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Collaborative Adaptive Management in the Greater Yellowstone Ecosystem: A Rangeland Living Laboratory at the US Sheep Experiment Station

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Abstract: Social conflict over rangeland-use priorities, especially near protected areas, has long pitted environmental and biodiversity conservation interests against livestock livelihoods. Social–ecological conflict limits management adaptation and creativity while reinforcing social and disciplinary divisions. It can also reduce rancher access to land and negatively affect wildlife conservation. Communities increasingly expect research organizations to address complex social dynamics to improve opportunities for multiple ecosystem service delivery on rangelands. In the Greater Yellowstone Ecosystem (GYE), an area of the western US, long-standing disagreements among actors who argue for the use of the land for livestock and those who prioritize wildlife are limiting conservation and ranching livelihoods. Researchers at the USDA-ARS US Sheep Experiment Station (USSES) along with University and societal partners are responding to these challenges using a collaborative adaptive management (CAM) methodology. The USSES Rangeland Collaboratory is a living laboratory project leveraging the resources of a federal range sheep research ranch operating across sagebrush steppe ecosystems in Clark County, Idaho, and montane/subalpine landscapes in Beaverhead County, Montana. The project places stakeholders, including ranchers, conservation groups, and government land managers, in the decision-making seat for a participatory case study. This involves adaptive management planning related to grazing and livestock–wildlife management decisions for two ranch-scale rangeland management scenarios, one modeled after a traditional range sheep operation and the second, a more intensified operation with no use of summer ranges. We discuss the extent to which the CAM approach creates opportunities for multi-directional learning among participants and evaluate trade-offs among preferred management systems through participatory ranch-scale grazing research. In a complex system where the needs and goals of various actors are misaligned across spatiotemporal, disciplinary, and

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social–ecological scales, CAM creates a structure and methods to focus on social learning and land management knowledge creation.

Keywords: working lands; range sheep production; wildlife conservation; social science; transdisciplinary; living laboratory

1. Introduction

Rangelands are the Earth's largest ecosystem, accounting for approximately 24–45% of the Earth's land surface (depending on how they are defined) and covering over 300 m ha of public and private land in the US [1,2]. Rangelands support extensive livestock production systems that frequently rely on the seasonal movement of herds across ecosystem types and elevations to match nutritional demand with changing forage resources. Rangelands are characteristically variable, rugged environments with limited resources, and are often large landscapes with sparse human populations and comparatively light infrastructure development. Partly as a consequence, rangelands frequently provide critical habitats for carnivores, wild herbivores, birds, and other wildlife [3,4]. Rangelands are often comprised of some level of public or common land and situated between wildlands and areas with intensified urban development or those used for agricultural production. Thus, like forests, they can function as working lands where biodiversity conservation goals coincide with uses such as hunting, timber harvests, recreation, and tourism activities [5–7]. Rangelands also host the cultures and activities of livestock-based livelihoods and rural communities. Their simultaneous value for both conservation and socioeconomic production means that rangeland ecosystems are often contested spaces, where social conflicts arise between groups that have contrasting goals for the same lands and resources [8,9]. This is particularly the case near the boundaries of protected areas, such as national parks, or during times when new protected areas, land use priorities, or regulations are established [10–12]. This context creates the need for innovative approaches to grazing and land management science that depart from disciplinary approaches to engage the goals of all relevant stakeholders within a systems-thinking and collaborative approach.

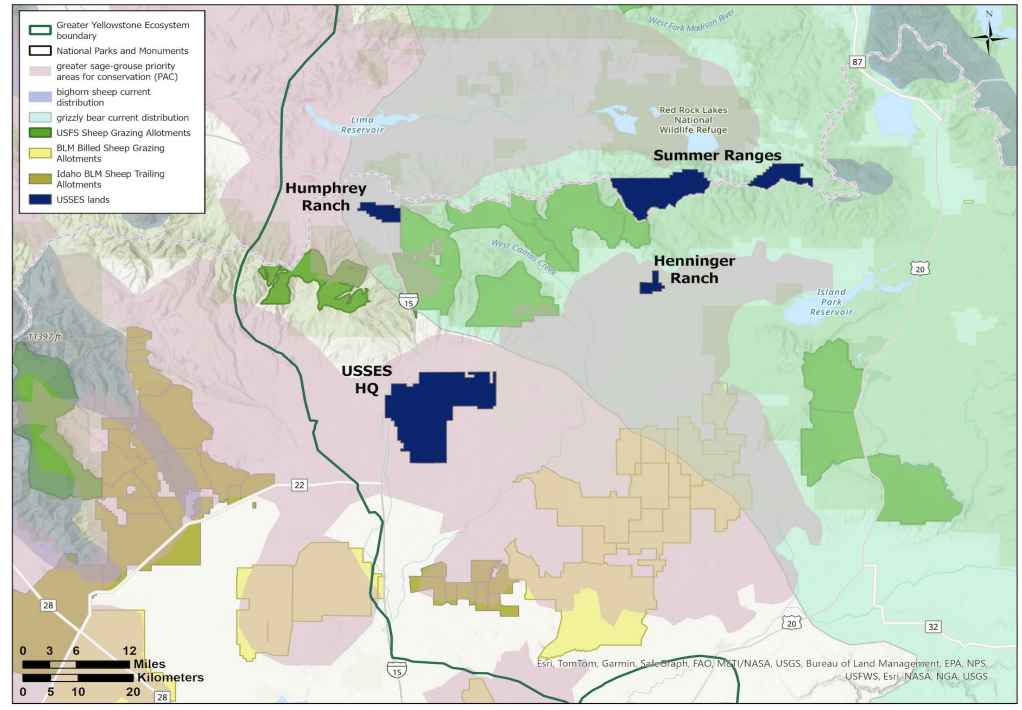
1.1. Multifunctional Land Management Challenges

Across many systems, such as the Greater Yellowstone Ecosystem (GYE) in the western US, extant or potential interactions on working lands between wildlife and livestock are often translated into ideological conflict between wildlife advocates and ranchers. These can drive broader legal, administrative, economic, and land management issues [13]. And, while the perception of a zero-sum relationship between livestock and wildlife has been common for decades or centuries, increasingly complex and volatile socio-political dynamics, land use change, and climate change impacts are increasing threats to both the social and ecological sustainability of rangelands [14–17].

In this context, isolated disciplinary understandings of rangelands (e.g., wildlife or animal agricultural systems science) are growing both less valid and less helpful. There is a growing need for research that transcends disciplines and conflicts [2,18]. Assuming that the demands of diverse social goals for the lands have some validity [19], working lands communities have increasingly called for more systems-based approaches to overcome the many mounting social frustrations about rangeland management [20–24]. Additionally, local land managers, ranchers, and communities often have strong collaborative traditions as well as ethical and institutional frameworks for community-based natural resource management [21,25,26]. Now, governmental land managers are establishing venues for transdisciplinary researchers and partners (here,

we use the term partners, sometimes known as stakeholders, to include societal actors from various backgrounds who are interested in or committed to some form of collaboration or coordination. See [27]). In the case of rangelands in the US, this may include local communities and governments, tribal governments, researchers/academics, public agencies or non-profit organizations, environmental and conservation advocates, students, and other private organizations, among others) to seek common ground—both literally and figuratively—through cross-boundary engagement and experimentation [28,29]. As examples of collaboration become increasingly common, new questions are emerging: what methodologies will enable actionable learning [30,31], and how can proven processes of collaborative management be scaled up and institutionalized across multi-jurisdictional landscapes?

The goal of this paper is to describe a promising collaborative adaptive management (CAM) methodology for addressing multifunctional land management challenges directly with transdisciplinary research, using a range sheep research ranch in the GYE (Figure 1) as a case study. This case study explores the potential of the US Sheep Experiment Station (USSES) in Idaho, USA, to contribute to working lands sustainability by directly addressing conflicting views of rangeland management in the GYE. Here, a new living laboratory project called the "USSES Rangeland Collaboratory" was established in 2023. The project brings diverse societal partners and scientists together through a ranch-scale rangeland management study to evaluate different scenarios for range sheep production systems, following the USDA-ARS Long-Term Agroecological Research Network common experiment design [32,33]. These scenarios reflect dominant, opposing visions for rangeland use. One is a "land sharing" model of extensive range sheep production desired by ranchers, wherein sheep are moved onto federal grazing allotments in the mountains during the summer, where they graze areas that may be used simultaneously or sequentially by wildlife. On range sheep operations, the specific research focus of the USSES, sheep typically graze in large bands (about 1000 ewes plus their lambs) with continuous attention from one or more herders. This emphasizes transhumance, disturbance ecology, biocultural diversity, and mobility while requiring specific attention to high-elevation wildlife–livestock conflict reduction [34–36]. Importantly, the extent to which livestock and any particular wildlife species of concern actually overlap temporally and spatially is highly variable and may not be well understood. Conflicts over the "land sharing" model can be fueled by assumptions of maximum or minimum wildlife presence that may have little factual basis. The second, a "land sparing" approach, is modeled after the desires of members of the conservation community, often those advocating for specific wildlife species. This model excludes livestock from certain high-elevation summer ranges to reduce the potential of certain forms of livestock–wildlife conflict but may require intensified land management practices and/or additional supplementation to bring lambs to market [37,38]. Notably, the "land sparing" model has the potential to spare mountain pastures from livestock grazing while increasing pressure on wildlife habitats at lower elevations. What management regime constitutes "land sharing" versus "land sparing" can thus depend on what species, habitat, resource, or feature one is focused on.



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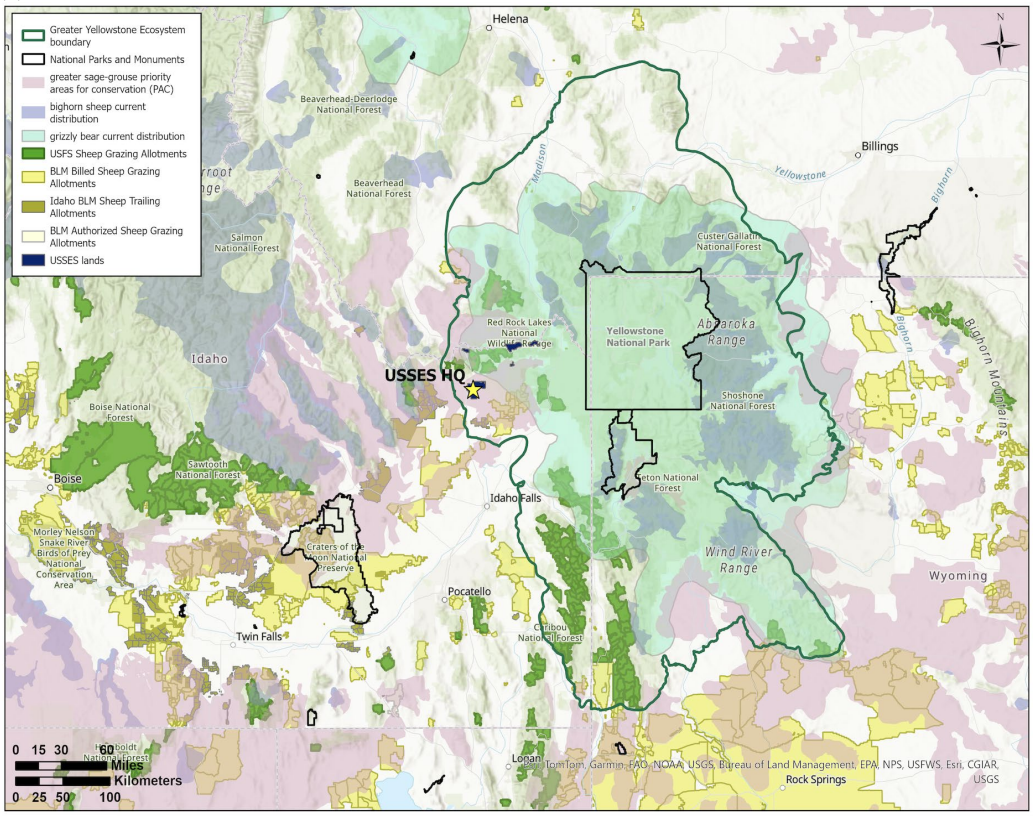

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Figure 1. (**a**). The US Sheep Experiment Station (USSES), headquartered in Dubois, Idaho, US, is a research ranch operating at a commercial scale as a range sheep production ranch. (**b**) The USSES sits on the western edge of the Greater Yellowstone Ecosystem. It includes lands in the Snake River Plain at the far northeastern reaches of the Great Basin, and mountainous areas in the Centennial Mountains, at the headwaters of the Missouri River basin. This region is a complex mosaic of ecosystems and jurisdictions in the US Intermountain West that include core habitat areas for multiple wildlife species, grazing uses, and growing populations. Maps by Nicole Strong.

