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Editorial

Deeper Engagement with Material and Non-Material Aspects of Water in Land System Science: An Introduction to the Special Issue

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Abstract: Water access and use impact land management decisions and livelihoods. Despite the integral role water plays in land systems, land system science (LSS) research often fails to explicitly incorporate water into analyses of socioecological systems (SES) resilience related to land. Nonetheless, water scarcity, especially in the face of climate change and resource degradation, is a pressing issue. Water availability is crucial to many ecosystem functions, from supporting biodiversity to mitigating extreme weather events such as flooding or drought. In this introduction to the "Water in Land System Science" Special Issue, we argue for deeper integration of land and water dynamics in LSS to increase SES resilience. First, we present an overview of the need for this integration, followed by a synopsis of the authored contributions in this Special Issue towards this goal. We then provide potential entry points researchers can use to foster this integration, exploring the following topics: water governance and hydrosocial territories, the cultural geographies of water, hydrophilia, water in agricultural transitions, remote sensing innovations, and participatory approaches to the study of the water component of land systems. We conclude that interactions between land, water, and people remain understudied, despite being more important than ever for ensuring future sustainability.

Keywords: water; land system science; material and non-material nature; socio-ecological systems; resilience

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1. Introduction

While ground and surface water are integral parts of land systems, stronger integration of land and water dynamics is needed for the development of a more robust Land System Science (LSS). Water access and use directly impact land managers and their livelihoods, especially agriculturalists. At the same time, water use has profound impacts on local biodiversity and riparian vegetation, including the health of watersheds and the proliferation of invasive and nuisance species. These dynamics, in turn, further impact land and resource managers.

The inclusion of water in LSS is timely, as water scarcity is increasingly a significant threat in much of the world [1]. The scarcity of natural resources (in general), in conjunction with climate change, exposes communities to more frequent and severe climate-related hazards [2]. Resource scarcity can lead to a decline in socioecological systems (SES) well-being, reduced ecological services, and increased health risks, exacerbating social, economic, and political dynamics. Conflict can arise within and between communities [3,4]. Urban and rural areas often compete for the same sparse resources. As a result, communities may become more vulnerable. For instance, a decrease in the ability to produce agricultural outputs due to scarce or degraded land and/or water resources poses a threat to (inter)national food security, as well as the social and economic underpinnings of rural communities, including local and community well-being and mental health [5–8]. Developing more holistic ways to conceptualize, systematically study, and support resilient SES is crucial for the adaptation, innovation, and mitigation necessary for long-term sustainability [9,10].

In this Special Issue, we argue that a deeper integration of land and water dynamics is needed in LSS. For the purposes of this article, we envision SES and LSS as overlapping yet distinct. In general, both LSS and SES frameworks focus on human–environment relationships, employ systems thinking, use mixed-methods approaches, are transdisciplinary and convergent in nature, and operate fluidly across porous borders. However, LSS and SES employ different approaches for understanding human–environment relationships. LSS research, rooted in land use and land cover change (LULCC), is more likely to incorporate geospatial technologies when analyzing environmental change [11]. SES research may or may not involve the use of geospatial technologies and is often centered in social science framings of LULCC [12]. Further, both SES and LSS engage with material and non-material nature in a distinct and overlapping range of ways. Overall, combining both SES and LSS models can make studies on human–environment systems more robust. To explore possibilities for deeper integration, first, we discuss why holistic water and land systems studies are needed for increasing SES resilience. Second, we explore the themes and lessons learned through the papers presented in this Special Issue. Third, we discuss five possible entry points for better integrating water and LSS. We conclude that incorporating water in both material and non-material ways into LSS is more important than ever.

2. Holistic Water and Land Systems Studies for Increasing Socioecological Systems (SES) Resilience

SES interact at different spatial and temporal scales, making their dynamics more difficult to untangle. Moreover, because climate change acts as a threat multiplier in SES, complex processes are even more difficult to discern [13–15]. Morton [16] argued that climate change is a "hyperobject" that is difficult to see and, therefore, difficult to address. For example, in many ecosystems, these threats include those to land (i.e., LULCC caused by the global/industrial agricultural complex), water (i.e., changing water dynamics, especially groundwater, due to intensive pumping for agriculture), and diverse peoples (such as those living and working in "middle America"). New holistic conceptualizations of complex and dynamic interactions between land, water, and people are needed to increase SES resilience in diverse communities. Many SES studies emphasize the causes of LULCC for system sustainability across time and space [17,18]. However, such studies often neglect the sheer complexity of water, seeing LULCC as a two-dimensional category on a static map.

