EDITOR COMMENT

The authors have been well served by four critical but constructive reviews. It seems from the review comments that, at the minimum, the presentation of the present needs substantial improvement. The authors are in agreement and so I would like a substantially revised manuscript to be submitted so I can get the revised manuscript revised one more time by (hopefully) most of the previous reviewers. However, I would like the authors to also pay attention to the main contributions of the paper. What has been learned from this that we did not know before, why is this research significant etc? In particular, in the abstract the authors state that this ".... is part of an extension of the emerging discipline of socio-hydrology". In what way is this an extension of socio-hydrology? The literature review of socio-hydrology is now substantial, although this is the first time there is work on focusing on atmospheric moisture recycling. Perhaps it is important to put this work in the context of what has been published before in socio-hydrology (I mean, if this is feasible). In spite of their claim, the literature cited is rather sketchy. Even if there is not an extensive literature review (there are other papers that do this already, e.g., Pande and Sivapalan in WIRES Water, Sivapalan and Bloeschl, WRR), it is important to draw a connection to previous work. Apart from that, from my reading of the paper (including revised manuscript), I think the paper is very interesting, timely and eventually publishable, provided these comments can be satisfactorily addressed. Please submit a revised manuscript soon, so I can get it reviewed again promptly. I look forward to receiving the revised manuscript soon.

RESPONSE TO EDITOR COMMENT

Dear Editor,

Thank you for the attention to our paper and for highlighting the need to better incorporate socio-hydrology perspectives into the text. We have highlighted (a) how this work connects to socio-hydrology generally, and (b) ongoing synthesis work among interdisciplinary human-water interactions research. We hope the updated text (particularly the expanded sections on socio-hydrology and hydrosocial analysis) fill the gap identified by the editor.

We look forward to the next stage of review of this manuscript.

Warm regards,
Patrick Keys on behalf of co-authors.

---

*ATTACHED TO THIS DOCUMENT:*

a) *Pages 2 thru 20: Compiled responses to reviewers 1-4 originally appearing in ESD Online Discussion*

b) *Pages 21 thru 54: Tracked changes from originally accepted article to present resubmission.*

COMPILED RESPONSES ORIGINALLY POSTED TO ESD DISCUSSION:

RESPONSE TO REVIEWER #1
Reviewer Comment = RC Author Comment = AC

RC: This study examines the social dimensions of moisture recycling taking the case of three countries: Mongolia, Niger, and Bolivia. The characteristics of sources and sinks of moisture are examined to understand the heterogeneity of moisture recycling socialecological systems. A moisture tracking model called the Water Accounting Model2layers (WAM-2layers) is used to track the sources and sinks of moisture starting from the moisture entering a grid cell as evaporation. The study finds that sources and sinks of moisture can experience different levels of human well-being and highlights the need to include power discontinuities in the description of moisture recycling socialecological systems, and aims to contribute to the ongoing discussion about the emerging discipline of socio-hydrology. The paper is well written and is a good fit for Earth System Dynamics, but significant revisions should be made before the manuscript can be considered for publication. Please find my comments below.

AC. We appreciate the careful consideration the Reviewer has given to the manuscript. We hope that our revised manuscript merits further consideration for publication in ESD.

- - -

RC1. The abstract is not fully representative of the paper. First, there is no mention about what model/tool is used to carry out the analysis. And second, the abstract is too qualitative. I suggest (a) adding some information about the model; (b) adding some quantitative information about the key findings; and (c) providing some take-home message about the differences in the coupled social-hydrological systems among the three selected regions in relation to the archetypes discussed in the paper.

AC1: Thank you for these comments. We have made the suggested changes, adding brief information about the analysis, some quantitative results, and more clearly articulated key messages contrasting the different MRSES.

RC2. Page 2, Line 28: It is not clear of how this paper provides information for land-water managers; I didn't find any discussion in the remainder of the paper. It is important to add this information because it has been highlighted as one of the major contributions of the paper.

AC2. Thank you for the comment. We recognize that we were unclear where this text appears. We now explicitly direct the reader to the sections "4.2 Guidelines for constructing MRSES", "4.3 Advancing human-water systems understanding", "4.4 Systems may be reinforced in unexpected ways", and "4.5 Power must be considered carefully". These four sections contain the information we originally referred to that could help land-water managers.

RC3. Section 2.1: The selection of the three countries for case studies is justified based on the authors' prior work and the global regions that receive significant precipitation from upwind evaporation. Given that the goal of the paper is to examine the connections between moisture recycling dynamics and social-ecological systems, wouldn't it be interesting to conduct the study in regions where there is an ongoing intensification of human activities and where hydrological-social systems are more tightly coupled and are fast evolving? In South America, the Cerrado Biome is one of such regions that is undergoing rapid land use/land cover change due to agriculture expansion. Studies have shown that the changes in land use in the Cerrado region have decreased the amount of water recycled to the atmosphere via evapotranspiration (Spera et al. 2016). There are also other regions where rainfall patterns and ET have been altered by human activities, especially land use change and irrigation (e.g., High Plains, Northwest India, Eastern China). Some of these regions also coincide with the regions of strong land-atmosphere coupling identified by Koster et al. (2004). Finally, from hydrologic point of view it would be more meaningful to conduct such a study over a river basin.

AC3. Thank you for these reflections. We were careful about the regions we selected, in that we wanted to ensure that we picked regions that were experiencing significant vegetation-regulated moisture recycling, which we used as a proxy for potential impacts from land-use change. Likewise, the countries are all quite similar in national area, providing a reasonable control on the spatial scale of the corresponding precipitationsheds. Also, for our purposes of emphasizing social dynamics, countries are more suitable than hydrologic basins. This is because: (a) Many regions experience limited runoff, suggesting the most meaningful hydrological flows are not river basins but sources and sinks of atmospheric moisture (for more on this see Weiskel et al. 2014); and (b) Countries provide a lens for evaluating social dynamics, especially land-use policies, since governance institutions (e.g. regulatory frameworks, transboundary legal arrangements, etc) are typically based on political or administrative units, such as countries, rather than hydrologic basins.

RC4. Page 4, Line 11: What are the necessary inputs for WAM model? What is the spatial resolution? Please provide detailed information about the model, data, and experiment settings.

AC4. We agree that it is important for the reader to have this information available. The inputs are described in Section 2.3 "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." There are no experiments, as such, since we use the WAM-2layers to calculate how moisture moves around the planet. However, we do explain how the WAM-2layers calculates this movement of moisture in Section 2.2. We hope that this explanation eliminates any confusion regarding the functioning of the WAM-2layers. Additionally, one of the other Reviewers commented on the need for more detail on the land-use change simulations/experiments. This is clearly a failing in our (the authors) communication, since there were no such experiments. In this regard, we have added clarification text in Section 2.2 of the revised manuscript to clear up this confusion: "We emphasize that the WAM-2layers is a moisture tracking scheme, and not a simulation. It is possible to couple the WAM-2layers with dynamic simulations of land-surface hydrology, including vegetation (e.g. Wang-Erlandsson et al., 2014; Keys et al., 2016), but that is not what we have done in this research. Thus, the results that we present are purely based on the implicit hydrological information contained within the ERA-Interim Reanalysis data."

RC5. Page 5, Line 19: ". . .coarsest grid resolution": Please specify the resolution/grid size?

AC5. Thank you for the comment, you and the other Reviewers requested this. We have included a table that summarizes the different datasets, including variable name, description of variable, source resolution, units, time period of analysis, and source reference. This table is found in the Methods section.

RC6. Section 3.3: This short section about the integration of moisture recycling and social features doesn't provide much information about such integration. The authors present a figure from their previous study and refer to the literature review section for further context. In the current form, I don't see this section providing any new information. I suggest the author to revise this section and make a strong case about this important integration.

AC6. Thank you for the comment, and we agree that this section needs to be revised. We have changed the format of the results presentation, based on Reviewer 2's suggestion of reporting each individual case study in its entirety. Thus, when we now present each case study, they are more coherent, with the results for the precipitationshed, social characteristics, and literature review of social dynamics presented in sequence. Additionally we have removed Fig 4 since it did not substantially improve the paper, and apparently led to confusion among the other Reviewers.

RC7. Section 3.4: This is related to the previous comment. This rather lengthy and descriptive section provides a good literature review, but it is purely qualitative and doesn't provide a good linkage with the quantitative analysis provided in other sections. A better integration of the "quantitative" and "qualitative" parts is needed.

AC7. Thank you for this suggestion. We agree that better integration among the different threads of each cast study is necessary. With the new format of each case study presented in its entirety, we hope this addresses this issue.

RC8. Sections 3.1 and 3.5: How is land use change considered in the model? What data is used and at what resolution? Is deforestation and agricultural and irrigation expansion considered? If so, does the model account for the changes in ET because of such land use changes? Please provide these details. I also suggest that the author strengthen Section 3.1 (the quantitative analysis) by including more results from the model (e.g., results of changes in land use and the impacts on moisture recycling). Currently, this section is too brief and focuses mostly on the precipitationsheds shown in Figure 2. Please also see comment 6 on better integration.

AC8. We apologize for the confusion on this issue, since it was clearly a failure in communication. As we stated in response to comment 4, there were no land-use change simulations in this analysis. We ran a single analysis of moisture recycling, using ERA-Interim data, which is output from the European Center for Mesoscale Weather Forecasting (ECMWF) forecast model. Thus, our analysis examines the observed record, with implicitly historical land-cover (i.e. inferred from various observational datasets).

RC9. Section 3.8: Please consider expanding the discussion by adding information about studying human-water interface using hydrological modeling, in line with the discussion provided by Wada et al. (2017).

AC9.Thank you for this suggestion, and this is discussed in detail in section 4.3 "Advancing human-water systems understanding"

RC10. Figure 2: This is a minor issue, but I suggest changing the unit to mm.

AC10. Thank you, we have made this change.

RC11. Page 8, Line 23: reference needed after "malnourished rangeland systems".

AC11. There is no reference for this, because it is based on our own analysis within this paper. Results from our case study analysis, including the analysis of land-uses and social characteristics of the sources and sinks of moisture, are more comprehensively reported in the results section. Likewise, we have re-written much of the literature review text so our statements ought to be much clearer to the reader.

RC12. Page 12, Line 21: change "lead" to "led"

AC12. Thanks for this suggestion. We have identified all past tense forms of "lead" and changed them to "led".

RC13. Page 12, Line 31: reference needed after "corrupt leaders".

AC13. Thanks, the corresponding reference has been added.

RC14. Page 14, Line 31: MRSES has already been defined.

AC14. We recognize that we already defined this, but given that it was defined much earlier in the manuscript, we decided to remind the reader here (at the beginning of the actual MRSES discussion) to ensure the reader does not now need to hunt through the paper for the definition.

References

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., ... Bechtold, P. (2011). The ERAâA˘ RInterim reanalysis: Configuration and performance ˘ of the data assimilation system. Quarterly Journal of the royal meteorological society, 137(656), 553-597.
Keys, P. W., Wang-Erlandsson, L., Gordon, L. J. (2016). Revealing invisible water: moisture recycling as an ecosystem service. PloS one, 11(3), e0151993.

Koster, R. D., P. A. Dirmeyer, Z. Guo, G. Bonan, E. Chan, P. Cox, C. T. Gordon, S. Kanae, E. Kowalczyk, D. Lawrence, P. Liu, C.-H. Lu, S. Malyshev, B. McAvaney, K. Mitchell, D. Mocko, T. Oki, K. Oleson, A. Pitman, Y. C. Sud, C. M. Taylor, D. Verseghy, R. Vasic, Y. Xue, and T. Yamada, 2004: Regions of Strong Coupling Between Soil Moisture and Precipitation. Science, 305, 1138-1140.

Spera, S. A., G. L. Galford, M. T. Coe, M. N. Macedo, and J. F. Mustard, 2016: Land-use change affects water recycling in Brazil's last agricultural frontier. Global change biology, 22, 3405-3413.

Wada, Y., M. F. Bierkens, A. De Roo, P. A. Dirmeyer, J. S. Famiglietti, N. Hanasaki, M. Konar, J. Liu, H. M. Schmied, and T. Oki, 2017: Human–water interface in hydrological modelling: current status and future directions. Hydrology and Earth System Sciences, 21, 4169.

Wang-Erlandsson, L., Bastiaanssen, W. G., Senay, G. B., van Dijk, A. I., Guerschman, J. P., Keys, P. W., Gordon, L. J., Savenije, H. H. (2016). Global root zone storage capacity from satellite-based evaporation. Hydrology and Earth System Sciences, 20(4), 1459.

Weiskel, P. K., Wolock, D. M., Zarriello, P. J., Vogel, R. M., Levin, S. B., Lent, R. M. (2014). Hydroclimatic regimes: a distributed water-balance framework for hydrologic assessment and classification. Hydrology and Earth System Sciences Discussions, 11, 2933-2965.

- - - -

RESPONSE TO REVIEWER #2 (Paul Dirmeyer)
Reviewer Comment = RC Author Comment = AC

RC Summary comments: This is a noble effort to develop and demonstrate a more substantial conceptual linkage between atmospheric water cycle research (based in the "precipitationshed" concept of the lead author) and the social and economic factors in the regions linked by these hydrologic connections. However, I feel there is quite a bit of room for improvement, even in this first attempt, in terms of clarity, consistency, and organization in the presentation. While the choice of the case studies is fine to illustrate the range of archetypes defined in the MRSES structure, the presentation is uneven, as I describe below. I think it may be an issue of completeness and communication of the ideas. The authors take on the difficult task of weaving together elements of climate, economics and social science, but are not always clear from sentence to sentence which they are talking about. It appears to be the case that the authors have become quite familiar with their own topic and forgotten how convoluted it can appear to newcomers. As a result, the paper rushes through a lot of material too quickly. More "handholding" would be appreciated! Several of the figures need improvement as well.

AC. We are pleased that the Reviewer has taken a considerable amount of time to both interpret our paper, and to provide detailed feedback on how to improve the work. We hope that our responses below will both answer the lingering questions and address the problems identified by the Reviewer.

- - -

General comments:
RC-A. For example, it took several readings before I really understood (I hope this is the point) that the important /input/ is how much evaporation in a precipitationshed is from managed land, inside or outside the country, and if that land is undergoing (or liable to undergo) land use

change. Connectivity, the ranges described in the 3 archetypes, stems from this (right?). A plot of managed evaporation, or a table, would do wonders for clarity. One possibility would be modification to Fig 3 with a more stark color key designed along the axis of the degree of human management/impact.

