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A Land Systems Science Framework for Bridging Land System Architecture and Landscape Ecology: A Case Study from the Southern High Plains

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Abstract: Resource-use decisions affect the ecological and human components of the coupled human and natural system (CHANS), but a critique of some frameworks is that they do not address the complexity and tradeoffs within and between the two systems. Land system architecture (LA) was suggested to account for these tradeoffs at multiple levels/scales. LA and landscape ecology (LE) focus on landscape structure (i.e., composition and configuration of land-use and land-cover change [LULCC]) and the processes (social-ecological) resulting from and shaping LULCC. Drawing on mixed-methods research in the Southern Great Plains, we develop a framework that incorporates LA, LE, and governance theory. Public land and water are commons resources threatened by overuse, degradation, and climate change. Resource use is exacerbated by public land and water policies at the state- and local-levels. Our framework provides a foundation for investigating the mechanisms of land systems science (LSS) couplings across multiple levels/scales to understand how and why governance impacts human LULCC decisions (LA) and how those LULCC patterns influence, and are influenced by, the underlying ecological processes (LE). This framework provides a mechanism for investigating the feedbacks between and among the different system components in a CHANS that subsequently impact future human design decisions.

Keywords: governance; patterns; social-ecological processes; CHANS; High Plains Aquifer Region; Ogallala

1. Introduction

More than 75% of the Earth's ice-free surface shows significant evidence of human-induced alterations [1], most commonly in the form of land-use and land-cover change (LULCC), with agriculture being a major driver of that change [2]. These human-induced alterations modify the climate system, biodiversity, and the water cycle [2–4] but are often undertaken to directly support socioeconomic and livelihood systems [5,6]. Rounsevell and colleagues ([7], p. 899) argue that the "land system"—the coupling of all human and natural aspects tied to land (e.g., soil, biodiversity, water, society, culture, institutions, etc.) [8,9]—is central to understanding the relationship between people and their environment. In particular, studying changes in the dynamics of decisions surrounding land-use alterations is critical for understanding the human dimensions of global environmental change, as land-use decisions impact both the ecological and human components of the system via complex feedbacks [10,11].

Land System Science (LSS) is a broad and dynamic field focused on modeling complex land processes through the integrated study of humans and the environment [10,12]. Originally rooted in 1960s cultural ecology [13], LSS reappeared decades later within the International Geosphere-Biosphere and International Human Dimensions Programmes [14,15] as an earth system science approach for assessing critical thresholds of sustainable resource management [7]. Beyond modeling complex land processes, a primary goal of LSS is developing future land-use scenarios that can be used as decision-making tools and policy formulation [16–18]. As a further step toward understanding land-use processes and drivers of land-use change [19], the related field of Land Change Science (LCS) specifically emphasizes the need to develop remote sensing, geographic information system (GIS), and modeling techniques to quantify land-cover change [2,20]. Key objectives of LCS include: building LULCC scenarios [18], ensuring social-ecological systems resilience [8], and making coupled human and natural systems (CHANS) studies relevant to policy makers [17]. These components are also critical for understanding LULCC feedbacks as mediated through land managers [21]. More recently, the term Sustainability Science [22] has emerged alongside LCS and LSS to incorporate environmental services, human designed land systems architecture [23], and other natural resources, such as water [1].

These interconnected fields often emphasize "big question", multidisciplinary problem solving related to issues surrounding sustainability, adaptation, and global environmental change [5,24,25], while also emphasizing CHANS in terms of patterns, processes, and prediction [12]. However, a critique of such frameworks is that they often fail to address the complexity and tradeoffs within and between the human and natural systems [26]. Working to overcome these constraints, land systems architecture, also referred to as land architecture [23], has been suggested as an alternative approach that can account for tradeoffs between the two systems at multiple levels/scales. Land system architecture (LA) refers specifically to the type, magnitude, and spatial pattern of LULCC [26], similar to the central tenets of landscape ecology (LE), which has roots in North America going back to the 1980s [27]. Both LA and LE focus, to varying degrees, on the structure of the landscape (i.e., composition and configuration of LULCC) and the processes (social and ecological) that result from and shape those patterns. However, despite these notable parallels, studies have only recently begun to examine the two fields in tandem [28]. While landscape ecology has always viewed humans as central to understanding ecosystem dynamics [28–31], land architecture advocates stronger, more active links between human-landscape design and LSS [26,30]. Landscape ecology, by comparison, focuses more directly on the impact of landscape structure and patterns on ecological processes [32,33], with considerable attention given to the impact of scale. However, more recently, landscape ecology has also begun to emphasize the role of human processes, with culture as a noted driver of landscape change [34,35] and connections to sustainability science [36]. Additionally, landscape ecology emphasizes the role of ecosystem services in shaping sustainable landscapes, stressing the need to explore linkages between landscape interactions at hierarchical scales [37]. Integrated together, the two complementary fields of land systems architecture and landscape ecology have the potential to form a richer foundation for understanding LSS through the composition and configuration of LULCC and their impacts on both social and ecological systems [23].

One reason for the notable lack of integration of these two fields to date may be that traditional CHANS models often treat the human and natural/environmental systems separately, linking them only through specific processes (Figure 1). This separation makes it difficult to bridge the two systems via the integrated coupling of both social and ecological processes suggested by land systems architecture and landscape ecology. The traditional CHANS model (Figure 1) also does not explicitly consider the multi-level/scalar dimensions of the human and/or natural system, which are key aspects of both land systems architecture (LSS in general) and landscape ecology.

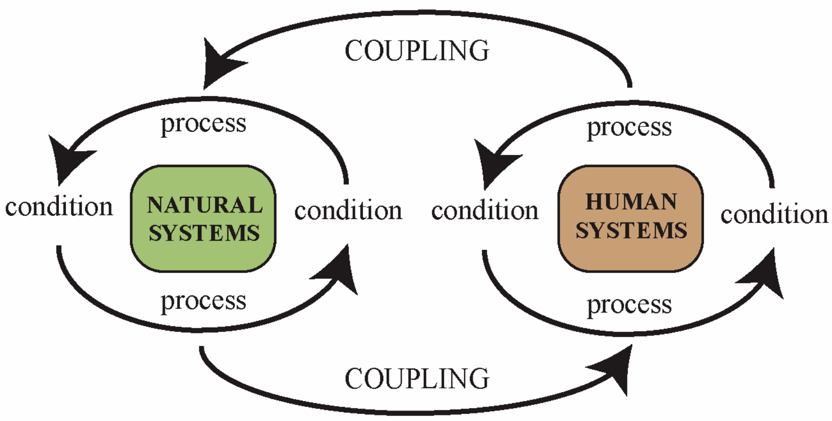

Figure 1. Traditional framework for coupled human and natural systems (CHANS) studies. Source: Figure adapted by the authors from National Science Foundation (NSF) 18-503 (2017: p. 4) (See: https://www.nsf.gov/pubs/2018/nsf18503/nsf18503.pdf).