Integrating the elements from both land and water systems, for example, considering interactions between water dynamics and LULCC, is a complex endeavor. Water is a critical resource in SES; it is vital for all living beings and crucial for food, fiber, shelter, energy, and cultural practices. The availability of water, whether it is surface water, vadose zone water, or groundwater, determines how societies use land and manage ecosystems. Likewise, the availability and quality of water regulate the services ecosystems can provide. Changes in these ecological services can impact SES [19]. Land management practices can have unintended consequences on water, including depletion and pollution [20].

Efforts to earnestly incorporate water into LSS are not new. Several researchers have argued that water needs a more integrated place in our conceptualization of land [21,22], emphasizing the direct effects and consequences of LULCC on water demands and hydrological processes, such as changes in water quality due to agriculture and urbanization. They also underline how the competition for water, along with its distribution, price, and policies, affect LULCC, and vice versa, as well as how LULCC affect the water cycle, supply, and quality [20]. Vadjunec and colleagues (eds) [23] combined water and land systems approaches to address SES resilience. They call for a more holistic and convergent approach, with a broad view of land, water, and people, including vegetation and soil dynamics [24], household livelihood, and community wellbeing [25]. Still, the holistic integration of land, water, and people into SES remains understudied.

2.1. Examples of SES Research and Water Dynamics

Many SES researchers incorporate water dynamics into their conceptual frameworks (e.g., [26–30]), especially those working on grassland and dryland studies involving agriculture [31,32]. The increased demand for food, fiber, and fuel associated with forecasted population growth will require increased agricultural outputs, which will require more water use [33–35]. Increased agricultural production may have negative environmental impacts, such as decreased water availability for other beneficial uses, water-quality impairment, aquifer drawdown, and habitat degradation [36–39]. Groundwater irrigation improves yields, livelihoods, economies, and short-term adaptation to climate variability, but groundwater is a diminishing resource [40–42]. Groundwater also plays a crucial role in global water circulation, weather patterns, soil moisture, and atmosphere moisture through evapotranspiration [40]. At the current levels of water demand, Smil [35] forecasts future water scarcity on a global scale.

Consequently, optimizing water availability is vital [43]. Researchers emphasize the importance of sustainable water management to prevent productivity decline and damage to local ecosystems [44–46], including changes in watersheds and runoffs [47–49]. Studies illustrate that water recharge may increase with the removal of woody vegetation but declines with woody plant encroachment [50,51]. Increases in water yields, though, do not always result in increases in soil water storage and can lead to soil erosion [52]. In particular, in grasslands, woody plant encroachment can lead to increases in net primary productivity but at an extreme cost, with increased concerns about water availability [53] and habitat loss [54,55]. Research on water availability also includes the food–water–energy nexus, which aims to help us understand the trade-offs needed for long-term sustainability [56–58]. Integrating sustainable water and land management remains difficult as it requires the cooperation of diverse fields of research, stakeholders, and governments across multiple temporal and spatial scales.

SES frameworks can help integrate these scales and model potential interactions [59,60]. For instance, Vadjunec et al. [61] address the challenges of managing land and water beyond formal political boundaries, exploring how these transboundary policies influence household decision-making processes, which, in turn, impact land and water use decisions. These impacts further guide policy changes, which are reflected as an iterative and dynamic cycle between land, water, and people [23].

2.2. Challenges for Integration

Integrating the diverse spatiotemporal scales associated with the complex dynamics of land, water, and people (including administrative and management structures) is challenging. Administrative scales comprise government boundaries, while institutional scales deal with laws and policies. Management scales encompass plans at local, regional, or higher levels; balancing the needs of different scales of governance can be a complex task [62]. The overlapping nature of water, for instance, complicates merging administrative, institutional, or management goals at different levels [62], making these various scales challenging to reconcile. Additionally, human and ecological temporal scales may vary; e.g., water issues require long-term policies that may not match short-term human goals [63]. This complexity challenges researchers to create holistic conceptual frameworks and methods for the creation of generalizable knowledge for developing resilient SES [64].

The effective management of natural resources requires the coordination of diverse stakeholders [40,65]. However, decision-making at the household level is influenced by various socioeconomic and policy factors that can impact outcomes [65]. Therefore, it is important to bring diverse stakeholders into the process of co-designing sustainable solutions [61,66,67]. Defries and Nagendra [68] (p. 1) argue that to increase resilience, we need "multisector decision-making, institutions that enable management to span across administrative boundaries, adaptive management, markets that incorporate natural capital, and collaborative processes to engage diverse stakeholders and address inequalities". For instance, groundwater, given its "invisible" nature and time scales, remains harder to integrate into SES approaches [61]. SES thinking generally employs conceptual and methodological models. The challenge is to co-design more holistic models that integrate local and external factors affecting SES, including diverse knowledge systems for fostering resilience [1,69]. Each paper in this Special Issue illustrates these challenges and possibilities differently.