AC-A. Thank you for the comment, and we appreciate that the Reviewer spent so much time attempting to glean this insight. Ultimately, 'managed evaporation' (as the reviewer puts it) or evaporation that can be or is actively changed is the implicit focal point of the biophysical system. If the Reviewer implies that 'managed' includes all the policies, cultural pressures, economic incentives, legal regimes, treaties, etc. then yes, 'managed evaporation' is the key input. While we think there could be merit in a table of managed evaporation, estimating this for all the systems, is an academic task in its own right. Our goal in this paper is to explore potential ways for characterizing the social connections that link the recipient of precipitation back to the sources of evaporation: i.e., (a) describing conceptual and actual social linkages among sinks of precipitation and sources of evaporation, and (b) developing a method for linking existing methods of quantitative moisture recycling analysis (e.g. precipitationshed calculation), with new methods of quantification (e.g. relating well-being indicators to moisture recycling sinks and sources), and qualitative analysis of economic and social policies related to land-use change. We recognize the value of a table that explores managed evaporation, so we include the following text in the new section "4.6 Limitations": "Evaporation can be or is actively changed through e.g., policies, cultural pressures, economic incentives, legal regimes, and treaties in the social systems, and limited by e.g., water availability, edaphic suitability, and energy limitation in the biophysical system. The type and nature of this manageable or managed evaporation is important for understanding the management space. Thus, future work could undoubtedly extend and perhaps substantiate social linkages by first identifying and quantifying managed evaporation within different administrative zones. Likewise, specific policies could be linked to these administrative zones, which could explicitly link legal, policy, and on-the-ground management efforts with particular flows of evaporation, and subsequently moisture recycling."

RC-B. The subsections in section 3.2 are only single paragraphs for each case. This, and the jumping around between cases later in the paper was quite jarring to this reader. I think it would be better to organize the results by presenting each case separately in its entirety, from the quantitative hydrologic and socioeconomic analysis to the social dynamics cases. Then Sec 3.5 can be the point where they are knitted back together in the framework of MRSES.

AC-B. Thank you for the comment, and we have used your suggested changes. We now present each case in its entirety, including (a) precipitationshed analysis, (b) land use distributions among the sources and sink, (c) social linkages between sources and sinks, and (d) literature review of policy and management.

RC-C. It would be helpful for the authors to draw the distinctions between "Market Influence" and the economic links between the case study countries and their neighbors, or even "global markets" as invoked in Sec 3.6. Without defining "Market Influence", which is really very local having only a vague implication that large cities link to global markets, there is a tendency to associate the two when they are not very related. Or do the authors, via Fig 4, try to assert that they are? This needs to be clarified.

AC-C. We agree that Market Influence needs to be better defined. Market Influence is calculated by multiplying normalized travel time to cities and ports, with national level per capita GDP in terms of purchasing power parity. Given that Verburg et al. (2011) goes into the nuanced relationship between market influence, wealth, and connection to global markets, it seems a bit redundant to do that again. We do cite Verburg to ensure it is clear where to explore those additional arguments.

RC-D. An element of the social connectivity analysis eludes me. What is a more favorable archetype to be in; isolated, regional or tele-coupled? Or are there a range of implications for each (I presume this is true)? There is a natural tendency to try to view these archetypes on a scale from bad to good. If this is not intended, the authors should proactively disabuse the readers from looking at MRSES in such a light.

AC-D. Thank you and we agree with the Reviewer. It would be wrong to conclude that one archetype is preferred to another and that there are (as the Reviewer suggests) a range of implications for each. We explore this and other aspects of the MRSES in section 4.1 "MRSES archetypes are idealized".

RC-E. Another detail that the authors need to spell out for unaware readers is that recycling rate (within nations) depends strongly on national area (cf. Dirmeyer and Brubaker (2007 http://dx.doi.org/10.1175/JHM557.1); the "scaled RR" in Dirmeyer et al. 2009 accounts for this). So comparing recycling among the study countries (or more generally any countries or regions) should acknowledge the strong effect of total area. Mongolia, Niger and Bolivia are in order of decreasing size and thus expected decreasing recycling rates given other factors like precipitation regime are controlled for.

AC-E. We appreciate this detail, and for mentioning "scaled RR". We do not scale the recycling ratios in this paper, as the biophysical reason for low or high recycling ratios have limited relevance for the social implications for individual nations. In fact, smaller nations already tend to be more reliant (or be subject to) outside influence beyond atmospheric moisture connections: e.g., in terms of global markets, national security, and climate change impacts.

Specific comments:
RC1. Fig 1: Please explain the red arrow at the bottom of panel C - what does this connote?

AC1. Thanks for the comment, this arrow is simply highlighting the social connection that is often missing from depictions of sources and sinks in moisture recycling research. The arrow is red to match the red boxes containing the "Social" node, and points in both directions indicating that social links can connect in multiple directions. We have clarified this in the updated caption to Fig 1.

RC2. P5 L10-11: It is not clear to me how this notion of using spatial sampling as a proxy for temporal sampling in social data has been exploited in this study. Can you point out, perhaps retrospectively in the conclusions or /in situ/ if there is a good example, where this has been applied?

AC2. We agree that this is unclear. In the revised version of the paper the sentence is no longer relevant, so it has been removed.

RC3. P5 L16: Please define Market Influence as used here. I did go to Verburg et al. (2011) to learn this, but it is a simple enough metric that it could be described here in one sentence.

AC3. We agree with the Reviewer, and as indicated in previous comments, we have expanded the definition of all variables in section 2.4 and Table 2.

RC4. P5 L18: Please give the specifics of the "various resolutions" of these data sets, including the time periods they each cover.

AC4. Thanks for the comment, and this feedback was echoed by other Reviewers. We have included this information in Table 2, which summarizes the different datasets, including variable name, description of variable, source resolution, units, time period of analysis, and source reference. This table is found in the Methods section.

RC5. Table 1: Naturally I compared these values to Dirmeyer et al. (2009) [by the way, the wrong paper is listed in the References; see: http://dx.doi.org/10.1016/j.jhydrol.2008.11.016] and found the recycling and nearfield percentages in Table 1 to be generally lower. Perhaps WAM-2layers and QIBT have systematic differences in moisture advection rates?

AC5. Thank you for comparing the values, and for noticing this error in the citation. Many apologies! It could be that we misinterpret the comment, but we ought to be comparing our results to Dirmeyer et al. (2009) Table 6 (i.e. “Top three external contributors of ES, expressed as a percentage of total precipitation over each nation.”) If this comparison is correct, the key countries, as well as corresponding percentages of contribution, match quite well, excepting for some differences in percent contributions to Bolivia. We will refer to this previous work given that it generally supports the results we find, while illustrating the disparity for volumes coming from Peru and Brazil to Bolivia.

RC6. P6 L6: Fig 5 is cited before Fig 4.

AC6. Thanks for the comment, and we have carefully checked all references to Figures and Tables to ensure that the references are (a) in the correct order, and (b) that the Figures and Tables do not preceed their first reference.

RC7. P8 L23: What is "malnourished"? As written, the rangeland systems are. I think you mean the people in those systems. Likewise in L26-27, "areas" are not hungry, the people in them are.

AC7. Thank you, and indeed we did not write this correctly. We have corrected these, and carefully read the text for similar errors.

RC8. Fig 3: I think this must be mislabeled. The open circles must mark the in-country sinks and the colored dots are the various evaporation sources, no? Also, please expand or define the abbreviations "Pop." and "Resi." (actually it would be good to point out the threshold population density of 10 people/km2 between the categories). Finally, what does the size of the circles indicate and what is the scale for that?

AC8. Thank you for the suggestions here. Based on your feedback Fig 3 has been completely remade (per your suggestion in Comment 9 below), and we no longer include the Anthrome data, nor the Anthrome colorbar. The land-use data is now presented as a histogram in a separate panel. A brief explanation of the Anthrome data, including that it incorporates a population density component, is found at the explanation of variables in section 2.4.

RC9. Secs 3.2.1 - 3.3.3 relative to Fig 3: It is not always evident by eye the assertions made regarding the relationships between elements in Fig 3. I think it would help to plot in each panel the first two moments (mean and standard deviation) as two crossed whiskers (along X and Y axes): one for all the source areas (weighted by contribution - is that the size of the circles?) and one for the in-country sink. Then their differences and the overlap of the ranges of standard deviations can be easily seen, and statements like P10 L3-4 and L9-10 would have a better basis.

AC9. Thanks for the comment. This is an excellent suggestion, and indeed adds to both the clarity of the results, as well as provides more robust information about differences among sources and sinks. We have made this change to the figure, and can be seen in each of the case studies.

RC10. Fig 4: The color bar is very unclear. Log scale? The numbers are linear, and appear to be multiplied by 10e4; clearly not what the authors intend and not commensurate with the ranges in Verburg et al. (2011).

AC10. Thank you for the comment, and we agree that the colorbar was incorrect. In the interest of streamlining the text, we have since deleted this Fig 4 from the text.

RC11. Also Fig 4: In fact, I cannot see how Bolivia has such a high Market Influence index (so blue) based on the data of Verburg et al. (2011); their Fig 3 shows this to be very low for Bolivia. The colors seem to have more to do with the "qualitative" descriptions in Sec 3.4 than the quantitative data.

AC11. Thank you for the comment, and we agree that the colorbar was incorrect. In the interest of streamlining the text, we have since deleted Fig 4 from the text.

RC12. Also Fig 4: It would be good to note somewhere that the X-axis naturally correlates with the size of the country (small=low) and its aridity (dry=low), while the Y-axis correlates with continentality of the climate.

AC12. Thanks for the comment, as stated, we have deleted this figure.

RC13. P11 L29: "detectable changes in vegetation and associated changes in nearsurface meteorology" - please provide a reference for this statement.

AC13. Thank you, and the relevant citation was mistakenly included in the sentence immediately prior. This has been fixed now.

C14. P12 L33-34: Not a sentence; appears to be missing a clause.

AC14. Thanks for the comment, and we have edited the sentence for clarity. It now reads: “This is relevant primarily because significant areas of land acquired for agriculture (estimated at 360,000 hectares in GRAIN (2012)), could lead to extensive potential modification of the land surface, with associated impacts on moisture recycling.”

RC15. Sec 3.4.2: The Niger case is missing a discussion of the economic links among neighboring countries like exists for the other cases. This makes the final paragraph much more "hand-wavy" than the discussions of the other two cases, in my opinion.

AC15. Thanks for the comment, and we have corrected this in the updated text. Please see the new section on the economic interlinkages among the region and beyond.

RC16. Sec 3.4.3: Much is made about the strength of national land use regulations, but (1) in the particular case of Brazil they are highly variable in time, depending on which party is in power; (2) enforcement lags behind (this is discussed somewhat) and (3) the spatial and population scale of the problem makes such statements about regulation almost meaningless. The Acre region of Brazil, noted as a main external moisture source for the Bolivian precipitationshed, has experienced significant deforestation over the last 40 years, albeit not as widespread as Rondonia, which also borders Bolivia. The problem seems to be soft-peddled a bit here.

AC16. Thanks for the detailed attention to this section. We agree with the Reviewer here, and have modified this text considerably. We particularly draw attention to the fact that there is in the cases of the interior of the Amazon considerable discrepancy between the stated aims of government policy and the actual impact on the ground.

RC17. P14 L11-12: Likewise, the notion that the "region’s land use is relatively wellgoverned with many controls in place to avoid large-scale change" seems untrue, and in contrast to the very next sentence. It is clear even from Google Maps that there is a very clear demarkation following the Bolivian border where deforestation is rampant in neighboring Brazil right up to the border.

AC17. The satellite imagery you point to on Google Maps is indeed compelling, and a literature review of relevant deforestation trends in this region bears out your observation. We have modified this section considerably to reflect this updated information. We hope the updated text on deforestation policy, enforcement, and reality is now more consistent with the Reviewer’s understanding of these systems.

RC18. Sec 3.5: In addition to explaining the archetypes and how they fit the previously presented data and social dynamics review, it should be frankly stated where they are unclear, or at odds.

AC18. Excellent point. We have included new Discussion section 4.1 “MRSES archetypes are idealized” where we explore these issues.

RC19. Fig 5: I also find this diagram somewhat unsatisfying, but perhaps I am not understanding it. Are the boxes meant to be static, or is it the fluctuations (changes) in the boxes that precipitate (pardon the pun) effects in other boxes by the arrows? For instance, Mongolia has a huge non-local (regional) evaporation source, small (9%) local source, and strong export connections to its large neighbors, yet is defined as "isolated" based on other factors. The synthesis and the weights given to the various factors seems either subject to interpretation, or not clearly enough defined. If the single driving /hydrologic/ factor is land use change in the precipitationshed, it could be demonstrated much more clearly and succinctly than has been done here (see General Comment above). Then it comes to the economic consequences to fill out the MRSES archetypes - am I seeing this correctly?

AC19. Thanks for the comment, and for the clearly deep consideration of this figure. The archetype classification is subject to interpretation, which is what we did based on the synthesis of the different aspects of our analysis. Other reviewers echoed this feedback about the issue of subjectivity, and we have added several sentences at throughout the text that emphasize the blending of methods, and the explicit use of of an interpretive and subjective set of methods. Furthermore, we include a new discussion section titled “MRSES archetypes are idealized” to discuss (a) where why the MRSES might be unclear or at odds with one another, (b) emphasizing that there are benefits and disadvantages to the different MRSES (per this Reviewer’s suggestion), (c) emphasize that understanding MRSES requires subjective interpretation of results, given the blending of analytical approaches and the presence of value-based judgements (e.g. higher child malnutrition is subjectively unfavorable).

RC20. P15 L6-7: "...large contributions..." of what? Be clear and complete. "...social processes driving the evaporation..." - this statement may be endemic of the communication problem. Presumably this is shorthand for "policy and economics drive land use change that affects evaporation potentially affecting downstream precipitation" but I think the authors forget how much better they understand their own material than their readers will.

AC20. We appreciate the feedback, and recognize that this ambiguous language can lead to confusion and frustration. We have modified the text in this specific location, and have considered this feedback throughout the entire paper.

RC21. P16 L5-6: This needs to be stated earlier, to clarify much of what goes before.

AC21. We agree, and have moved this to the beginning of the explanation of the archetypes indicating that since it is contained within all the archetypes it ought to be stated clearly at the beginning.

RC22. P16 L33-34: It is sentences like this that lead to confusion; the "regional factors that can influence...." means land use changes affecting moisture sources, right? If so, just say that. I think the hydrologic underpinnings get lost at times in this manuscript.

AC22. Thank you again, and we have fixed this language.

RC23. P17 L8: I think this is a typo: "and Brazil" should be "from Brazil"

AC23. Thanks, fixed.

RC24. Sec 3.5.3: Aren't the actual drivers of land use change (deforestation in the Amazon) much more from developed nations than is the case in Niger? Doesn't this also have implications for "tele-coupling", or not as defined?

AC24. Yes, and this was intended to be part of our point. Evidently we did not make the point well, so we have clarified the text.

RC25. P17 L28-30: This sentence would benefit from a concrete example or pointer to the specific data presented earlier.

AC25. Thank you for the comment, and we have provided a concrete example referring back to the isolated archetype Mongolia, in the form of Mongolian land-use policy.

