Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2017-120
Manuscript under review for journal Earth Syst. Dynam.
Discussion started: 6 December 2017

Earth System Dynamics
Discussions
Open Access

On the social dynamics of moisture recycling

Patrick W. Keys[1,2] and Lan Wang-Erlandsson[2,3]

[1]School of Global Environmental Sustainability, Colorado State University, Fort Collins, USA
[2]Stockholm Resilience Centre, Stockholm University, Sweden
[3]Research Institute for Humanity and Nature, Kyoto, Japan

Correspondence to: patrick.keys@colostate.edu

Abstract. The biophysical phenomenon of terrestrial moisture recycling connects distant regions via the atmospheric branch of the water cycle. This process, whereby the land surface mediates evaporation to the atmosphere and the precipitation that falls downwind, is increasingly well-understood. However, recent studies highlight a need to consider an important and oft missing dimension - the social. Here, we explore the social dimensions of three case study countries with strong terrestrial moisture recycling: Mongolia, Niger, and Bolivia. Based on our case studies we present a set of three system archetypes that capture the core features of the moisture recycling social-ecological systems (MRSES): isolated, regional, and tele-coupled. We further explore the heterogeneity of human well-being within MRSES, by examining the characteristics of sources and sinks of moisture. We find that the sources and sinks of moisture can experience very different levels of human well-being, suggesting that power discontinuities must be included in the description of MRSES dynamics. We argue that geophysical tele-connections are complemented by social tele-couplings forming feedback loops, and consequently, complex adaptive systems. This exploration of the social dimensions of moisture recycling is part of an extension of the emerging discipline of socio-hydrology, and a suggestion for further exploration of new disciplines such as socio-meteorology or socio-climatology, within which the Earth system is considered as a co-evolutionary social-ecological system.

1 Introduction

Humanity is unequivocally leaving its mark on Earth, in terms of changes to the land surface (Ellis and Ramankutty, 2008), biostratigraphic layers (Zalasiewicz et al., 2015), and global hydrologic cycles (Zhou et al., 2016). Against this backdrop of heedless, anthropogenically-driven Earth system change, there have emerged new insights into the interactions between land-use change and the atmospheric branch of the water cycle. That the land-surface can and does influence the atmosphere is well-known (Dirmeyer and Brubaker, 1999; Dominguez et al., 2006; Tuinenburg et al., 2011; Bagley et al., 2012; Keys et al., 2016). What is relatively new is the extent of the impact from anthropogenic land-use change on the amount of water that is cycled through the atmosphere (Gordon et al., 2005). The general process of water evaporating from the surface of the Earth, traveling through the atmosphere as water vapor, and eventually falling out as precipitation downwind is known as moisture recycling (Lettau et al., 1979; Koster et al., 1986). The component of this process that takes place over land is often distinguished as terrestrial moisture recycling (as opposed to oceanic moisture recycling) (van der Ent et al., 2010). However, in the context of this paper and for the sake of brevity, we will use the phrase moisture recycling to refer specifically to the terrestrial component. Considering the recent debate regarding human impacts to large-scale hydrology (Rockström et al., 2012; Heistermann, 2017), there is a need to clarify and highlight the importance of anthropogenic modification of terrestrial moisture recycling. Moreover, it is incumbent on the scientific community to begin unpacking how the constituent components of the Earth system interact with the *social*.

Any research on moisture recycling that is either driven by anthropogenic land-use change or is seeking to understand how changing moisture recycling impacts land-use, has a social focus. The range of social topics that have been explored in the context of moisture recycling include: natural hazards and flooding (Dirmeyer and Brubaker, 1999; Dominguez et al., 2006), irrigation impacts to moisture recycling (Lo and Famiglietti, 2013; Tuinenburg et al., 2014), rainfed crop production (Bagley et al., 2012; Keys et al., 2012), ecosystem services (Ellison et al., 2012; Keys et al., 2016), urban water vulnerability, and even the import and export of moisture among nations (Dirmeyer et al., 2009; Keys et al., 2017). Land-use change impacts to rainfall via moisture recycling has been suggested to be potentially linked to the Sahel drought during the 1970s and this moisture recycling mechanism was suggested to be an integral part of the socio-hydrology discipline (Sivapalan et al., 2012).

These preliminary examinations of moisture recycling in the context of social issues have been revealing, but the social domain has often been investigated outside the biophysical system feedback boundaries, either as initiator of hydrological change (e.g., land-use change) or as receiver of hydrological change (e.g., decreasing crop yields), but almost never as dynamic modifier of hydrological change. Here, we address the social dynamics of moisture recycling by posing the following questions:

1. How are moisture recycling patterns linked to social characteristics of human well-being?
2. Are there dynamic social connections that link precipitation sinks and sources?
3. What are the system architectures that create feedbacks among geophysical, ecological and social drivers?

1.1 Rationale

This work will be useful for three key reasons. First, the conceptual approach will provide Earth system scientists generally, and hydrologists specifically, with the basics of how social systems (that are the sinks of upwind moisture recycling) are connected in many different ways back to the moisture sources. We do this through a combination of quantitative analysis and qualitative literature review.

Second, this conceptual insight provides an entry-point for more accurate modeling of the feedbacks that could affect moisture recycling patterns (rather than only considering, e.g. geophysical phenomena). Third, this manuscript provides insights for resource managers, particularly land and water managers, who are searching for new leverage points within their dynamic social-ecological systems. Understanding where key feedbacks, bottlenecks, and potential cascades are located within a system can provide managers with better information about the consequences of direct or indirect intervention within their systems.

We argue that exploring the social dynamics of moisture recycling improves our understanding Earth system dynamics by providing general insight into how humanity modifies the Earth system, but also into the heterogeneity of moisture recycling social-ecological systems.

1.2 Conceptual development

A social-ecological system is a complex adaptive system, whereby a social system is tightly coupled with an ecological system e.g. a small-scale agricultural village in Kenya (Enfors, 2013). The classic social-ecological systems (SES) diagram (Holling, 2001; Folke et al., 2004; Folke, 2006) includes an ecological node, a social node, and arrows connecting the two nodes to one another, as well as feeding back on themselves (Fig 1a). The simplest representation of a moisture recycling system is the source of evaporation and the sink of precipitation (Fig 1b). Typically, the direction flows from the source to the sink, with some amount of internal recycling within the source as well as the sink. The absence of a connection from the sink back to the source is because the moisture recycling relationship is based on purely biogeophysical connections, with water evaporating from the source, traveling along prevailing wind currents as water vapor, and condensing and falling as precipitation elsewhere. However, it is possible to place an SES within both the source and sinks (Fig 1c). This conceptual basis of a Moisture Recycling Social-Ecological System (MRSES) will be used to develop archetypes that can guide model development and practitioner prioritization. To construct the archetypes, we explore three case studies to identify how the geophysical and social connections interact to create feedbacks, and how these feedbacks lead to broader system dynamics.