3. The Papers

The papers in this volume illustrate the opportunities for better incorporating water into land system science. The research is largely empirical, drawing on qualitative, quantitative, and mixed methodologies. Key themes emerging from these papers are the importance of adopting the (historic) long view in understanding water, LULCC, and policy; seeing water features as a cultural artifact, as part of both a symbolic (non-material) and material landscape; and understanding land cover dynamics and surface runoff dynamics as part of a SES. Overall, these papers show us why LSS studies would benefit from more explicit engagement with water.

In "Lessons from the Archives: Understanding Historical Agricultural Change in the Southern Great Plains", geographers Carrasco Galvan and colleagues [65] showcase the benefits and methods of examining historical archives of complex interactions within the Southern Great Plains (SGP) to understand the current state of environmental resources and future LULCC. The authors use the Dust Bowl, a major socioecological disaster in the SGP in the 1930s, as a flash point to frame and analyze agricultural policy, changes related to land and water, technological advances, production trends, and community transformations before, during, and after the Dust Bowl [65]. As shown through a historical archival analysis, the permittance of poor policies led to unintended consequences, such as soil erosion, dust storms, and a reduction in ecological resources that damaged community livelihoods and future generations [65]. Governmental policy and agricultural communities' drought experiences transformed residents' perceptions of the environment in the SGP concerning rights to resources, control, and entitlement to their environment, leading to current production practices. Thus, past conditions and community experiences influence water and land trajectories and are necessary actors to consider when developing and supporting resilient SES. Contextual analysis frames ecological change alongside human impacts and deepens understandings of the complex feedback and tradeoffs within human–environment systems [61]. As the authors demonstrate, implementing policy in grassland agroecosystems comes with an interconnected web of considerations for the convergence of water and land resources in line with social systems across space and time.

In "Living by the Symbolic River: Landscape Effects of Post-Industrial Water Narratives of the Susquehanna River", geographer Ben Marsh [25] argues that LSS would benefit from the incorporation of a cultural landscape approach, which focuses on the continuous modification of the environment by humans, in dialectic understanding, and use by a culture or cultures, over time and space [70]. While cultural landscape studies share foci with LSS, the latter often overlooks the role of symbolic landscapes in land management decisions. Here, symbolic landscapes are "the structures of meaning and values that people-individually and as groups-use to understand the world and evaluate possible changes in it" [25] (p. 3). Focusing on a section of the Susquehanna River in Pennsylvania, Marsh describes the values, symbols, and narratives attached to the riverscape. Through the combined use of ethnographic methods and qualitative analysis, Marsh analyzes primary and secondary sources to gauge diverse opinions about the river based on lived experiences, thereby arriving at a deeper understanding of land and water management decisions. Beyond the environmental aspects of river management, this work illustrates how the values, symbols, and narratives, all entangled with human emotions, impact land management decisions and the material realities of riverscapes. This paper further illustrates that while ethnographic methods are rarely used alone in LSS, they are crucial for revealing a community's formal and informal governance practices [61] as well as the cultural connections to and understanding of place. By integrating cultural perspectives and land/river/people dynamics, Marsh provides a holistic, nuanced view of water as an inextricable component of LSS.

In "Response of Surface Runoff and Sediment to the Conversion of a Marginal Grassland to a Switchgrass (*Panicum virgatum*) Bioenergy Feedstock System", ecohydrologist Zou and colleagues [24] explore the relationships between land cover dynamics and surface runoff. Research shows that LULCC can alter runoff regimes, affecting surface and groundwater availability and other components of the hydrologic cycle, such as evapotranspiration [71] and infiltration rates [72,73]. Here, the authors demonstrate that the conversion of marginal grasslands impacted by woody plant encroachment (WPE) to switchgrass (*Panicum virgatum*) bioenergy feedstock can mitigate some of the adverse effects of WPE, such as reductions in groundwater recharge and annual runoff [74]. Zou and colleagues' research, while experimental, illustrates the critical linkages between land use decisions, land cover dynamics, and hydrological flows. Moreover, this research demonstrates the need for tighter linkages between the land and water components in LSS research. As climate change further drives both LULCC [75] and hydrological fluxes [76], understanding these dynamics, the critical linkages between them, and the ways of mitigating associated adverse effects becomes paramount.

4. Possible Entry Points for Better Integrating Water in Land System Science (LSS)

The papers presented in this volume emphasize how LSS might engage more fully with water in both cultural (non-material) and material (environmental) ways for SES resilience. Here, we expand on five possible entry points for better integrating water into LSS for SES resilience. These include water governance and hydrosocial territories, hydrophilia and the cultural geographies of water, water and agricultural transitions, remote sensing innovations for water, and participatory methods and informal education regarding land and water SES (Figure 1).