2. An Integrated Coupled Human and Natural Systems (CHANS) Framework Linking Land System Architecture and Landscape Ecology

By integrating human design aspects that are central to land systems architecture with the already-coupled, multi-level/multi-scalar relationships between landscape patterns and social and ecological processes that are central to landscape ecology, we establish a comprehensive framework for investigating the complexity in CHANS. The proposed framework (Figure 2) explicitly accounts for tradeoffs within and between the human and environmental subsystem at multiple levels/scales, while simultaneously accounting for the coupling of environmental patterns and ecological processes. This framework provides a foundation for investigating the mechanisms of these couplings, specifically to understand how and why governance impacts human LULCC decisions (LA) and how those LULCC patterns influence, and are influenced by, the underlying ecological processes (LE). The proposed framework also provides a mechanism for investigating the feedbacks between and among the different system components in a CHANS that subsequently impact future human design decisions.

By conceptualizing CHANS as a nested system of multiple scalar dimensions, we can investigate the single-level/scale couplings between the human and environment systems by focusing on the linkages between governance (or another human variable(s) such as economy, etc.), patterns, and processes at a single level/scale (individual circles in Figure 2). We can also investigate the linkages across the various levels/scales. For example, governance often impacts policy at a regional or national level, but these formal decisions also influence individual and household decisions at the local level (i.e., individual/household). Linking the local landscape patterns that emerge as a result of household LULCC decisions to landscape patterns and processes at broader scales (e.g., regional hydrology dynamics) is critical, especially when studying common, shared resources, such as public lands and water [38,39]. By capturing human design actions, landscape patterns, and ecological processes at a finer scale (Figure 2, local level), we can better understand why LULCC decisions are made at the regional scale (Figure 2, regional level). Similarly, by capturing regional-scale design decisions (i.e., governance and policy), landscape patterns, and ecological processes, it is possible to better understand the broader impacts of individual or household design decisions. Together, such understandings can lead to improved land-use and governance policies [37].

In this conceptual framework, it is important to recognize that *land* refers to both the terrestrial and water system components. Defries and Eshleman ([40], p. 2183) argue that integrating land-use change and hydrologic processes is a “major need for the future”. Alterations to natural landscapes through irrigated and dryland agriculture, or even overgrazing, can trigger imbalances in Earth’s hydrologic and thermodynamic cycles and, hence, weather patterns [4]. Existing knowledge of geospatial variability in water demand and the impact of human land-use decisions on water resource management for sustainability under climate change conditions is very limited. In fact, some argue that the level of attention needed for land management in the policy framework should be equivalent to, if not more than, the level of attention afforded greenhouse gas effects on the environment and sustainability [4].

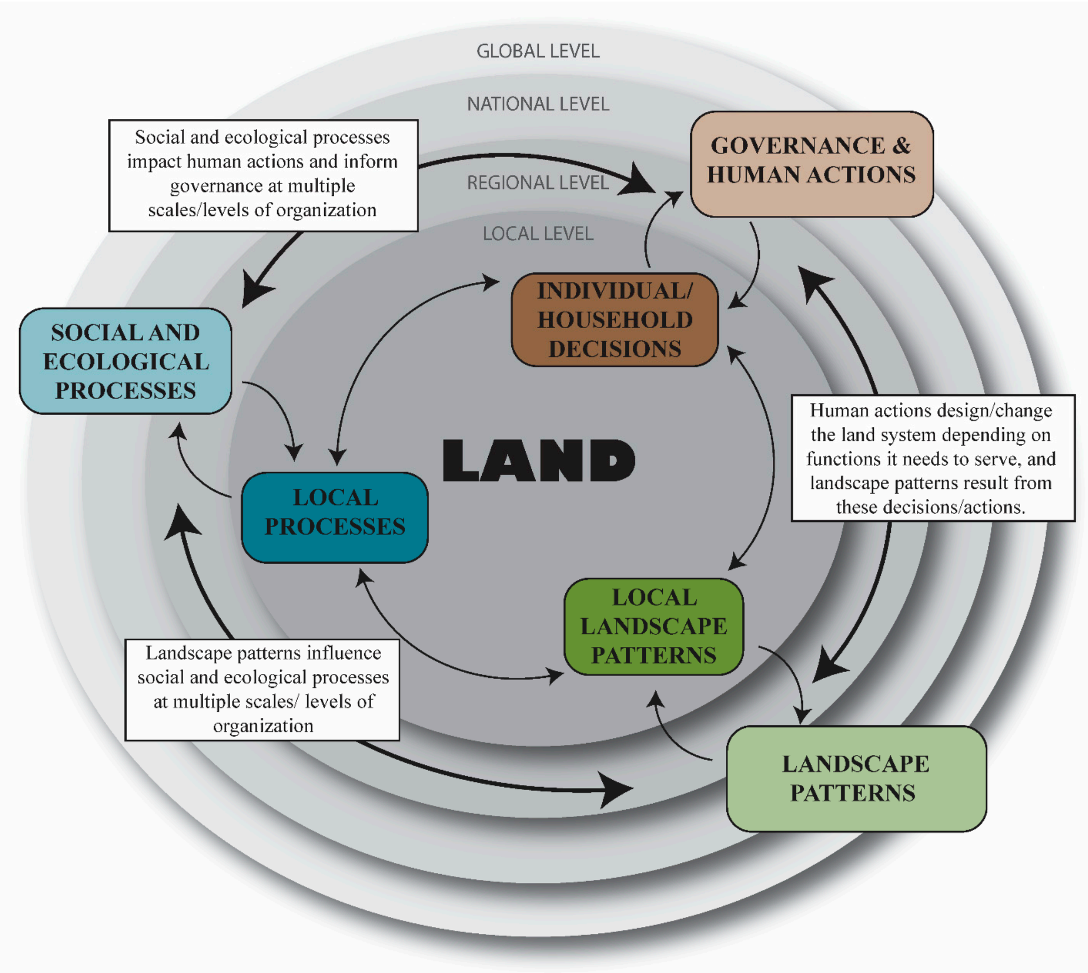

Figure 2. Proposed framework for CHANS studies. Linkages between human action, landscape patterns, and social and ecological processes occur at each level—the local level is highlighted here, with governance as an example. Multi-level/scalar couplings between the individual components also occur across levels/scales.

To demonstrate how this integrated framework may be used to analyze the dynamics of a CHANS, we investigate the evolution of common property land and water resources within a southern portion of High Plains (Ogallala) Aquifer. Focusing on a transboundary region spanning the states of New Mexico, Oklahoma, and Texas, we examine how governance of public lands and water resources impacts individual LULCC decisions and how those decisions alter landscape patterns and ecological processes, which, in turn, may lead to further changes in governance and land use. We center our attention on these common or "mixed" property resources because they present a pair of unique resource management challenges [41]. First, the subtractable nature of common property such as water resources is exacerbated in the study region because replenishment (i.e., groundwater recharge) occurs on longer time scales than use ([41], p. 6). This mismatch makes it challenging for managers to balance social, economic, and ecological concerns. Second, land and water resources in this region are geographically complex because they cover large physical spaces that cross multiple political and administrative boundaries, making coordinated management and monitoring difficult [42].