2 Methods and Data

2.1 Case study selection

To find regions that are both relevant to terrestrial moisture recycling dynamics, as well as (potentially) relevant to social dynamics, we use the regions selected from the work in (Keys et al., 2016), which identified global regions that are particularly reliant on current vegetation for rainfall from moisture recycling (Keys et al., 2016, see Fig 2b). The regions that receive the most (relative) precipitation from upwind vegetation-regulated evaporation are East and Central Asia, parts of the Sahel, southwestern Africa, the southern Amazon and La Plata river basin in South America, and much of Canada. We also aimed to select regions that were ‘socially-relevant’ which, in this work, we define as having potential dynamics of power and wealth inequalities between the downwind beneficiaries of moisture recycling and the upwind providers of moisture recycling.

Based on these criteria, the selected case studies are Mongolia, Niger, and Bolivia. These three sink regions are distributed across three continents, providing separate moisture recycling dynamics, and distinct social systems, while having a relatively similar spatial footprint (with subsequently comparable moisture recycling source and sink footprints).

For each of these case studies, we will identify: (a) the discrete sources of evaporation falling as precipitation within the case study, i.e. the precipitationshed (Keys et al., 2012); (b) the dominant land-use types that are present in the sink and the

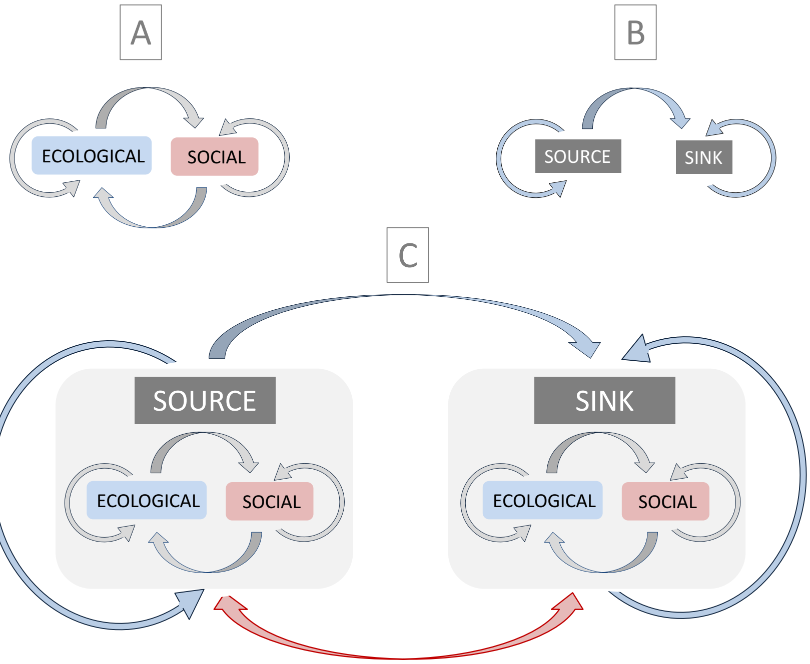

Figure 1. Conceptual construction of moisture recycling social ecological system (MRSES) archetypes.

precipitationshed; (c) several proxies for ecosystem-related human well-being; and, (d) a literature review of the types of social connections present within the precipitationshed.

2.2 Tracking the sources of moisture

We use an 'offline Eulerian' moisture tracking scheme called the Water Accounting Model-2layers, hereafter, WAM-2layers (for original model configuration, van der Ent et al. (2010); for two-level update van der Ent et al. (2013)). For a single gridcell and corresponding column of air, the model works as follows: first, the amount of moisture entering the column as evaporation is tracked; second, the evaporated water mixes with the moisture in the lower and upper levels of the column; third, moisture blows into and out of the column from adjacent columns; and, fourth, a certain amount of precipitation exits the lower level of the column. This tracking procedure is replicated across the entire planet for each timestep of the model. In this way, moisture can be tracked across the entire planet, simultaneously.

We use the backtracking feature of the WAM-2layers (Keys et al., 2012), which allows for the identification of the source region of precipitation - i.e., the precipitationshed. As input to the WAM-2layers, we use ERA-Interim Reanalysis data, from the European Center for Mesoscale Weather Forecasting (Dee et al., 2011). We downloaded global, model-level data at the 1.5 deg. by 1.5 deg. resolution. The WAM-2layers uses 6-hourly data for horizontal and vertical wind, humidity, and surface pressure; and it uses 3-hourly data for evaporation and precipitation. The data are interpolated into two levels, an upper- and lower-level of the atmosphere, to accommodate the upper and lower atmosphere processes, namely wind shear (van der Ent et al., 2013), and this separation roughly corresponds to the 800 mb level. Many approaches for precipitationshed boundary selection have been described (Keys et al., 2012, 2014, 2017), and we will employ the 1mm boundary as used in Keys et al. (2014). The 1mm boundary refers to a boundary that includes all regions that contribute 1mm or more of annual precipitation to the sink region. The precipitationshed is the spatial footprint that we will use in our analysis of the direct social connections from the precipitation sink to the sources of evaporation. The results of the precipitationshed analysis are visible in Fig 2.

2.3 Quantifying social features of the precipitationshed

One approach to capturing the social attributes of moisture recycling is to create a snapshot of the various social, political, economic, and other factors that could be aspects of social dynamics. A snapshot is obviously only static, so we do not reveal the dynamics of the whole area. However, sufficient spatial sampling has been fruitfully used as a proxy for temporal sampling (Hirota et al., 2011), and we adopt this approach simply for lack of temporal data. We are broadly interested in data that can reveal connections and dynamics in the social dimensions of moisture recycling. In this way, we have identified 'biophysically-relevant' social datasets, that can provide insight into the dynamics among the sources and sinks of moisture. These data are: land-use types characterized using the anthropogenic biomes data, i.e. Anthromes (Ellis and Ramankutty, 2008), food sufficiency using the proxy of child malnutrition (Center for International Earth Science Information Network CIESIN, 2005), and economic wealth using the proxy of Market Influence (Verburg et al., 2011). These three datasets will help structure the literature-based analysis of the social-dynamics within these precipitationsheds. Each of these datasets is spatially-gridded, at various resolutions. We interpolated the various data to the coarsest grid resolution so that they were comparable with one another in subsequent analyses of the sources and sinks of moisture. We display some of these comparisons in Fig 3.