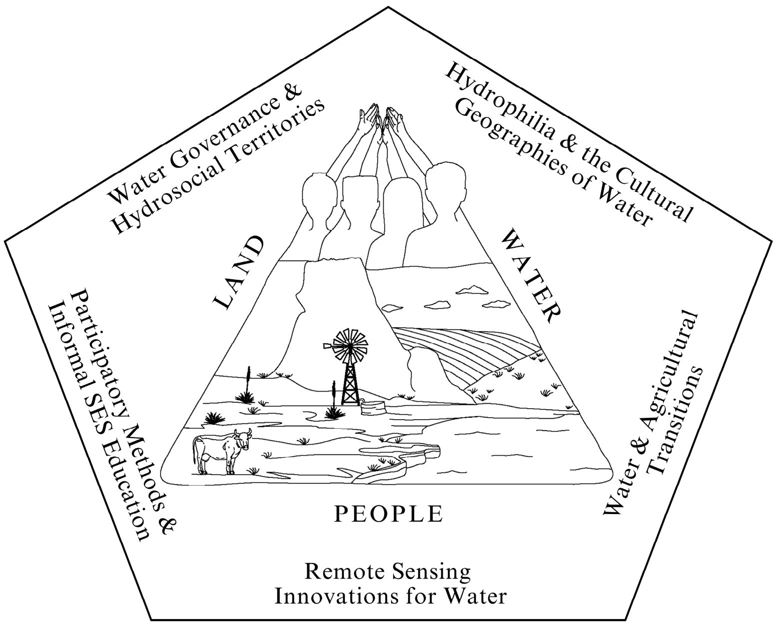

Figure 1. Possible entry points for integrating water into land system science. Figure made by the authors.

4.1. Water Governance and Hydrosocial Territories

Governance continues to be a major focus of SES research [20]. In LSS research, "human design" and governance aspects related to LULCC are associated with a robust tradition [77]. However, common and/or mixed property resources (CPRs) are often compounded by coupled common resources such as land *and* water (i.e., public lands such as state, federal, private, and Tribal *and* both surface and groundwater). Water is also a transboundary resource, making institutional arrangements more complex [63]. The proper management of CPRs has been controversial since Hardin [78] described the inevitable "Tragedy of the Commons", advocating for the enclosure and/or privatization of the commons. CPRs are hard to manage for two primary reasons [79]. First, they are subtractable in nature. For instance, depleted groundwater can take millennia to replenish and degraded land can have long-term impacts on soil and biodiversity. Second, the immensity of CPRs and their complex (often overlapping and transboundary) geographies make them difficult to manage [80]. This complexity also means that degradation is often not perceived until the resource passes a threshold resulting in dramatic loss. Researchers argue that these challenges make CPRs more susceptible to being open-access in nature, leading to inevitable resource degradation [78]. As a result, critics of commons resources press for leviathan, strong arm, privatization, or conservation approaches to natural resource governance [78,81–84].

In defense of the commons, CPR governance approaches have gained increasing popularity over the last 40 years through the work of Elinor Ostrom [85,86]. CPR approaches are "pro-people, equitable, low-cost, easily enforceable and adaptable to local cultures" and may be more appropriate in instances where property is "multidimensional, having both private and common property aspects" [87] (pp. 151–152). The complex geographical and interconnected nature of such natural resources also provides a strong reason to prevent the parceling of these resources into private ownership arrangements. Instead, pro-CPR advocates argue for "institutional arrangements for the cooperative (shared, joint, collective) use, management, and sometimes ownership of natural resources" [88] (p. 27). In the CPR literature, institutions refer not to entities themselves but 'rules in use' [89]: the "do's and don'ts" of CPR management [86]. Institutions can be formal (i.e., legal or policy governance) or informal (e.g., cultural norms or local customs). Researchers are increasingly stressing the importance of having both sound formal and informal governance structures for successful resource management [90]. In fact, past research illustrates that groundwater governance may be more impactful at the informal and local scales [42,91]. Resource governance remains a major priority of the Global Land Project [20] and represents an essential component of human design in SES thinking.

Water governance is further complicated by the legal geographies of land and water dynamics operating differentially across time and space [92] as well as their interaction and lag effects [93]. Political ecology also has much to offer in regard to contemplating water, especially water conflicts and identity in studies related to land [94] (see also the discussion below). For instance, Boelens and colleagues [95] (p. 1), add yet another layer of complexity to thinking about water systems as "hydrosocial territories: socially, naturally, and politically constituted spaces that are (re)created through the interactions amongst human practices, water flows, hydraulic technologies, biophysical elements socio-economic structures and cultural-political institutions". Wilson [96] (p. 1) argues that the role of "sociocultural relations is currently underacknowledged in the water governance literature". For instance, Indigenous peoples often see water as more than a resource to govern [97]. Instead, water, like land, also has spiritual, cultural, and historical significance and is often seen as an embodied being in its own right [98].