1.2. Regional Social–Ecological Systems in the Greater Yellowstone Ecosystem

As the largest functionally intact temperate ecosystem in the world, the Greater Yellowstone Ecosystem (GYE) is an iconic conservation priority area, spanning some 19 million acres and hosting two national parks, other federal lands managed by multiple departments (including US Departments of Agriculture and Interior), state, private, and tribal lands [17,39]. The GYE still contains large expanses of wildlife summer and winter habitats, and migration corridors between the two. Thus, wildlife conservation is a priority issue for agencies and the public. The GYE is also home to working lands communities and is important for regional economies and food systems as it draws tourism, recreation, and service industries [40].

In this context, major social and ecological concerns for the future sustainability of the region are inclusive of issues related to livestock production, social conflict reduction, and rural community well-being, as well as biodiversity conservation (Table 1). These include the challenges of continually adapting extensive range livestock production systems to harsh environments and complex socio-environmental contexts [35]. On range sheep operations, the specific research focus of the USSES, sheep graze in large bands (about 1000 ewes plus their lambs) with continuous attention from one or more herders. Ranchers leverage knowledge of landscape-scale heterogeneity, changing water resources, and diverse plant community types to adapt to changing forage quality, weather/climate, and economic/social dynamics [41,42]. Range sheep social–ecological systems also produce patterns in grazing, social–environmental connectivity, and ranching community dynamics that affect the timing and rate of herbivory, nutrient, and carbon cycling and shape the vegetation community structure. They also create transportation and land management infrastructure, influence fire and wildlife ecology dynamics, and support a class of actors. Although the range sheep industry was a dominant industry, shaping communities and landscapes here and across the west [43,44], this industry has shrunk in recent decades [36]. Today, as in the past, the agroecological challenge of the range production system is to maintain and bolster adaptive capacity, or the ability of the system to better cope with, manage, or adjust to some changing condition, stress, hazard, risk, or opportunity [45]. This includes drawing from a repertoire of relational practices, including human and non-human relationships [46].

Significant challenges to sustainability in the GYE also stem from divergent land uses and goals [47,48]. Especially notable examples of this conflict include those between livestock production and a rich assemblage of migrating ungulates in Yellowstone's Northern Range, including with issues related to grazing ecology and the transmission of diseases such as brucellosis [39,49–53]. More dramatically, the reintroduction and rapid establishment of grey wolves (*Canis lupus*) in the 1990s across a multi-state area has played a large role in the context of the GYE [54–56]. This was vigorously opposed by livestock and hunting interests, and has resulted in predation issues and financial losses for domestic stock owners [57]. A further major concern for the wildlife conservation community is disease transmission between domestic and wild sheep (*Ovis canadensis*) [58]. This concern led to the removal of domestic sheep from public lands to the north and east of the region in the Absaroka and Beartooth mountains by the 2010s [59], and the loss of USSES grazing allotments to the west in the central Idaho mountains [36]. On the western side of the GYE, where the USSES operates, concerns center on the recovering grizzly bear (*Ursus arctos horribilis*) populations and improving connectivity from the GYE to broader Northern Rockies landscapes [60,61]. Greater sage grouse (*Centrocercus urophasianus*) is also an important species of concern that is threatened by a loss of habitat due to urban and exurban development, as well as changes in vegetation communities and fire regimes [62–66].

Table 1. Motivating factors for rangeland system well-being at the USSES are organized around core challenges identified in initial stakeholder engagement meetings held online by USDA-ARS staff between 2021 and 2022 during the early stages of the Collaboratory project.

Sub-System	Core Challenge	Examples
Ecological system	Food and fiber production	• Reduced meat and wool production
	Ranch operational needs	• Loss of traditional ranching practices, knowledge, and relationships • Need for management flexibility • Reduced mobility and access to diverse grazing land ecosystem types • Reduced flexibility in matching animal nutritional demand to supply • Lack of resilience to disturbance events (i.e., drought) • Need for technological and adaptive management innovations
	Social and ranch profitability issues	• Rising input, labor, and other production costs • Limited marketability and revenue of lamb and wool • Reduced social license to operate and conflict with wildlife conservation goals • Challenges passing knowledge and working operations to the next generation
	Rangeland vegetation management	• Barriers to sustaining pattern and process of heterogeneous, biologically diverse landscapes that provide habitat, forage, and ecosystem function • Risk for encroachment of undesirable annual grasses and woody species • Risks from harsh climates and increased variability: shifting phenology, seasonality, hydrology, and fire ecology • Wildlife ecology and management • Urgent need to conserve large carnivore populations, including grizzly bear and grey wolf (risk of lethal conflict with livestock) • Risks to wild sheep population recovery (disease transmission risk with domestic sheep) • Loss of sagebrush ecosystems; risks to sagebrush-obligate species from development, grazing pressure, invasive plant species, and changing fire regimes
Social system	Social–ecological issues	• Conflict between biodiversity and agriculture and/or other users • Increased social demand for hunting/recreation access to landscapes
	Food systems	• Growing disconnects between producers and consumers • Limited community access to high-quality, regionally or locally raised food • Vulnerability of food system to shocks and stressors, including local and national events
	Conflict reduction	• Hard-line positions drive persistent conflict over land use priorities • Limited trust, communication, and collaboration among actors • Little capacity to prevent or address conflict
	Adaptive capacity and social learning	• Barriers to learning and adaptation in complex systems • Institutional and governance structures create barriers to enabling collaborative problem-solving, experimentation, and growth mindset. • Need for multiple-loop learning, whereby actions, objectives, and overarching goals are re-evaluated and modified based on new information • Disciplinary silos and exclusion of local knowledge

At the intersection of ranching and conservation land uses, we find a complex political ecology in the GYE [67]. Ranchers operate on private, state, tribal, and federal lands, many of which are near protected areas (e.g., national parks and wildlife refuges) and are thus influenced by the management and social priorities of protectionist paradigms. Ranching organizations argue that extensive rangeland production systems can be remarkably adaptive to harsh climates and environments, contribute to environmental management for biodiversity, and support broader positive outcomes for cultural, economic, and sociological systems. But the conservation community has continually argued that livestock impact riparian areas and upland plant communities, and that livestock and wildlife cannot coexist because of depredation or disease transmission. As the public pushes to prioritize wildlife conservation goals, particularly on public lands, and society becomes more disconnected from local food systems and agricultural economies, ranchers face reduced public license to operate traditional extensive production systems. This contributes to reduced rancher access to public grazing lands, which, coupled with land use change, drives concerns about the slow disappearance of traditional livestock production systems, local knowledge systems, economic and cultural impacts on rural communities, and wildlife habitat loss [21,40,68,69].

Despite the potential of an economic model of working lands conservation, decades of local and regional discursive, political, and legal conflict have eroded trust among conservation and industry groups such that persistent "othering" and stigma reinforce these divides [13]. Solutions to these problems are further constrained by social and ecological variability and complexity, including multiple overlapping bureaucratic land management and regulatory jurisdictions, shifting ecological dynamics (fire regimes, climate, and populations of large carnivores), as well as rapid land use and social change during a recent period of economic growth [70].

In recent decades, these dynamics have motivated the formation of land management collaboratives comprised of ranchers, conservation organizations, recreationists, public agencies, and other stakeholders. These groups convene to contribute to land use planning and management projects that address economic, social, and ecological issues. Successful cases include the US Forest Service's Collaborative Forest Landscape Restoration Program, which authorized collaboratives and led to improved trust among partners, improved restoration project outcomes, and the diffusion of best practices beyond project boundaries [71]. However, the US Department of Agriculture-Agricultural Research Service, USDA's in-house research agency, has not yet conducted research to inform the collaborative adaptive management of rangelands for multiple ecosystem services in the GYE.

2. Materials and Methods

2.1. Study Location: The US Sheep Experiment Station

The US Sheep Experiment Station is a United States Department of Agriculture-Agricultural Research Service location and University of Idaho Experiment Station, home to the Range Sheep Production Efficiency Research Unit (RSPER). This laboratory was chosen for this project because it has sufficient land, animal, and scientific resources to offer a living laboratory for a collaborative adaptive management project addressing complex and integrated questions for rangeland managers and livestock producers. With headquarters in Dubois, Idaho, the USSES is a commercial-scale (>3000 ewe flock) range sheep operation that includes 19,000 ha (47,000 ac) of land within the Snake River Plain (NRCS MLRA 11, diverse sagebrush steppe) and montane zones of Clark County, Idaho, and in the Centennial Mountains (Central Rocky Mountains–MLRA 43B, diverse forb, open woodland and sub/alpine areas) in Beaverhead County, Montana (Figure 1). The USSES was established in 1916 and specializes in animal production genetics and rangeland ecosystem sciences. Furthermore, given the social–ecological dynamics around livestock–wildlife management at the USSES, this Collaboratory offers a valuable case study that can inform social processes for community-driven and science-based land management practices more broadly.

The USSES Rangeland Collaboratory project marks the first attempt by researchers at the location, and broadly within USDA-ARS, to address complex social–ecological conflicts with a living laboratory project [72,73]. The project was motivated by requests from producer and conservation stakeholders following decades of legal and social conflict over the USSES's use of their extensive rangeland pastures for sheep research [36]. The project's methods respond to clear demands from both ranching and conservation stakeholders that the location's research address issues related to conflicts between agricultural and biodiversity goals. These issues are specifically focused on mountain "summer ranges", where domestic sheep may graze land home to large herbivores, grizzly bears, wolves, and wild sheep, and on lower elevation spring and fall pastures, where greater sage grouse, a suite of shrubland birds, large herbivores, and other biodiversity depend on intact sagebrush ecosystems (Figure 1). The ecological and social context of the USSES makes research here broadly relevant to areas where sheep and cattle graze US Forest Service

and BLM lands across the GYE and Intermountain West, including in Idaho, Montana, Wyoming, and Utah [36,74–78].