2.4 Literature-review of social dynamics

To complement the quantitative characterization of the precipitationsheds, we performed a literature review focused on each of the sink regions (i.e. Mongolia, Nigeria, and Bolivia), exploring potential dynamics that exist among the social, biophysical, and other aspects of the precipitationshed. The literature review is specifically intended to help reveal some of the qualitative, social interactions (e.g. land use policies, regulatory interactions) that static data cannot provide. We used the hypothetical moisture recycling social-ecological system (MRSES) concept diagram as a guiding heuristic for how to search for important dynamics.

The general approach was to use the precipitationsheds as spatial boundaries and to reveal the land-uses within the footprints. Then, we evaluated the dominant processes governing those land-uses and the types of connections between the sink region and the source regions. A blend of journal articles, grey literature, and web sources provided the key information for building the qualitative description of the social connections. The result of the case study analysis is a blend of quantitative and qualitative information, which combined to form a narrative for each of the regions.

Table 1. List of countries that provide moisture to each nation, with fraction of total annual precipitation provided indicated.

MONGOLIA	
Russia	29%
China	13%
Mongolia	13%
Kazakhstan	9%
Other land	15%
NIGER	
Niger	9%
Chad	6%
Nigeria	6%
Sudan	5%
Democratic Republic of the Congo	2%
South Sudan	2%
Central African Republic	2%
Other land	27%
BOLIVIA	
Brazil	28%
Bolivia	18%
Peru	7%
Argentina	2%
Other land	7%

2.5 Construction of archetypes

We distilled the insights from the three case studies into the creation of several archetypes of moisture recycling social-ecological systems (MRSES). The MRSES are based on the conceptual archetype presented in Fig 1, but infused and modified using quantitative analysis and case studies. System dynamics models expose how different components of a system interact with one another, and they can help reveal the relative importance of different connections and interactions. The archetypes are visible in Fig 5.

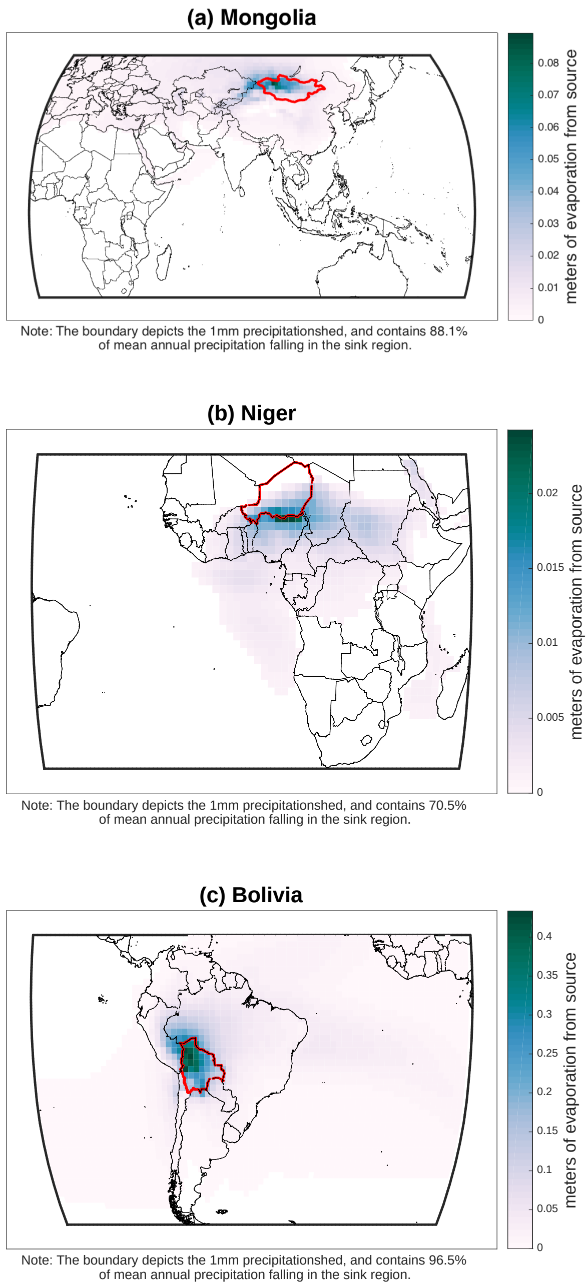

Figure 2. Precipitationsheds for the (a) Mongolia, (b) Niger, and (c) Bolivia case study regions. Note that the total amount of sink region precipitation that is included in the 1mm evaporation-contribution boundary is indicated below each panel.

3 Results and Discussion

3.1 Sources of precipitation

Precipitation in the three case study countries - Mongolia, Niger, and Bolivia - comes from predominantly terrestrial sources, as shown in Fig 2 and Table 1. In general, there is a concentration of terrestrial moisture sources within or near the country borders, and there is a large plume of precipitation source distributed over large continental areas. Based on previous work, land-use change will likely have larger effects on nations' precipitation moisture supply in the areas with the highest precipitation source concentrations (Bagley et al., 2014; Badger and Dirmeyer, 2015; Swann et al., 2015; Keys et al., 2016).

In Mongolia, the precipitation source is located in the northern half of the country and along its north-western border. Aggregated over space (Table 1), the largest moisture contributor of Mongolia's precipitation is Russia (Fig 2a). In Niger, the precipitation source is concentrated along the southern border (Fig. 2b), with a moisture supply plume fading towards the south. Niger supplies just 9% of its own moisture, but because of the large number of neighboring countries, this percentage suffices to make Niger top the list over individual moisture suppliers.

In Bolivia, the source of the precipitation is distributed across the country, with a slight concentration in the north (Fig. 2c). Despite the high concentration of moisture supply sources within the country, Brazil is the most important moisture supplier thanks to both a high concentration of moisture supply just north of Bolivia's border, and to a low concentration of moisture supply covering Brazil's entire domain.

3.2 Social features of the precipitationshed

Next, we present the results of our quantitative exploration of human well-being indicators that may be related to moisture recycling processes, namely: the prevalence of hunger (using sub-national child malnutrition data, Center for International Earth Science Information Network CIESIN (2005)), the distribution of wealth (using Market Influence, Verburg et al. (2011)), and the type of anthropogenic biome (using the Anthromes classification, Ellis and Ramankutty (2008)).

3.2.1 Mongolia case

In the Mongolia case study, we see that Mongolia is dominated by relatively poor, malnourished rangeland systems, with most of the key evaporation sources coming from rangelands (within and outside Mongolia), as well as from wild and remote woodland systems. There is some contribution from a heterogeneity of other systems (e.g. rained and irrigated crops), but in general the dynamic is evaporation arising from relatively wealthier, less hungry areas falling out as precipitation in poorer, hungrier areas.