Additionally, degradation of regional resources is often hard to perceive because they occur over extended time periods and, in the case of groundwater, are primarily a sub-surface process.

Theorists argue that the subtractability and complexity of common property resources increase the likelihood that they will be governed through open-access systems with uncontrolled use, which may lead to degradation and the "Tragedy of the Commons" [43]. As a result, many critics of the commons have proposed solutions ranging from privatization to heavily controlled public conservation, or mainly strong-arm, Leviathan approaches [43–47]. However, the complexity and geographic extent of these common property resources provides valid reason to prevent parceling them into private ownership, while their subtractability also favors common property approaches to resource management. As Ostrom [48] argues, "common property" is, indeed, someone's "property", unlike Hardin's [23] view of commons as completely open access. As such, many common property resource management approaches advocate "institutional arrangements for the cooperative (shared, joint, collective) use, management, and sometimes ownership of natural resources" ([49], p. 27). In this framework, institutions refer to the formal (e.g., legal) and informal (e.g., local customs) "rules in use" for resource management [50]. Crucially, institutional governance of common property resources implicitly recognizes the acquisition of knowledge from localized observation of landscape patterns and ecological process, which informs the development of the "dos and don'ts" of resource use ([51], p. 21). Our framework seeks to make this connection explicit as a means of facilitating improvement of human design of the land system.

3. Methods: Synthesizing Results of Previous and Expanded Research from a Land Architecture-Landscape Ecology (LA-LE) Framework Perspective

Building on 10 years of mixed-method, ethnographic, and participatory fieldwork [52–54], we examine the relationship between evolving common property land and water resources, landscape patterns, and social-ecological processes within a southern portion of the High Plains (Ogallala) Aquifer (hereafter, HPA). Our past research focused on adaptation of ranchers and farmers to drought in the grasslands of the American West using mainly Social-Ecological Resilience and Governance theory in Union County, NM and Cimarron County, OK specifically (see http://biosurvey.ou.edu/Grasslands/main.html). The LA-LE framework presented here is the result of efforts to adequately address the interaction effects of multiple scales and processes in the region. To illustrate the framework presented above, we draw on secondary sources including aquifer data from the U.S. Geological Survey (USGS), producer statistics from the U.S. Agricultural Census, vegetation data from the National Land Cover Database (NLCD), and others. We also draw on results from previously published research including a remote sensing LULCC analysis of woody plant encroachment [53], a time series analysis of the growth and contraction of Center Pivot Irrigation (CPI) in relation to changing governance [54], and ethnographic research (key-informant interviews and oral histories) on the governance and contested nature of public lands [52]. Here, we expand our study site to include Dallam County, TX as it has a longer history of industrialized agriculture and a distinct governance resource regime, thus providing depth to our framework. While focusing on the components presented in the framework (Figure 2), we synthesize the results of our previous and current research as part of an illustrative case study. For each component of the framework (governance and human actions, landscape patterns, social and ecological processes, and feedbacks), we present specific background, as well as methods and results (for more information on methods, results, scope, or limitations of prior studies, please see [52–54]).

4. Case Study: Applying the Framework to a Transboundary Region of the Southern High Plains

4.1. Land and Water Governance and Human Actions in the Southern High Plains

Our study area is a semi-arid region covering 1.84 million ha across Cimarron County, OK; Dallam County, TX; and Union County, NM (Figure 3). Dominated by shortgrass prairies, coarse and sandy soils, and rolling, irregular plains [55], much of the study region is underlain by the HPA, which residents use to support extensive agricultural production [54]. Agriculture dominates the economy and landscape of all three counties. Farmland accounts for 88 percent (1.6 m ha) of the study area, of which 76 percent (1.2 m ha) is pastureland. Cattle is the region's dominant commodity, accounting for 77 percent of total market value of agricultural goods [56]. Cimarron and Dallam counties each rank in the top three percent of U.S. counties for cattle production. The USDA [56] classifies approximately 57 percent (0.2 m ha) of the region's cropland (0.35 m ha) as harvestable, with wheat, corn, sorghum, and silage crops as the primary crops.

