeuwen, J. J. E., Bastin, J.-F., & Teuling, A. J. (2022). Shifts in regional water availability due to global tree restoration. *Nature Geoscience*, *15*(5), 363–368.

Hubau, W., Lewis, S. L., Phillips, O. L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A., Daniels, A. K., Ewango, C. E. N., Fauset, S., Mukinzi, J. M., Sheil, D., Sonké, B., Sullivan, M. J. P., Sunderland, T. C. H., Taedoumg, H., Thomas, S. C., White, L. J. T., Abernethy, K. A., Adu-Bredu, S., … Zemagho, L. (2020). Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature*, *579*(7797), 80–87.

IPBES. (2019). *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (E. S. Brondizio, J. Settele, S. Díaz, & H. T. Ngo (eds.)). pesquisa.bvsalud.org.

Keys, P. W. (2016). *The precipitationshed: Concepts, methods, and applications* [Stockholm Resilience Centre, Stockholm University]. https://www.diva-portal.org/smash/record.jsf?pid=diva2:951928

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.

Keys, P. W., & Falkenmark, M. (2018). Green water and African sustainability. *Food Security*, *10*, 537–548. https://doi.org/10.1007/s12571-018-0790-7.

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.

Keys, P. W., & Wang-Erlandsson, L. (2018). On the social dynamics of moisture recycling. *Earth System Dynamics; Gottingen*, *9*(2), 829–847.

Keys, P. W., Wang-Erlandsson, L., & Gordon, L. J. (2016). Revealing invisible water: Moisture recycling as an ecosystem service. *PLoS ONE*, *11*(3), e0151993.

Keys, P. W., Wang-Erlandsson, L., & Gordon, L. J. (2018). Megacity precipitationsheds reveal tele-connected water security challenges. *PLoS ONE*, *13*(3), e0194311.

Keys, P. W., Wang-Erlandsson, L., Gordon, L. J., Galaz, V., & Ebbesson, J. (2017). Approaching moisture recycling governance. *Global Environmental Change: Human and Policy Dimensions*, *45*, 15–23.

Keys, P. W., Warrier, R., van der Ent, R. J., Galvin, K. A., & Boone, R. B. (2022). Analysis of Kenya's atmospheric moisture sources and sinks. *Earth Interactions*, *26*(1), 139–150.

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*, 471–493.

Koster, R., Jouzel, J., Suozzo, R., Russell, G., Broecker, W., Rind, D., & Eagleson, P. (1986). Global sources of local precipitation as determined by the Nasa/Giss GCM. *Geophysical Research Letters*, *13*(2), 121–124.

Mason, N., Ward, M., Watson, J. E. M., Venter, O., & Runting, R. K. (2020). Global opportunities and challenges for transboundary conservation. *Nature Ecology & Evolution*, *4*(5), 694–701.

Meier, R., Schwaab, J., Seneviratne, S. I., Sprenger, M., Lewis, E., & Davin, E. L. (2021). Empirical estimate of forestation-induced precipitation changes in Europe. *Nature Geoscience*, *14*(7), 473–478.

Menton, M., Larrea, C., Latorre, S., Martinez-Alier, J., Peck, M., Temper, L., & Walter, M. (2020). Environmental justice and the SDGs: From synergies to gaps and contradictions. *Sustainability Science*, *15*(6), 1621–1636.

Millennium Ecosystem Assessment, M. E. A. (2005). Ecosystems and human well-being. *Synthesis*. http://www.alexandrina.org/CSSP/Event/Material/MEA_businessesdocument.353.aspx.pdf

Miralles, D. G., Nieto, R., McDowell, N. G., Dorigo, W. A., Verhoest, N. E. C., Liu, Y. Y., Teuling, A. J., Johannes Dolman, A., Good, S. P., & Gimeno, L. (2016). Contribution of water-limited ecoregions to their own supply of rainfall. *Environmental Research Letters: ERL [Web Site]*, *11*(12), 124007.

Molina, R. D., Salazar, J. F., Martínez, J. A., Villegas, J. C., & Arias, P. A. (2019). Forest-induced exponential growth of precipitation along climatological wind streamlines over the Amazon. *Journal of Geophysical Research, D: Atmospheres*, *124*(5), 2589–2599.

Mu, Y., Biggs, T. W., & De Sales, F. (2021). Forests mitigate drought in an agricultural region of the Brazilian Amazon: Atmospheric moisture tracking to identify critical source areas. *Geophysical Research Letters*, *48*. https://doi.org/10.1029/2020gl091380.