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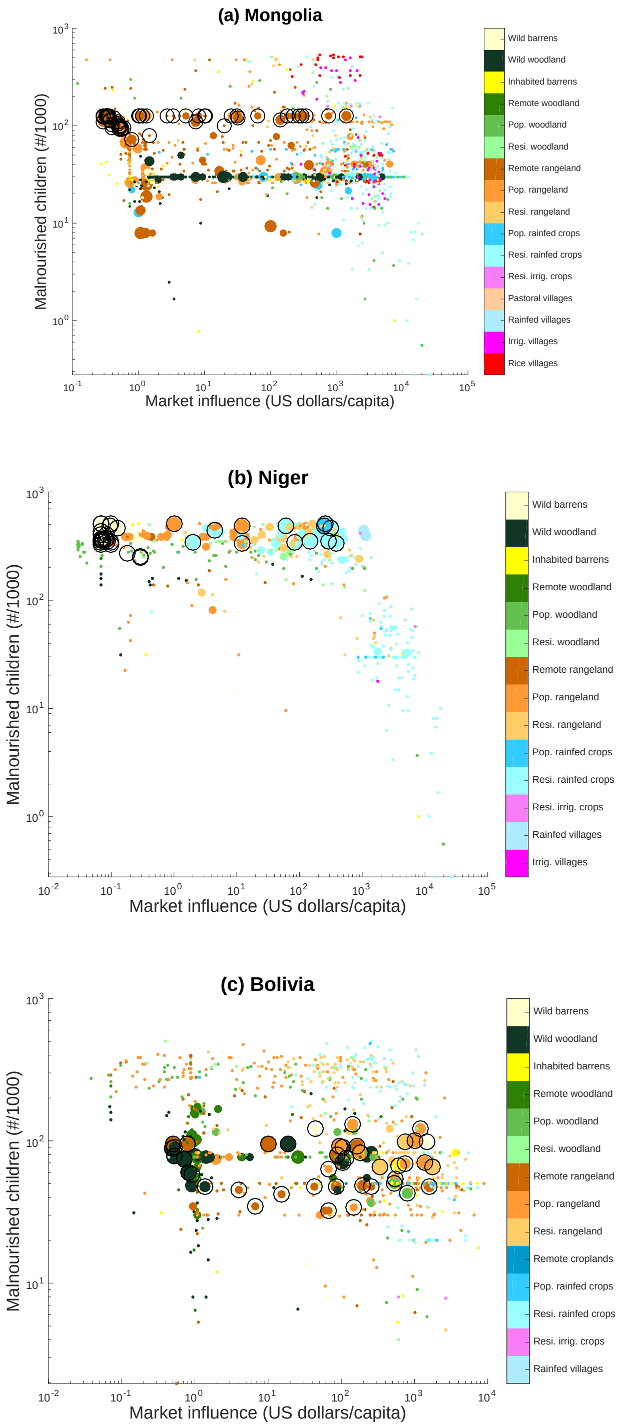

Figure 3. Human well-being indicators and moisture recycling for the (a) Mongolia, (b) Niger, and (c) Bolivia cases. The open circles indicate evaporation sources for the sink region (indicated by enclosed circles). The color of the circles indicates the dominant anthropogenic biome, and the position on the graph indicates both the relative wealth and the fraction of malnourished children per thousand of the different evaporation sources (note the log scale on both the x and y axes).

3.2.2 Niger case

In the Niger case study, we see that most of the evaporative contribution is from either barren land, rained croplands, or rangelands. Likewise, most of the evaporation flows to sinks with very similar levels of child malnutrition. However there is a flow of moisture from wealthier areas to poor areas (relatively).

3.2.3 Bolivia case

In Bolivia, we see a pattern that is less clear, compared to Mongolia and Niger. First, we see that there is a high heterogeneity of malnutrition and wealth in both the sources of evaporation and sink of precipitation. Within Bolivia itself, there is a cluster of wealthier rangelands and populated woodlands, and a cluster of much poorer remote and wild forest systems. Surprisingly the range of malnutrition is very similar for both clusters. In general, it appears that much of the moisture from outside Bolivia is coming from relatively poorer areas, especially forests, to wealthier areas dominated by rangelands.

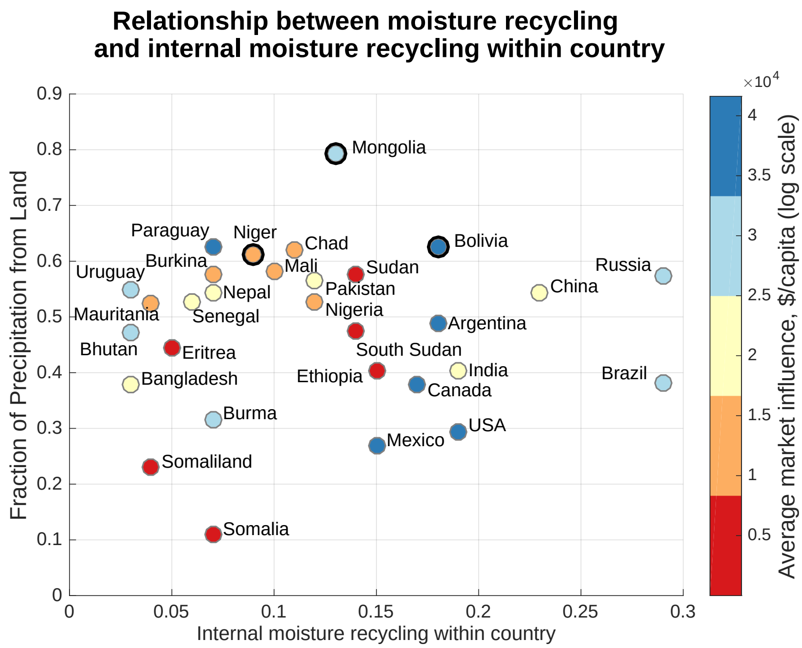

Figure 4. A sampling of countries from around the world in terms of mean national terrestrial moisture recycling (y-axis), internal moisture recycling (x-axis), and market influence (colorbar). Note, the colorbar is a log scale, and the three case studies are indicated with thicker black circles.

3.3 Integrating moisture recycling with social features

We integrate the findings of the terrestrial moisture recycling analysis with the market influence data to characterize how our case study nations compare to a sampling of other nations, based on moisture recycling data from Keys et al. (2017) (Fig 4). The three cases are among the highest in the terrestrial moisture recycling ratio (y-axis) and exhibit a range of values in internal moisture recycling (x-axis) and market influence (colors). From this, we might draw the conclusion that Niger has the lowest socially-relevant moisture recycling connectivity and Bolivia the highest socially-relevant connectivity. However, our literature review provides additional context for determining the dominant social dynamics that are relevant to moisture recycling.