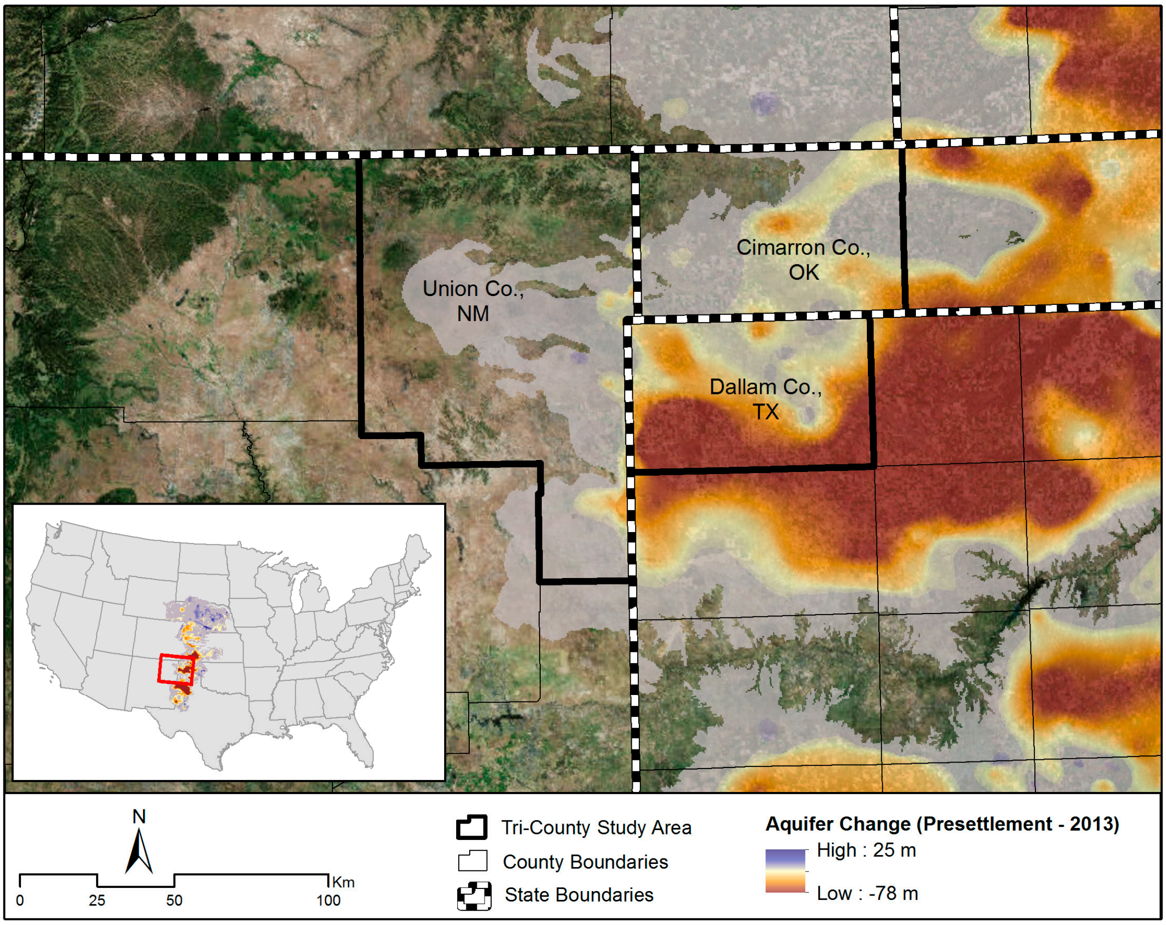

Figure 3. Study area counties within the tri-state region of the Southern High Plains. Source: Figure created by the authors using aquifer data from the U.S. Geological Survey.

While agriculture is a primary driver of LULCC within the study region, climatic variation in the form of cyclical drought has shaped the practices of regional agriculturalists. The tri-state, three-county area has experienced six major drought events during the last 125 years, including the Dust Bowl of the 1930s and the recent drought of the 2000s. From 2000 to 2015, extreme (D3) to exceptional (D4) drought enveloped the study region [57]. During this period, dry conditions (in terms of precipitation and temperature), at times, exceeded those of the Dust Bowl [58,59]. Across the Southern High Plains, agriculturalists adapted to the long-term cyclical drought by increasing reliance on two key common property resources: water and public lands [54]. Within the study region, 97,565 ha (~27%) of cropland are now irrigated, and 101,640 ha (~28.5%) of cropland are enrolled in the Conservation Reserve Program (CRP) [60].

There are considerable differences in the land tenure across the three-county study region (Table 1). Governance of public lands varies across the study region (Table 2), and different systems of governance overlap in complex ways that offer both opportunities and constraints for land managers. Indeed, past research in the region reveals the highly contested nature of land and water governance systems [52–54]. Facing recurrent, cyclical drought, ranchers have become increasingly dependent on leasing public lands [52] to sustain operations and maintain levels of production [61]. In both Cimarron and Union Counties, ranchers may lease state lands, which account for ~20 percent of the land area in each county [52]. However, considerable differences exist in the bidding process and sustainability incentives available in each county (Table 2). In contrast, Dallam County contains no state lands but the most federal lands (Table 1). All three counties have national grasslands, which are managed by the government for multi-use purposes. In particular, ranchers rely on national grasslands to help sustain grazing operations through the purchase of grazing rights [62]. In some cases, ranchers lease public lands to help compensate for adverse changes in cattle stocking rates on their own private lands in order to maintain and/or expand their cattle operations (herd size). Overuse of public lands, especially during times of drought, may foster woody plant encroachment and species invasion with adverse effects on landscape patterns and ecological processes [53].

Table 1. Land tenure composition (ha and %) in the tri-state, three-county study area.

Land Tenure	Cimarron Co., OK	Dallam, Co., TX	Union, Co., NM
Total Area	480,940	373,255	989,185
Private Land	380,096 (79%)	341,938 (92%)	788,790 (80%)
State Land	92,575 (19%)	0	176,563 (18%)
State Park/Other	1254 (0.26%)	0	128 (0.01%)
Federal Land	6345 (1%)	31,314 (8%)	23,703 (2%)

Source: Adapted by the authors from [53] using creative commons attribution permissions. Data source: Protected Areas Database of the United States (PADUS), U.S. Geological Survey [63].

Water governance also varies significantly across the three states and counties. In Cimarron and Dallam counties, surface water is held in trust by the state, but groundwater is considered private property and governed under prior appropriation laws. In Union County, both surface and groundwater are considered public goods controlled by the state. As a result, well permitting, water reporting, and monitoring requirements differ (Table 2). Beginning in the 1940s, the total irrigated acreage drawing from the HPA rapidly increased [54,64] leading to unsustainable depletion of this resource [65,66]. In areas where it was allowed, many farmers added CPI to ameliorate semi-arid conditions [54]. In addition to these formal governance mechanisms, there are several active, yet informal, water governance structures that operate throughout the region, such as soil and water conservation districts, which may lead to stronger water governance. Recent research [54] indicates that these differential groundwater governance structures drive resource management and related LULCC dynamics.

An important outcome of the land and water governance systems in the study area is differential management and use of these common property resources. For example, in Cimarron and Dallam Counties where groundwater is considered private property, farming and ranching operations may essentially extract vast quantities of water as needed from the HPA. This (mostly) unchecked use has resulted in an increase of certain land-use types (e.g., CPI), allowing farming practices to occur in areas that were previously unsuitable. Conversely, in Union County, where groundwater is increasingly controlled by the state, CPI has fluctuated over time. Complicating matters further, the governance of public lands and water continually intermingles, causing distinct patterns on the landscape. For instance, on public lands with longer lease terms or stronger preference rights, land managers may be more likely to install CPI or other more permanent structures.

Table 2. Formal land and water governance in the tri-state, three-county study area.

State Lands Policy	Cimarron Co., OK	Dallam Co., TX	Union Co., NM
Lease/Term	5 years	–	5+ years
Open Bidding?	Yes	–	No. Preference rights attached to deeded land.
Sustainability Incentives Offered?	No	–	Yes. Reduced rents (up to 25% off)
State Water Governance			
Ownership	SW: Belongs to state. GW: Private property	SW: In trust by State. GW: Private property—"First in time, first in right".	SW: Belongs to public, controlled by state. GW: Usage under state jurisdiction
Regulations	GW: "Subject to reasonable use". Well permits required	Rule of Capture- no permitting required, some exceptions	GW: (wells/usage) via permit (and amounts withdrawn) from State Engineer
Reporting/Monitoring	No Metering required, Self-reported	Required Metering, Self-reported	Required Metering, Self-reported

GW = groundwater. SW = surface water. Source: Adapted by the authors from [53] using creative commons attribution permissions. Additional Table Sources: [53,54,67].

In sum, public land and water governance systems overlap in complex ways, offering both opportunities and constraints for land managers. Indeed, past research in the region reveals the sometimes highly contested nature of land and water governance systems operating in some states [52–54]. Understanding how common property resources are governed, and how scale influences analyses [68], is critical for achieving sustainable natural resource management, as governance and human actions at the regional scale influence individual and household decisions at the local scale [8,9,69–74]. This relationship is reflected as the cross-scale coupling of regional governance and individual decision-making. In the integrated CHANS framework (Figure 3), we argue that differential land and water governance systems lead to the emergence of different LULCC patterns on the landscape, and that those patterns continue to alter processes. We examine each of these linkages in the three sections below.