2.2. Methodology

The methodology for the USSES Rangeland Collaboratory is motivated by the rising presence of land management collaboratives operating across rural landscapes and public land contexts throughout the western US. These collaboratives are often organized around public land management units such as a National Forest (e.g., "Forest Collaboratives") where different interest groups have multiple, often disparate ideological views of land management [71]. The underlying theory of these groups is that collaboratives create a space where people can turn their different ideological concepts into management decisions about ecosystems at a designated geographic scale [79].

By modeling a science-based process, the USSES Collaboratory seeks to develop paths through entrenched socio-environmental conflict and promote social learning. The framework of the project draws from multiple traditions to bring societal partners and researchers together in a participatory process of adaptive management [80,81]. We chose to develop the Collaboratory as an Agroecological Living Lab (ALL), which is a transdisciplinary farm systems research approach [73]. This approach seeks to improve the pace and uptake of research innovation via user-centered, co-produced scholarship that applies and evaluates agroecological research in real landscapes. This brings attention to farm-scale transformations and to transdisciplinary research that is action-oriented, in line with agroecological traditions [82].

This project is explicitly transdisciplinary. While much recent discourse around public lands management conflict emphasizes the need for conflict reduction, few projects have sought to actively integrate different stakeholders into research for explicit conflict reduction. Transdisciplinary research seeks to improve trust and the application of research around complex systems issues by sharing research decision-making, engaging local knowledges, and including diverse societal goals. Transdisciplinary scholars recognize that society will need to weave diverse knowledges to develop solutions to complex or "wicked" issues [83,84] and can help break persistent human/nature binaries that limit these solutions. Therefore, a core part of the Collaboratory approach involves the integration of ecological, production, and social science expertise and modes of collaboration that can work with the viewpoints brought by scientists from different traditions, land and wildlife managers, and ranchers in respectful and meaningful ways [85,86]. Weaving various knowledges into transdisciplinary research alongside social and biophysical research expertise is vitally important to multi-scalar knowledge generation and application [87,88]. This project also aims to document and evaluate this methodology to provide a more scientific picture of if and how the approach leads to effective conflict reduction and adaptive management.

Because the USSES operates as a working sheep ranch, it provides the opportunity to apply these methodological concepts through a process called collaborative adaptive management (CAM) [80,89]. CAM combines adaptive management (the dynamic application of experimental or scientific methods to improve the effectiveness of management planning and action [90,91]) with collaborative processes (the integration of democratic and inclusive processes to enhance action, learning, and social–ecological outcomes) [89]. This centers on iterative steps to "plan", "do", and "evaluate and adapt". These include assessing baseline conditions, establishing goals and objectives, developing and implementing treatments and controls, collecting and interpreting data, and adjusting management based on new information. The Collaboratory thus brings diverse partners into the "plan", "do", and "evaluate and adapt" phases of adaptive management by co-managing the range sheep

operation at the USSES to enhance learning through a community of practice, trust, and engagement with new information and management approaches [92].

2.2.1. Links to Other Living Laboratories

While CAM is a long-standing methodology in natural resource management, it has never been implemented in a high-conflict rangeland management system, making its application via the USSES Collaboratory to the GYE novel. We draw from methods used in ARS's flagship CAM project—another Living Lab and a Long-Term Agro-ecological Research (LTAR) network location—in Eastern Colorado, USA, called The Collaborative Adaptive Rangeland Management (CARM) Experiment. Here, a ranch-scale study brought ranching and conservation advocates together to quantify trade-offs among multiple objectives, including ranching and grassland bird conservation, over ten years. Ranch-scale collaboration provides the opportunity for diverse partners to plan, implement, and assess the material, economic, and social consequences of different theories of land use. CAM requires participants to address one another's goals as they face the weather, markets, and social challenges in management decision-making [81] and sets the stage for collaborative learning [93]. The method models a way to foster shared responsibility and reconciliation among managers, advocates, and researchers, who, having inherited complex systems problems, have the opportunity for shared responsibility, accountability, learning, and solidarity in stewardship [94] via experimentation at the USSES. To quote one project scientist, "Shared accountability, within the confines allowed by our affiliations, is where the rubber really meets the road". If successful, the project will help us learn together and update our knowledge of how the rangeland system works. The Collaboratory applies the CARM methodologies to a more conflict-laden and complex landscape near the world's first national park, requiring greater attention to social dynamics and carnivore and big game issues.

Additionally, this design follows the ARS-LTAR common experimental design, which compares "business as usual" and "aspirational" agroecosystem approaches [33]. Engaging in this model provides an additional across-site comparative capacity, as the LTAR network includes 18 research locations around the US and collaborates with living labs around the world [95]. Finally, the approach has similarities to a process used in US land management planning by federal agencies to comply with the National Environmental Protection Act, wherein multiple alternative management scenarios, including those from the most divergent viewpoints, are considered. By bringing two distinct visions of land use to life in a comparative research approach, the study provides an opportunity to inform these land management planning processes on landscapes far beyond the boundaries of the USSES (Figure 1).

2.2.2. Peace Studies Contributions

The Collaboratory is informed by peace studies and collaboration scholarship and praxis [19]. This literature addresses conflict management and violence prevention at multiple social scales, from interpersonal to international, and is accompanied by resources for practitioners [93]. This literature is important when dealing with public lands and livestock–wildlife issues, where unresolved conflict has historical precedent for escalation at multiple scales [96]. The field of peace studies provides the concepts of negative peace (the absence of violence) and positive peace, a more sustainable peace built on investments in positive social structures that support well-being at multiple scales (from individual to societal). These concepts help inform the development of social indicators in the project, which include evidence of peaceful conflict outcomes, the development of tools and strategies to deal with conflict, and evidence that participants are developing positive social

values for their relationships with one another and nature (see Supplementary File S1). Peace studies scholars also theorize multiple potential outcomes of a conflict. These include a "winner takes all" scenario, withdrawal, or compromise, all of which are eventually satisfactory for one or more parties [18,19]. The development of long-lasting peace, or positive peace, may require transcendent and transformational outcomes that fully reframe and reimagine the scenario, digging conflicting parties up out of the entrenched, original situation (the "TRANSCEND" method [97]). The Collaboratory integrates these ideas by explicitly aiming to move rangeland management issues towards compromise, which pairs nicely with classic CAM approaches, and further still towards transformational outcomes that co-produce structures and resources that promote well-being and peace. For example, the Collaboratory seeks to create space for collective visioning wherein diverse stakeholders can imagine, enact, and evaluate alternative scenarios of ranching systems and bring new paradigms into existence.

2.3. Study Design

This theoretical background informs three stages of the USSES Collaboratory: (1) baseline social and agroecological assessment; (2) collaborative adaptive management planning; and (3) a ranch-scale experiment. Stages 1 and 2 were initiated in 2024, while stage 3 is scheduled to begin after 2025 (pending funding) (Figure 2, with timeline in Appendix A, Table A1).

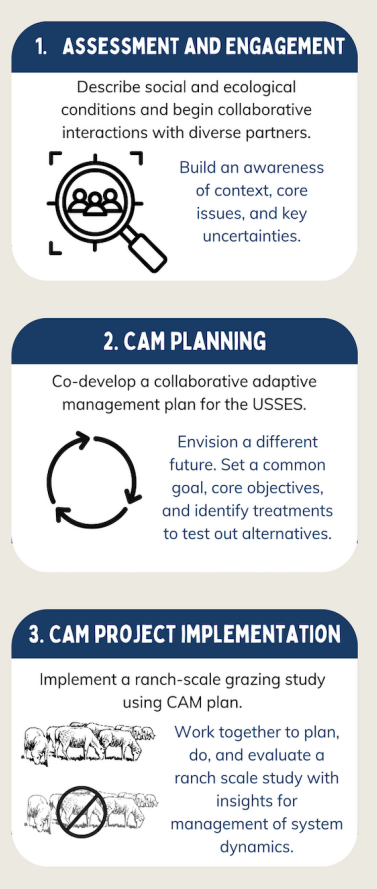

Figure 2. The US Sheep Experiment Station Collaboratory includes three stages to enact a ranch-scale collaborative adaptive management project.

2.3.1. Social Baseline Assessment (Stage 1)

To describe a starting point for social dynamics related to rangeland management in the region, we follow the natural resource collaboration literature [97,98]. This research

was approved by the University of Idaho Internal Review Board (IRB) Protocol: 24-004, Reference: 026642. In 2023–2024, we identified key partners and public groups interested in the USSES based on past stakeholder meetings and engaged individuals from these groups (e.g., agriculture industry groups and ranchers, conservation and environmental law organizations, outreach professionals, public agency staff, recreation organizations, regional collaboratives, researchers) in semi-structured interviews. These focused on understanding how they relate to the systems in which they work [99] and prompted conversations about their goals, mental models of system dynamics, and research needs [74,98]. Adult informants from target sub-groups and viewpoints were recruited with a network ("snowball") sampling method, whereby participants were contacted from known networks first; then, researchers asked for referrals to previously unknown groups or individuals [100]. These discussions continued until the target sample size (60 total participants, with at least 10 in each sub-group, approximately three times the number of regular participants in the project meetings) and conceptual saturation were reached (meaning that additional interviews do not lead to qualitatively novel insights). This qualitative sampling frame was not intended to sample a representative or random sample and results cannot be used to make predictions about a population. Qualitative data analysis steps included transcribing interviews and systematically coding the data to identify patterns, themes, and outcomes using a computer spreadsheet. We enhanced the validity and credibility of the research (called "trustworthiness" in qualitative methods) using systematic coding protocols for a grounded theory approach, which iterates between codes developed from the interview guide and emergent codes [101,102].

The study design follows an inductive comparative case approach that builds theoretical knowledge about the interviewee's backgrounds as well as the experience of the participants from interaction at meetings. Specifically, the coding process involved the open and thematic coding of each interview to identify participant's goals, key uncertainties, and mental models of social–ecological systems. We then wrote analytic memos and summarized these into themes that highlight agricultural and conservation views. Emergent themes include the motivations, goals, and methods of specific sub-groups, including conservation and environmental actors and ranching industry actors. Additionally, we identified different scales at which these actors interact with knowledge feedback and management contexts. We elaborate on these themes in Section 3.

The choice of qualitative methodologies enables us to study nuanced, complex, and subjective aspects of social processes where larger sample sizes are not required or feasible and when the research is in an inductive phase [103]. Qualitative analysis produces themes and middle-range theory or hypotheses using a case-study sampling logic to compare case outcomes, not a random sampling procedure, and the findings can be evaluated with quantitative survey research in the future. Our approach allows us to contribute to natural resources social science while also co-creating a context-specific set of social indicators, similar to those for ecological and agricultural subsystems (described below). Additionally, the process is highly social and enables the team to engage new partners, developing relationships and building trust.

2.3.2. Ecological Baseline Assessment (Stage 1)

The agroecological assessment focuses on sheep production and ecological systems at the scale of the USSES. Elements of the ecological assessment include rangeland vegetation and ecological indicators of ecosystem service provisioning, and draw on more than a century of ecological research conducted on the USSES [77,104–106]. (Table 2). Existing datasets and new sampling efforts evaluate vegetation production, hydrologic function, soil health, forage quality, and plant and pollinator biodiversity [107,108]. Categories of

indicators for this assessment and the future monitoring of progress towards ecological goals include annual net primary production, water and soil health, plant and insect biodiversity, wildlife habitat quality, and wildlife biodiversity (see Supplementary File S1). Wildlife habitat heterogeneity and species occupancy provide a starting point for adaptive decision-making during the second phase of the project. Livestock performance metrics include common indicators of lamb birth and weaning weights, grease wool production, and body weight and body condition scores collected at the USSES (see Supplementary File S1), which can be paired with input costs and market data to model economic outcomes. Baseline social and ecological data will inform the development of the CAM plan (Stage 2) and plan components in Stage 3.