RC26. P18 L1-2: Similarly, this sentence would benefit from an actual example of reinforcement/surprise, and not merely describing the situation.

AC26. Agreed. We have added an example of this in the context of Amazonian policy within Bolivia

RC27. Sec 3.8: This section I found to be more clearly presented. I am reminded of the interesting case evident in Wei et al. (2013; http://dx.doi.org/10.1175/JHM-D-12-079.1) where evaporation from irrigation in Northeast China appears to supply a significant amount of rainfall to North Korea!

AC27. Thanks for the comment, and this is an excellent example. We have added this in the second paragraph of this section.

RC28. P19 L9: "...gives Brazil power over Bolivia in potentially significant ways." I would phrase it that it gives Brazil "responsibility to Bolivia" - this is the other side of the coin from air pollution (including nuclear fallout), where it is pretty easy to track sources to those affected downstream. We are not used to thinking of water vapor in that way, but "responsibility" gives a more overarching concept to such linkages.

AC28. Thank you for the suggestion. We have thought about this phrasing, and have switched it to the following: "For example, demonstrating that Brazil is very important for Bolivia's rainfall potentially adds a matter for negotiation between the two countries, with all that entails, especially in terms of responsibility and power."

- - - -

RESPONSE TO REVIEWER #3
Reviewer Comment = RC Author Comment = AC

RC Overview: The paper by Keys et al presents three case studies of links between the social and terrestrial moisture recycling system. This study combines quantitative modeling of terrestrial moisture recycling with metrics and a literature review of social factors. In this way, the study estimates the major sources of precipitation (i.e. precipitationsheds) for three case study countries. Gridded social variables are then evaluated for the source and sink nodes in each case study. Finally, a literature review is performed to reveal additional context for each case study and enable the development of moisture recycling social ecological systems archetypes. Overall, I think this is an innovative, well-executed, and (reasonably) well-written paper that would make a unique contribution to the literature. I recommend publication after consideration of my comments below.

AC. We are pleased that the Reviewer has considered this work carefully. We hope the responses below address the Reviewers' concerns. -

- - -

Major comments:
RC1. Human well-being/welfare has a precise definition in the social sciences literature. The term(s) "well-being" and "welfare" are used several times in the paper. I don't think these is the best term to use, since they mean something precise in the economics literature that is distinct to the meaning here. I think it would be better to refer to "social" aspects/variables/indicators of source and sink nodes. Then, the precise metric references should be specified whenever possible.

AC1. Thank you for the comment. We note that the phrase human well-being and welfare have specific definitions. As suggested by the reviewer, we use the specific phrases that describe the variable /indicator/ etc. and we make clear when using a general phrase that it is not already laden with pre-existing meaning.

RC2. Why not perform a global scale analysis? The literature review would be too difficult to perform for all countries in the world. However, a global scale analysis of precipitation-sheds and receiving countries would be relatively straightforward to perform. It appears the authors have all the information they need for this. They have WAM-2 pixels, social variables at the pixel scale. So, couldn't this be a global scale analysis for most aspects? Then, the 3 case study countries could be used for the literature review portion of the paper. If a global scale analysis is performed, then the authors will have more data to run some interesting regressions. For example, they can calculate "precipitation-sheds" and "sink" nodes for all countries. Then, they can obtain average values of social variables in each source/sink. In this way, they will have enough statistical power to run multivariate regressions of the driving factors of the terrestrial moisture recycling system.

AC2. Thank you for the suggestion, but this level of analysis is beyond the scope of this present work of understanding the social aspects of a moisture recycling system. In terms of practical usefulness for stakeholders and the construction of MRSES, we think it is necessary to go deeper in understanding each moisture recycling system. Running the WAM-2layers for all countries globally, would be a considerable computational undertaking that, while compelling, addresses a somewhat different research question and target audience than at present. We also removed Fig 4 in order to streamline the paper. Thus, we suggest that a global scale analysis could be set aside for future work.

RC3. Fig 3 is confusing and could be simplified. There is a lot of information in Fig 3. I don't think most of it is necessary. For example, does the biome information convey anything interesting? There does not appear to be any trend between malnourished children (y-axis) and GDP/capita (x-axis), so this information could be made easier to read. I think this figure would be better if it presented the average value of malnourishment and GDP/capita explicitly for the source and sink region of each country. This might be able to be accomplished with a simple bar graph or box-whisker plot for each variable for each source/sink node. A table might even best illustrate upstream/downstream differences. This simplicity would better illustrate the main points made in sections 3.2.1-3.2.3.

AC3. We appreciate this suggestion for a revised Fig 3, and much of this is consistent with Reviewer 2. We have updated this figure to be a much simpler plot showing sources and sinks, with corresponding mean and standard deviation. Also, the figures have been re-combined so that each case studies figures appear all together. This hopefully simplifies the information and assists interpretation.

RC4. The section on power dynamics could be improved. There seem to be many similarities between upstream/downstream power dynamics in precipitationsheds and watersheds. I think this section would benefit from drawing from the power dynamics concepts in the transboundary watershed literature. A lot of work has been done on power/politics in international river asins that section 3.8 would benefit from referencing. Generally, section 3.8 could use a bit of a rewrite for clarity. Have any papers quantified the impact of upstream precipitation-sheds on downstream droughts? This seems like it would be the most clear example of upstream-downstream conflict/power issues. Also, can you expand on the Daw et al (2011) Reference? Does this paper specifically focus on power dynamics in teleconnected systems?

AC4. Thank you for this comment, and this is a very interesting suggestion. We have added several new sentences reflecting on the upstream/downstream power dynamics in watersheds, and how they are potentially similar or different to precipitationsheds. The Daw paper focuses specifically on how there are trade-offs in ecosystem service benefits, and that a winner is often associated with a loser elsewhere. However, this is tangential to the core message of the research, and so we have removed this citation.

RC5. A bit more connection with the SES and socio-hydrology literature would be helpful. How does this work relate to socio-ecological systems (SES) work? Have similar archetypes (Fig 5) been presented in SES literature? Or socio-hydrology? What outcome variables are primarily of interest in the SES literature?

AC5. This is a great suggestion, and we have looked into similar discussions in the SES and socio-hydrology literature. The new section 4.3 “Advancing humanwater systems understanding” and corresponding figure are included in the revised manuscript to address these considerations. Minor comments:

RC6. The term “average market influence” is not clear and confusing. Please just call it what it is, i.e. GDP per capita.

AC6. The variable “average market influence” is actually a specific variable calculated in Verburg et al., (2011), that is a combination of (a) access to markets (calculated using proxies transport infrastructure, travel distance, and travel costs to major cities), and (b) per capita GDP. Thus, GDP per capita is not actually what the value is. However, other Reviewers have also pointed out that this variable is unclear, so we added a table that (among other things) provides clearer definitions of all variables throughout the text.

RC7. Figure 4 doesn’t seem to show much. What happens if you just plot national international moisture recycling (y-axis) against GDP per capita (x-axis)?

AC7. Thank you for the comment, and this feedback echoes the concerns of other reviewers. However, Fig 4 was considered no longer useful and has been removed from the manuscript.

RC8. P 18 line 14: “Though the analysis of environmental justice flows has been simplified (Fig 3). . ..”. Environmental justice flows are not quantified or presented in Fig 3. This statement is not warranted.

AC8. We agree with the Reviewer, and have removed the language of environmental justice, and refer more plainly to the specific variables we examine.

RC9. P 19 line 5: This sentence is a bit ironic. It seems to be a call for interdisciplinary scientists to engage and communicate with one another. However, this sentence is laced with jargon that is not widely understood (i.e. “positivism”, “normative terminology”)

AC9. This is ironic. We have defined these terms clearly now. Likewise, this feedback is generally consistent with other Reviewers, so we have read the text carefully and replaced or defined any remaining jargon.

- - - -

RESPONSE TO REVIEWER #4
Reviewer Comment = RC Author Comment = AC

RC Major comments: The authors investigated terrestrial moisture recycling in three inland countries, namely, Mongolia, Niger, and Bolivia, by focusing on land-use change in moisturesource regions. By investigating land-use change policy of the countries in question and surrounding countries, the authors tried to explore the social dynamics of moisture recycling. Although I found the attempt quite interesting and novel, the manuscript in present form lacks clarity and quantitative evaluations in many parts. Hope the comments below are useful for further improvements.

AC. We appreciate the time that the Reviewer took to respond to the manuscript. We have made many improvements to the manuscript in response to all of the Reviewers, and hope that the updated manuscript meets the expectations of this Reviewer.

- - -

RC Specific comments

RC1. Page 1 line 8 "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": How moisture "can experience different levels of human well-being"? What are "power discontinuities"?

AC1. Thank you for pointing out these issues, which were indicative of broader problems related to jargon and lack of clarity in our text. We have made major changes throughout the text to define terms and remove jargon.

RC2. Page 1 line 11 "This exploration of the social dimensions of moisture recycling": It seems an important precondition of this work that the "social dimension" plays an important role in terrestrial moisture recycling, but this is hardly proved (quantified) in text. I suppose the direct impacts of land-use change on the terrestrial hydrological cycle would be marginal. Exceptions are the cases for quite intensive irrigation (e.g. DeAngelis et al. 2010; Puma and Cook, 2010) and land-use change at continental and century-scale (e.g. Takata et al. 2009).

AC2. Thank you for this comment. In the original Introduction we stated "That the land-surface can and does influence the atmosphere is well-known (Dirmeyer and Brubaker, 1999; Domenguez et al., 2006; Tuinenburg et al., 2011; Bagley et al., 2012; Keys et al., 2016)." It is apparent from the Reviewer's comment, however, that this sentence is insufficient to provide a convincing basis for proceeding toward the discussion of how social drivers of land-use change are a reasonable topic of discussion. As such, we have added a brief paragraph to clarify how land-use change modifies atmospheric moisture recycling, and then clearly state that a land-use change analysis is not the point of the present study, and that the interested reader should seek the original works that explore this topic. This updated text appears in the Introduction "That land-use change can and does influence the atmospheric water cycle is wellsupported (e.g. Lo and Famiglietti, 2013; Wei et al., 2013; Halder et al., 2016; de Vrese et al., 2016). Impacts can include modifications of the energy budget (e.g. Swann et al., 2015), impacts to local or regional circulation (e.g. Tuinenburg et al., 2013), and impacts to the atmospheric water cycle (e.g. Spracklen et al., 2015; Badger and Dirmeyer, 2015)."

RC3. Page 4 line 3 "2.2 Tracking the sources of moisture": The authors applied the WAM2layers model to estimate the evaporation and precipitation of their study domain. First, I would suggest providing more detailed information on the boundary condition (i.e. simulation period, land-use assumption, validation data). Second, I would suggest conducting some additional simulations under counterfactual land-use which implies historical land-use change mentioned in Section 3.4.

Such simulations would be highly effective to convince readers how significantly "social dynamics" would change precipitation or evaporation.

AC3. We appreciate the reviewers comments regarding the WAM-2layers and additional simulations. Evidently, our explanation of the WAM-2layers was insufficient, since the WAM-2layers does not in fact simulate anything. Rather, it is a moisture tracking scheme, that keeps track of the atmospheric water budget. In section 2.3, we explain how the WAM-2layers tracks moisture, and that we employ the ERA-Interim Reanalysis data. Given that this Reviewer, and Reviewer 1, both thought we were simulating something, we have improved and clarified our explanation of the WAM-2layers to ensure there is no confusion of what the WAM-2layers does and does not do. This text may be found in section 2.3: "We emphasize that the WAM-2layers is a moisture tracking scheme, and not a simulation. It is possible to couple the WAM-2layers with dynamic simulations of land-surface hydrology, including vegetation (e.g. Wang-Erlandsson et al., 2014; Keys et al., 2016), but that is not what we have done in this research. Thus, the results that we present are purely based on the implicit hydrological information contained within the ERA-Interim Reanalysis data." While it would be very interesting to conduct counterfactual land-use changes to explore how various land covers influence the moisture recycling patterns, this is outside the scope of what we are writing about in this research. Additionally, we recognize that the Reviewer would like to see additional evidence for how land-use change can significantly change precipitation and evaporation. However, we highlight (as noted in the previous comment) that the evidence for land-use change impacts on moisture recycling are well-established, and are thus not necessary to establish in this paper.

RC4. Page 8 line 26 "in general evaporation arising from relatively wealthier, less hungry areas falling out as precipitation in poorer hungrier areas": This part sounds very subjective. Add figures and tables to make this part quantitative and concrete.

AC4. Thank you for the comment, and we agree that this is unclear. Throughout Section 3.2 (in the original manuscript), we are referring to the results in Fig 3. However, this comment along with the feedback from the other Reviewers, suggests that we need to improve both the clarity of the text of Section 3.2 as well as the clarity of Fig 3. So, we have significantly modified Fig 3 to be much simpler and convey the information of evaporation source and precipitation sink characteristics much more robustly and clearly. Also, given that we now present each case study in its entirety, Fig 3 has been divided among the three case studies.

RC5. Page 10 line 3 "However there is a flow of moisture from wealthier areas to poor areas (relative)": Same comment as above. AC5. Thank you for the comment, and we agree. Please see above comment for full details of the changes we made.

RC6. Page 10 line 7 "Within Bolivia itself, there is a cluster of wealthier rangelands and populated woodlands, and a cluster of much poorer remote and wild forest systems" Same comment as above. What is a cluster?

AC6. Thanks, and please see the comment above. We used cluster to refer to general grouping of the circles in the figure. However, since we have replaced Fig 3, with a much simpler figure, we have removed all text that refers to clusters (or the distribution of circles generally).

RC7. Page 10 line 8 “Surprisingly”: Explain what is surprising. The authors tend to connect factor and factor subjectively. What are the solid knowledge based on established evidence here? In what sense surprising?

AC7. Excellent point, and we have removed this text. We agree that we should not be injecting phrases like ‘surprisingly’ or ‘interestingly’ into the text.

RC8. Page 11 line 10 “affect moisture recycling policy”: What is moisture recycling policy? In my view, the impact on moisture recycling is one of many (often unintended) secondary-impacts of land-use/industrial policy.

AC8. Moisture recycling policy (as far as I know) does not yet exist. The Reviewer is correct that changes to moisture recycling are going to be secondary impacts of land-use/industrial policy. Some work has been done to identify potential policies for direct governance of moisture recycling as well as for integrating moisture recycling into existing policy (e.g. Keys et al., 2017). However, no policies exist yet. We removed this sentence since it was confusing and unnecessary.

RC9. Page 14 line 29 “Construction of archetypes”: Although it is an interesting idea that inland moisture recycling could be subdivided into three categories, I’m wondering how to find thresholds among them. Any region is neither fully isolated nor fully teleconnected. What to do with regions in between?