4.2. Linking Governance to Landscape Patterns

An important first step toward making a connection between governance and landscape patterns is measuring and comparing those patterns across the differently governed areas. Patch-based landscape metrics have been the primary tool for quantifying the composition and configuration of landscape patterns in landscape ecology for decades [75–78], and they are also used for pattern analysis within the LSS and land systems architecture communities [23]. Patch-based metrics are conceptually simple and easy to compute for categorical land cover maps using readily available software programs such as FRAGSTATS [79]. While there are many complex and interrelated factors operating on the landscape, spatial pattern analysis can act as a first step in understanding whether or not there are different landscape patterns across the study area, thus providing a foundation from which to investigate how human decisions may have contributed to the different patterns.

4.2.1. Impacts of Land Governance on Landscape Patterns

In a previous study, we assessed the relationship between different state land governance policies and landscape degradation in the form of woody plant encroachment across Cimarron and Union Counties [53]. In that study, we reclassified land cover data from two periods (1992 and 2011) of the NLCD to a modified Anderson Level I classification scale [80]. We then used the Protected Areas Database [63] to delineate governance structures through different land tenure regimes, specifically state lands and private lands (Table 3). While the illustrative case study presented here also includes

Dallam County, that county does not include any state lands, therefore it is not included in this portion of the analysis.

Table 3. Land area by land tenure, land cover type, and year in Cimarron, Co., OK and Union, Co., NM, 1992–2011. All values in ha and (%).

		State Lands		Private Lands	
Land Cover Type	**Year Change**	**Cimarron Co., OK**	**Union Co., NM**	**Cimarron Co., OK**	**Union Co., NM**
Herbaceous	1992	93,608 (96.7)	148,510 (84)	271,421 (70.8)	680,958 (86.1)
	2011	76,921 (79.5)	166,585 (75.6)	248,224 (64.7)	632,434 (79.9)
	Δ	−16,687 (−17.8)	−14,925 (−10.1)	−23,197 (−8.6)	−48,524 (17.12)
Shrubland	1992	749 (0.8)	11,220 (6.4)	4460 (1.2)	39,607 (5.0)
	2011	17,422 (18)	24,418 (13.8)	22,653 (5.9)	80,014 (10.1)
	Δ	16,673 (2226)	13,198 (117.6)	15,193 (408)	40,407 (102)
Forest	1992	199 (0.2)	15,134 (8.6)	139 (0.04)	36,737 (4.6)
	2011	199 (0.2)	16,864 (9.5)	138 (0.04)	42,678 (5.4)
	Δ	0 (0)	1730 (−11.4)	1 (0.7)	5941 (16.2)
Cultivated	1992	1769 (1.83)	1214 (0.7)	100,033 (26.1)	28,093 (3.6)
	2011	1593 (1.7)	1096 (0.6)	100,084 (26.1)	29,524 (3.7)
	Δ	−175 (−9.9)	−118 (−9.7)	51 (0.01)	1431 (5.1)

Source: Adapted by the authors from [53] using creative commons attribution permissions.

Using the land cover maps, we computed basic patch- and class-level landscape metrics for the herbaceous (i.e., grassland) and woody vegetation (i.e., forest and shrubland) classes using FRAGSTATS [79]. Metrics included the mean patch size (MPS: average size of all patches of a particular land cover) and patch density (PD: number of patches per total area). Given the environmental characteristics of the two counties, we expected to see a decrease in the contiguity of grassland (herbaceous) patches and an increase in the amount and spatial connectedness of the woody vegetation (forest and shrubland) in both. However, given the different governance regimes, we expected these changes to be more pronounced in Cimarron County where governance structures are weaker. To test this hypothesis, we computed landscape pattern changes between 1992 and 2011 (change/no change) and ran a series of binary logistic regressions for approximately 10,000 randomly located pixels using two independent variables: land tenure and the topographic wetness index (TWI) [81], which was included to account for biophysical differences between the locations. Additional details on the methodology can be found in Fagin et al. [53].

Our results show distinct differences between Cimarron and Union counties according to land tenure (Table 4). In Cimarron County, where few incentives are offered for good stewardship of state lands, PD increased by almost 300 percent between 1992 and 2011 [53]. The average size of those patches increased by 500 percent, indicating widespread encroachment of woody vegetation. These results can be compared directly to the private lands in Cimarron County, where the number of patches per hectare of land increased by only about 30 percent, and the size of those patches grew by half as much compared to the state lands. In Union County, where stable preference rights and incentives are offered for sustainable stewardship of the land (Table 2), densities of woody patches decreased between 1992 and 2011 by 43 percent. While a decrease in patch density may indicate that patches of woody vegetation are being actively removed from the landscape, with the general trajectory of woody plant encroachment in the region, this decrease likely indicates that several smaller patches coalesced to form larger patches in some places. Considered alone, this decrease in PD might signal unchecked growth. However, when these results are interpreted in conjunction with the smaller growth in mean patch size compared to both the state lands in Cimarron County as well as the private lands in Union County, it suggests that woody vegetation encroachment is being managed on these lands to some degree (Figure 4).

Table 4. Landscape metrics computed for shrubland on state and private lands in Cimarron, Co., OK and Union, Co., NM, 1992–2011.

	State Lands		Private Lands	
Landscape Metrics	**Cimarron Co., OK**	**Union Co., NM**	**Cimarron Co., OK**	**Union Co., NM**
Patch Density (#/ha)				
1992	1.0	6.61	1.09	5.5
2011	3.92	3.75	1.42	2.53
Change (%)	292%	−43.3%	30.3%	−54%
Mean Patch Size (ha)				
1992	0.8	1.0	1.1	0.9
2011	4.8	3.7	3.7	4.0
Change (%)	500%	270%	236%	344%

Source: Adapted by the authors [53] using creative commons attribution permissions. Data sources: 1992 and 2011 National Land Cover Database (NLCD) land cover database. See [53] for more details.