Nepstad, D. C., Stickler, C. M., Filho, B. S.-, & Merry, F. (2008). Interactions among Amazon land use, forests and climate: Prospects for a near-term forest tipping point. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *363*(1498), 1737–1746.

O'Connor, J. C., Dekker, S. C., Staal, A., Tuinenburg, O. A., Rebel, K. T., & Santos, M. J. (2021). Forests buffer against variations in precipitation. *Global Change Biology*, *27*, 4686–4696. https://doi.org/10.1111/gcb.15763.

Oki, T., & Kanae, S. (2006). Global hydrological cycles and world water resources. *Science*, *313*(5790), 1068–1072.

Oliveira, L. J. C., Costa, M. H., Soares-Filho, B. S., & Coe, M. T. (2013). Large-scale expansion of agriculture in Amazonia may be a no-win scenario. *Environmental Research Letters: ERL [Web Site]*, *8*(2), 024021.

Oshima, K., Tachibana, Y., & Hiyama, T. (2015). Climate and year-to-year variability of atmospheric and terrestrial water cycles in the three great Siberian rivers. *Journal of Geophysical Research, D: Atmospheres*, *120*(8), 2014JD022489.

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I.-C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., … Williams, S. E. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, *355*(6332). https://doi.org/10.1126/science.aai9214

Pranindita, A., Wang-Erlandsson, L., Fetzer, I., & Teuling, A. J. (2021). Moisture recycling and the potential role of forests as moisture source during European heatwaves. *Climate Dynamics*, *58*, 609–624. https://doi.org/10.1007/s00382-021-05921-7.

Riggio, J., Baillie, J. E. M., Brumby, S., Ellis, E., Kennedy, C. M., Oakleaf, J. R., Tait, A., Tepe, T., Theobald, D. M., Venter, O., Watson, J. E. M., & Jacobson, A. P. (2020). Global human influence maps reveal clear opportunities in conserving Earth's remaining intact terrestrial ecosystems. *Global Change Biology*, *26*, 4344–4356. https://doi.org/10.1111/gcb.15109.

Sachs, J., Schmidt-Traub, G., Kroll, C., Lafortune, G., Fuller, G., & Woelm, F. (2020a). *The Sustainable Development Report 2020 – The Sustainable Development Goals and COVID-19*. Cambridge University Press. https://s3.amazonaws.com/sustainabledevelopment.report/2020/2020_sustainable_development_report.pdf

Sachs, J., Schmidt-Traub, G., & Lafortune, G. (2020b). Speaking truth to power about the SDGs. *Nature*, *584*(7821), 344.

Schleicher, J., Zaehringer, J. G., Fastré, C., Vira, B., Visconti, P., & Sandbrook, C. (2019). Protecting half of the planet could directly affect over one billion people. *Nature Sustainability*, *2*(12), 1094–1096.

Sircely, J., Conant, R. T., & Boone, R. B. (2019). Simulating rangeland ecosystems with G-range: Model description and evaluation at global and site scales. *Rangeland Ecology & Management*, *72*(5), 846–857.

Spracklen, D. V., Baker, J. C. A., Garcia-Carreras, L., & Marsham, J. H. (2018). The effects of tropical vegetation on rainfall. *Annual Review of Environment and Resources*, *43*(1), 193–218.

Spracklen, D. V., & Garcia-Carreras, L. (2015). The impact of Amazonian deforestation on Amazon basin rainfall. *Geophysical Research Letters*, *42* (21), 9546–9552.

Staal, A., Fetzer, I., Wang-Erlandsson, L., Bosmans, J. H. C., Dekker, S. C., van Nes, E. H., Rockström, J., & Tuinenburg, O. A. (2020a). Hysteresis of tropical forests in the 21st century. *Nature Communications*, *11*(1), 4978.

Staal, A., Flores, B. M., Aguiar, A. P. D., Bosmans, J. H. C., Fetzer, I., & Tuinenburg, O. A. (2020b). Feedback between drought and deforestation in the Amazon. *Environmental Research Letters: ERL [Web Site]*, *15*(4), 044024.

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.

Teuling, A. J., Seneviratne, S. I., Stöckli, R., Reichstein, M., Moors, E., Ciais, P., Luyssaert, S., van den Hurk, B., Ammann, C., Bernhofer, C., Dellwik, E., Gianelle, D., Gielen, B., Grünwald, T., Klumpp, K., Montagnani, L., Moureaux, C., Sottocornola, M., & Wohlfahrt, G. (2010). Contrasting response of European forest and grassland energy exchange to heatwaves. *Nature Geoscience*, *3*, 722.

te Wierik, S. A., Gupta, J., Cammeraat, E. L. H., & Artzy-Randrup, Y. A. (2020). The need for green and atmospheric water governance. *WIREs Water*, *7*(2), 17.