3.4 Literature-review of social dynamics

Here, we delve into the details of the societies (primarily nations) that control key land-use change processes and decisions that may affect moisture recycling policy. We especially explore the social connections that may, or may not, exist between sink and source regions.

3.4.1 Mongolia case

Mongolia's precipitationshed includes significant contributions from local recycling within Mongolia, as well as significant contributions from the East Siberian Taiga to the north, the steppes in Kazakhstan, and Xinjiang province in northwestern China. Mongolia's land-use policy has had several distinct phases of management in the recent past, with traditional management of grasslands via customary nomadic herder institutions, then with the *negdel* 'pastoral cooperative' policy, followed by post-*negdel* policies largely dependent on local government management (Ojima and Chuluun, 2008). The transition from widespread mobility of herders to much more confined mobility (in large part due to expansion of agricultural lands) has lead to significant changes in land- and water-use. Recent analyses find that if present trends of agricultural expansion continue, then water shortages may become common (Priess et al., 2011). Similarly, if irrigated agricultural continues for a significant period of time, and soils are not drained properly (as has happened throughout much of Inner Mongolia in China), then it is possible that soils and landscapes will become salinated and less able to sustain vegetation (Kendy et al., 2003). The segmentation of Mongolia's traditionally managed grassland landscapes into grazing land and agricultural land, and the associated fragmentation or prohibition of seasonal movements of livestock, may lead to significant land-use change in the near future.

Kazakhstan, to Mongolia's west, provides a significant amount of moisture especially from its northern steppes, and from the Altai and Tien Shan mountains. Following the collapse of the Soviet Union, Kazakhstan's livestock population decreased significantly, with a concurrent reduction in grazing land pressure (Robinson et al., 2003; De Beurs and Henebry, 2004). This change in grazing pressure has lead to replacing of previously grazed land with other grasses and weedy species during fallow periods, and importantly has lead to detectable changes in vegetation and associated changes in near-surface meteorology. This has direct implications for evaporation and subsequently moisture recycling.

In terms of politics, the ascendent Mongolian People's Party has strong ties to Russia's Vladimir Putin, suggesting that political and diplomatic levers of power may flow not through adjacent China, but rather north to Russia (Jargalsaikhan, 2017).

Likewise, Mongolia is currently experiencing significant crises with regard to its management of debt, and thus it is beholden to both international lending agencies, as well as the international mining conglomerates fueling its development. Though Mongolia is reliant on China for export goods (China is the recipient of 79% of Mongolia's trade by volume), China is not reliant on Mongolia in nearly the same way (Simoes and Hidalgo, 2011). Likewise, Mongolia relies on imports from China and Russia in nearly equal measure (31% and 26%, respectively) (Simoes and Hidalgo, 2011). Aside from mining concessions and the associated resource use, these political and economic connections are not directly linked to large-scale land-use change, but rather to the underlying conditions and connections that might provide motivation (or lack thereof) for managing land-use in a manner that is most sustainable for moisture recycling specifically, and water resources generally.

To summarize, Kazakhstan's abandonment of former grazing land, the low level of land-use change in the East Siberian Taiga, and the isolation of the Altai and Tien Shan mountain regions suggest relatively low social connectivity from source to sink. Likewise, the fact that Mongolian institutions are stronger (than e.g. in Kazakhstan and in Xinjiang) and that the departure from historic land-use and land-management is more pronounced in Mongolian grasslands, we suggest that the social connections are strongest within Mongolia itself, leading to a somewhat isolated state of precipitationshed social connectivity.

3.4.2 Niger case

Niger generates a significant fraction of its own rainfall, primarily from the southern section of the country that is used for semi-arid agriculture and grazing. Land use in Niger is varied, ranging from barren deserts in the north, to livestock grazing and rainfed agriculture in the south. Land use change over the last several decades has seen increases in cropland cover (where possible) with corresponding decreases in fallow land (Hiernaux et al., 2009). The ownership of land, i.e. land tenure, in Niger has historically been governed by customary systems administered by communal Chiefs, however in the mid-1980s there was a push to formalize land tenure via government-sponsored registration efforts, especially in rural areas of Niger (Toulmin, 2009). This process lead to large-scale confusion in part due to poorly executed policies, underfunded and understaffed government agencies, and unintended entrenchment of rural power hierarchies (Benjaminsen et al., 2009). Thus, current land-tenure in Niger is working towards clearer ownership and tenure, yet remains challenged by underfunded institutions and intractable overlapping claims of ownership. Also, Niger has not been subject to the global phenomena of land acquisitions (aka land grabs, large-scale land acquisitions, etc), perhaps as a result of low rainfall overall, slowly-improving land tenure, or lack of available land.

Directly to the south, Nigeria provides a considerable fraction of Niger's rainfall, and has a uniform, national land-use policy (i.e. the Land Use Act), which essentially grants the authority of land ownership to the governor of each Nigerian state (Damilola, 2017). This was originally meant to avoid problems of land speculation, overlapping or competing claims of ownership, and protection against foreign interference with land issues. However, the current issue of land-acquisitions by foreign entities, often for large amounts of money, makes this process of land ownership vulnerable to corrupt leaders. Currently, Nigeria has experienced many such land acquisitions, and is among the top 20 nations globally involved in land acquisitions (Osabuohien, 2014). This is relevant primarily because significant areas of land (estimated at 360,000 hectares in GRAIN (2012)), suggests extensive modification of the land surface, with potential associated impacts on moisture recycling.

Chad, located to the east of Niger, provides around 6% of moisture, but suffers from chronic poverty. Reliance on agriculture or livestock rearing provides 80% of Chadian's employment, but open access policies for land have lead to over-grazing, and inadequate management has lead to deforestation and desertification around dense population centers. These dynamics contribute to an uncertain and rapidly changing land-use regime in Chad (Walther, 2016; USAID, 2010). Sudan, like Chad, is also experiencing rapid land-use change, though with more-pronounced land-tenure insecurity and the ability of centralized government to lease land without consulting local communities. Sudan has been a key target of land acquisitions, leading to internal conflict and potentially displaced persons. As with Chad, there is high potential for unpredictable land-use changes including both increased evaporation from agricultural expansion and desertification from unsustainable land and water management (USAID, 2013).