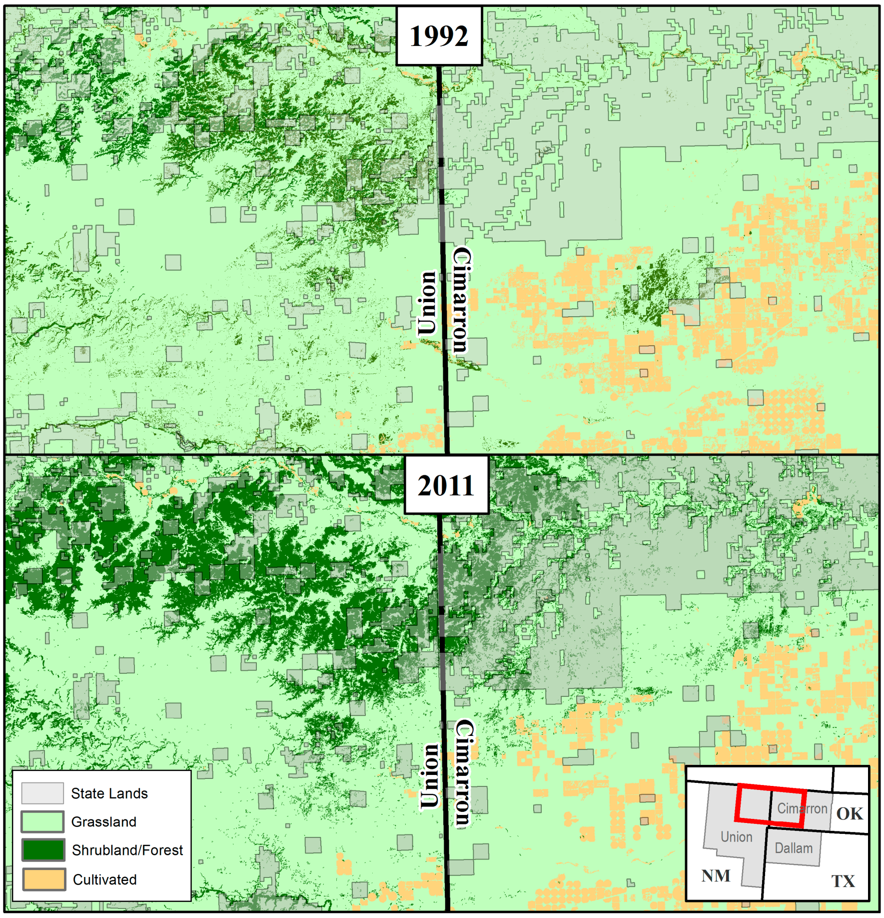

Figure 4. Example of woody plant encroachment across the New Mexico (Union Co.)-Oklahoma (Cimarron Co.) state line in 1992 and 2011. Source: Figure created by the authors using the National Land Cover Database.

The landscape metric results provide a simple and efficient measure of woody vegetation pattern changes across the landscape, but alone they do not provide an indication of the likelihood of land transitioning from grassland to shrubland during the study period in the different land tenure regimes. To compare this likelihood across the different land tenures, we ran the binary logistic regressions described above. Regression results show that in both counties, the odds of land transitioning from herbaceous to woody shrubland were significantly greater on state lands compared to private lands (Table 4). However, these odds were greater in Cimarron County (1.868) compared to Union County (1.607), which supports our hypotheses stated above that governance is impacting land cover patterns. Additionally, the model predicted that 18 percent of state lands in Cimarron County would change from herbaceous to shrubland, while only 13 percent of state lands in Union County would change. The incorporation of TWI in the model did not diminish the importance of land tenure [53] (Table 5). Together, the metric and regression findings capture the relationship between governance and land cover patterns. In Cimarron County, where state land governance is arguably weaker, grasslands on state lands are more likely to transition to shrubland compared to both private lands in Cimarron County, as well as compared to state lands in Union County. Thus, there appears to be a link between the human actions at the regional scale (i.e., governance) and landscape patterns at a regional scale with respect to a common resource (land) in the study area.

Table 5. Logistic regression results for predicting woody plant encroachment based on land tenure and the topographic wetness index (TWI).

County	β	P	Odds Ratio
Cimarron Co., OK			
Land tenure	0.625	0.000	1.868
TWI	−0.352	0.000	0.703
Union Co., NM			
Land tenure	0.474	0.000	1.607
TWI	−0.496	0.000	0.609

Source: Adapted by the authors from [53] using creative commons attribution permissions.

4.2.2. Impacts of Water Governance on Landscape Patterns

Distinct landscape patterns appear to correlate with the different water governance regimes across the three counties (Table 2). All three counties are underlain to some degree by the HPA (Figure 3), making them potentially suitable for agriculture. There was a dramatic increase in center pivot irrigation (CPI) across the region between the 1950s and the mid-1980s [54] as technology improved and farmers converted pasture and rangelands into agricultural plots. However, as drought conditions intensified in the area between 2005 and 2014, we hypothesized that the growth or decline of CPI in the three counties would be closely related to governance policies. To test this hypothesis, we manually digitized CPI land-use at two time periods (2005 and 2014) from aerial imagery. This approximately 10-year time span captures the sustained period of drought from 2000 to 2015 in which extreme (D3) to exceptional (D4) conditions enveloped the area [57]. We found that in both Cimarron and Dallam Counties, where groundwater is considered private property, CPI acreage increased by 7.76 percent and 19.25 percent, respectively. In Union County, where groundwater is more heavily controlled by the state, there was a net decrease (−5.66 percent) in CPI acreage between 2005 and 2014 (Figure 5).

In summary, many of the patterns that emerge on the landscape are the result of governance and the associated human actions in which humans specifically design the landscape to suit their needs. This human-driven landscape design is a central tenet of land systems architecture theory [26], and quantifying the patterns that result is a primary focus of the field of landscape ecology [32]. Equally important in landscape ecological studies is understanding the impact that the composition and configuration of the landscape patterns have on ecological processes and vice versa [32,33]. Through LSS, we recognize also that landscape patterns affect, and are affected by, the social processes occurring on the landscape. In the following section, we present an example of how the landscape patterns impact an ecological process. However, it should be noted that within the proposed framework (Figure 2), similar linkages could also be made between landscape patterns and social processes, such as farmer cooperatives, which would ultimately feed back into governance and human actions.