AC9. This is an excellent point and we agree with the Reviewer. Undoubtedly some regions may fall in between these archetypes, if not manifesting additional (as yet uncharacterized) dynamics that may yield entirely new archetypes. Nonetheless, in the updated Section 3.4 and Section 4.2, we discuss the process of classification and how MRSES are likely to move from isolate toward regional toward tele-coupled, and that once they have become tele-coupled they are unlikely to reverse that trajectory

RC10. Page 18 line 15 “in isolated systems (e.g. Mongolia) there can still be a wide range of well-being (e.g. wide range in poverty and malnutrition)”: I couldn’t follow the authors’ logic. In every isolated systems the authors’ claim holds true? Which figures/tables/sub-sections clearly do clearly support this claim?

AC10. This is a good point, and we have removed this text since it is unclear.

RC11. Figure 3: Very hard to understand. What does each plot represent (grid cells of each nation or those for each precipitationshed)? Also clearly indicate in text what we should focus on. These panels look random scatter without meaningful information at first glance.

AC11. Thank you, and your comment echoes the comments from all the Reviewers. We have re-made Fig 3 to be much clearer and communicate the intended information more simply. Likewise, given the restructuring of the cases (based on Reviewer 2 feedback), we present each panel of Fig 3 with its corresponding case study.

References:
DeAngelis, A., Dominguez, F., Fan, Y., Robock, A., Kustu, M. D., and Robinson, D.: Evidence of enhanced precipitation due to irrigation over the Great Plains of the United States, J. Geophys. Res., 115, D15115, 2010.

Puma, M. J., and Cook, B. I.: Effects of irrigation on global climate during the 20th century, J. Geophys. Res., 115, D16120, 2010.

Takata, K., Saito, K., and Yasunari, T.: Changes in the Asian monsoon climate during 1700-1850 induced by preindustrial cultivation, P. Natl. Acad. Sci. USA, 106, 9586-9589, 10.1073/pnas.0807346106, 2009

# 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~~ dynamics of three case study countries with strong terrestrial moisture recycling: Mongolia, Niger, and Bolivia. ~~Based on~~ We first use the WAM-2layers moisture tracking scheme, and ERA-Interim climate reanalysis, to calculate the evaporation sources for each country's precipitation, aka the precipitationshed. Second, we examine the social aspects of source and sink regions, using economic, food security, and land-use data. Third, we perform a literature review of relevant economic links, land-use policies, and land-use change for each country and its evaporation sources. The moisture recycling analysis reveals that Mongolia, Niger, and Bolivia recycle 13%, 9%, and 18% of their own moisture, respectively. Our analysis of social aspects suggests considerable heterogeneity in the social characteristics within each country relative to the societies in its corresponding evaporation sources. We synthesize our case studies~~we present~~ , and develop 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~~ Our key results are: (a) geophysical tele-connections of atmospheric moisture are complemented by social tele-couplings forming feedback loops, and consequently, complex adaptive systems; (b) the heterogeneity of the social dynamics among our case studies renders broad generalization difficult, and highlights the need for nuanced individual analysis; and, (c) there does not appear to be a single desirable or undesirable MRSES, with each archetype associated with benefits and disadvantages. 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~~ land-use change can and does influence the ~~atmosphere is well-known (Dirmeyer and Brubaker, 1999; Dominguez et al., 2006; ?; 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).~~atmospheric water cycle is well-supported (e.g. Lo and Famiglietti, 2013; Wei et al., 2013; Halder et al., 2016; de Vrese et al., 2016). Impacts can include modifications of the energy budget (e.g. Swann et al., 2015), impacts to local or regional circulation (e.g. Tuinenburg et al., 2013), and impacts to the atmospheric water cycle (e.g. Spracklen et al., 2015; Badger and Dirmeyer, 2015).

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 (Keys et al., 2018), and even the import and export of moisture among nations (Dirmeyer, P. A. 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~~ Socio-hydrology has expanded to include many social dynamics, including explicit inclusion of systems-thinking (Pande and Sivapalan, 2015), yet integration of the social dynamics of moisture recycling remain largely unexploredThese 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.

Social-ecology, however, departs from the view that human and environmental systems are separate, and that social-ecological systems (SES) are tightly coupled complex adaptive systems. In its simplest form, the classic social-ecological systems 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. Recognizing that systems exist within hierarchies, the concept of panarchy was developed for understanding the cyclic dynamics of combined human-nature systems across scales (Gunderson and Holling, 2002). For the purpose of analysing the likelihood of self-organisation in SES, Ostrom (2009) proposed a general multilevel, nested framework comprised of resource system, resource unit, governance system, and users, which are all embedded within ecological as well as social-economical-political settings. In terms of water management and governance, this type of SES thinking have been primarily applied to rivers and lakes (Cosens and Williams, 2012; Gunderson et al., 2017), but not to atmospheric moisture flows.

### 1.1 Research questions and rationale

Here, we take inspiration from the SES type of thinking to 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~~interlinked with social dynamics?
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?

### 1.2 ~~Rationale~~

~~This~~ We want to be clear that our analysis includes both objective analysis of moisture recycling and social data, as well as subjective assessment of ongoing policy and management activities related to land-use change. This blending of quantitative and qualitative, as well as objective and subjective, is at the heart of our approach to understanding social dynamics of moisture recycling.

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.

## 2 Methods and Data

### 2.1 Conceptual development

~~A~~ We propose to develop a framework for moisture recycling 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~~ , starting with the classical social-ecological systems concepts (Holling, 2001; Folke et al., 2004; Folke, 2006) (Fig 1a). ~~The~~ A key feature of SES are the connections among, different system components, creating loops. These system loops allow for feedbacks within the system, leading to complex, emergent behavior. Likewise, the systems can adapt to changing conditions, making them complex adaptive systems. In parallel, we use the simplest representation of a moisture recycling system~~is~~ , which comprise of 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~~ nesting of SES within the moisture recycling system suggests the emergence of a social connection back from the evaporation source to precipitation sink (Fig 1c, red), and represents the fundamental basis for our current research. Furthermore, this concept 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. A table of key terms is provided for reference, especially given the interdisciplinary nature of this research (Tab 1).

## 3 ~~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~~ social-ecological inequalities (e.g. differences in child malnutrition) among the downwind beneficiaries of moisture recycling and the upwind providers of moisture recycling. Furthermore, since this research is about

**Table 1.** Definitions of key terms used in this research.

| KEY TERM | DEFINITION |
|---|---|
| Moisture recycling | The process of evaporation arising from the surface of the Earth traveling through the atmosphere and returning elsewhere as precipitation. |
| Precipitationshed | An area B that is upwind of region A, that provides evaporation for A's precipitation. The extent of precipitationshed is determined by the area that contributes moisture (source region) to a selected region (sink region). |
| Source region | The source of evaporation (in a moisture recycling context) |
| Sink region | The sink of precipitation (in a moisture recycling context). A user-selected region for which the source of precipitation is tracked and determined. |
| Complex adaptive systems | A system with many parts that interact to produce system-wide behavior that cannot easily be explained in terms of interactions between the individual constituent elements. |
| Social Dynamics | Social drivers, feedbacks, interactions or other social features of a complex adaptive system. |
| Social-ecological systems | A system in which human and nature are intertwined, and system dynamics include both biophysical and social feedbacks. |
| MRSES | Moisture recycling social-ecological system. A framework for considering social, ecological, and moisture recycling feedbacks. |
| Tele-connection | A connection between bio- or geophysical processes that are separated by time, space, or both. |
| Tele-coupling | A connection among social processes that are separated by time, space, or both. |
| Socio-hydrology | The emerging scientific discipline that jointly considers hydrological and social dynamics. |

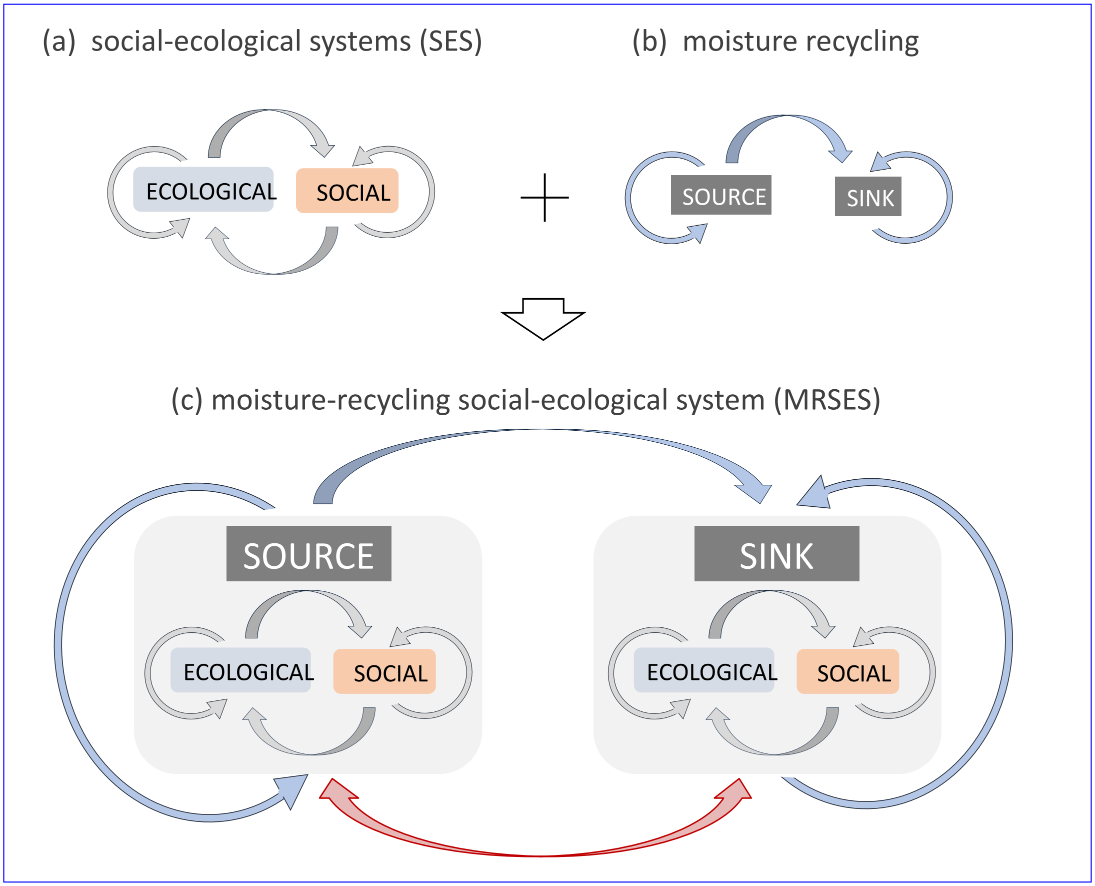


**Figure 1.** Conceptual construction of moisture recycling social ecological system (MRSES) archetypes. A hypothetical, idealized social-ecological system (a) is nested within the idealized moisture recycling system (b), creating a linked moisture recycling social-ecological system (c). The red arrow at the bottom of (c) emphasizes the fact that the social aspects of a MRSES are what link the precipitation sink back to its evaporation sources. The arrow points in both directions, since social links are not restricted by biophysical constraints.

social dynamics, we select countries as our unit of analysis, rather than hydrological units (e.g. basins) or biophysical units (e.g. specific landscapes).

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~~ comparable 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 precipitationshed; (c) ~~several proxies for ecosystem-related human well-being~~a quantitative comparison of social dynamics in sources and sinks; and, (d) a qualitative literature review of the types of social ~~connections~~ dynamics 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. We emphasize that the WAM-2layers is a moisture tracking scheme, and not a simulation. It is possible to couple the WAM-2layers with dynamic simulations of land-surface hydrology, including vegetation (Wang-Erlandsson et al., 2016; Keys et al., 2016), but that is not what we have done in this research. Thus, the results that we present are purely based on the implicit hydrological information contained within the ERA-Interim Reanalysis data.

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~~ social dynamics among the precipitation sink ~~to the~~ and its sources of evaporation. ~~The results of the precipitationshed analysis are visible in Fig ??.~~

### 2.3 Quantifying social features of the precipitationshed

One approach to capturing the social ~~attributes~~ dynamics of moisture recycling is to ~~create a snapshot of the~~ characterize 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 (?), 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 ‘~~are biophysically-relevant ~~’ social datasets,~~ and that can provide insight into the dynamics among the sources and sinks

**Table 2.** Summary of metadata for anthromes, child malnutrition, and market influence data.

| VARIABLE NAME | DESCRIPTION | SOURCE RESOLUTION | UNITS | TIME PERIOD | SOURCE |
|---|---|---|---|---|---|
| Anthromes | Anthropogenic biomes, incl. type of human land-use and population density | 5 arc minute | [categories] | 2000 to 2005 | Ellis and Ramankutty, 2008 |
| Child malnutrition | The number of children under five years of age, who are malnourished, per 1000 children | sub-national or national | #/1000 | 2005 | SEDAC, Columbia U, |
| Market influence | Per capita GDP multiplied by market access (e.g. composite of travel distance, time, etc) | 5 arc minute | $/ person | 2010 (per cap GDP), 1979-2005 (market access) | Verburg et al., 2011 |

of moisture. ~~These data are:~~ In our analysis, we use land-use ~~types characterized using the~~ based on anthropogenic biomes data, i.e. ~~Anthromes~~ anthromes (Ellis and Ramankutty, 2008), food ~~sufficiency~~ security using the proxy of child malnutrition (Socioeconomic and Data Applications Center SEDAC, 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 datasetsis~~ market influence Verburg et al. (2011) (Table 2). The anthromes data are a land-use classification scheme explicitly developed to account for both the various human uses of landscapes and density of human populations. For example, rather than having land-use categories that are uniformly 'cropland', the anthromes data range from densely populated 'Rice villages' (>100 people per $km^2$), to sparsely inhabited 'Remote croplands' (<1 person per $km^2$).

The child malnutrition data represent the number of malnourished children per thousand under the age of five years, and is available at the scale of countries (e.g. Russia has a single value), as well as sub-national (e.g. Sudan has may different values). The market influence data is a calculated from a variety of other datasets, and is a combination of (1) access to markets (calculated using data on infrastructure, travel distance, and travel costs to major cities), and (2) per capita GDP (for more on calculation, see (Verburg et al., 2011)). As seen in Table 2, these datasets are spatially-gridded, at various resolutions. We interpolated the various data to the ~~coarsest grid resolution~~ resolution of the moisture recycling information (i.e. 1.5 deg. by 1.5 deg.) 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 ??.~~

Note, the 'source' results (presented in the social characteristics figures, Figs 2-4), refer to the sources of precipitation excluding the sink itself. In other words, despite the presence of internal moisture recycling, the description of source characteristics do not include the case study country itself.

### 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~~ case study 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~~ , economic interlinkages) that quantitative analysis 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~~ For each case study, the general approach was to use the ~~precipitationsheds as spatial boundaries and to reveal the land-uses within the footprints. Then,~~ precipitationshed as the spatial boundary within which we evaluated the dominant processes governing ~~those land-uses~~ land-use change and the types of ~~connections between~~ dynamics among 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~~these social dynamics. 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.~~ coherent representation of the social dynamics of moisture recycling for each case study.