Formal governance, existing at county, state, and national scales, can affect peoples' attitudes and access to water resources. In the SGP, for instance, water governance is often more congruent for surface water but may be highly variable across scales when it comes to groundwater [60]. Likewise, formal and informal governance can serve to support farmers in adopting new practices, as long as they are perceived as valuable within the agricultural sector [99]. For instance, De Boon et al. [100] studied the relationship between the theoretical normative and perceived sociological legitimacy launched in England after Brexit. Additionally, intersectional identities including gender, race, ethnicity, and class play a role in hydrosocial territories [101,102]. Sultana [103] researched drinking water in Bangladesh and found that gender-related resource struggles could be observed in everyday interactions with water and water resource management. Power dynamics associated with intersectional identities were both formally governed, found in policy and regulation, and informally governed within cultural norms and practices [103]. Such studies provide valuable insights into the practical application of policies and the necessary changes required for their adoption and effectiveness in achieving sustainable outcomes. Consequently, there remains ample opportunity for integrating the complex bundled governance and hydrosocial aspects of land and water into LSS studies.

4.2. Hydrophilia and the Cultural Geographies of Water

Researching the convergence of both human and nonhumans in resilient SES (e.g., [104,105]) is difficult. In general, the majority of SES and LSS frameworks do not yet holistically integrate complex material and non-material (cultural) human–environment components, especially when water is added. Studying nonhumans alone remains difficult, yet it has been a topic of concern for decades [106]. However, an in-depth examination of the human dimensions of water should be conducted to avoid the "sociological black box" that skims the surface of human complexity that is attentive to the convoluted feedback systems within human–environment interactions [25] (p. 2). Humankind's relationships with water and land, or non-humans, can vary spatially and culturally and exist in both formal and informal spaces [107]. Thus, incorporating concepts and terminology from cultural geographies such as cultural landscapes, attitudes, identities, and *hydrophilia* in discussions of land systems contributes to a better understanding of the convergence of land and water resource systems in both material and non-material ways.

Cultural geographies and cultural landscapes can be employed to further understand the social qualities of water and land in conjunction with environmental systems. The aim in cultural geographies is to unveil the "diverse cultural meanings of nature, and the complex, multi-faceted role of nature in knowledge and practice" [108] (p. 362) and cultural landscapes to understand humans' complex, material interactions with natural systems and resources as being interconnected [70]. Waterscapes, i.e., cultural landscapes specific to water resources, are a "fleeting, dynamic, and transgressive", characteristic of human nature and uphold the "ontological question of what water is" that drives interactions with water [109] (p. 3). Consistent and attentive research on humans in non-human or natural systems becomes crucial for obtaining actionable insights and opportunities for community involvement.

As a key necessity for all life, water has a symbolic meaning that is reflected in human–water interactions within communities [25,99,107]. Water is closely linked with identity, as humans are largely composed of water, and presents an "essential similarity" that gives rise to "co-identification" with one's environment [110] (p. 160). The culture and identities attached to water can be seen as one of the many social actors or influences behind the use, control, and mitigation of water resources, factors that vary globally. Situating one's knowledge of water presents opportunities for the representation of community values and increases the longevity of solutions. For instance, many Indigenous origin and creation stories include water deities with related ceremonies to remain connected to the "sacredness of water" [97] (p. 2). People often materially situate themselves in the physical settings of their environment, which becomes part of their being or identity [109,110]. Thus, identities tied to nature can be strong community motivators for protecting and preserving natural resources that increasingly need attention in LSS.

Defining and understanding hydrophilia, while difficult, have been beneficial for uncovering people's strong attachments to water systems. Topophilia, or the "affective bond between people and place or setting", has a considerable influence in humans' interactions with natural systems [106] (p. 4). By extension, hydrophilia describes an attraction to water and can be a useful guide to unravel the reasonings behind humans' interactions with water. In Marsh's [25] research on the Susquehanna River's riverscape, people's past and current innate connections to water reflect their desire to protect their water resources. Including narratives pertaining to water resulted in a "highly functional element of community efforts" supporting the protection of natural resources and returning both agency and value to the community [25] (p. 17). Similarly, Wade and colleagues [111] (p. 20) researched the importance of waterscapes for people's well-being and quality of life in San Marcos, Texas, during the COVID-19 pandemic and found that waterscapes were an important outlet for communities to "mitigate negative mental health effects". Additionally, water bodies are highly valued socially, culturally, and environmentally and linked to overall human well-being [30].