Table 2. Collaborative adaptive management plan parameters for the USSES Collaboratory.

Experimental parameters	• The project must address social, sheep production, and biodiversity outcomes at the same time. • Treatments are determined by a collaborative adaptive management plan that includes goals, objectives, indicators, treatments, monitoring plans, and triggers for adaptation. • When the partner group makes a decision, they hypothesize outcomes for all objectives. • Land access is predetermined by design, but partners make adaptive decisions within the season. • USSES will not install additional permanent fencing or roads. • Actions are subject to federal policies/procedures, research ethics considerations, and best management practices.
Components of CAM plan	1. Collaborative process 2. Framework for decision-making 3. Project overall goals and objectives 4. Indicators for success 5. Annual adaptive rangeland management 6. Among season grazing use, within sequence and duration of grazing 7. Contingencies for drought, water, toxic plant, or other limitations 8. Wildlife–livestock conflict reduction approaches 9. Other vegetation management (e.g., prescribed fire) 10. Weaning dates 11. Operational narrative and marketing strategy 12. Triggers for when/when not to implement management decisions 13. Additional social or collaborative activities
Who makes decisions? How are decisions made?	Participation is open to the public, with specific invitations sent from USSES staff to a list of organizations and individuals identified by a regional conservation leader to have an existing interest in USSES research. Meetings are advertised in a local collaborative newsletter. The collaborative adaptive management plan is developed and modified by a smaller volunteer group of "board of stakeholders" with balanced representation from various agency, agriculture, and conservation backgrounds in conjunction with scientists; meetings and discussions are open to the public. Project decisions are made with a consensus-based process within the board and are open to comment from all participants.
Annual decision cycle	Winter meeting: In-depth data review, propose new decisions Spring meeting: Final grazing season decisions Mid-May-October: Implement treatments, monitor Summer: Field tours, data collection volunteer opportunities Fall meeting: Review initial grazing season results Throughout the year: Digital team communication

2.3.3. Collaborative Adaptive Management Planning (Stage 2)

The second stage of the project kicked off in late 2024 with the identification of a core group of engaged stakeholders from divergent backgrounds and interests with whom to co-develop a collaborative adaptive management plan at USSES. The process involves a series of meetings during which information from Stage 1 and collective expertise and

discussion shape an overarching goal and objectives for a forthcoming CAM plan (Table 2). To achieve the selected goal and objectives, the group will be tasked with identifying experimental treatments, project timelines, data collection and monitoring plans, social and economic considerations, and steps for evaluation and adjustment, including triggers for adaptive change [109,110].

Next came the collaborative decision-making process. CAM also involves the co-design of the project's collaborative structure, including decision-making processes and the identification of logistical and scientific sideboards, meaning the limits on experimental design and treatments established by scientists (Table 2). Examples include parameters that the study should evaluate ranching livelihoods, biodiversity, and social learning outcomes for the research partners (ranchers, conservation groups, land managers), following previous research on indicators of agroecological sustainability and ecosystem services [89,107,111].

Stage 2 also included the development of a ranch-scale management study. The Living Lab model centers on biophysical science co-production and experimentation at realistic spatiotemporal scales. While the collaborative adaptive management process involves direct participation from public partners in the research at all steps, the possibilities of this plan are necessarily constrained by the physical, logistical, and scientific limitations of the research facility and staff. During the CAM planning processes, the research team worked to establish the logistical constraints to the experimental design and prepared the facility to implement the study in the future (Tables 2 and 3). Establishing the grazing study design was likened to establishing the "rules of the game" and gathering resources with which partners would experiment with different management approaches once the CAM study was implemented.

Table 3. Physical design for ranch-scale management study to be implemented in future Stage 3. The adaptive management plan for each scenario will be developed collaboratively (see Table 2).

Land base	Ranch-scale scenarios developed from within current USSES land resources. Land resources for each scenario are paired within seasonal ranges based on ecological sites/states, water resources, and location.	
Phase of production calendar	Scenario A: Extensive system sheep grazing "Land sharing scenario"	Scenario B: Intensive system sheep grazing "Land sparing scenario"
Grazing Spring range 1 June–1 July	Sheep grazing sagebrush steppe at Headquarters	Sheep grazing sagebrush steppe at Headquarters
Grazing Summer range 1 July–1 September	Sheep move to summer range in Centennial Mountains	Sheep grazing restricted to sagebrush steppe at Headquarters
Grazing Fall Range 1 September–30 December	Sagebrush steppe at Headquarters, breeding in feedlot, fall grazing on crop aftermath	Sagebrush steppe at Headquarters, breeding in feedlot, fall grazing on crop aftermath
1 January–1 May	Feedlot for winter feeding, sheering, and lambing	Feedlot for winter feeding, sheering, and lambing
Livestock and management resources	Each treatment has access to one band of sheep (300–500 ewes with lambs) from 1 June to 1 October. Each band is supported by full operational staff, including manager, camp tenders, water tenders, and, when necessary, one herder. Within each band, approx. 100 resident sheep from the Targhee breed and 100 from a fast-growing terminal composite breed will follow each treatment for the life of the study, with the remaining ewe numbers randomly assigned from the USSES flock.	
Stocking parameters	For the first year, stocking rates held constant among treatments and determined based on rancher/herder preferences for sheep band manageability with consideration of other objectives.	

To do this, we identified multiple alternative operational structures that reflect various approaches to range sheep production under seasonal range access scenarios that align with conservationist or production-focused viewpoints identified from our interactions with stakeholders and reviewed above [36]. The Collaboratory was established in response to entrenched regional conflicts over livestock grazing in areas with high values for both range sheep production and conservation and the experiment was designed to inform these challenges. This is why the seasonality of grazing was the primary variable around which to design the experiment. Scenario A reflects a full transhumant range sheep operation, with expanded access to seasonal summer ranges (a land-sharing scenario) [36]. Scenario B was based on restricted grazing to seasonal ranges (a land-sparing scenario), with no summer range grazing in the Centennial Mountains (Table 3). The project scientists identified a single sheep breed (Targhee) for which a sufficient number of ewes (100) is available to remain with a larger band (300–500 ewes) in each treatment permanently to control for the effects of animal genetics and improve the tracking of animal performance outcomes.

2.3.4. Ranch-Scale Management Study

The ranch-scale management study will be fully implemented after the baseline data are collected and reported (post-2025), and when the CAM plan is finalized under consensus from the participants. Over five years, participants will then have the opportunity to compare how changes to the season of grazing (as a result of simulated loss of or access to seasonal ranges because of social conflict) and adaptive vegetation management choices (grazing rest, prescribed fire, and sequence of pasture rotation) during the growing season (May–October) impact social, agricultural, and ecological outcomes deemed important to the collaborative team. Indicators of progress towards objectives will be documented by the research team and evaluated iteratively by participants.

3. Results

Here, we report key early insights from the first year of the project, including social baseline assessments (Stage 1) and collaborative meetings devoted to co-developing management structures and actions on the USSES (Stage 2) that might serve as a model for reducing range conflicts across the GYE and beyond. We focus on insights from the social and collaborative aspects of the project, as agroecological and deeper social science analyses are forthcoming in other publications.

3.1. Documenting a Complex Context: Insights from Stage 1

We identified dominant actors in the region's range landscapes and core challenges to sustainability (Table 1). We identified a wide range of actors and projects ongoing across the region that worked within and across public and private lands, with a patchwork of federal, state, and tribal jurisdictions, and were motivated by a wide range of missions and values (Appendix B).

Qualitative data provide insights into the motivations, goals, and methods of specific sub-groups, including conservation and environmental actors and ranching industry actors. Environmental and ranching industry groups both actively engage with several methods from policy advocacy, litigation, education, and research to achieve their goals. There is a wide range of conservation and environmental groups operating in the region, including wilderness, sportsmen's groups, and environmental law organizations. In various ways, these stakeholders have taken the role of protecting or fighting for nature or wildlife. In interviews, environmental advocates express a range of views towards their own role in the system and toward agriculture. Only a few expressed animosity and the dismissal of the ranching way of life and goals and many noted that the conservation community holds that

certain landscapes, including some traditionally used for sheep summer range in the GYE, are not appropriate for food production. However, members of the environmental and conservation community largely remained positive about opportunities for collaboration and the value of working with ranchers, focusing on the importance of sustaining or improving wildlife populations and asserting the need to protect grizzly bears and wild sheep.

For example, co-author Bruce Mincher, from the Idaho Wild Sheep Foundation, provides an in-depth look at how wildlife conservation issues across the region could be informed by collaborative research at USSES (Box 1). This outlines the historical context, benefits, and limitations of the framework of wildlife conservation from which his organization operates. It also provides context for how conflicting goals between wildlife and agricultural interests have both challenged sustainability outcomes and inspired collaboration and research efforts to address complex rangeland problems.

Box 1. A conservation advocate, Bruce Mincher from the Idaho Wild Sheep Foundation, describes his views on wildlife as a use of the land.

"By the end of the 19th Century, populations of wild species like elk and pronghorn antelope that we now consider common had been nearly eliminated in the GYE and elsewhere across the West. This occurred mainly by a combination of direct mortality through unregulated market hunting and shooting to protect crops, as well as the modification of key habitats on winter range and along migration routes for agricultural use. Predator populations were intentionally reduced to benefit domestic stock for obvious reasons. The introduction of livestock to western rangelands also inadvertently introduced microbes with adverse disease effects for wildlife, most notably those implicated in the large-scale die-offs of bighorn sheep. These mass mortality events were a common feature of wild sheep management until very recently.

The precipitous decline of wildlife was brought to public attention by the hunter-naturalists of the 19th Century. They popularized the plight of wild species in their writing and thus gave rise to a nascent wildlife conservation movement in the early 20th Century, finally resulting in a proliferation of game protection legislation and the creation of wildlife management agencies at the state and federal levels, evolving into what is today known as the North American Model of wildlife conservation. The model posits that wildlife is owned by the public but managed in trust by the government. Wildlife cannot be used frivolously or commercialized and conservation is largely funded by taxes and fees on anglers and hunters. The North American conservation model (e.g., [112]) has been a spectacular success. North America is a highly industrialized continent that still contains large numbers of free-ranging, migratory wild animals.

While state wildlife managers have the responsibility to manage those species not under the federal jurisdiction of the Federal Endangered Species Act (ESA), they do not control the land upon which most wildlife habitat is found. The habitat is managed by other state and federal entities, with competing priorities, including public lands livestock grazing. The USSES is a case in point, where USDA manages high-elevation pastures in the Centennials that are home to a suite of wild ungulates and predators. While this system is complex and attempts to balance land use priorities it often presents a conundrum for wildlife conservation. How does one properly manage wildlife without control of the land?