### 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.~~

~~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.~~

~~List of countries that provide moisture to each nation, with fraction of total annual precipitation provided indicated. Russia 29% China 13% Mongolia 13% Kazakhstan 9% Other land 15% Niger 9% Chad 6% Nigeria 6% Sudan 5% Democratic Republic of the Congo 2% South Sudan 2% Central African Republic 2% Other land 27% Brazil 28% Bolivia 18% Peru 7% Argentina 2% Other land 7%~~

## 3 ~~Results and Discussion~~

### 2.1 ~~Sources of precipitation~~

~~Precipitation in~~ We distilled the insights from the three case ~~study countries - Mongolia, Niger, and Bolivia - comes from predominantly terrestrial sources, as shown in Fig ?? and Table ??. 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 (?Badger and Dirmeyer, 2015; ?; Keys et al., 2016)~~studies into the creation of several MRSES archetypes. The conceptual model presented in Fig 1 formed the basis of the MRSES, and was infused and modified using the case studies.

## 3 Results

### 3.1 Mongolia case study

#### 3.1.1 Precipitationshed analysis

In Mongolia, the precipitation source is located in the northern half of the country and along its north-western border ~~.~~ (Fig 2a). Mongolia provides about 13% of its own precipitation largely from the northwestern half of the country. Aggregated over space (~~Table ??~~Fig 2b), the largest moisture contributor of Mongolia's precipitation is Russia (~~Fig ??a). In Niger, the precipitation source is concentrated along the southern border (Fig. ??b), with a moisture supply plume fading towards the south. Niger supplies just~~ 29%), primarily due to the very large spatial extent of Russia. The only large evaporation contributions originate in the Russian steppe between Kazakhstan and Lake Baikal, and the rest are very small amounts across much of the Russian land surface. The same is generally true of China (13%), with significant contributions from the Tian Shan mountains to Mongolia's west, and small contributions from the rest of China's land surface. The eastern tip of Kazakhstan is also a key evaporation source region (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.~~ %), with smaller contributions from the rest of central Asia.

~~In Bolivia, the source of the precipitation is distributed across the country, with a slight concentration in the north (Fig. ??c). 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, Socioeconomic and Data Applications C~~
~~, 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)).~~

#### 3.1.1 ~~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~~

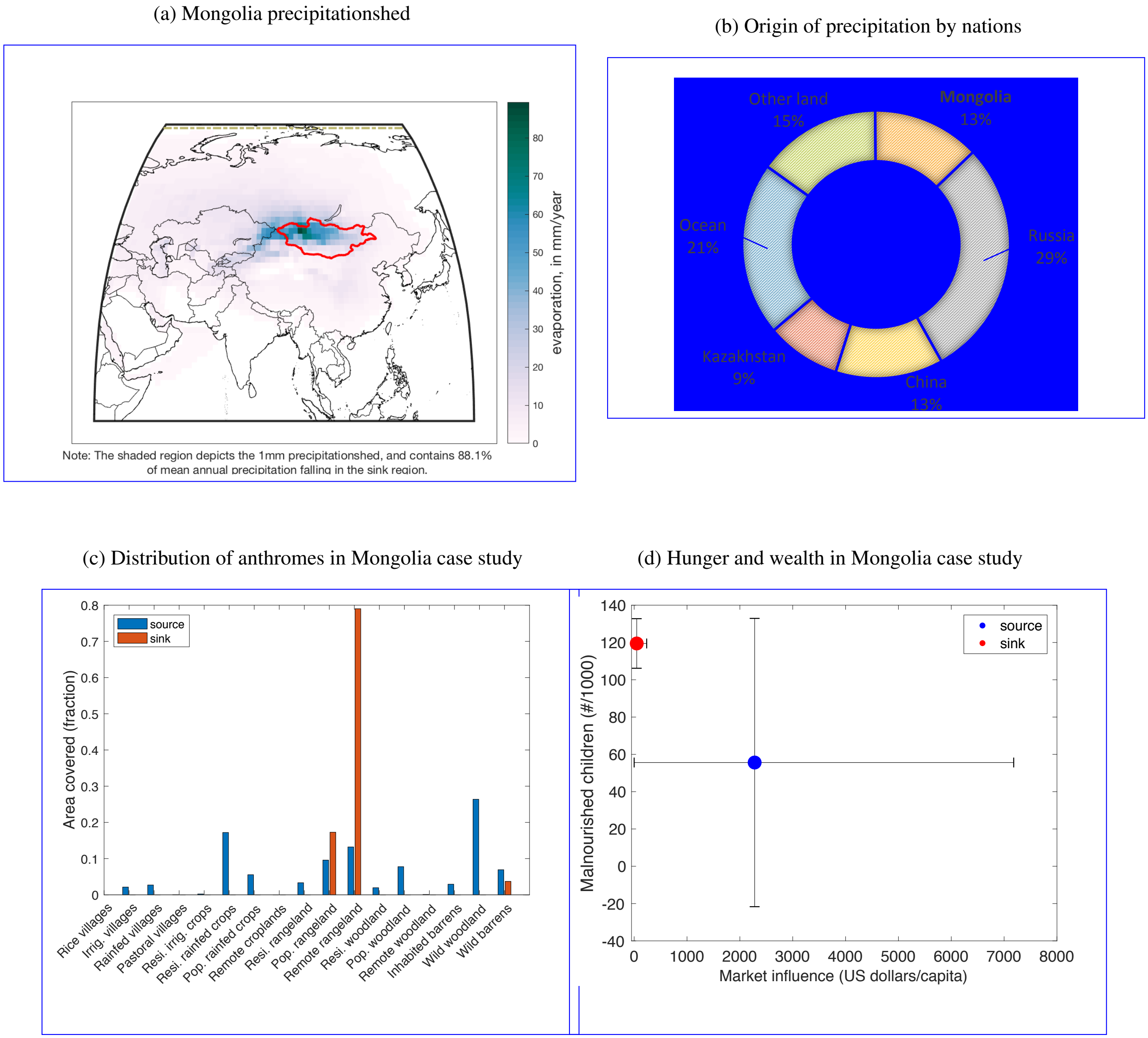


**Figure 2.** ~~Human well-being indicators and moisture recycling for the~~ Mongolia case study including (a) ~~Mongolia~~precipitationshed analysis, (b) ~~Niger~~key source countries, ~~and~~ (c) ~~Bolivia cases. The open circles indicate evaporation sources for the sink region~~ comparison of land-uses between country and precipitationsheds, and (~~indicated by enclosed circles~~d) ~~. The color~~ comparison of ~~the circles indicates the dominant anthropogenic biome,~~ economic and ~~the position on the graph indicates both the relative wealth and the fraction~~ food security aspects of ~~malnourished children per thousand of the different evaporation sources (note the log scale on both the x~~ country and ~~y axes)~~source regions.

#### 3.1.1 Social characteristics

Mongolia is predominantly classified as remote rangeland ( 80%) with some populated rangelands and wild barren land (Fig 2c). Mongolian society is generally quite poor (mean market influence of $48.40 per capita), with relatively high child malnutrition (around 12% or 120 in 1000 kids) (Fig 2d). Most of Mongolia's evaporation key sources are 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.~~ woodlands. The societies in Mongolia's source regions are on average richer (market influence of $2,279.50), and experiencing less hunger (5.6%).

#### 3.1.2 ~~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).~~

#### 3.1.2 ~~Bolivia case~~

~~In Bolivia, we see a pattern that is less clear, compared to Mongoliaand 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.~~

~~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.~~

### 3.2 ~~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 **??**). 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.~~

### 3.2 ~~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.~~

### 3.1.1 ~~Mongolia case~~Literature-review of social dynamics

Mongolia's precipitationshed includes significant contributions from ~~local~~ internal 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~~ led 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)~~(Robinson et al., 2003). This change in grazing pressure has ~~lead~~ led to replacing of previously grazed land with other grasses and weedy species during fallow periods, and importantly has ~~lead~~ led to detectable changes in vegetation and associated changes in near-surface meteorology (De Beurs and Henebry, 2004). 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.

## 3.2 Niger case study

### 3.2.1 Precipitationshed analysis

In Niger, the precipitation source is concentrated along the southern border (Fig. 3), 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 other moisture suppliers. There is significant contribution from Nigeria to the South (6%), and Chad (6%) and Sudan (5%) to the east. There is some contribution from coming from the Democratic Republic of the Congo, the Central African Republic, and South Sudan (all 2%). Beyond that, there is diffuse contribution from some West African countries, as well as the Mediterranean.

### 3.2.2 Social characteristics

Land-use in Niger is predominantly "wild barrens", given that much of its land surface is in the Sahara. Among the populated anthromes, Niger is equally distributed among rainfed croplands, rangelands, and inhabited (i.e. very low population density) barren lands. Residential rainfed crops are a dominant anthrome type among Niger's moisture sources, along with some rangelands and woodlands. Niger's hunger and wealth characteristics are different from its source countries with the mean values of $49.20 per capita market influence, and 40.2% child malnutrition, barely within the standard deviation of the societies in its evaporation sources. The average market influence among Niger's sources is $4,081, with a very wide standard deviation ranging from nearly $0 to more than $11,000. Likewise, the mean child malnutrition is 23.8% with a standard deviation from a high of 40% to a low of around 7.5%.

### 3.2.3 Literature-review of social dynamics

Niger ~~caseNiger~~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~~ 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~~. 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~~ led 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

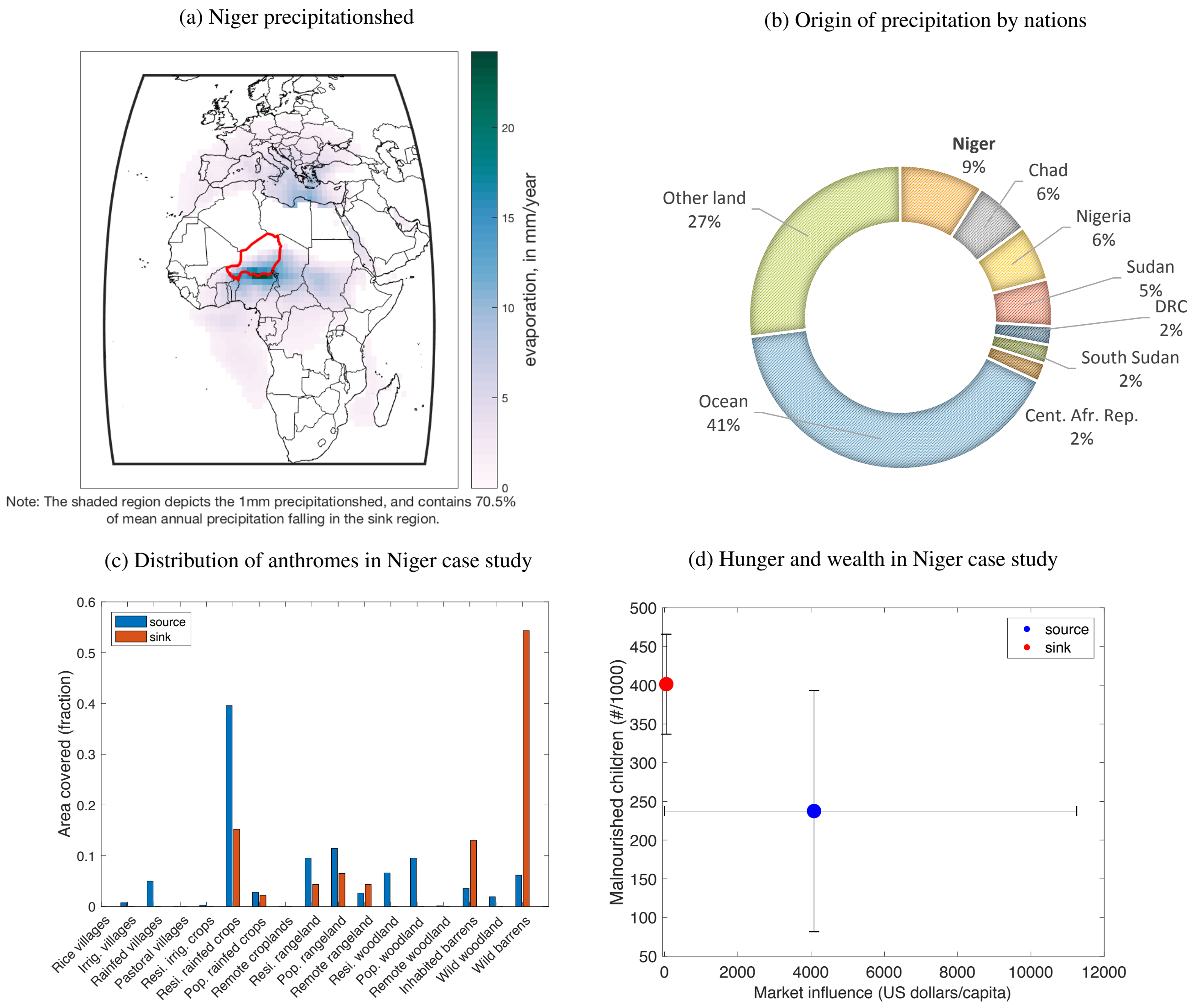


**Figure 3.** Niger case study including (a) precipitationshed analysis, (b) key source countries, (c) comparison of land-uses between country and precipitationsheds, and (d) comparison of economic and food security aspects of country and source regions.

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 (Damilola, 2017). 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 potential 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~~ led to over-grazing, and inadequate management has ~~lead~~ led 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).

Niger's primary trading partners are France, Thailand, Malaysia, and China, with Nigeria as the only notable regional trade partner. France is the destination and origin of greater than 30% of both exports and imports. Regionally, Nigeria is the destination of 9.5% of Niger's total export volume, primarily in the form of refined petroleum. Similarly, Niger receives about 5.8% of its total imports from Nigeria, primarily in the form of cement, electricity, and tobacco. Niger, however, represents a tiny trade partner for Nigeria, providing only 0.25% of Nigerian imports, and 0.18% of Nigerian exports. Beyond this, Chad and Sudan are very poorly integrated in terms of total trade volume with Niger and Nigeria. Thus, the countries in this region appear to be much more economically tied to countries outside the region, than within the region. Overall, this suggests limited regional economic integration.

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.

## 3.3 Bolivia case study

### 3.3.1 ~~Bolivia caseBolivia's precipitationshed includes~~ Precipitationshed analysis

In Bolivia, the source of the precipitation is distributed across the country, with a slight concentration in the north (Fig. 4). 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 in the Acre region, and to a low concentration of moisture supply covering Brazil's entire domain. The Peruvian Amazon is also an important contributor, as is the extreme north of Argentina.