People are emotionally bound or attached to their environment based on past experiences, a phenomenon termed place attachment, which can influence peoples' current and future interactions [65,112]. For instance, Tar Creek in northeastern Oklahoma was designated a U.S. Superfund site in 1983 due to high levels of lead and zinc contamination in water systems stemming from decades of mining operations in the Tri-State Region. However, communities remained in or close to the area despite expert health advice to leave because "they lived the experience" and had an attachment to the place as part of their identity [113] (p. 48). Persistent sinkholes and other environmental threats, however, including a devastating EF-4 tornado, eventually led to a complete buyout and relocation of residents of the community of Picher, OK (i.e., the center of the Tar Creek Superfund site) [114]. However, due to place attachment, most people moved to the surrounding area. Similar attitudes have long existed in the SGP, where the Dust Bowl survivors and generations after them feel inclined to stay in the area despite unfavorable environmental conditions (e.g., persistent, cyclic droughts), as resisting drought is deeply intertwined with their community and cultural identities [65,115].

The opposite can also be true where place attachment is weak and individuals feel a sense of disempowerment or that they have little agency over their environment compared to larger formal institutions [116], such as in Flint, Michigan [117], which experienced a water crisis after a state-appointed emergency manager switched drinking water sources without input from the community. In other cases, communities show little response or begin to "lose" their ability to recognize the deterioration of their environment as their attachments and connections to place are weakened in response to environmental disasters and associated consequences [118] (p. 98). In some cases, water users can be distrustful of the quality of their environments due to the negative view of the relationship between water systems and related institutions, which can further damage one's attachment or hydrophilia [110]. Therefore, institutions have a responsibility to foster cultural landscapes, identities, and attachments to place.

Further research on an area's cultural landscape can indicate opportunities for institutional intervention to remind communities of their influence on their environments. Reinstating and validating cultural identities and place (and water) attachments can be beneficial for the longevity of sustainable solutions to ecological change. As shown by Tilley and Comeron-Daum [112], hands-on volunteer work on heathlands was motivated by individuals' strong attachment to the area in question and fruitful for the environment as well as fostering cultural identities. By thoroughly understanding a cultural landscape and the actors within them, solutions that aid degrading natural resource systems can return agency to communities and increase the overall longevity of these solutions.

4.3. Water and Agricultural Transitions

The growing world population, coupled with higher living standards, is driving a demand for greater per capita agroecosystem services [35,119], inevitably leading to sustainability challenges. Furthermore, agroecosystems face numerous threats, such as climate-change-driven increases in drought duration and severity, diminishing surface and groundwater resources, and LULCC, all of which threaten food security and livelihoods. These threats are not mutually exclusive. Drier conditions, for instance, can lead to increased dependency on irrigation to sustain and expand production, leading to groundwater drawdown [23]. Currently, agriculture accounts for ~70% of human freshwater consumption worldwide [120], a value expected to increase. Additionally, other factors are driving the reliance on water for agriculture, namely, economics and government subsidies, both of which drive the production of water-intensive crops (e.g., corn), often in areas that cannot otherwise support such production [42]. Moreover, a boon in cash crops, such as hemp, may put extra pressure on dimensioning water supplies [121–124].

To address these challenges, stakeholders are reconsidering a transition that has the potential to promote rural development sustainably and equitably, benefiting both nature and community [125–127]. Currently, the farming population includes those deeply ensconced in conventional agriculture practices and producers adopting next-generation technologies, such as precision agriculture or climate-ready crops [128]. SES research based on conventional land and water governance regimes, LULCC dynamics, and other empirical evidence is needed to help foster place- and community-specific agroecosystem transitions [126,129]. Participatory approaches that help agrarian communities achieve sustainable land and water management objectives could be beneficial (see below). Such research could consider the implications of shifts in agricultural markets, such as cannabis production, as both commercial hemp and medicinal and recreational marijuana gain broader acceptance [121–124]. Similarly, SES research should consider transitions to climate-smart practices designed to increase agricultural efficiency predicated on near-term and mid-century climate projections.

Equally important is research focused on shifts in consumption. Consumer preferences are powerful drivers of animal and crop selection [130] that can slow agroecological transitions to sustainable practices (see zu Ermgassen et al. [131] and Galvan-Miyoshi et al. [132] for examples from the beef industry). Preferences for idealistic physical characteristics of food (e.g., color and shape) also hinder the transition because there is an almost nonexistent market for so-called "ugly food", leading to food waste [133] and promoting the use of pesticides and fertilizers to achieve market standards. Finally, both economic and political factors, such as price swings, governmental policies, shocks (for instance, the war in Ukraine), and investment returns, drive producers' decisions; therefore, research on these areas can guide the way to the agricultural transition [134,135]. It is incorrect, though, to consider these issues solely from an agroecosystems perspective. In 2007, urban populations exceeded those of rural populations for the first time in human history, an ongoing trend as the populations of rural areas continue to dwindle and urban areas continue to expand [136]. Urbanization has several key benefits, such as providing more economic, health, education, and cultural opportunities; on the other hand, urban areas are increasingly facing challenges related to limited land and water resources [137], inevitably leading to resource competition between urban and agriculture areas [138–140]. Population growth, urbanization, and rapid technological changes often result in the overexploitation of diminishing resources and, without proper management and planning, can lead to SES collapse [141].