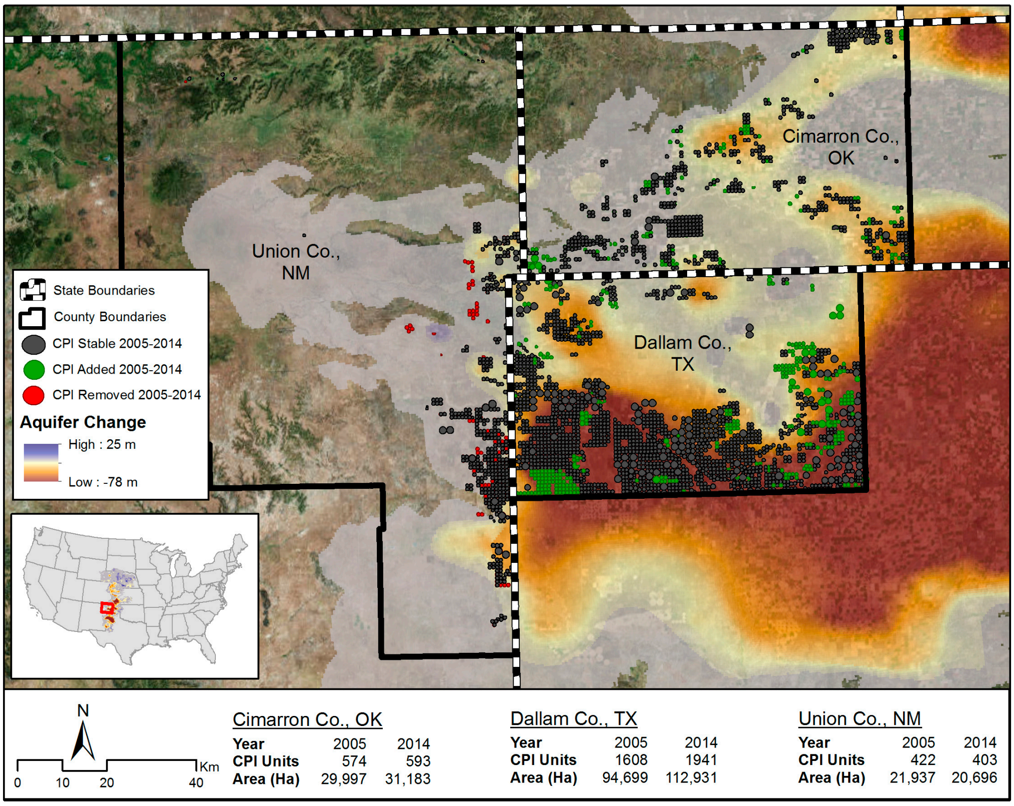

Figure 5. Center pivot irrigation (CPI) in the tri-state area showing areas added and removed between 2005 and 2014 overlain on the High Plains Aquifer change (presettlement to present) map. Source: Figure created by the authors using aquifer data obtained from the U.S. Geological Survey.

4.3. Linking Landscape Patterns to Ecological Processes

Within the study area, various ecological processes are critical for sustaining lives and livelihoods, such as water and nutrient cycling, climatic processes, energy flows, and natural disturbance regimes, among others. Here, we discuss one of these key ecological processes, groundwater recharge, to illustrate an example of the coupled framework. During drought, farmers in primarily rain-fed areas may implement short-term irrigation (i.e., a LULCC) to increase soil moisture, which puts pressure on regional aquifers and surface water sources [82,83]. These irrigation practices are a key management response to drought conditions [84], but they alter the landscape pattern (e.g., through creating CPI) in a manner that affects the entire hydrologic processes [85,86], which has an important impact on water cycling and community dynamics [87]. We test the relationship between CPI and groundwater recharge to establish a linkage between the pattern and process.

The study area is underlain by the HPA, and the USGS estimates that total water storage in the HPA has decreased by eight percent since 1950, with 25 percent of the aquifer experiencing saturated thickness declines of over ten percent [64,88]. Despite government policy intervention and conservation efforts, water loss continues, with 13.5 percent of aquifer depletion occurring between 2011 and 2013 [88]. As farmers have increased their reliance on groundwater for CPI, the draw-down of this slow-to-replenish commons resource has hastened. To effectively manage these groundwater processes, policy makers and stakeholders need consistent, reliable data that connects their water use to land cover patterns at multiple spatial scales [89]. Here, we associate the growth in CPI in each county with aquifer drawdown using Bayes theorem [90]. Specifically, we computed the probability of considerable drawdown in the HPA given the landscape was being used for CPI using Equation (1):

$$P(D|C) = \frac{P(C|D)P(D)}{P(C)} \quad (1)$$

where $P(D|C)$ is the probability that the HPA has experienced net drawdown of more than 15 m (approximately 50 feet) since presettlement given the presence of CPI in each county, $P(C|D)$ is the probability of CPI land use given the presence of aquifer drawdown greater than 15 m in each county, $P(D)$ is the probability of aquifer drawdown greater than 15 m since presettlement across the entire county, and $P(C)$ is the probability of land being used for CPI across each county.

In Dallam County, where groundwater is subject only to the rule of capture and permits are not required (Table 2), we found that CPI land use is associated with a 77 percent chance that net aquifer drawdown has been greater than 15 m since record keeping began. In Cimarron County, where groundwater is subject to reasonable use, and in Union, where permits are required for groundwater withdrawal (Table 2), the presence of a center pivot on the landscape is associated with only an 8 percent and 4 percent probability of aquifer drawdown greater than 15 m, respectively. Thus, there is reasonable evidence that governance and landscape patterns have combined to impact the hydrological process of aquifer recharge differently across the three counties. A visual representation of these differences can be seen in the abrupt contrast in aquifer drawdown at the Texas–New Mexico state line (Figure 6). To the east, in Dallam County, aquifer drawdown amounts are greater than 45 m in places (i.e., recharge less than −45 m). To the west, in Union County, aquifer drawdown is much less compared to Dallam (−15 to 0 m). In Union County, a small pocket of net recharge (0–15 m) is visible (Figure 6).