To conclude, the rapid land-use change taking place in many parts of Niger's precipitationshed suggest there is a high potential for change in moisture recycling driven by social-ecological processes. The ability to influence one another's land-use, and subsequently moisture recycling, is thus possible. However, active coordination among key sources in Niger's precipitationshed is relatively low. Some international institutions, such as the International Water Management Institute's Water Land and Ecosystems programme, enable some trans-boundary policy coordination on key water and ecosystem issues (Saruchera and Lautze, 2015). Meanwhile, other types of activities, such as Forest Stewardship Council certifications, have considerably less influence (Nasi et al., 2012; Malhi et al., 2013). The pace of land-use change, the dense and growing dynamism of populations in all nations in Niger's precipitationshed, and the mixture of internal and external policy effectiveness suggests a medium level of social connectivity.

3.4.3 Bolivia case

Bolivia's precipitationshed includes key contributions from within Bolivia itself, from Brazil, and from Peru. The dominant land-uses throughout the key source regions are rangelands and forests. The strength of land-use management, in terms of governance effectiveness varies among these three nations, as does the level of land-use change, ranging from well-developed land-use methods (such as in Brazil) and much lower impact, though with high potential (as in Peru). Bolivia itself generates 18% of its own rainfall, and this primarily from tropical forests and the pantanal wetland, as well as from rangelands. Historically, Bolivia's government has had a strong control on protection of forests from change, such as the first "debt-for-nature swap" in 1987 (Hansen, 1989). These, and other projects such as REDD and REDD+ projects aimed at keeping forests intact, have also been criticized for simply leading to 'leakage' of land-use change to other regions, either within Bolivia or beyond its borders (Verweij et al., 2009).

In adjacent Peru, the key forested areas that could change, and thus lead to changes in moisture recycling, are very difficult to access, yet as population migration to the Peruvian Amazon is high, the current rate of deforestation is steadily increasing (Perz et al., 2005). Many overlapping jurisdictions and leases both among owners of land, as well as owners of different types of resources (e.g. timber, land, minerals, and fossil fuels), has lead to contentious claims of ownership (Finer et al., 2008; Killeen et al., 2008).

Likewise, recently built roads from Brazil through southern Peru will likely spur greater development of the region. A key challenge is that Brazil's land-use regulations and enforcement are stronger than Peru's, leading to leakage of deforestation activity, primarily for expansion of cattle grazing land. Land-use policy in Brazil is quite strong, and at least on public land, deforestation is fairly well-controlled. However, much of the deforestation is taking place on private land, primarily being converted to grazing land. Brazil's Forest Code requires that land-owners keep 80% of occupied land as forest, but enforcement of this is difficult (Perz et al., 2005). Importantly, the key source regions of Bolivia's moisture are in the Acre region of Brazil which is both remote, and has fairly strong protections (Kainer et al., 2003). Because of this, the risk of land-use change there is somewhat low, and perhaps comparatively less vulnerable than elsewhere in Bolivia's Amazonian sources.

The quality and strength of land-use policy within these three countries is strongly tied to both national-level policy, as well as participation in international land-use management efforts (e.g. REDD+), along with international trade efforts (e.g. Forest Stewardship Council certification) (Killeen et al., 2007). As a result, this region's land-use is relatively well-governed with many controls in place to avoid large-scale change. However, land-use change leakage (Verweij et al., 2009) is more difficult to control, thus the feedbacks of strong policies within countries may lead to other problems, especially if one of these three nations becomes more vulnerable to land-use change leakage from internal changes.

Bolivia's dominant exports are fossil fuels (45%) and minerals (zinc, precious metals, lead, gold, etc. nearly 30%) (Simoes and Hidalgo, 2011). Bolivia's dominant export to Brazil is Natural Gas (97% of exported trade flow to Brazil), and this represents 48% of Brazil's natural gas imports (Simoes and Hidalgo, 2011). In terms of trade, this is the largest trade flow between these nations, and is facilitated by pipelines connecting to Brazil. Given the dependence of Bolivia on natural gas exports to Brazil for its economy, and Brazil's dependence on Bolivian natural gas, this interdependency could be a basis for cooperation on other topics such as land-use policy around natural gas reserves and pipelines, particularly the leakage of Brazilian deforestation. The shared issues of deforestation in Peru, Brazil, and Bolivia, as well as strong legacies of deforestation policy in Bolivia and Brazil, suggests relatively strong institutional capacity for managing change. Likewise, the economic connection, albeit in the form of natural gas pipelines connecting Bolivia to Brazil, suggests reliable economic connection (Finer et al., 2008). Additionally, the strong engagement of Bolivia's source regions in international programs targeting land-use change (e.g. REDD+, FSC) implies a social tele-coupling beyond the precipitationshed that is directly interacting with land-use policy. Finally, the international drivers of land-use change, especially in Brazil regarding soya cultivation, suggests global-scale social connections (Flach et al., 2016). Thus, we suggest Bolivia and its precipitationshed experiences strong social coupling, as well as global tele-coupling.

3.5 Construction of archetypes

The different dynamics of land-use change, social organization, and social connectivity create distinct archetypes of moisture recycling social-ecological systems (MRSES) ranging from isolated to tele-coupled (Fig 1 and 5). Acknowledging that no system is as simple as this, and that there are many other interacting variables, drivers, and components to these loops, we are aiming to illustrate the relationships specifically related to land-use change mediated moisture recycling feedbacks. Based on the results from case study analysis, we see three basic patterns of social dynamics in moisture recycling systems. First, there