Under the US wildlife conservation model ungulate populations rebounded, but predators such as grizzly bears and wolves declined until recent times. ESA protections were necessary to recover grizzly bears and wolves and both have now exceeded their legally-mandated recovery goals. Both are common animals in the Centennial Mountains of interest to the USSES. Although wild sheep once occurred in the Centennials they are now essentially absent there, with the possible exception of foraying individuals from the Beaverhead Mountains in the west and the Lionhead population in the east. These wayward individuals present a risk of contact with domestic sheep, potentially facilitating disease transmission between wild herds and domestic flocks. Given this history it was inevitable that wildlife conservationists would sometimes develop adversarial relationships with the agricultural community. These are among the wildlife conflict challenges that the USSES faces in its attempt to develop a research plan acceptable to disparate stakeholders. How can domestic sheep be grazed on summer pasture in the Centennials while providing for adequate separation of wild and domestic sheep? How can domestic sheep be grazed with minimum losses to predation with the least adverse effects on grizzly bears and wolves that rely on these mountains as a habitat corridor for expansion of their populations? Understanding that a collaborative approach among disparate stakeholders is most likely to result in beneficial outcomes for all concerned, these are among the significant issues that the Collaboratory is attempting to address".

At the same time, some environmental advocates had stronger objections to grazing research, from assertions that recovery goals had been met for wolves and grizzly or that these decisions were originally based on science, to framings of the problem that considered the "land sharing" scenario. One noted, "It is outside of our mission to strive to support domestic sheep operations in any context, let alone in prime wildlife habitat. Putting sheep back in these places will never have more of a benefit to wildlife, if it has any at all, than keeping sheep off of these landscapes. My goal is to protect wildlife". This viewpoint reflects a discourse in the conservation community taken by multiple regional and national environmental groups.

We also learned about the worldview of ranchers (Box 2), many of whom identify as land stewards with a responsibility to care for and manage ecosystem function and community-based businesses. Ranchers emphasized the importance of food and fiber production and expressed frustration over a lack of respect or recognition by environmentalists or those outside of agriculture, particularly for their self-perceived role in taking care of the land and rural communities. A mental model articulated in rancher interviews describes how disturbances such as grazing and fire play a critical role in maintaining rangeland health. As the rancher quoted in Box 2 explains, mountain grazing lands—where many conservation actors thought ranching and sheep were not appropriate—produce high-quality forage for sheep. The loss of access to these lands would reduce management flexibility and livestock nutritional opportunities, costing ranchers money and re-shaping their way of life. Ranchers also described a complex political ecology surrounding public land use (Box 2). The ability to graze on public land allotments contributes to operations' profitability, which results in keeping the associated private land holdings undeveloped, thereby providing wildlife habitats and ecosystem services. Several ranchers identified land fragmentation and development as serious threats to their operational viability. Within rancher interviews, there was a consistently expressed positive view of collaboration and science to support land management.

Across the GYE, shifting public priorities for land use, combined with changing farm and trade policies and consumer demands, and other industry challenges, have spurred concern from ranching and conservation communities about a loss of access to grazing land resources and the implications of development on wildlife habitats [21,68]. For example, in Box 2, an anonymous Utah rancher we interviewed describes an interaction between himself and an environmental advocate in which he explains the importance of summer range access to business and conservation outcomes. (The working lands conservation hypothesis is expressed here [68]. Note that empirical evaluations of this hypothesis are rare. These rangeland issues are experienced globally; compensation for wildlife damage is not typically sufficient to mitigate conflict or displacement trade-offs in the global south [11]. In the GYE, transformation away from extensive production does reshape adaptive capacity and production systems [36]. Economic growth rates above the national average [113] land use conversion, water and resource conflicts, and land prices continue to challenge agriculture's sustainability in the region [114]). These dynamics, coupled with rising high-net-worth land ownership [115] have created a sense of urgency among conservation and agricultural actors alike around the need for transformative change to ensure the sustainability of food, social, and ecological systems, and prompted a trend towards collaborative approaches to land management.

Box 2. Anonymous Utah rancher describes his views on the importance of summer range access.

"Yeah, well, there was another guy and we was at one of these Forest Service meetings, you know, the direction of the forest, how's the what's the direction of the forest? And we was at the same table, and they broke us out into tables of half a dozen people from all, you know, all walks of life, and here, sit down and talk about it. They kind of built the arena for us to sit down and talk about it. And this guy, this guy said, and he was an active environmentalist in the [valley], and I, you know, I'd known of him. Never really talked to him, just stayed away from him, like we do, and now we're forced to sit at the table and he says, 'Why don't you just take your sheep somewhere else?' He says, 'Why do you have to have your sheep on the, on the wilderness, on the [name] wilderness, on the mountain? Why do you have to have your sheep there? Why don't you just take them somewhere else?'

I was okay, okay. I said, 'Okay. Let me explain this to you'. And I did. I explained to him that those sheep had to be there for 60 days, 60 to 80 days. I says, 'Without that, 60 to 80 days, I'm out of business. I can't function without that 60 or 80 days to finish my lambs. There's no way I can do it without that. You can't go without anything to eat or sleep. You can't, you can't be homeless and foodless for 60 or 80 days. And neither can my sheep. They have to have a home, and they have to have something to eat, and it's too hot anywhere else. They have to be in those cool, in that cool mountain setting, or it's just too hot. They have, I have to have that. Without that, I'm out of business'.

And I says, 'You're thinking right now, 'So what?'' I said, 'So let me, let me answer the 'so what' question'. I said, 'I have a 300 acre farm on the river. It's got all kinds of great vistas and views for houses. People would die to have a building lot on my farm, on the river, they'd pay a lot of money. Well, my family's not going to starve. Up for sale all the farm ground and the river pastures, and that is now housing, and all the noxious weeds that I spray are now going to seed. And all the wildlife cover that exists there now is gone, and the geese and ducks that enjoy the river are going to enjoy it in front of somebody's house now. And that's if that's not enough, then let's go to my transitional range, my private ground above Avon, where the deer transition, where the elk transition, where the sharp tail grouse are, where they lek, where they have their leks or their species discontinues. Now I'm going to sell that too, for 50-acre ranchettes. Same thing happens. No one sprays the noxious weeds anymore, no one, no one manages the ground anymore. But I, but I got a lot of money, but I'm off your precious wilderness. Is it worth it? Is it worth it for me to be off your precious wilderness now that I sold these private properties for development because I had to have, I have to live, and if I can't use them if I can't utilize them, I can't even afford to pay the taxes on them. So, so, now I'm done. Is that worth it, yeah? And he put his papers down, and he sat back in his chair'".

3.2. Sowing the Seeds of Collaboration: Insights from Stage 2

3.2.1. Scales of Knowledge That Shape Collaboration

A core contribution of local collaborative processes, such as a CAM-based living lab, is that it provides a space for various management ideologies to engage within a constrained spatial scale and with limited resources through management action, therefore creating a venue for productive social learning and positive ecological outcomes [71,116]. Early insights from the first year of the project provide insights into the scales of knowledge and action that shape perspectives and issues for various stakeholders. Tables 4 and 5 present a hypothesis as to how the USSES Collaboratory places temporal and spatial boundaries on the knowledge feedback and management context for these diverse partners. This reflects the management realities of ranchers, incorporating frequent inputs from daily and seasonal management time scales across the landscape, but also incorporates the consideration of multiple ecosystem services, recognizing that the operation exists within a broader social and ecological context. In this way, it also has the potential to inform land management beyond the ranch scale with new knowledge and relationships. Additionally, individuals within groups have different disciplinary training and modes of truth finding than are used in collaborative science. For example, a participating lawyer spent additional time clarifying the intended roles of participants and discussed distinctions between their typical mode of advocating for clients and the role of co-investigators in the Collaboratory.

Table 4. Spectrum of scales of information input for various participant groups in the USSES Collaboratory. Participants generally expressed a high level of care and concern about ecosystems in the GYE, but they had distinct experiences and relationships with the ecosystems in terms of the spatial and temporal scales of the input information.

	Ranchers and Operations Managers	**Land Management Agency Staff**	**Large Herbivore Conservation NGO**	**Environmental Protection NGO**	**USSES Rangeland Collaboratory**
Scale					
Spatial	Operational scale (animal, flock, pasture, and ranch)	Thousands of square km	State, regional, and international, with a focus on key areas	State, regional, and national, with a focus on key areas	Operational scale including individual animal, flock, pasture, and ranch
Temporal	Real-time or daily and seasonal input over career or multiple generations	Daily, seasonal over career or duty assignment time frame	Annual to multi-year strategic planning horizons	Annual to multi-year strategic planning horizons	Seasonal and annual input over 5–10 years
Example of information input	Weather, pasture production curves, livestock performance, wildlife activities, market and community dynamics	Federal regulation, national, regional, and forest management priorities and plans, monitoring data, stakeholder feedback	Board and member input, regional knowledge of wildlife biology/population monitoring, partner agency, public support, volunteer expertise	Board and member input, staff expertise on broader ecological or conservation issues, public support, legal or political activities, scientific expertise	Weather, vegetation, and livestock performance indicators, annual statistical summaries

Table 5. Spectrum of scales of action for various participant groups in the USSES Collaboratory. While no group is a monolith, this table summarizes hypothesized distinctions among ranchers, federal land management staff working in a local district or management office, conservation non-governmental organizations (NGOs) such as sportsman's groups, and environmental organizations or law groups based on interview data collected in 2023–2024.

	Ranchers and Operations Managers	**Land Management Agency Staff**	**Large Herbivore Conservation NGO**	**Environmental Protection NGO**	**USSES Rangeland Collaboratory**
Scale					
Spatial	Pasture, ranch, and regional	Thousands of square km	Local project coordination, state, national, and international projects or advocacy	State or federal	Pasture, herd, and landscape, with collaboration reaching community and regional actors
Temporal	Daily decisions with career and multigenerational planning horizon	Daily, annual decisions within agency planning horizons, budget, and administrative cycles	Monthly to annual project activities; mission carried out over generations	Monthly to annual project activities, multi-year campaigns	Annual plans drive daily, seasonal decisions and operational scale changes
Examples of action	Manage grazing, livestock-wildlife interactions, genetic selection, marketing, and business operations; community and industry involvement	Staff and land management project administrative priorities, forest and grazing plan administrative, dispute resolutions, cross-disciplinary coordination	Education programs, policy advocacy, management projects, collaborative effort with managers, resource support	Public awareness campaigns, political advocacy, legal action, cross-NGO coordination	Manage grazing, livestock-wildlife interactions, marketing, and business operations; community and industry involvement
Core issues	Family ranch business sustainability, local community well-being, access to grazing lands	Stewardship of public land, service to the public, relationships with local people	Promoting conservation and management of wild sheep	Protecting wildlife, habitat, and connectivity, with a focus on endangered species and mountain areas	Knowledge co-generation to support sustainable land, food, and social systems

3.2.2. The Value of the Experiment Station

Social data and the experience of the first year suggest that bringing collaborative partners together within the bounds of the USSES is valuable for several reasons. The

group valued meeting in a specific landscape where they could gain inspiration and build connections to the land that enable in-depth conversations about ecosystem and social dynamics. The research station provides a foundational site where participants can spend time defining the scale of the rangeland system, participating in field data collection, scoping problems to be addressed, and discussing baseline data with specific pastures in mind. The research station also provides low-risk, long-term opportunities for experimentation, for example removing financial risks for producers trying new practices that may take years to implement and evaluate.