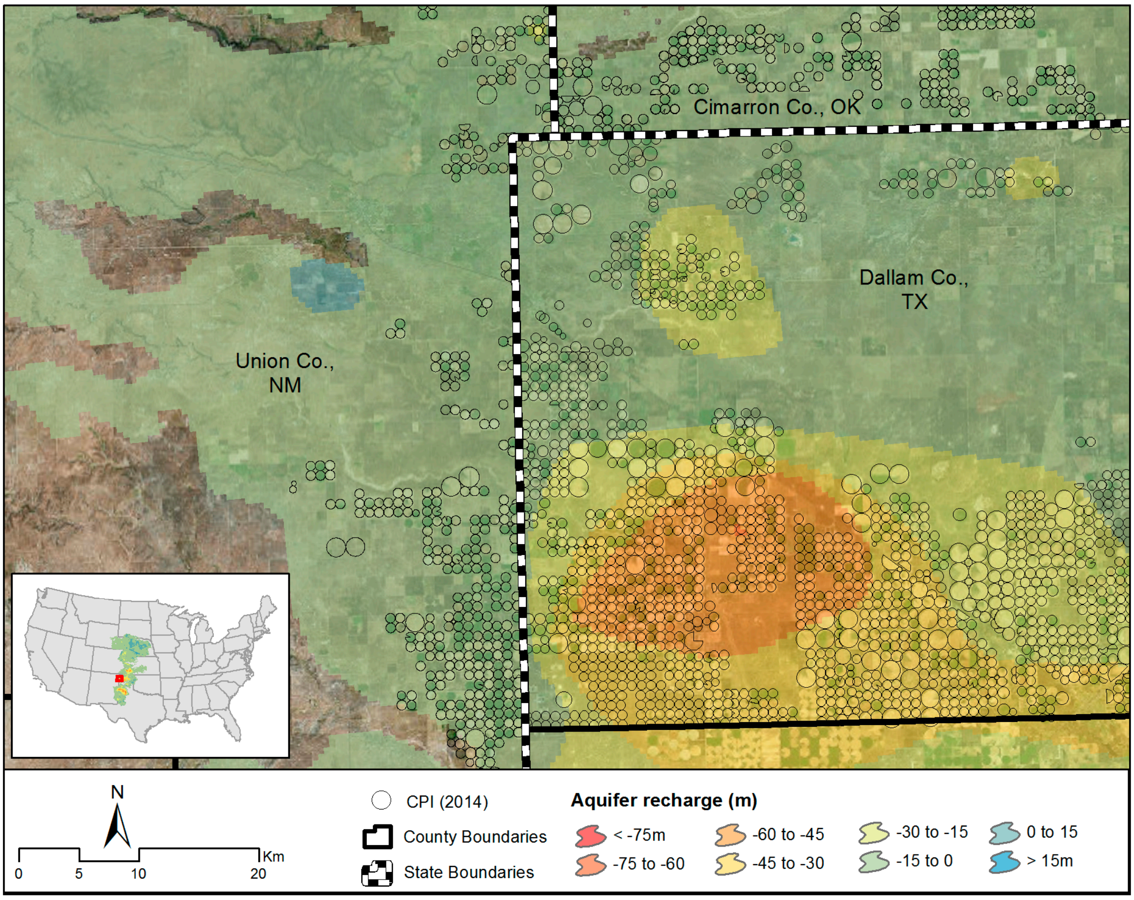

Figure 6. Groundwater recharge and drawdown with center pivot irrigation. Source: Figure created by the authors using aquifer data obtained from the U.S. Geological Survey.

4.4. Linking Processes to Governance via Feedbacks

Long-term processes, such as aquifer drawdown, continuously re-shape governance at the state level, creating changes over both the short- and long-term. For instance, growing concern over aquifer drawdown in the 1980s led some counties to enact significant changes in groundwater regulations. In Oklahoma, maximum annual yields and new well permitting requirements were established to ensure 20 years of sustainable water usage [91]. In 2012, after 12 years of extreme drought conditions, several additional regulations were introduced in Cimarron County, including drawdown limits of two-acre feet per year and minimum well spacing of 1320 feet for new wells [92]. Similarly, in 2005, the New Mexico state engineer named the HPA a "declared basin", requiring permitting for well drilling as well as mandates for metering, monitoring, and reporting [93]. Given the long-term impacts of climate change along with the importance of regional agriculture to the security of the nation, water governance arrangements in the region are expected to continue evolving.

Informal governance arrangements have also shifted the water use of Union County substantially. A prime example of this is the 2011 creation of the Union County Hydrology Project. Supported by the Union County Soil and Water Conservation District, the project educates citizens about the HPA and maps and monitors aquifer recharge and drawdown. These different and changing water governance scenarios gradually influence the local landscape patterns again (hence repeating the cycle, Figure 2). While water governance in all three counties appears to be strong on paper, in reality the interpretation and results of that governance varies considerably. In contrast, Cimarron and Dallam County residents have much less involvement with water governance processes [54,94]. For instance, well metering is not required in Oklahoma, and in Dallam County, water districts often operate across multiple counties, making communication and community buy-in more difficult [94]. On the other hand, Union County residents are actively involved with water governance through informal processes and peer-education, and well metering is required [54]. Overall, the net increase in CPI in Cimarron and Dallam Counties since 2005 and the net loss in Union County suggest that both formal and informal water governance matter.

State land governance will continue to evolve and shape shift as well. The 1982 Oklahoma Supreme Court decision that pressed for maximizing the state school trust led to an open-bidding system. This system sought to maximize profits, often resulting in the degradation of state lands in Cimarron County [52]. In terms of woody plant encroachment, past results [53] using several patch-based metrics, including the number of land cover patches, the average size of those patches, and the contiguity of those patches, show that differences in state land governance in New Mexico and Oklahoma partly led to differential land management practices. Variation in management practices resulted in increased woody plant encroachment, particularly on state lands in Oklahoma. Similarly, the limited pattern-based analysis described above suggests some pattern distinctions across land tenure and state/county. Although the Oklahoma State Supreme Court decision leads to significant barriers in terms of creating a flexible system for changing state land governance, some state and federal governments have responded to sustained drought and degradation (i.e., woody plant encroachment) in the region by temporarily reducing or even eliminating cattle stocking rates on public lands or by allowing residents to access emergency grazing permits for CRP lands [52]. Residents have responded to these policies by moving cattle to other owned or leased lands during times of drought, changing pasture rotational grazing systems, or even switching from cow-calf to yearling-feedlot operations [52]. Over the long-term, one can expect public (both federal and state) land governance and the resulting land use to continue to change and evolve, especially given the compounding impacts of drought and land degradation.

In sum, regional processes impact human decisions to redesign the landscape (here, land and water) to fulfill their needs and also inform governance both now and into the future. These changes are part of an historic and ever-changing trajectory that links governance and human actions, landscape patterns, and regional processes.

5. Conclusions

By integrating the human design (here, governance) aspects central to land systems architecture with the already-coupled, multi-scalar relationships between landscape patterns and processes central to landscape ecology, we expand upon previous work integrating LA and LE, both directly and indirectly [23,25,26,34,37]. We present a comprehensive framework (Figure 2) to investigate the complexity in CHANS that explicitly accounts for tradeoffs within and between the human and environmental subsystem at multiple scales [26] while simultaneously accounting for the coupling of environmental patterns and ecological processes. This framework also provides a foundation for investigating the mechanisms of these couplings at multiple scales, specifically to understand how and why governance impacts human LULCC decisions (LA) and how those LULCC patterns influence, and are influenced by, the underlying ecological processes (LE). Using our framework similarly provides a mechanism for investigating the feedback between and among the different system components in a CHANS that subsequently impact future human design decisions.

Our conceptual framework contributes to LSS theory by exploring the social-ecological resilience of grassland communities (as a CHANS) by focusing on governance of two key commons resources, public land and water, both critical to grassland ecosystem sustainability and community wellbeing. We build on traditional CHANS models (Figure 2) to better capture the complexity in these linked systems and address the tradeoffs within and between the human and environmental systems. We suggest a multi-scalar, nested framework using elements from LA and LE where the human and natural systems are coupled within and across different scales. This framework permits stand-alone investigations of the human or natural system at any one particular scale, multi-scalar investigations of either system at multiple scales, and integrated assessments of the land system at single or multiple scales. It should be noted that while our paper focuses mainly on three scales (household, county, and the three states), the framework can easily be extended to include additional scales (e.g., national, global, etc.).

Lastly, this framework creates a foundation for contributing to governance theory in robust ways with implications for land system sustainability, natural resource management, and ecosystem services [37,95,96]. Current challenges facing the CPR/LSS community include several needs: to better understand interactions of commons dilemmas across multiple scales [69,97–99]; for transboundary/trans-jurisdictional governance studies in the face of global environmental change (especially for depleting resources such as water, or public lands [42,100]; and to better understand complex interactions between multiple commons resources (here, public-private land and water governance) across multiple scales [97,101]. Such LSS approaches are primed to address these complex multi-scalar challenges through their emphasis on CHANS. Additionally, this case study reveals the importance of incorporating ethnographic approaches [102] to study both formal and informal governance [89], and the potential role of community participation and co-production in creating co-adaptive governance structures [103].

Supplementary Materials: For related materials, please see http://biosurvey.ou.edu/Grasslands/main.html.

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