### 3.3.2 Social characteristics

Bolivia's anthromes are more than 50% rangelands, and a little more than 25% woodland, i.e. the Amazon. The key source areas are the Amazon in Brazil in Peru, but broadly speaking, Bolivia's precipitationshed includes a high fraction of rangelands (about 50%). Rainfed croplands comprise much of what remains (about 10%). Bolivia is characterized by relatively low child malnutrition (mean of 72%, with a standard deviation ranging from 5% to 10%), and market influence of $341, ranging from just above $0 to more than $800. This is not very wealthy compared to some regions, but this is considerably better off than other region's chid malnutrition (especially the Niger case study). Bolivia's sources of moisture are characterized by societies with higher mean malnutrition (14%) and higher wealth ($506), though the standard deviation exceeds all of Bolivia's values. This means that in terms of the standard deviation, Bolivia's social characteristics are well-within the range of the societies in its precipitationshed.

### 3.3.3 Literature-review of social dynamics

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~~ and 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~~ led 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

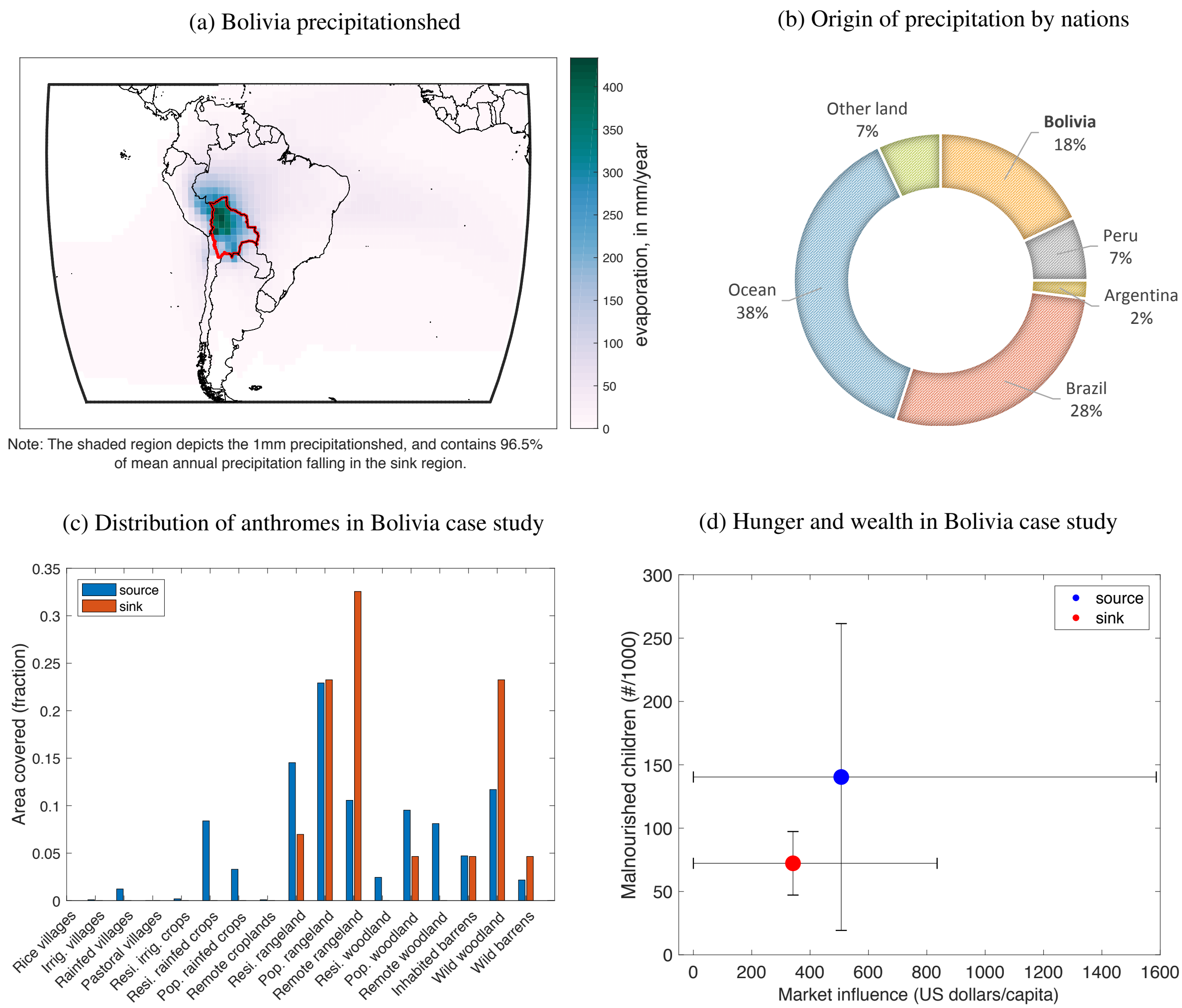


**Figure 4.** Bolivia case study including (a) precipitationshed analysis, (b) key source countries, (c) comparison of land-uses between country and precipitationsheds, and (d) comparison of economic and food security aspects of country and source regions.

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~~ led to contentious claims of ownership (Finer et al., 2008; Killeen et al., 2008).

~~Likewise~~Additionally, 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~~paper. However, ~~much of the deforestation is taking place on private land, primarily being converted to grazing land.~~ the regulatory environment is inconsistent, and the enforcement strongly depends on which political party is in power (Hurrell, 1991). According to Brazil's Forest Code~~requires that~~, the central policy regulating deforestation, land-owners are required to 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~~ quite 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.~~ under considerable existing deforestation pressure (Kainer et al., 2003). Notably, there is a stark contrast between existing deforestation patterns in Brazil (especially in Acre and Rondonia states), relative to deforestation in Bolivia and Peru. Also, deforestation in Brazil is rising again, after years of successful implementation of anti-deforestation policy.

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 actual land-use ~~is relatively well-governed with~~ management exhibits a wide range of effectiveness, despite many controls in place to avoid large-scale change. ~~However, land-use~~ 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~~.~~, due to management decisions in an adjacent country. In addition to historic trends in land-use change, recent evidence suggests a large shift is taking place in Amazonian deforestation away from Brazil to Bolivia and Peru. This is driven by several factors, including the opening up of Peru's interior via new transport networks, the moratorium on soya cultivation in Brazil, and previous deforestation estimates not accounting for small-scale and artisanal deforestation (Kalamandeen et al., 2018).

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 internal social coupling, as well as global tele-coupling.

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

### 3.4 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 is an isolated dynamic~~: (1) an isolated system archetype, dominated by internal processes; ~~second, there is a regional dynamic~~ (2) a regional archetype linking adjacent countries~~and diffuse connectivity~~; and, ~~third, there is~~ (3) a tele-coupled ~~dynamic~~ aechetype that links precipitation sink regions with regions outside the precipitationshed boundaries.

#### 3.4.1 ~~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'~~ each 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~~water resources

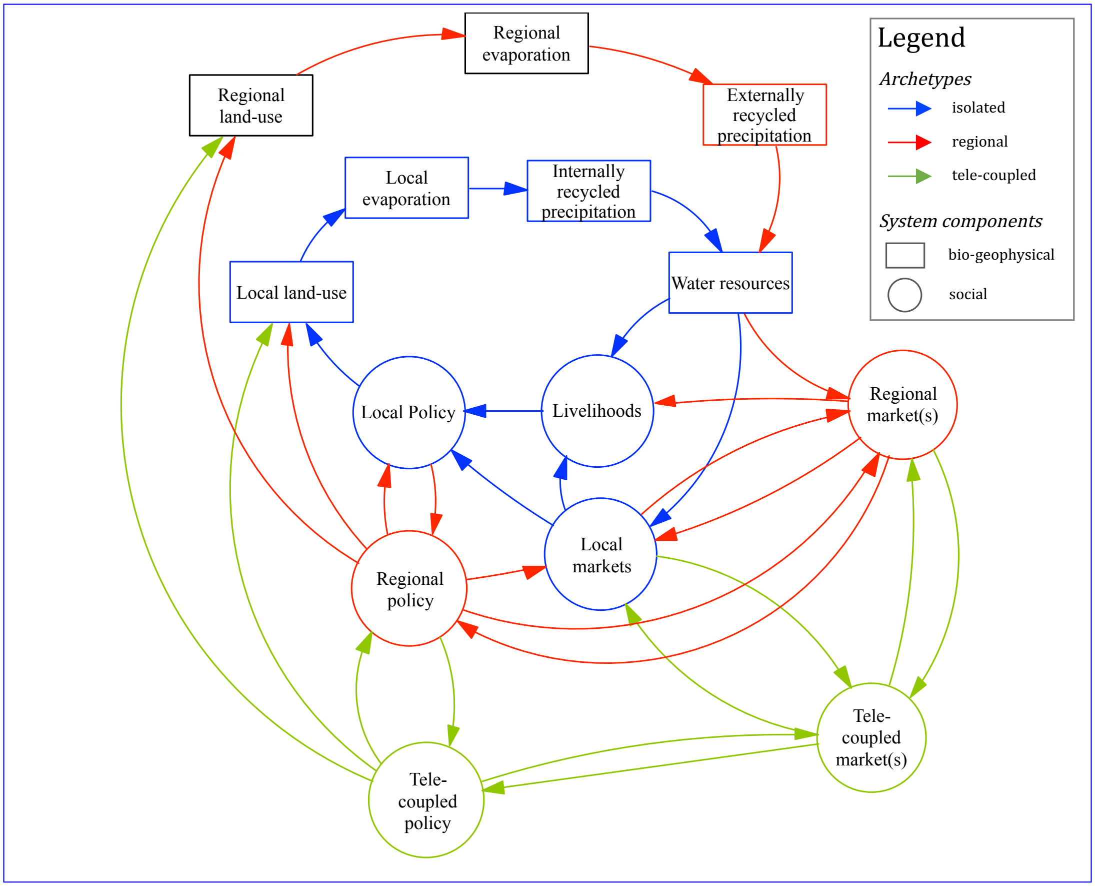


**Figure 5.** Archetypes of moisture recycling social ecological system (MRSES), with blue corresponding to 'Isolated', red to 'Regional', and green to 'Tele-coupled'.

to local livelihoods, 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 isolatedsystems also exist at sub-national levels, but in our analysis we evaluate national-scale precipitationsheds, and look at feedbacks at that social level.~~

#### 3.4.1 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. 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 large contributions from China and Russia 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.

#### 3.4.2 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 actorsthat can influence and interact with the social dimensions of the central~~ now connected to regional actors, since regional land-use changes affect moisture recycling, and the subsequent social aspectxs of the core 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~~ interactions with regional markets, land management, and policy. Specifically, regional and sub-regional actors have feedbacks among themselves and with ‘local’ ~~well-being~~livelihoods, markets, and policy nodes.

#### 3.4.3 Tele-coupled archetype

The third MRSES is ‘tele-coupled’, and this structure draws attention to the spatially disconnected, i.e. tele-coupled, actors that can influence the social connections in ~~either the centralfeedback loop, or the regional~~the central, regional, or tele-coupled feedbacks. Bolivia, which relies on rainfall ~~and~~ from Brazil for nearly half its rainfall would seem to be a ‘regional’ archetype, were it not for the dense connections to global forest conservation, deforestation driven by developed nations, and transnational agribusiness present in Bolivia, Peru, 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.

## 4 Discussion

### 4.1 ~~Guidelines for constructing~~ MRSES archetypes are idealized

~~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~~ Our analysis ends up with three archetypes that are idealized in structure and interaction. However, there are situations where certain aspects of the archetypes as they are represented may actually be at odds with one another. For example, in Fig 5 the policy nodes are uniformly going towards 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 ’~~. However, there is no distinguishing how Local policies might be at odds with Regional or Tele-coupled policy (e.g. local efforts to discourage deforestation could be hindered by national policies encouraging the settlement of rural forested areas). Additionally, there is greater uncertainty associated with the social nodes (Fig 5, circles) of the MRSES archetypes than with the bio or geophysical nodes (Fig 5, rectangles). This is partly because there has been much more study devoted to understanding the geophysics of moisture recycling, relative to the social dynamics of moisture recycling. Additionally, the agency of human individuals (and more broadly within societies) is a key component of the emergent complexity within MRSES.

The archetypes themselves are also idealized in that they are depicted as separate, distinct systems. Yet, in reality they are likely to exist along a spectrum from isolated to 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,~~. Thus, for example, in moving from isolated to regional, the MRSES might first integrate the regional moisture recycling components, and then begin incorporating regional markets, regional policy, etc. The spectrum of the MRSES from isolated to tele-coupled is not meant to convey any sort of desirability one way or another; each has benefits and disadvantages. For example, in an isolated case with intense contribution from nearby regions, there is a greater concentration of risk from accelerating feedbacks. Conversely, diffuse contribution suggests less risk from a single location, but concomitantly less ability to manage or influence land-use. In addition to this, our results may suggest that 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.

### 4.2 Advancing human-water systems understanding

The proposed MRSES framework offers a new conceptual lens to delineate system boundaries in regions where moisture recycling and human land-use decisions are substantial in comparison to other dynamics at play. This complements the various frameworks, theories, and mental models that has been developed for understanding human-water systems in terms of spatial scale, complexity of dynamics, and part of the water cycle considered (Fig 6).

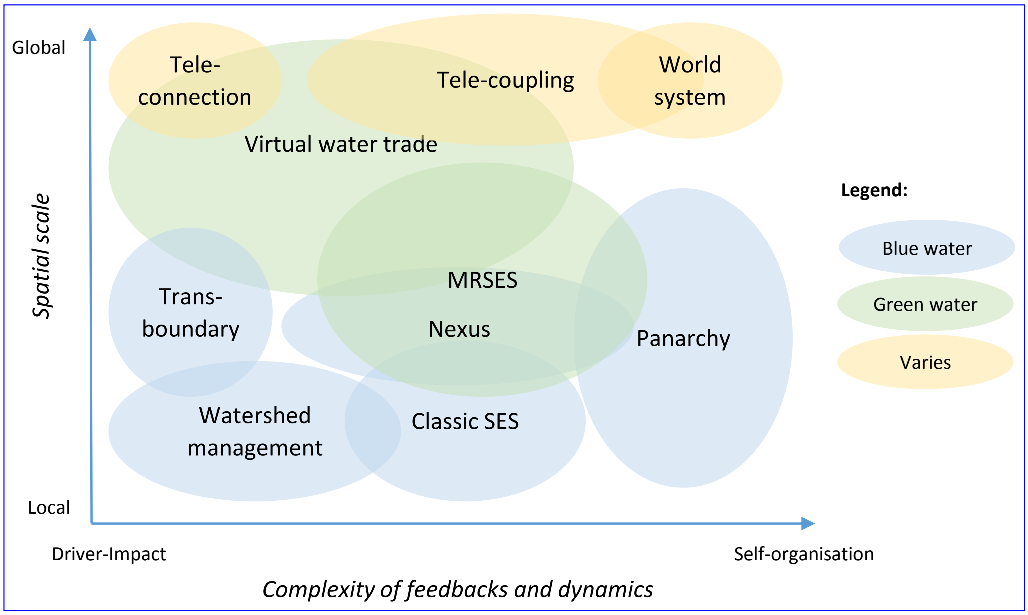


**Figure 6.** Concept of MRSES in relation to other concepts pertinent to human-water system research along the axes of spatial scale and feedback complexity considered, and in terms of water flows considered. Blue water refers to liquid water in rivers, lakes, and aquifers, whereas green water here refers to terrestrial evaporation and moisture flows.