3.2.3. Challenges to Setting a Central Management Goal

Setting an overarching goal for the management study is a first step in CAM. Researchers initially envisioned using the USSES resources to create the opportunity for divergent interests to take on decision-making responsibility and co-experimentation with material outcomes (e.g., real land and real sheep). By the conclusion of the first year, participants had spent extensive time framing the problems to be addressed but had not agreed to an overarching management goal. It became clear that participants could not jump into establishing the precise design of the experiment until they had developed a shared understanding of one another's views and working ranch contexts. For example, key research questions around livestock–wildlife conflict required additional attention to interdisciplinary problem scoping. However, by 14 months into the project (in 2025), one participant proposed the goal of "Producing a financially viable domestic sheep operation that has a positive impact on the range and wildlife".

The language for the tentative integrative management goal was put forth by a conservation organization representative with a particularly acute interest in supporting the project. A representative of another environmental organization (at the time of writing) objected to the framing, asserting that wildlife benefits must come before sheep use of the land. That position has shaped much of the regional land conflicts to date, but it is also a minority position within the Collaboratory. The USSES is, after all, funded to research sheep production efficiency and is premised on benefiting the sheep industry. The proposed integrative management goal for the Collaboratory is an acknowledgment of this basic fact. It allows the USSES to meet its mission and funding obligations while simultaneously establishing a process by which conservation organizations gain some measure of input into the research process used by the USSES—a sheep-based organization by definition—to study its lands and flocks. Nonetheless, the involvement of stakeholders with contradictory positions is critical to the success of the project because those viewpoints are reflected in the dynamics of the broader social–ecological context in which the project operates. Goals and objectives (Table 6) can be developed and refined as learning continues throughout the project.

Table 6. Initial project objectives for the USSES Collaboratory were established by participants in the fall of 2024.

Social Systems	Ecological Systems	Livestock Systems
Multiple uses multiple perspectives; reduce conflict; promote healthy local food systems; increase community adaptive capacity; transhumance range systems	Wildlife: maintain and improve connectivity and biodiversity; reduce conflict with humans. Vegetation: maintain or increase habitat heterogeneity and connectivity, and core native rangeland plant communities; reduce invasion by undesirable plants	Improve animal performance and ranch profitability

The barriers we faced to agreeing on an overarching goal highlights the diversity of the group. Through this process, we recognized the value of collaboratively minded participant leaders to set the tone and intention of the project around problem-solving and collaboration. For example, senior members of the wild sheep and ranching communities both offered mentorship and collegiality with participants from various backgrounds, expressing interest in finding common ground. Some gathered to share more than their views on ecosystem management, including music, stories, and comradery with diverse participants around a campfire. This created the opportunity for multigenerational learning. When a sheep rancher offered to answer questions from conservation group members about his business experiences, and later when a retired game warden shared knowledge of how he identified bear tracks on a rural road with younger participants, these efforts set the stage for increased respect and curiosity across social groups.

3.2.4. Ranch-Scale Study Design: Insights from Stage 3

We also gained lessons from the process of developing and reviewing the ranch-scale study design with participants. This brought forth concerns from wildlife advocates that any grazing plan would need to ensure that negative livestock–wildlife interactions would be minimized, potentially through the use of innovative livestock management practices and new technologies. It also raised interest in using prescribed fire on the landscape, and attention to the project's growing camera trap array (a low-cost approach to monitoring wildlife and wildlife–livestock interactions and animal performance and behavior) [117]. The inclusion of multiple types of objectives (ecological, economic, logistical/operational) in the study design requires a significant number of disciplinary experts to evaluate the various indicators for success, including wildlife biology expertise not currently housed at the ARS. Therefore, additional collaboration and resource development are needed to fully address the complex system research needs.

The first year brought further collaborative discussions about the grazing study design. We discussed the limitations of the case study (n = 1) research design relative to broad-scale, tightly controlled experiments [118] and to replicated, controlled experiments conducted at smaller scales, which are more common in ecology [119,120]. Another key issue was the need in adaptive management for the inclusion of control or comparison groups. Without these, grazing case studies have failed to provide credible consideration of environmental (weather, climate, soil) or other confounding factors. The USSES is relatively heterogeneous and will require additional attention to adequately develop meaningful control or comparison treatments in the study design. Some ranch-scale management treatments, such as prescribed fire, lend themselves to replicated treatments/comparisons even at the landscape scale. Other objectives, such as changes in vegetation biodiversity as a result of band-scale grazing, may not be amenable to randomized treatment assignment and thus require the use of observational designs like BACI (before, after, control, impact), the inclusion of small control areas, e.g., grazing exclosures or synergistic experiments [121] or case study methods [103]. Finally, the first year highlighted the value of pilot projects and prototyping in collaborative adaptive management to set the groundwork for more fully developed landscape-scale experiments.

4. Discussion

This paper outlines the methodology and early insights drawn from a new collaborative adaptive rangeland management project at the US Sheep Experiment Station in Idaho/Montana USA. The path ahead for the Collaboratory will be a challenging effort to build stronger social relationships and social–ecological ties [116]. The CAM process provides an experimental space where groups with different ideologies can meet under con-

strained scales of knowledge, action, and ecological complexity to address the sustainable management of rangelands, food systems, and the broader GYE.

Lessons from the LTAR network (including CARM) and other existing research on transdisciplinary methods provide important guideposts for this journey. For example, the CARM project emphasized the importance of building trust as a precursor to social learning and the value of participatory, ranch-scale studies that engage partners directly in research decisions. While transdisciplinary and participatory approaches are an area of rapid methodological development [29,82,83,122], they are underexplored within US Department of Agriculture research efforts and in the GYE region on rangelands where conservation, ranching, recreation, and other diverse interests have long been in conflict with one another. Furthermore, there remain challenges to the broader adoption of Living Labs innovations across wider geographic or social scales. The degree of maturity within collaborative relationships, the extent of context knowledge within a team, and the intensity of the engagement efforts improve successful outcomes [83]. This is all the more challenging in contexts with deep or extended conflict and polycentric governance environments like public land management contexts. These are defined as a public policy and governance environment in which multiple, independent centers of decision-making are actually functionally interdependent [92].

4.1. Social Science and Interdisciplinary Engagement Foster Dialogue

A lack of trust and social networks among local managers and government agencies or environmental advocates is a known barrier to sustainable management and collaboration [123]. During engagement activities in the first year, participants acknowledged prolonged conflicts among agricultural and environmental actors in the region and expressed hope that simultaneous collaborative efforts have emerged in recent decades. Additionally, multiple participants have motivated the group with expertise, energy, and social–ecological curiosity. Various individuals came ready to make collaboration happen in multiple ways, reflecting a gift economy logic that holds that information is not a commodity but an "economy of abundance" [124,125]. However, the methodologies applied in the Collaboratory are novel for many of the partners, who have heretofore not operated as scientists, and viewed the public grazing question as a struggle for control or among value systems, not in terms of research questions and conflict transformation. Therefore, additional time and attention are needed to develop trust, clarify roles, and create norms for systems thinking and curiosity. Conservation and wildlife interest groups have long had an interest in land and wildlife management in the GYE and also in the specific activities of the USSES, but that interest has only recently turned towards support and engagement in the research. Qualitative methods remain an important tool to facilitate empathetic dialogue and to explore the motivations, methods, and goals of diverse partners. It helps us see that gaps remain in engagement with tribal and under-served communities, and in addressing rural community economic well-being through engagement with local leaders. Most importantly, early engagement brings to light areas where research can better address clear stakeholder needs. For example, spatial risk modeling [126] is a tool that could address the challenges with wild herbivore conservation and livestock–wildlife interaction outlined by partner Bruce Mincher in Box 1.

4.2. The Realities of Action Research

Early lessons from the project contribute to our knowledge of action–research methods in complex rangeland systems. While future quantitative assessments of social networks and power structures are still needed, early findings illustrate the complexity of decision-making and science forums that interact across multiple dimensions to create complex

problems across the GYE. The geographic and social variability of the relevant stakeholder groups poses a barrier to place-based collaboration and shape the type and timing of meetings in the early stages of the project. We learned that addressing this complexity requires a multi-scalar, complex systems approach to defining the problem space. Collaboratively engaging both this complexity and the real-world management implications challenges different groups to situate their individual interests within a broader context and potentially highlights the limitations and trade-offs of fixating on single issues or species.

Additionally, the social science reveals the potential of certain boundary-spanning organizations (e.g., technology transfer partners, collaboratives, inter-agency science teams, and even individual ranchers and sportsmen's group leaders) to bridge social worlds and policy arenas as the need for collaboration and adaptation increases [127]. However, because the scope of the social system here is reflected by the scale and complexity in the ecological and climate realms (not examined here), the task for collaborators and research organizations remains humbling. These same complexities motivated the rise of collaboration at local levels and across federal agencies a decade ago [28,48], but today's managers and community members continue to face interactive challenges from multiple social–ecological dimensions [61]. Our transdisciplinary methodology does explicitly intend to make positive change in the world, but the complexity and scope of the interactions identified prompt Collaboratory leaders and participants to reflect on their role as *members of* a broader social–ecological system and to consider ways to orient their work towards care, responsibility, and solidarity [128].

4.3. Implications of the Application of Peace Studies Framework

Early insights from the project are also informative relative to peace studies frameworks that focus on transforming conflict. Many partners have acknowledged that they respect the goals of other parties but also expressed an unwillingness to compromise on their core goals for the system in question. Others have stepped out of the process, withdrawing from the forum due to memories of interpersonal or legal conflict. This dynamic likely contributed to challenges in setting an overall management goal for the project and reflects strong disciplinarity within the group. This suggests that the adoption of a middle-ground theory, such as the working lands conservation hypothesis [68] as suggested by range scientists—or even Aldo Leopold's "Land Ethic", as suggested by a rancher participant [128]—may not be immediately realistic. We attribute the group's ability to outline disciplinary objectives, but initial struggles to agree on an overarching management goal, to the deep and prolonged nature of the conflict [19,129]. The GYE context requires distinct methods from those applied in CARM where a common management goal ("To pass the land down to future generations economically and ecologically") was easily developed by ranchers, conservationists, and agency staff in their first meeting [81]. Our qualitative social assessment brings nuance to the well-known dichotomy between preservationist and conservationist viewpoints and attitudes. Because several groups may remain distant from the Collaboratory process despite best efforts to engage them, considerable conflict around USSES grazing research or land use issues in the region is likely to remain.

The peace studies framework offers methodological tools here to shift focus away from "winner-takes-all" or compromise scenarios (Table 7), and to aspire to create ways to transform the situation, whether that is at an interpersonal, local, or larger scale [18]. (Galtung uses a metaphor with a scenario where there is one orange on a table and two kids seated at the table. Rather than have them fight it out, walk away, or split the orange in half, work instead to "get one more orange; get more people to share the orange; bake an orange cake, have a lottery and split the proceeds; sow the seeds, make a plantation, and take over the market" (p. 9, 96)). Through Stages 1 and 2, the Collaboratory has the opportunity to

establish a productive environment and structures we can apply in Stage 3 to "sow the seeds" of change and reproduce resources and positive social–ecological outcomes. Conceptually, shared accountability to land health and the shared value of food systems may help bridge new relationships and nourish common ground. Additionally, we observed that diverse participants held in common a love of the land and some sense of dread over the thought of endless indoor meetings with repetitive, unproductive conversations where some actors (lawyers and academics) may be more comfortable and powerful than others. Ranchers and conservation stakeholders alike suggested an emphasis on meeting outside and fostering dialogue through collaborative data collection, working with animals, and sharing food or a campfire in the field. These themes could offer a starting place for future productive directions and meaningful co-production.