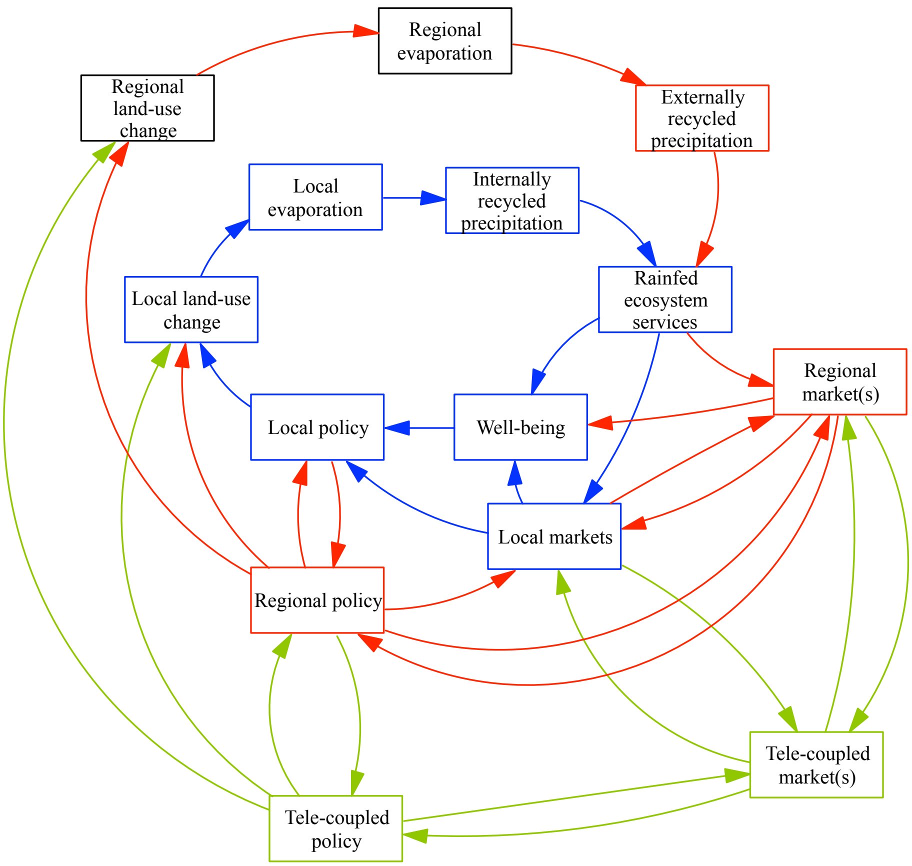

Figure 5. Archetypes of moisture recycling social ecological system (MRSES), with blue corresponding to 'Isolated', red to 'Regional', and green to 'Tele-coupled'.

is an isolated dynamic, dominated by internal processes; second, there is a regional dynamic linking adjacent countries and diffuse connectivity; and, third, there is a tele-coupled dynamic that links precipitation sink regions with regions outside the precipitationshed boundaries.

3.5.1 Isolated archetype

The 'isolated' archetype is the simplest of the proposed MRSES. In terms of social dynamics actively driving change in the precipitationshed, Mongolia is isolated. The large contributions from China are so diffuse that the social processes driving the evaporation are unable to be meaningfully discussed. Likewise, the diffuse evaporation contribution from Russia are predominantly coming from Siberian Taiga which has not experienced much land-use change. If anything there has been moderate reforestation from post-Soviet land-abandonment (Meyfroidt et al., 2016), but in the regions relevant to Mongolia this has been minimal.

In the 'isolated' archetype, we draw attention to the fact that there are few connections or feedbacks beyond local government, nor with other regional actors (Fig 5, blue arrows). The core structure of the 'isolated' archetype is empirically grounded, given that it is well understood that land-use change directly affects evaporation, with increased vegetation typically increasing evaporation, and decreased vegetation typically decreasing evaporation (Gordon et al., 2005; Wei et al., 2013; Spracklen and Garcia-Carreras, 2015). Likewise, changes in evaporation can have direct influences on the moisture recycling that returns locally (Badger and Dirmeyer, 2015; Lawrence and Vandecar, 2015). This precipitation then provides rainfall for local ecosystem services (Bagley et al., 2012; Keys et al., 2016). These rainfed ecosystem services contribute directly to well-being, including both subsistence agriculture as well as 'off-farm ecosystem services' such as livestock forage and timber (Ojima and Chuluun, 2008; Descheemaeker et al., 2011).

How well people are doing (e.g. whether they are hungry or not) will inform the decisions they make about further modifications to the landscape (Rockström et al., 2002; Enfors, 2013), such as increasing labor and investment to maintain crop yields or foregoing labor and investment with coincident decreases in crop yield, and possibly land abandonment (Mortimore and Tiffen, 1994). Local land-use change policy is formulated and implemented at least partially in response to rainfall changes. These policies are based tacitly on the confidence and knowledge on precipitation patterns and moisture recycling feedbacks, as well as on how the benefits and negative impacts are distributed among different social groups (Roncoli et al., 2002). Finally, these decisions may include further land-use change or regrowth of natural land, strengthening or weakening the feedback loop. These isolated systems also exist at sub-national levels, but in our analysis we evaluate national-scale precipitationsheds, and look at feedbacks at that social level.

3.5.2 Regional archetype

As the social connections between different sources and sinks become more numerous, regional interactions emerge (Fig 5, red arrows). Niger experiences some recycling, but also relies on contributions from neighbors in Nigeria, Chad, and Sudan. Likewise, all of these countries have active, socially-driven land-use change taking place that is impacting evaporation rates (Savenije, 1995; Foley et al., 2003; Tschakert, 2007; Salih et al., 2013). The regulatory regime in these four countries varies considerably ranging from corrupt to fair and from decentralized to centralized.

To generalize, as the importance of internal moisture recycling decreases, the activities of key source regions must be considered. Where the rule-of-law is present, changes in regional evaporation will be related to government regulations or policies that serve to influence how land-use change unfolds. However, in more lawless regions where governance and institutions are absent or corrupt, large-scale land-use change is typically driven by national or international corporate actors (Galaz et al., 2017). In this way, MRSES can have multiple configurations and these configurations do not necessarily exist along a continuous spectrum from isolated to regional to tele-connected. In this archetype, we see the addition of an external driver, notably 'regional policies' and 'regional markets'. Essentially, we are highlighting the fact that the inner loop is no longer isolated from regional actors that can influence and interact with the social dimensions of the central feedback loop. Notably these actors are spatially connected, e.g. within the same precipitationshed, or in adjacent countries. We also illustrate how regional interactions can more directly drive changes in external moisture recycling. Other key differences between the 'isolated' and 'regional' MRSES, are additional moisture recycling impacts and changes in interactions with well-being and policy. Specifically, regional and sub-regional actors have feedbacks among themselves and with 'local' well-being, markets, and policy nodes.

3.5.3 Tele-coupled archetype

The third MRSES is 'tele-coupled', and this structure draws attention to the spatially disconnected actors that can influence the social connections in either the central feedback loop, or the regional feedbacks. Bolivia, which relies on rainfall and Brazil for nearly half its rainfall would seem to be a 'regional' archetype, were it not for the dense connections to global forest conservation and transnational agribusiness present in Bolivia and Brazil (Galaz et al., 2015; Flach et al., 2016). These tele-coupled actors can drive land-use change in the precipitationshed, but these actors are not directly impacted by any changes in the land-use aside from perhaps changes in export commodities. Also, these tele-coupled actors are not necessarily affected by the consequences of any changes to internal moisture recycling (though they can be), while nonetheless driving changes in the MRSES itself.