As illustrated in Fig 6, some of the most important conceptual system boundaries considered in water management research include (increasing in scale and complexity): watershed (Giordano and Shah, 2014), transboundary river basin (Giordano and Shah, 2014), nexus approach to account for synergies across sectors (Endo et al., 2015), to concepts of water footprint and virtual water that account for the trade of embedded water (Allan, 1997). The classical SES concept (Holling, 2001; Folke et al., 2004; Folke, 2006) and panarchy (Gunderson and Holling, 2002) has typically considered social dynamics more profoundly, but also mainly been limited to blue water (i.e., river flows, groundwater, lakes) (Gunderson et al., 2017). This is similarly true of the socio-hydrology discipline, which tends to emphasize basin-scale analyses (Sivapalan et al., 2012; Pande and Sivapalan, 2015), albeit with sophisticated, systems-thinking approaches (Elshafei et al., 2016). In land system science, teleconnection has been used to describe remote drivers of land use change, and tele-coupling has been used to describe multidirectional feedbacks (Friis et al., 2016) of which water has been considered a link through e.g., virtual water and land acquisition (Johansson et al., 2016). Other holistic concepts include world system analyses (Gotts, 2007), system integration (Liu et al., 2015), and planetary boundaries (Rockström et al., 200 which while all-encompassing, tend to have a weak local to regional perspectives of operationally policy relevant human-water interactions.

Socio-hydrological analysis similar to Fig 6 has been completed (Pande and Sivapalan, 2015) with spatial scales of socio-hydrological analysis spanning basin to regional and global scales (though global scale analyses being somewhat more limited). However, it has thus far tended to be much more on the 'driver-impact' side of the x-axis in Fig 6, rather than the 'self-organization' side of the x-axis in Fig 6, though some authors suggest there is much to be learned from complex adaptive systems (Troy et al., 2015). Hydrosocial analysis, conversely, is also focused on basin-scale perspectives, but has its roots in critical geography and Marxist theory, and is much more oriented towards articulating social hierarchies that lead to power imbalances in decision-making and equality (Wesselink et al., 2017). Thus, hydrosocial analysis is more likely to occupy the right side of the x-axis in Fig 6, and to span local to global scales, with an emphasis on the ways that power imbalances at multiple scales produce inequality in human water interactions.

Thus, the MRSES concept, while lacking the cross-sectoral or holistic perspective in comparison to nexus or world system approaches, fills a conceptual gap by accounting for social feedbacks and atmospheric moisture flows at with consideration of local to regional scale socio-economic dynamics and policy processes. Potentially, MRSES could be woven into large-scale hydrological modeling or form part of a hydro-economic model, in addition to other human interference such as irrigation, inter-basin transfer, and virtual water (Wada et al., 2017). In especially moisture recycling intense regions, MRSES could also be considered for analyzing complex co-evolutionary systems, as distilled conceptualization can be useful for exploring such dynamics (Thompson et al., 2013).

### 4.3 Systems may be reinforced in unexpected ways

The MRSES archetypes ~~we propose~~ all exhibit some complexity, and also increase in complexity when moving from isolated to tele-coupled. ~~This increased complexity~~ 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. For example, a consequence of policy decisions to graze the Kazakh steppe and then abruptly abandon this grazing, was a change in moisture recycling dynamics, and likely the rain falling in Mongolia.

A notable feature is the role of tele-coupled, ~~spatially disconnected~~ spatially-disconnected actors for driving change in the precipitationshed. For example, the change in the spatial distribution of Amazonian deforestation, i.e. in Peru and Bolivia, is apparently driven by palm oil and soya cultivation in Peru and Bolivia (Kalamandeen et al., 2018). This is further emphasized in our discussion of ~~moisture recycling~~ soya-related deforestation in Brazil, ~~in the context of multiple, overlapping~~ and how international agri-business interests with regard to ~~livestock production and soya cultivation(Flach et al., 2016)~~soya cultivation, combined with Brazil's soya moratorium, are pressuring deforestation leakage into Bolivia (Flach et al., 2016; Kalamandeen et al., 2018).

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~~to commodity crop price fluctuations. 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).

### 4.4 Power must be considered carefully

Though ~~the analysis of environmental justice flows~~ our analysis of the relationship between moisture recycling, wealth and hunger has been simplified (~~Fig ??~~e.g. Fig 2d, 3d, 4d), we highlight a few key considerations with regard to power and equity in MRSES. First, in 'isolated' ~~systems~~ MRSES (e.g. Mongolia) there can still be a wide range of ~~well-being~~ social characteristics (e.g. ~~wide range in poverty~~ in wealth and malnutrition). The ability to influence land-use change policies that are impacting terrestrial moisture recycling ~~will~~ may be distributed similarly. Thus, ~~this imbalance in the ability of the human drivers and recipients of terrestrial moisture recyclingchange~~ inevitably, some groups of society will have more of an ability to influence land-use change and moisture recycling, while others may simply be impacted by these changes. This sort of imbalance in control and power over resources ought to be considered.

Second, as MRSES expand to include more than one country, the ~~power imbalances~~ potential for some parts of society within the MRSES to have more control over others may become more complex, and furthermore, the political power balance 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. This sort of relationship has been noted in other work as well, such as the ability for Chinese land-use decisions to impact North Korean precipitation (Wei et al., 2013).

Other work has suggested the importance of existing institutions for governing moisture recycling (Keys et al., 2017), but difficult questions ~~remain, such as~~ have yet to be answered, e.g. "who gets to change the rain?" ~~, and have yet to be answered. Finally, in~~ 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 furtherresearch in this area could build off of the work of **?** 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~~Transboundary water management, can offer useful lessons and warnings regarding tradeoffs among upstream and downstream users. For example, recent analysis of hydropower on the Mekong River has revealed major gaps in how upstream and downstream users are considered, particularly in terms of what is equitable (Grumbine et al., 2012). The study of water justice and governance is an active discipline (Neal et al. , 2014), and if MRSES are explored further, we hope that justice and equity form an integral part of that research. Hydrosocial analysis has much to offer in this regard, given its explicit "articulation of water and social power relations", and subsequently the impact that social power imbalances can have on decision-making, and “political and material inequity” (Wesselink et al., 2017). The ’power’ aspects of MRSES, and human water interactions in general, could be further improved by integration with the critical, power-oriented perspective of hydrosocial analysis.

### 4.5 ~~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~~their own scientific worldview. For example, natural scientists are nearly all ‘positivist’, meaning they assume that every meaningful assertion ought to be scientifically verifiable and provable logically, or mathematically. This is not the worldview of much of the social science community, let alone in the practitioner community or the broader public. An awareness of the diversity of scientific worldviews is critical for successfully addressing inherently value-based questions (i.e. normative questions). 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~~, potentially adds a matter for negotiation between the two countries, with all that entails, especially in terms of responsibility and power. Recognition of these implications is critical for natural scientists to become better interdisciplinary scholars, as well as responsible and conscientious members of society.

### 4.5 Limitations and Future Work

Evaporation can be or is actively changed through e.g., policies, cultural pressures, economic incentives, legal regimes, and treaties in the social systems, and limited by e.g., water availability, soil suitability, and energy limitation in the biophysical system. The type and nature of this ‘managed evaporation’ is important for understanding the entire policy and resource management space. Thus, future work could undoubtedly extend and perhaps substantiate social linkages by first identifying and quantifying managed evaporation within different administrative zones. Likewise, specific policies could be linked to these administrative zones, which could explicitly link legal, policy, and on-the-ground management efforts with particular flows of evaporation, and subsequently moisture recycling.

The analysis of moisture recycling relationships, market influence, and child malnutrition suggests a reasonable basis for exploring the social dynamics of moisture recycling more broadly. Existing work has examined the import and export of moisture among nations (Dirmeyer et al., 2009), and this work has presented an approach for developing an interdisciplinary understanding of the feedbacks within MRSES. Future work could explore the social dynamics of the specific countries with the lowest market influence and highest child malnutrition. This type of effort could align well wth research agendas targeting the Sustainable Development Goals (SDG), and specifically with efforts to link moisture recycling to SDG achievement (Keys and Falkenmark, 2018).

## 5 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 (MRSES). 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 (Socioeconomic and Data Applications Center SEDAC, 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.

*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.

## References


Allan, J. A.: ‘Virtual water’: a long term solution for water short Middle Eastern economies?, School of Oriental and African Studies, University of London London, 1997.

Badger, A. M. and Dirmeyer, P. A.: Climate response to Amazon forest replacement by heterogeneous crop cover, Hydrology and Earth System Sciences, 19, 4547, 2015.

Bagley, J. E., Desai, A. R., Dirmeyer, P. A., and Foley, J. A.: Effects of land cover change on moisture availability and potential crop yield in the world’s breadbaskets, Environ. Res. Lett., 7, 014 009, https://doi.org/10.1088/1748-9326/7/1/014009, 2012.

Benjaminsen, T. A., Holden, S., Lund, C., and Sjaastad, E.: Formalisation of land rights: Some empirical evidence from Mali, Niger and South Africa, Land use policy, 26, 28–35, 2009.

Budds, J. and Sultana, F.: Exploring political ecologies of water and development,Environ. Plan. D, 31, 2 5, 2013.

Socioeconomic and Data Applications Center SEDAC, C. U.: Poverty Mapping Project: Global Subnational Prevalence of Child Malnutrition, data retrieved from Socioeconomic Data and Applications Center (SEDAC), http://dx.doi.org/10.7927/H4K64G12, 2005.

Cosens, B. A. and Williams, M. K.: Resilience and water governance: adaptive governance in the Columbia River basin, Ecology and society, 17, 2012.

Damilola, A.: LandUse Act in Nigeria - Explained, https://www.tolet.com.ng/blog/land-use-act-in-nigeria-explained/, 2017.

De Beurs, K. M. and Henebry, G. M.: Land surface phenology, climatic variation, and institutional change: analyzing agricultural land cover change in Kazakhstan, Remote Sensing of Environment, 89, 497–509, 2004.

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., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kå llberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J. N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society, 137, 553–597, https://doi.org/10.1002/qj.828, 2011.

Descheemaeker, K., Amede, T., Haileslassie, A., and Bossio, D.: Analysis of gaps and possible interventions for improving water productivity in crop livestock systems of Ethiopia, Experimental Agriculture, 47, 21–38, 2011.

Dirmeyer, P. A. and Brubaker, K. L.: Contrasting evaporative moisture sources during the drought of 1988 and the flood of 1993, Journal of Geophysical Research D: Atmospheres, 104, 19 383–19 397, 1999.

Dirmeyer, P. A., Brubaker, K. L., and DelSole, T: Import and export of atmospheric water vapor between nations. Journal of hydrology, 365(1-2), 11-22. 2009

Dominguez, F., Kumar, P., Liang, X. Z., and Ting, M.: Impact of atmospheric moisture storage on precipitation recycling, Journal of Climate, 19, 1513–1530, https://doi.org/10.1175/JCLI3691.1, 2006.

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

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

Elshafei, Y., Tonts, M., Sivapalan, M., and Hipsey, M. R.: Sensitivity of emergent sociohydrologic dynamics to internal system properties and external sociopolitical actors: Implications for water management. Water Resources Research, 52, 6, 4944–4966, 2016.

Endo, A., Burnett, K., Orencio, P. M., Kumazawa, T., Wada, C. A., Ishii, A., Tsurita, I., and Taniguchi, M.: Methods of the water-energy-food nexus, Water, 7, 5806–5830, 2015.

Enfors, E.: Social - ecological traps and transformations in dryland agro-ecosystems. Using water system innovations to change the trajectory of development, Global Environmental Change, 23, 51–60, https://doi.org/10.1016/j.gloenvcha.2012.10.007, http://linkinghub.elsevier.com/retrieve/pii/S0959378012001203, 2013.

Finer, M., Jenkins, C. N., Pimm, S. L., Keane, B., and Ross, C.: Oil and gas projects in the western Amazon: threats to wilderness, biodiversity, and indigenous peoples, PloS one, 3, e2932, 2008.

Flach, R., Ran, Y., Godar, J., Karlberg, L., and Suavet, C.: Towards more spatially explicit assessments of virtual water flows: linking local water use and scarcity to global demand of Brazilian farming commodities, Environmental Research Letters, 11, 075 003, 2016.

Foley, J. A., Coe, M. T., Scheffer, M., and Wang, G.: Regime Shifts in the Sahara and Sahel: Interactions between Ecological and Climatic Systems in Northern Africa, Ecosystems, 6, 524–532, https://doi.org/10.1007/s10021-002-0227-0, http://www.springerlink.com/openURL.asp?genre=article&id=DOI:10.1007/s10021-002-0227-0, 2003.

Folke, C.: Resilience: The emergence of a perspective for social–ecological systems analyses, Global Environmental Change, 16, 253–267, https://doi.org/10.1016/j.gloenvcha.2006.04.002, http://linkinghub.elsevier.com/retrieve/pii/S0959378006000379, 2006.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., and Holling, C.: Regime Shifts, Resilience, and Biodiversity in Ecosystem Management, Annual Review of Ecology, Evolution, and Systematics, 35, 557–581, https://doi.org/10.1146/annurev.ecolsys.35.021103.105711, http://www.annualreviews.org/DOI/abs/10.1146/annurev.ecolsys.35.021103.105711, 2004.

Friis, C., Nielsen, J. Ø., Otero, I., Haberl, H., Niewöhner, J., and Hostert, P.: From teleconnection to telecoupling: taking stock of an emerging framework in land system science, Journal of Land Use Science, 11, 131–153, 2016.

Galaz, V., Gars, J., Moberg, F., Nykvist, B., and Repinski, C.: Why ecologists should care about financial markets, Trends in ecology & evolution, 30, 571–580, 2015.

Galaz, V., Tallberg, J., Boin, A., Ituarte-Lima, C., Hey, E., Olsson, P., and Westley, F.: Global Governance Dimensions of Globally Networked Risks: The State of the Art in Social Science Research, Risk, Hazards & Crisis in Public Policy, 8, 4–27, 2017.

Giordano, M. and Shah, T.: From IWRM back to integrated water resources management, International Journal of Water Resources Development, 30, 364–376, 2014.

Gordon, L. J., Steffen, W., Jönsson, B. F., Folke, C., Falkenmark, M., and Johannessen, A.: Human modification of global water vapor flows from the land surface, Proceedings of the National Academy of Sciences, 102, 7612–7617, https://doi.org/10.1073/pnas.0500208102, 2005.