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

Tuinenburg, O. A., Hutjes, R. W. A., Stacke, T., Wiltshire, A., & Lucas-Picher, P. (2014). Effects of irrigation in India on the atmospheric water budget. *Journal of Hydrometeorology*, *15*(3), 1028–1050.

Tuinenburg, O. A., Theeuwen, J. J. E., & Staal, A. (2020). High-resolution global atmospheric moisture connections from evaporation to precipitation. *Earth System Science Data*, *12*(4), 3177–3188.

Turnbull, L., Wilcox, B. P., Belnap, J., Ravi, S., D'Odorico, P., Childers, D., Gwenzi, W., Okin, G., Wainwright, J., Caylor, K. K., & Sankey, T. (2012). Understanding the role of ecohydrological feedbacks in ecosystem state change in drylands: Ecohydrological feedbacks and ecosystem change in drylands. *Ecohydrology*, *5*(2), 174–183.

TWI2050-The World in. (2018). *Transformations to achieve the Sustainable Development Goals. Report prepared by The World in 2050 initiative*. https://doi.org/10.22022/TNT/07-2018.15347

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), W09525.

van der Ent, R. J., Tuinenburg, O. A., Knoche, H.-R., Kunstmann, H., & Savenije, H. H. G. (2013). Should we use a simple or complex model for moisture recycling and atmospheric moisture tracking? *Hydrology and Earth System Sciences*, *17*(12), 4869–4884.

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.

Vázquez, M., Nieto, R., Liberato, M. L. R., & Gimeno, L. (2021). A data base of contributions of major oceanic and terrestrial moisture sources on continental daily extreme precipitation. *Data in Brief*, *35*, 106830.

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.

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.

Wang-Erlandsson, L., van der Ent, R. J., Keys, P. W., Fetzer, I., Taniguchi, M., & Gordon, L. J. (n.d.). Dry periods increase Amazon and Congo forests' dependence on their own supply of rainfall. *In Preparation*.

Wei, J., Dirmeyer, P. A., Wisser, D., Bosilovich, M. G., & Mocko, D. M. (2012). Where does the irrigation water go? An estimate of the contribution of irrigation to precipitation using MERRA. *Journal of Hydrometeorology*, *14*(1), 275–289.

Weng, W. (2020). Aerial river management for future water in the context of land use change in Amazonia. https://edoc.hu-berlin.de/handle/18452/21901

Wilcox, B. P., Sorice, M. G., & Young, M. H. (2011). Dryland ecohydrology in the Anthropocene: Taking stock of human–ecological interactions. *Geography Compass*, *5*(3), 112–127.

Wood, S. L. R., Jones, S. K., Johnson, J. A., Brauman, K. A., Chaplin-Kramer, R., Fremier, A., Girvetz, E., Gordon, L. J., Kappel, C. V., Mandle, L., Mulligan, M., O'Farrell, P., Smith, W. K., Willemen, L., Zhang, W., & DeClerck, F. A. (2018). Distilling the role of ecosystem services in the Sustainable Development Goals. *Ecosystem Services*, *29*, 70–82.

Wunderling, N., Donges, J. F., Kurths, J., & Winkelmann, R. (2021). Interacting tipping elements increase risk of climate domino effects under global warming. *Earth System Dynamics*, *12*(2), 601–619.

Wunderling, N., Gelbrecht, M., Winkelmann, R., Kurths, J., & Donges, J. F. (2020). Basin stability and limit cycles in a conceptual model for climate tipping cascades. *New Journal of Physics*, *22*(12), 123031.

Zeitoun, M., Goulden, M., & Tickner, D. (2013). Current and future challenges facing transboundary river basin management. *Wiley Interdisciplinary Reviews. Climate Change*, *4*(5), 331–349.

Zemp, D. C., 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*, 14681.

Zipper, S. C., Jaramillo, F., Wang-Erlandsson, L., Cornell, S. E., Gleeson, T., Porkka, M., Häyhä, T., Crépin, A.-S., Fetzer, I., Gerten, D., Hoff, H., Matthews, N., Ricaurte-Villota, C., Kummu, M., Wada, Y., & Gordon, L. (2020). Integrating the water planetary boundary with water management from local to global scales. *Earth's Future*, *8*(2), e2019EF001377.