3.6 Guidelines for constructing MRSES

In this work we only examine three case study regions that roughly correspond to three archetypes, yet we are able to provide some guidance for the construction of additional archetypes using our method. First, it is important to note the number of countries providing significant evaporation contribution, in which social processes are driving rapid land-use change. Second, the precipitationshed can have low or high connectivity to global markets. When combined, these two classifications would make four archetypes. However, we suggest only three archetypes, since global market connectivity will make a MRSES 'tele-coupled' regardless of whether there is one country where social processes are important (e.g. Mongolia) or many countries (e.g. 'Niger'). In other words, once a country crosses the threshold from being disconnected to connected to global markets it moves inexorably from being either 'isolated' or 'regional' to 'tele-coupled'. Furthermore, this dynamic is unlikely to be reversed given the momentum and increasing networked complexity of global markets and institutions, with notable exceptions, such as post-Soviet nations.

3.7 Systems may be reinforced in unexpected ways

The MRSES archetypes we propose increase in complexity when moving from isolated to tele-coupled. This increased complexity indicates the potential for surprises induced by feedbacks (Levin et al., 2013). This is most apparent in the local and regional land-use change policies since those simultaneously have the strongest policy influence and affect regions with the highest moisture recycling values. A notable feature is the role of tele-coupled, spatially disconnected actors for driving change in the precipitationshed. This is further emphasized in our discussion of moisture recycling in Brazil, in the context of multiple, overlapping international agri-business interests with regard to livestock production and soya cultivation (Flach et al., 2016).

Additionally, the relationships we identified as potentially existing in the system underline the reality that the system has different kinds of leverage points. For example, in the feedback loop of the isolated archetype, where policy influence and moisture recycling are tightly interconnected, there is potential for faster change but also for more immediate intervention. Conversely, the geophysically separate, socially tele-coupled drivers of land-use change can influence a region's rainfall, while the recipients of that rain have much less of an ability to influence those tele-coupled drivers of change. Moreover, the tele-coupled international actors have the potential to influence both economic policy in the sink region as well as apply market pressure to societies that are regulating rainfall. All the while these tele-coupled actors experience very little feedback from the moisture recycling system, aside from indirect changes to e.g. commodity crops. All of these different dynamics suggest that a portfolio of governance strategies will be necessary to address different kinds of challenges (see more on institutional challenges in Keys et al., 2017).

3.8 Power must be considered carefully

Though the analysis of environmental justice flows has been simplified (Fig 3), we highlight a few key considerations with regard to power and equity in MRSES. First, in 'isolated' systems (e.g. Mongolia) there can still be a wide range of well-being (e.g. wide range in poverty and malnutrition). The ability to influence land-use change policies that are impacting terrestrial moisture recycling will be distributed similarly. Thus, this imbalance in the ability of the human drivers and recipients of terrestrial moisture recycling change ought to be considered.

Second, as MRSES expand to include more than one country, the power imbalances among nations become more important. In the Bolivia and Niger cases, the ability of precipitationshed nations to drive change (e.g. Brazil for Bolivia, and Nigeria for Niger) begins to matter. Moreover, in tele-coupled systems, international and non-state actors can begin driving significant terrestrial moisture recycling change, for example by interference (or control) of land-use change on commodity prices.

Other work has suggested the importance of existing institutions for governing moisture recycling (Keys et al., 2017), but difficult questions remain, such as "who gets to change the rain?", and have yet to be answered. Finally, in many poor countries and regions, land-use change is a necessary part of subsistence and survival. Acknowledging a need for fairness, equity, and perhaps a right to modify terrestrial moisture recycling (e.g. by indigenous people) may be an equitable component of moisture recycling governance.

Fundamentally, this analysis suggests that as Earth system scientists continue to make strides in understanding moisture recycling and its impacts, it will be vital to acknowledge how the benefits or costs are distributed through society. Likewise, though we could not evaluate it here, we suggest further research in this area could build off of the work of Daw et al. (2011) who explore how efforts to improve human well-being in one area are very likely to have unintended (and likely negative) consequences for the well-being of others.

3.9 A note on engaging social science

As we move forward as a scientific community, and potentially if the concept of precipitationshed gains traction in the practitioner community, it will become increasingly important to have tools that allow us to answer questions related to justice, equity, and livelihoods. Interdisciplinary scientists, especially those trained in the natural sciences, must recognize the inherent, and potentially dangerous, pitfalls of positivism, and practice an awareness of normative terminology. At a core level introspection is prerequisite for evaluating the questions being asked and how those questions are posed.

Furthermore the natural science community needs to recognize that description of current relationships in moisture recycling (e.g. sources and sinks of moisture) are inherently charged with social import. For example, demonstrating that Brazil is very important for Bolivia's rainfall gives Brazil power over Bolivia in potentially significant ways. Recognition of these implications is critical for natural scientists to become better interdisciplinary scholars, as well as responsible and conscientious members of society.

4 Conclusions

Here, for the first time, we systematically explored the social dynamics of moisture recycling. We provide an approach, based on multiple quantitative and qualitative methods, for revealing the structure of moisture recycling social-ecological systems. We demonstrate this approach using three case studies - Mongolia, Niger, and Bolivia - and describe the social dynamics that have the potential to impact evaporation and subsequently moisture recycling. The key conclusion is that quantitative analysis is not enough to determine which drivers are most important for the social dynamics of moisture recycling systems. A qualitative understanding, particularly strengthened by a familiarity with relevant land-use change drivers, is critical to unraveling whether a region has social dynamics that are 'isolated', 'regional', or 'tele-coupled'. Finally, we argue that Earth system scientists need to explicitly consider the social dynamics of their work to more holistically represent reality, as well as to better engage interdisciplinary science.

Data availability. All data used in this paper are available from other work. The moisture recycling data for Mongolia, Niger, and Bolivia are available here: https://hdl.handle.net/10217/184640. The market influence data is associated with Verburg et al. (2011), and is available here: http://www.ivm.vu.nl/en/Organisation/departments/spatial-analysis-decision-support/Market_Influence_Data/index.aspx. The malnutrition data is from (Center for International Earth Science Information Network CIESIN, 2005) and is available here: http://sedac.ciesin.columbia.edu/data/set/povmap-global-subnational-prevalence-child-malnutrition. Finally, the Anthromes are from (Ellis and Ramankutty, 2008), and is available here: http://ecotope.org/anthromes/v2/data/.

Author contributions. Both authors contributed to conceptual development, data analysis, and manuscript preparation.

Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2017-120
Manuscript under review for journal Earth Syst. Dynam.
Discussion started: 6 December 2017

Competing interests. The authors disclose no competing interests.

Acknowledgements. We appreciate the encouragement of many academic peers to work outside our comfort zone, especially Line Gordon, Thorsten Blenckner, and Sarah Cornell.

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