Gotts, N. M.: Resilience, panarchy, and world-systems analysis, Ecology and Society, 12, 2007.

GRAIN: The great food robbery: how corporations control food, grab land and destroy the climate, Fahamu/Pambazuka, 2012.

Grumbine, R. E.,Dore,J.,Xu, Jianchu: Mekong hydropower: drivers of change and governance challenges, Frontiers in Ecology and the Environment,10(2),91–98,2012.

Gunderson, L., Cosens, B. A., Chaffin, B. C., Arnold, C. A., Fremier, A. K., Garmestani, A. S., Craig, R. K., Gosnell, H., Birge, H. E., Allen, C. R., et al.: Regime shifts and panarchies in regional scale social-ecological water systems, Ecology and Society, 22, 2017.

Gunderson, L. H. and Holling, C. S.: Panarchy: understanding transformations in systems of humans and nature, 2002.

Hansen, S.: Debt for nature swaps?overview and discussion of key issues, Ecological Economics, 1, 77–93, 1989.

Heistermann, M.: HESS Opinions: A planetary boundary on freshwater use is misleading, Hydrology and earth system sciences, 21, 3455, 2017.

Hiernaux, P., Ayantunde, A., Kalilou, A., Mougin, E., Gérard, B., Baup, F., Grippa, M., and Djaby, B.: Trends in productivity of crops, fallow and rangelands in Southwest Niger: Impact of land use, management and variable rainfall, Journal of Hydrology, 375, 65–77, 2009.

Holling, C. S.: Understanding the Complexity of Economic, Ecological, and Social Systems, Ecosystems, 4, 390–405, https://doi.org/10.1007/s10021-001-0101-5, http://link.springer.com/10.1007/s10021-001-0101-5, 2001.

Hurrell, A.: The politics of Amazonian deforestation. Journal of Latin American Studies, 23(1), 197-215. 1991.

Jargalsaikhan, M.: Mongolia's domestic politics complicate foreign policy in a precarious international setting, Tech. Rep. Asia Pacific Bulletin, No. 399, Washington, DC: East-West Center, https://www.eastwestcenter.org/system/tdf/private/apb399.pdf?file=1&type=node&id=36311, 2017.

Johansson, E. L., Fader, M., Seaquist, J. W., and Nicholas, K. A.: Green and blue water demand from large-scale land acquisitions in Africa, Proceedings of the National Academy of Sciences, 113, 11 471–11 476, 2016.

Kainer, K. A., Schmink, M., PINHEIRO LEITE, A. C., and da Silva Fadell, M. J.: Experiments in forest-based development in western Amazonia, Society & Natural Resources, 16, 869–886, 2003.

Kalamandeen, M., Gloor, E., Mitchard, E., Quincey, D., Ziv, G., Spracklen, D., Spracklen, B., Adami, M., Aragão, L. E., and Galbraith, D.: Pervasive Rise of Small-scale Deforestation in Amazonia, Scientific reports, 8, 1600, 2018.

Kendy, E., Molden, D. J., Steenhuis, T. S., Liu, C., and Wang, J.: Policies drain the North China Plain: Agricultural policy and groundwater depletion in Luancheng County, 1949-2000, vol. 71, IWMI, 2003.

Keys, P., Barron, J., and Lannerstad, M.: Releasing the pressure: water resource efficiencies and gains for ecosystem services, 2012.

Keys, P. W., Barnes, E. a., van der Ent, R. J., and Gordon, L. J.: Variability of moisture recycling using a precipitationshed framework, Hydrology and Earth System Sciences, 18, 3937–3950, https://doi.org/10.5194/hess-18-3937-2014, 2014.

Keys, P. W., Wang-Erlandsson, L., and Gordon, L. J.: Revealing invisible water: moisture recycling as an ecosystem service, PloS one, 11, e0151 993, 2016.

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

Keys, P. W., Wang-Erlandsson, L., and Gordon, L. J.: Megacity precipitationsheds reveal tele-connected water security challenges, PloS one, 13(3): e0194311. https://doi.org/10.1371/journal.pone.0194311, 2018.

Keys, P. W. and Falkenmark, M..: Green Water and African Sustainability. Food Security. In review.

Killeen, T., Guerra, A., Calzada, M., Correa, L., Calderon, V., Soria, L., Quezada, B., and Steininger, M.: Total historical land-use change in eastern Bolivia: Who, where, when, and how much?, Ecology and Society, 13, 2008.

Killeen, T. J., Calderon, V., Soria, L., Quezada, B., Steininger, M. K., Harper, G., Solórzano, L. A., and Tucker, C. J.: Thirty years of land-cover change in Bolivia, AMBIO: A journal of the Human Environment, 36, 600–606, 2007.

Koster, R., Jouzel, J., Suozzo, R., Russell, G., Broecker, W., Rind, D., and Eagleson, P.: Global sources of local precipitation as determined by the NASA/GISS GCM, Geophys. Res. Lett., 13, 121–124, 1986.

Lawrence, D. and Vandecar, K.: Effects of tropical deforestation on climate and agriculture, Nature Climate Change, 5, 27–36, 2015.

Lettau, H., Lettau, K., and Molion, L. C.: Amozonia's hydrological cycle and the role of atmospheric recycling in assessing deforestation effects, Monthly Weather Review, 107, 227–238, 1979.

Levin, S., Xepapadeas, T., Crépin, A.-S., Norberg, J., De Zeeuw, A., Folke, C., Hughes, T., Arrow, K., Barrett, S., Daily, G., et al.: Social-ecological systems as complex adaptive systems: modeling and policy implications, Environment and Development Economics, 18, 111–132, 2013.

Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K. C., Gleick, P., Kremen, C., et al.: Systems integration for global sustainability, Science, 347, 1258 832, 2015.

Lo, M. and Famiglietti, J. S.: Irrigation in California's Central Valley strengthens the southwestern U.S. water cycle, Geophysical Research Letters, 40, 301–306, https://doi.org/10.1002/grl.50108, 2013.

Malhi, Y., Adu-Bredu, S., Asare, R. A., Lewis, S. L., and Mayaux, P.: African rainforests: past, present and future, Phil. Trans. R. Soc. B, 368, 20120 312, 2013.

Meyfroidt, P., Schierhorn, F., Prishchepov, A. V., Müller, D., and Kuemmerle, T.: Drivers, constraints and trade-offs associated with recultivating abandoned cropland in Russia, Ukraine and Kazakhstan, Global Environmental Change, 37, 1–15, 2016.

Mortimore, M. J. and Tiffen, M.: Population Growth and a Sustainable Environment, Environment, 36, 16, 1994.

Nasi, R., Billand, A., and van Vliet, N.: Managing for timber and biodiversity in the Congo Basin, Forest Ecology and Management, 268, 103–111, 2012.

Neal, M. J., Lukasiewicz, A., Syme, G. J.: Why justice matters in water governance: some ideas for a ?water justice framework?. Water Policy, 16(S2), 1-18, 2012.

Ojima, D. and Chuluun, T.: Policy changes in Mongolia: implications for land use and landscapes, Fragmentation in semi-arid and arid landscapes, pp. 179–193, 2008.

Osabuohien, E. S.: Large-scale agricultural land investments and local institutions in Africa: The Nigerian case, Land Use Policy, 39, 155–165, 2014.

Ostrom, E.: A general framework for analyzing sustainability of social-ecological systems., Science (New York, N.Y.), 325, 419–22, https://doi.org/10.1126/science.1172133, 2009.

Pande, S. and Sivapalan, M.: Progress in socio-hydrology: a meta-analysis of challenges and opportunities,WIRES: Water, 4, 4, 2017.

Perz, S. G., Aramburú, C., and Bremner, J.: Population, land use and deforestation in the Pan Amazon Basin: a comparison of Brazil, Bolivia, Colombia, Ecuador, Perú and Venezuela, Environment, development and sustainability, 7, 23–49, 2005.

Priess, J. A., Schweitzer, C., Wimmer, F., Batkhishig, O., and Mimler, M.: The consequences of land-use change and water demands in Central Mongolia, Land Use Policy, 28, 4–10, 2011.

Robinson, S., Milner-Gulland, E., and Alimaev, I.: Rangeland degradation in Kazakhstan during the Soviet era: re-examining the evidence, Journal of Arid Environments, 53, 419–439, 2003.

Rockström, J., Barron, J., and Fox, P.: Rainwater management for increased productivity among small-holder farmers in drought prone environments, Physics and Chemistry of the Earth, 27, 949–959, 2002.

Rockström, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., and Gerten, D.: Future water availability for global food production: The potential of green water for increasing resilience to global change, Water Resour. Res., 45, W00A12, https://doi.org/10.1029/2007WR006767, 2009.

Rockström, J., Falkenmark, M., Lannerstad, M., and Karlberg, L.: The planetary water drama: Dual task of feeding humanity and curbing climate change, Geophysical Research Letters, 39, 2012.

Roncoli, C., Ingram, K., and Kirshen, P.: Reading the rains: local knowledge and rainfall forecasting in Burkina Faso, Society &Natural Resources, 15, 409–427, 2002.

Salih, A. A. M., Körnich, H., and Tjernström, M.: Climate impact of deforestation over South Sudan in a regional climate model, Int. J. Climatol., 33, 2362–2375, https://doi.org/10.1002/joc.3586, 2013.

Saruchera, D. and Lautze, J.: Measuring transboundary water cooperation: learning from the past to inform the sustainable development goals, vol. 168, International Water Management Institute (IWMI), 2015.

Savenije, H. H. G.: New definitions for moisture recycling and the relationship with land-use changes in the Sahel, Journal of Hydrology, 167, 57–78, 1995.

Simoes, A. and Hidalgo, C.: The Economic Complexity Observatory: An Analytical Tool for Understanding the Dynamics of Economic Development, https://atlas.media.mit.edu/en/, 2011.

Sivapalan, M., Savenije, H. H., and Blöschl, G.: Socio-hydrology: A new science of people and water, Hydrological Processes, 26, 1270–1276, 2012.

Spracklen, D. and Garcia-Carreras, L.: The impact of Amazonian deforestation on Amazon basin rainfall, Geophysical Research Letters, 42, 9546–9552, https://doi.org/10.1002/2015GL066063, 2015.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., de Wit, C. A., et al.: Planetary boundaries: Guiding human development on a changing planet, Science, 347, 1259 855, 2015.

Thompson, S., Sivapalan, M., Harman, C., Srinivasan, V., Hipsey, M., Reed, P., Montanari, A., and Blöschl, G.: Developing predictive insight into changing water systems: use-inspired hydrologic science for the Anthropocene, Hydrology and Earth System Sciences, 17, 5013–5039, 2013.

Toulmin, C.: Securing land and property rights in sub-Saharan Africa: the role of local institutions, Land use policy, 26, 10–19, 2009.

Troy, T. J., Konar, M., Srinivasan, V., and Thompson, S.: Moving sociohydrology forward: a synthesis across studies,Hydrology and Earth System Sciences, 19, 3667–3679, 2015.

Tschakert, P.: Views from the vulnerable: Understanding climatic and other stressors in the Sahel, Global Environmental Change, 17, 381–396, https://doi.org/10.1016/j.gloenvcha.2006.11.008, http://linkinghub.elsevier.com/retrieve/pii/S0959378006000938, 2007.

Tuinenburg, O. A., Hutjes, R. W. A., Stacke, T., Wiltshire, A., and Lucas-Picher, P.: Effects of Irrigation in India on the Atmospheric Water Budget, Journal of Hydrometeorology, 15, 1028–1050, https://doi.org/10.1175/JHM-D-13-078.1, 2014.

USAID: Country Profile: Chad, https://www.land-links.org/country-profile/chad/, 2010.

USAID: Country Profile: Sudan, https://www.land-links.org/country-profile/sudan/, 2013.

van der Ent, R. J., Savenije, H. H., Schaefli, B., and Steele-Dunne, S. C.: Origin and fate of atmospheric moisture over continents, Water Resour. Res., 46, W09 525, https://doi.org/10.1029/2010WR009127, 2010.

van der Ent, R. J., Tuinenburg, O. A., Knoche, H., Kunstmann, H., and Savenije, H. H. G.: Should we use a simple or complex model for moisture recycling and atmospheric moisture tracking?, Hydrology and Earth System Sciences, 17, 4869–4884, https://doi.org/10.5194/hess-17-4869-2013, 2013.

Verburg, P. H., Ellis, E. C., and Letourneau, A.: A global assessment of market accessibility and market influence for global environmental change studies, Environ. Res. Lett., 6, 034 019, https://doi.org/10.1088/1748-9326/6/3/034019, http://stacks.iop.org/1748-9326/6/i=3/a=034019?key=crossref.82c85047c68669fbf91200ddb8c980df, 2011.

Verweij, P., Schouten, M., Van Beukering, P., Triana, J., Van der Leeuw, K., and Hess, S.: Keeping the Amazon forests standing: a matter of values, 2009.

Wada, Y., Bierkens, M. F., De Roo, A., Dirmeyer, P. A., Famiglietti, J. S., Hanasaki, N., Konar, M., Liu, J., Schmied, H. M., Oki, T., et al.: Human–water interface in hydrological modelling: current status and future directions, Hydrology and Earth System Sciences, 21, 4169, 2017.

Wang-Erlandsson, L, Bastiaanssen, Wim GM, Senay, Gabriel B, van Dijk, Albert IJM, Guerschman, Juan P, Keys, Patrick W, Gordon, Line J, Savenije, Hubert HG: Global root zone storage capacity from satellite-based evaporation, Hydrology and Earth System Sciences, 20, 1459, 2016.

Walther, B. A.: A review of recent ecological changes in the Sahel, with particular reference to land-use change, plants, birds and mammals, African Journal of Ecology, 54, 268–280, 2016.

Wei, J., Dirmeyer, P. A., Wisser, D., Bosilovich, M. G., and Mocko, D. M.: Where Does the Irrigation Water Go? An Estimate of the Contribution of Irrigation to Precipitation Using MERRA, Journal of Hydrometeorology, 14, 275–289, https://doi.org/10.1175/JHM-D-12-079.1, 2013.

Wesselink, A., Kooy, M., and Warner, J.: Socio-hydrology and hydrosocial analysis: toward dialogues across disciplines: Socio-hydrology and hydrosocial analysis. WIREs Water, 4, 2, e1196, 2017.

Zalasiewicz, J., Waters, C. N., Williams, M., Barnosky, A. D., Cearreta, A., Crutzen, P., Ellis, E., Ellis, M. A., Fairchild, I. J., Grinevald, J., et al.: When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal, Quaternary International, 383, 196–203, 2015.

Zhou, T., Nijssen, B., Gao, H., and Lettenmaier, D. P.: The contribution of reservoirs to global land surface water storage variations, Journal of Hydrometeorology, 17, 309–325, 2016.