Table 7. The multiple potential outcomes of a conflict with implications for rangeland socio-environmental conflicts [97]. This table outlines how the ideas are broadly applicable to rangeland systems outside of the GYE.

Outcome	Description	Application to Rangelands
One party prevails	Fight it out, adjudicate, try random methods, broaden and deepen conflict	Persistent social/legal conflict; land use priorities benefit either wildlife or agricultural interests; one party wins. "The battle for the future of the West"
Withdrawal	Avoid conflict, put issue on hold, and stop acting	Avoidance does not solve the problem. Resentment and low levels of trust drive burnout and resentment among parties; high levels of bureaucratic red tape or fear of lawsuits limit action by public management organizations. "Walk away"
Compromise	Negotiate a middle path, divide the resource among goals, identify and quantify trade-offs, and choose among alternatives.	Collaborate or negotiate land use in different places or select a middle path plan that balances benefits to different parties; engage science to evaluate trade-offs and inform decisions with more rigorous data; compromise may satisfy no one. "Science-based approaches to multi-use land management"
Transformation	Dialogue about creative ways to transcend the conflict and transform the situation; obtain more resources, bring more people in to share resources, and enhance the capacity to nurture and restore resources through collaboration. "Sow the seeds" of positive peace	Design and implement a vision for a different future. Use empathetic dialogue, experimentation, and real-life practice of ecosystem land management for multiple goals to create an environment and structures that reproduce desirable social and ecological outcomes. "Co-production of a different future"

4.4. Complexities of Ranch-Scale Systems Research

The Collaboratory approach provides researchers and communities with a real-life opportunity to evaluate the trade-offs of selecting among "land sharing" and "land sparing" approaches to production and conservation (see Supplementary File S1 for indicators). In terms of (forthcoming) Stage 3, challenges remain in implementing a long-term, ranch-scale study design needed to properly assess the group's objectives (Table 3) and progress toward the experiment's goals and objectives). Despite these complexities, the forthcoming Stage 3 is an opportunity to quantify core agroecological relationships related to range sheep production, including the role of weather, plant diversity, and seasonality in driving productivity, and the ability of adaptive grazing and fire to shape wildlife habitat and livestock performance that have not been examined holistically at this scale at USSES. Critically, it also provides an opportunity to make these results immediately available to a larger group of stakeholders through collaborative processes. Core metrics tracking rangeland plant community and forage quality, livestock outcomes, and the input requirements from

the two distinct treatments will also enable bioeconomic modeling and experimentation with different weaning or marketing approaches (see: Supplementary File S1). These findings may inspire innovative marketing, livestock–wildlife conflict mitigation strategies, income diversification or value-added strategies, and other ways to better link range sheep production to consumers. The study design also provides a baseline biophysical platform upon which additional interdisciplinary research questions can be applied. For example, bioeconomics systems modeling can integrate data from different fields to understand decision-making processing and outcomes [130]. Further work comparing product quality (e.g., meat taste or wool quality), sagebrush-nesting bird abundance outcomes, or whole-system carbon cycle modeling could be layered onto the existing framework as resources allow.

We recognized that other disciplinary or transdisciplinary questions not easily addressed within the study design will likely arise during the CAM process. For example, the USDA-ARS does not conduct research on large carnivores, despite their important role in the social–ecological system. Future opportunities to coordinate with non-profit, university, and federal resources to develop additional working groups or research efforts to fill these gaps will be essential to a systems-based approach.

4.5. Implications for Sustainable Management of Rangelands

The Collaboratory methodology, which infuses an CAM approach with concepts from peace studies and local knowledge from the GYE, leverages the scientific power of living laboratories and the local spirit of collaboration to address complex problems on rangelands. Early lessons from the USSES can be applied in other systems and contexts where goals and uses of working lands are contested or where social conflicts arise between groups that have contrasting goals for the same lands and resources [8,9]. The project may also have particular utility for cases near the boundaries of protected areas, such as national parks, or during periods when land use priorities or regulations are dynamic [10–12], and where scientists chose to engage directly with socio-political dynamics in order to address these challenges. The Collaboratory provides nuanced insights into the CAM process that other communities and practitioners can use to improve stakeholder engagement in research and land management. These are as follows: (1) social science and integrative engagement are necessary to foster dialogue; (2) action research is challenging and requires commitment to nuance and non-linear learning; (3) seeking transformative outcomes from conflict, rather than just compromise, may promote broader social–ecological well-being; and (4) interdisciplinary landscape scale experiments offer important benefits in that they put stakeholders in the driver seat of learning, but they also require cooperative frameworks among multiple groups of researchers. This approach builds off of a generation of co-produced and cooperative research in agriculture and rangeland science that effectively engaged local expertise, while providing an advantage over previous grazing land management research in that it more explicitly addresses conflicting worldviews.

Additionally, by building a method to examine divergent goals for “land sharing” and “land sparing” into a grazing experimental design, projects can inform how managers assess the trade-offs of different systems of production and conservation. Finally, by providing an integrative methodology to combine the goals of diverse social actors with the scientific process, this research can potentially serve as a model for public land management administration and working land collaboratives seeking to overcome rigid or inefficient paradigms to public lands management.

5. Conclusions

Today, as communities continue to call for increased collaboration and problem-solving around complex socio-environmental conflicts throughout the western US, cross-boundary collaborative processes are gaining increased attention [28]. Our paper provides an overview of the CAM method, its application in range sheep systems in the GYE, and early lessons from the USSES Collaboratory. It highlights major advantages of the methodology, including that CAM is a novel approach to conflict reduction and learning that can bring divergent social groups together around common responsibility and care for the land, and that the scientific process can promote social, environmental, and agricultural learning. However, disadvantages of the approach include that it requires additional considerations of a landscape-scale study design and creates complex and time-consuming team science challenges relative to a conventional disciplinary research. Additionally, CAM is one of many possible tools available to help societies address environmental conflict and should not be considered a "silver bullet". The continued evaluation and development of CAM methodologies will be necessary to evaluate whether the approach effectively reduces conflict, enables sustainable land management, and addresses climatic and land use change.

Moving forward, science–management partnerships will be increasingly challenged by complex systems dynamics that go well beyond "environmentalists vs. ranchers" narratives and conflicts. Climate, land use, and community change dynamics—including an uptick in high-net-worth landowners, social polarization, increasing ecological variability, agricultural consolidation, labor issues, and booming recreational use on rangelands are already reshaping the conversation [16,114]. Now, the old debates of the "new West" look qualitatively different to upcoming generations of managers, scientists, and advocates who must grapple with shifting baselines and increasingly tele-coupled dynamics [21]. Collaborative adaptive management processes hold potential not only to develop and model innovative social processes for community-driven and science-based management, but to inform a broader landscape of novel partnerships that advance sustainability across the GYE and beyond.

This paper outlines a case study effort to bridge multiple scientific disciplines and societal partners from agricultural, wilderness, and wildlife conservation advocacy, public agency, and community leadership backgrounds to improve system-level outcomes. The USSES Collaboratory creates the opportunity for a wide range of stakeholders to build locally actionable agroecological knowledge and to engage in productive activity towards a shared, sustainable future. Our ability to achieve this goal, and to provide a model that can be scaled to other areas, will depend not only on methodological rigor but also on the ability of all parties to actively share, listen, and engage in the learning needed to transcend persistent conflicts and imagine new futures for rangeland systems. We recognize that collaboratives in public lands management contexts do fail [31] but that any steps towards learning and new relationships are an important success. After an initial process of problem scoping and engagement, the Collaboratory team sees that the challenge of finding common ground now requires more than a recognition of social–ecological values and the mediation of divergent goals, but a concerted effort to transform the conflict via depolarization, systems-thinking, and science-based solutions. This is a creative search for a new, peaceful reality that requires work at the individual, group, and inter-group or structural levels [18].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17073086/s1, File S1: Indicators for the USSES Collaboratory.

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Abbreviations

The following abbreviations are used in this manuscript:

ARS	Agricultural Research Service
CAM	Collaborative Adaptive Management
CARM	Collaborative Adaptive Rangeland Management
GYE	Greater Yellowstone Ecosystem
LTAR	Long-Term Agro-ecological Research network
USDA	United States Department of Agriculture
USSES	US Sheep Experiment Station

Appendix A

Table A1. Three phases of the Collaboratory methodology include 1: assessment and engagement initiation; 2: collaborative adaptive management planning; 3: a participatory range management study. Origin of methods refers to the disciplinary realms (i.e., animal science, rangeland ecology, economics, wildlife biology, social science) or transdisciplinary traditions from which methods are derived.

Step	Description	Origin of Methods	Actors
Stage 1: Baseline Assessment			
1.1 Year 1	Outline pertinent issues and themes via initial stakeholder listening sessions, literature, and document review	Disciplinary realms	Core research team: range and animal sciences; conservation non-profit, and ranching community leadership
1.2 Year 1	Conduct baseline data collection on social and ecological conditions	Disciplinary realms: range, social, and animal science	All partners: researchers, extension professionals, non-profit and industry representatives from conservation, ranching/agriculture, public land management, rural community, and education/tech transfer backgrounds
1.3 Year 1, ongoing	Initiate stakeholder engagement in collaborative meetings; identify core positions, begin empathetic dialogue	Social science realms; collaborative adaptive management literature; conservation non-profit and ranching community leadership	Organizational leadership and collaboration facilitation; rangeland science and University Extension

Table A1. *Cont.*

Step	Description	Origin of Methods	Actors
1.4 Year 1	Conduct collaborative problem or conflict scoping and system-scale modeling; identify data needs	CAM methods; creative problem solving; bioeconomic modeling	All partners
1.5 Year 1	Build group awareness of social and political context through activities that highlight diverse viewpoints and goals. Share baseline data	Ethnography; natural resource social science; agriculture systems economics; conservation, ranching, and agency expertise	All partners
1.6 Year 1	Identify core project mission, identify gaps in participation, expertise, and resources needed to address that mission; organize sub-working groups to address important topics outside of the core mission	Transdisciplinary methods; conservation non-profit and ranching community leadership	All partners
Stage 2: Collaborative Adaptive Management Planning			
2.1 Year 1	Identify overall management goals and objectives for sub-systems; outline core questions, data gaps, and hypothesize relationships within and among subsystems, treatments, and desired outcomes	CAM methods; social–ecological systems theory	All partners
2.2 Year 2	Identify initial indicators and metrics for success; discuss synergies among objectives	Disciplinary realms; interdisciplinary conservation, ranching, and agency expertise	All partners
2.3 Ongoing	Organize decision-making process and collaborative event calendar	CAM methods; ethnography and natural resource social sciences	Core research lead in coordination with all partners
2.4 Year 2	Organize biophysical study sideboards and treatment options	CAM methods; individual disciplines with interdisciplinary coordination	Core research lead in coordination with all partners
2.5 Year 2	Observe or review business as usual production calendar	Transdisciplinary methods; conservation, ranching, and agency expertise	All partners
2.6 Year 2	Facilitate individual or group reflection on sticking points for contradictions, and brainstorm creative paths toward learning, compromise, or transcendence of conflict	Peace studies; collaboration facilitation expertise	Social science lead with all partners
2.7 Year 2, ongoing	Strategize treatment options, triggers for action, and contingency plans	CAM and transdisciplinary methods; researcher, conservation, ranching, and agency expertise	Core research team lead with all partners
2.8 Year 2	Secure commitment from most invested stakeholders to co-author the first adaptive management plan; and finalize the plan	CAM and transdisciplinary methods; researcher, conservation, ranching, and agency expertise	Social science lead with core partners
Stage 3: Biophysical study			
3.1 Year 2–3	Coordinate research study infrastructure and logistics	CAM methods	Core research team
3.2 Ongoing	Continually facilitate collaborative and trust-building social interactions that bring people together on the land and highlight diverse goals, perspectives, and knowledge	Collaborative facilitation expertise	Social science, conservation non-profit, and ranching community lead with all partners
3.3 Year 2–5	Implement treatments	Individual disciplines with interdisciplinary coordination	Core science team
3.4 Year 2–5	Conduct monitoring	Individual disciplines with interdisciplinary coordination	Core science team
3.5 Year 2–5	Report initial data for collaborative review; conduct field tours and data walks as necessary	Individual disciplines with interdisciplinary coordination; transdisciplinary methods	Core science team lead with all partners
3.6 Year 3–5	Synthesize major lessons; adjust management treatments based on first-year results	Transdisciplinary methods	All partners
3.7 Year 5+	Repeat (3–5 years) until single, double, and triple loop learning occurs; evaluate trade-offs among objectives; collaboratively review and report results	Transdisciplinary methods	All partners