The need for a transformative shift in agricultural practices is evident. The challenges posed by water scarcity, climate change, a decreasing farming population, and urbanization necessitate a comprehensive and inclusive approach to secure sustainable futures. The agricultural transition must be underpinned by agroecological principles, emphasizing productivity, environmental stewardship, and social equity. Collaborative and forward-thinking efforts considering the diverse impacts of gender, race, and historical context are crucial in ensuring an inclusive and just transition for all stakeholders. Furthermore, research on scenarios and exploring potential trade-offs to navigate the complexities of agricultural transitions at various scales should inform policy initiatives and pathways to achieve sustainability goals.

4.4. Remote Sensing Innovations for Water

Remote sensing has long been inextricably linked to the development of LSS, specifically in terms of documenting LULCC dynamics [11,66,142]. However, the role of remote sensing in analyzing the water component of land systems has largely been limited to quantifying changes in categorical land cover classes, e.g., water, lake, or stream [143]. Otherwise, remote sensing of the water component of the land system is largely indirect. For instance, remote sensing has been used to estimate the areal extent of and changes in irrigated agriculture [23,42], from which surface and groundwater usage can be inferred. Thus, remote sensing could benefit researchers by identifying crops on agricultural lands when estimating water use to better monitor our finite natural resources. Estimates of water use are important and provide an avenue for exploring linkages between LSS and biophysical processes related to water. Moreover, new and emerging remote sensing techniques, coupled with complex hydrologic models, are creating opportunities to estimate hydrological fluxes (such as evapotranspiration) from croplands using thermal and optical remote sensing bands [144]. Such estimations, in turn, provide producers and natural resource managers with information that can help foster better water resource use decisions.

There is an emerging interest in the linkages between LULCC and water quantity and quality (see Mashala et al. [145]). Time series analysis can document changes in freshwater resources [146], while advances in radar remote sensing are leading to accurate quantifications of changes in groundwater storage [147]. Such analysis becomes paramount as these resources become further stressed due to climate-change-related increases in water scarcity (e.g., surface and groundwater depletion) and water-related hazards (e.g., flooding or drought). The World Health Organization [148], for instance, estimated that two billion people worldwide currently lack access to safe, readily accessible drinking water. Coupled with increasing populations and greater demands on water resources for agriculture and industry, ~60% of the world's largest aquifers are shrinking [149]. Moreover, increased likelihoods of drought in semiarid agriculture regions, such as the U.S. Great Plains [150], further exacerbate these issues. Conversely, climate change may lead to increased flooding in some areas [151], and projected sea level rise can further impact freshwater resources through saltwater intrusion [152].

The challenges threatening SES are clear. Sustainable development will require the ability to quantify how LULCC dynamics are impacting water resources and how water stressors, ranging from drought to excess precipitation, are affecting land systems. Remote sensing and other geospatial technologies (e.g., GIS) can play an increasingly important role in the assessment of the land and water components of SES. In addition to optical sensors for the classification of land cover (including water), advances in active remote sensing, such as radar, LiDAR, and microwave technology (e.g., GRACE), are improving our ability to directly measure groundwater fluctuations [153]. Advances in GeoAI, such as deep learning algorithms, are improving our ability to detect irrigated agriculture over large areas [154]. Moreover, these tools can be integrated with other remote-sensing-based applications, such as the OpenET [144], to estimate evapotranspiration across agricultural systems. Lastly, emerging geospatial technologies, such as small unoccupied aerial systems, colloquially known as drones, ref. [155] can be used by both researchers and community members to gather high-resolution land and water data related to SES [156], though typically over much smaller areas than those addressed by traditional remote sensing platforms.

4.5. Participatory Methods and Informal Education in SES of Land and Water

One aspect of the land–water nexus not expressly addressed in this Special Issue is the incorporation of participatory and community-engaged research on SES. We maintain it is essential to involve the public in addressing these critical issues via on-the-ground, direct engagement. For instance, iterative, equitable, and just stakeholder involvement can lead to the co-production of policies and practices to achieve desirable, sustainable, and feasible outcomes at multiple scales, including the household, community, county, region, country, and even international scales [126]. Co-production is an iterative process that involves both researchers and stakeholders working together equally to address shared problems, resulting in "new knowledge and understandings of the world" [157] (p. 33). This process is inclusive and respectful of diverse cosmologies, weaving together local, folk, and/or Traditional Environmental Knowledge (TEK) systems and scientific approaches [157,158]. Using current co-production frameworks (see, for example, Schuttenberg and Guth [159] and Iwaniec et al. [160]) or reimagining them could assist researchers in developing studies with participatory and co-produced methods for impactful outcomes regarding sustainable land and water futures.

To ensure holistic research and collaboration, participatory approaches should include marginalized communities and recognize the intersectional dynamics influencing human–environment relationships [161]. Action outside of institutions is necessary, and communities play a crucial role in the materialization of sustainable solutions. Additionally, marginalized communities and users can express complex, intersectional identities and disadvantages that necessitate sustainable solutions. Globally, women often lack access to water resources and are excluded from water management practices [102]. Many colonia communities on the US–Mexico border exist outside of the jurisdiction for "basic water infrastructure", which compounds water-related and socioeconomic inequities [162] (p. 5). Detroit, Michigan, which has a predominantly African American population, is subject to complex water inequities associated with long histories of racial segregation and systematic oppression that immobilize communities by labeling water as a commodity [162,163]. Another water resource challenge outlined by Chief and colleagues [97] includes the years of federal rights denied to Tribal Nations in conflicts related to natural resource sovereignty. Accordingly, a variable, dynamic, collaborative perspective is an ethical necessity for land and water resource management to ensure that community needs are met [97]. Furthermore, researchers should avoid treating TEK as a transaction and instead support diverse voices and leadership by "making room and moving over" [164] (p. 9). With many marginalized communities experiencing land and/or water inequities, participatory, inclusive approaches to resource management that do not further intensify present disparities and inequities have become necessary.

Including participatory methods in research also allows the co-designing of formal and informal educational tools to achieve co-created and community driven outcomes [165]. For example, Olvermann et al. [166] note that in agriculture, consultation and support are seen as obstacles to transitioning to more sustainable practices. Farmers seek training and learning opportunities that could be covered in collaboration with agricultural extension. Similarly, Tran and Touch [167] created an innovative platform, "co-learning-to-act", allowing extensionists and farmers to share experiences and learn from each other. Stakeholders like grassroots movements and NGOs can stimulate public interest in local and regional topics and advocate for legislation or help establish self-organizing structures to conserve natural resources [126]. These efforts are especially vital for sustainable land–water dynamics with an emphasis on solutions for the Global South and in areas other than agriculture. By emphasizing local priorities for sustainable land–water interactions, participatory research enables a more efficient translation of results into, and feedback from, the community, enhancing research quality through more informed contexts and social validity [168,169].

Participatory methods also provide rich opportunities for involving students in the research process, improving their skills, and training future scientists and professionals in land–water dynamics with community engagement perspectives. Students' participation also reinforces social capital and community involvement [165]. Overall, participatory research encourages a meaningful mutual flow of ideas and knowledge; additionally, it reinforces established links between the researchers, the wider community, and stakeholders, setting up prospects for future and meaningful research projects [170].

More research is needed on how participatory studies can have a positive impact on the SES resilience of the community involved. Such studies should focus on how participatory approaches can be used to better frame wicked problems grounded in local communities to re-imagine just and equitable futures, evaluate possibilities, and co-produce sustainable solutions. There are opportunities to become involved with participatory research ethics, such as how to create long-lasting relationships with local communities and diverse stakeholders while also acknowledging other ways of knowing (beyond science) regional land and water interactions. Overall, incorporating participatory methods and informal education in an LSS of land and water can advance knowledge by supporting the weaving of diverse knowledge systems in an inclusive, respectful, and open forum to share knowledge and ideas while also improving SES resilience.

5. Conclusions

Complex and dynamic, land, water, and people interactions in LSS remain understudied yet more important than ever for ensuring future sustainability. In this Special Issue, we suggest that a deeper integration of land and water dynamics is needed in LSS research for building SES resilience. Treating human and natural systems as fixed and two-dimensional has limiting implications for communities and water resource availability. Instead, we need more integrative and dynamic ways of understanding SES resilience. While LSS and SES are interconnected, the gaps in LSS outlined in this article reveal opportunities for growth using SES research framings that expand on the complex, human, non-material interactions that remain invisible at first glance in empirical, static representations of environmental change. The contributions of the authors and editors in this Special Issue suggest various material and non-material ways in which we might begin to rethink relationships between land, water, and people. Ultimately, we argue that it is time to make water more explicit in LSS research, with implications for SES resilience. Furthermore, we argue that to better integrate land, water, and people, we need to move beyond the traditional remote sensing and models prominent in LSS research to also promote the participation of diverse stakeholders while also incorporating deeper qualitative understandings of material and non-material aspects of water and land dynamics such as those forged from culture, community, and identity, among others.

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