Appendix B

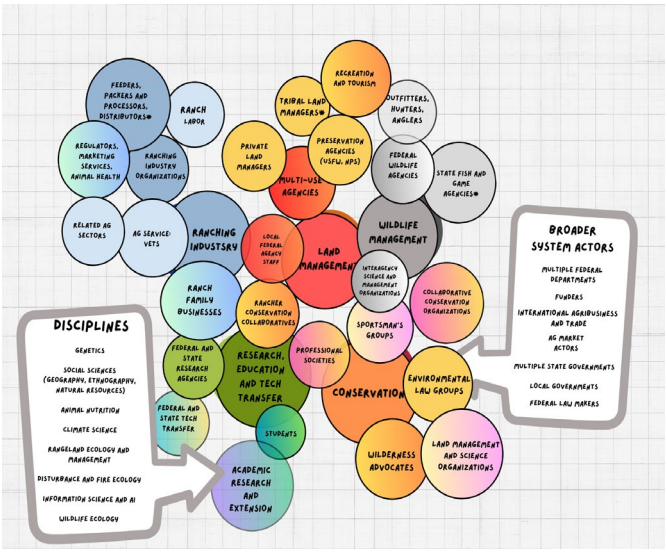

Figure A1. Conceptual depiction of various actors in the stakeholder assessment for the USSES (2023–2024). * Key regional groups with whom the team and formal assessment have not yet engaged.

References

1. Havstad, K.M.; Peters, D.P.; Skaggs, R.; Brown, J.; Bestelmeyer, B.; Fredrickson, E.; Herrick, J.; Wright, J. Ecological Services to and from Rangelands of the United States. *Ecol. Econ.* **2007**, *64*, 261–268. [CrossRef]
2. Reid, R.S.; Fernández-Giménez, M.E.; Wilmer, H.; Pickering, T.; Kassam, K.-A.S.; Yasin, A.; Porensky, L.M.; Derner, J.D.; Nkedianye, D.; Jamsranjav, C.; et al. Using Research to Support Transformative Impacts on Complex, "Wicked Problems" with Pastoral Peoples in Rangelands. *Front. Sustain. Food Syst.* **2021**, *4*, 600689. [CrossRef]
3. du Toit, J.T.; Cross, P.C.; Valeix, M. Managing the Livestock–Wildlife Interface on Rangelands. In *Rangeland Systems: Processes, Management and Challenges*; Springer: Berlin/Heidelberg, Germany, 2017; Volume 17, pp. 395–425. [CrossRef]
4. Remington, T.E.; Deibert, P.A.; Hanser, S.E.; Davis, D.M.; Robb, L.A.; Welty, J.L. *Sagebrush Conservation Strategy—Challenges to Sagebrush Conservation*; Open-File Report; US Geological Survey: Reston, VA, USA, 2021.
5. Barry, S. Livestock Mobility through Integrated Beef Production-Scapes Supports Rangeland Livestock Production and Conservation. *Front. Sustain. Food Syst.* **2021**, *4*, 549359. [CrossRef]
6. Barry, S.; Huntsinger, L. Rangeland Land-Sharing, Livestock Grazing's Role in the Conservation of Imperiled Species. *Sustainability* **2021**, *13*, 4466. [CrossRef]
7. Goodwin, J.; Porensky, L.M.; Meiman, P.; Wilmer, H.; Derner, J.D.; Iovanna, R.; Monlezun, A.C.; Vandever, M.W.; Griggs, J.; Price, F.; et al. *Rangeland Ecosystem Services: Connecting Nature and People*; Society for Range Management: Wichita, KS, USA, 2023.
8. Butler, C.K.; Gates, S. African Range Wars: Climate, Conflict, and Property Rights. *J. Peace Res.* **2012**, *49*, 23–34. [CrossRef]
9. Nori, M.; Scoones, I. Rethinking Policies for Pastoralists—Governing the Rangelands. *Rangel. J.* **2023**, *45*, 53–66. [CrossRef]
10. Cernea, M.M.; Schmidt-Soltau, K. Poverty Risks and National Parks: Policy Issues in Conservation and Resettlement. *World Dev.* **2006**, *34*, 1808–1830. [CrossRef]
11. Woodhouse, E.; Bedelian, C.; Barnes, P.; Cruz-Garcia, G.S.; Dawson, N.; Gross-Camp, N.; Homewood, K.; Jones, J.P.; Martin, A.; Morgera, E. Rethinking Entrenched Narratives about Protected Areas and Human Wellbeing in the Global South. *UCL Open Environ.* **2022**, *4*, e050. [CrossRef]
12. Xu, W.; Butt, B. Rethinking Livestock Encroachment at a Protected Area Boundary. *Proc. Natl. Acad. Sci. USA* **2024**, *121*, e2403655121. [CrossRef]
13. Farrell, J. *The Battle for Yellowstone: Morality and the Sacred Roots of Environmental Conflict*; Princeton Studies in Cultural Sociology: Princeton, NJ, USA, 2015; Volume 66.
14. Barrera, L. Portraits of Climate Change: The Rocky Mountains. *World Watch* **2009**, *22*, 8–16.
15. Briske, D.D.; Joyce, L.A.; Polley, H.W.; Brown, J.R.; Wolter, K.; Morgan, J.A.; McCarl, B.A.; Bailey, D.W. Climate-change Adaptation on Rangelands: Linking Regional Exposure with Diverse Adaptive Capacity. *Front. Ecol. Environ.* **2015**, *13*, 249–256. [CrossRef]
16. Halofsky, J.E.; Peterson, D.L. *Climate Change and Rocky Mountain Ecosystems*; Advances in Global Change Research; Springer: Berlin/Heidelberg, Germany, 2018; ISBN 3-319-56927-9.

17. Turner, M.G.; Braziunas, K.H.; Hansen, W.D.; Hoecker, T.J.; Rammer, W.; Ratajczak, Z.; Westerling, A.L.; Seidl, R. The Magnitude, Direction, and Tempo of Change in Greater Yellowstone in a Warmer World with More Fire. *Ecol. Monogr.* **2022**, *92*, e01485. [CrossRef]
18. Webel, C.; Galtung, J. *Handbook of Peace and Conflict Studies*; Routledge: London, UK, 2007; Volume 7, ISBN 978-0-203-08916-3.
19. Galtung, J. Peace Studies and Conflict Resolution: The Need for Transdisciplinarity. *Transcult. Psychiatry* **2010**, *47*, 20–32. [CrossRef]
20. Hawkes, K.L.; McClaran, M.P.; Brugger, J.; Crimmins, M.A.; Howery, L.D.; Ruyle, G.B.; Sprinkle, J.E.; Tolleson, D.R. *Guide to Co-Developing Drought Preparation Plans for Livestock Grazing on the Southwest National Forests*; University of Arizona Cooperative Extension Publication AZ1764; College of Agriculture and Life Sciences, University of Arizona: Tucson, AZ, USA, 2018.
21. Knight, R.L. Ranchers as a Keystone Species in a West That Works. *Rangelands* **2007**, *29*, 4–9. [CrossRef]
22. Meadow, A.M.; Ferguson, D.B.; Guido, Z.; Horangic, A.; Owen, G.; Wall, T. Moving toward the Deliberate Coproduction of Climate Science Knowledge. *Weather Clim. Soc.* **2015**, *7*, 179–191. [CrossRef]
23. Sayre, N.F. *The Politics of Scale: A History of Rangeland Science*; The University of Chicago Press: Chicago, IL, USA, 2017; ISBN 978-0-226-08311-7.
24. Sayre, N.F.; Knight, R.L. Potential Effects of United States-Mexico Border Hardening on Ecological and Human Communities in the Malpai Borderlands. *Conserv. Biol.* **2010**, *24*, 345–348. [CrossRef]
25. Ostrom, E. *Governing the Commons: The Evolution of Institutions for Collective Action*; Cambridge University Press: Cambridge, UK, 1990; ISBN 0-521-40599-8.
26. White, J.C. *Revolution on the Range: The Rise of a New Ranch in the American West*; Island Press/Shearwater Books: Washington, DC, USA, 2008; ISBN 978-1-59726-174-6.
27. Reed, M.S.; Merkle, B.G.; Cook, E.J.; Hafferty, C.; Hejnowicz, A.P.; Holliman, R.; Marder, I.D.; Pool, U.; Raymond, C.M.; Wallen, K.E.; et al. Reimagining the language of engagement in a post-stakeholder world. *Sustain. Sci.* **2024**, *19*, 1481–1490.
28. Murphy, D.J. Rethinking Climate Change Adaptation and Place through a Situated Pathways Framework—A Case Study from the Big Hole Valley, USA. *Landsc. Urban Plan.* **2017**, *167*, 441–450.
29. Steger, C.; Klein, J.A.; Reid, R.S.; Lavorel, S.; Tucker, C.; Hopping, K.A.; Marchant, R.; Teel, T.; Cuni-Sanchez, A.; Dorji, T.; et al. Science with Society: Evidence-Based Guidance for Best Practices in Environmental Transdisciplinary Work. *Glob. Environ. Change* **2021**, *68*, 102240. [CrossRef]
30. Morrison, T. *Actionable Learning: A Handbook for Capacity Building through Case Based Learning*; ADBI Policy Papers No 2; Asian Development Bank Institute: Tokyo, Japan, 2001; ISBN 4-89974-1-8.
31. Swette, B.; Huntsinger, L.; Lambin, E.F. Collaboration in a Polarized Context: Lessons from Public Forest Governance in the American West. *Ecol. Soc.* **2023**, *28*, 29.
32. Augustine, D.J.; Derner, J.D.; Porensky, L.M.; Hoover, D.L.; Ritten, J.P.; Kearney, S.P.; Ma, L.; Peck, D.; Wilmer, H.; CARM Stakeholder Group. The LTAR Grazing Land Common Experiment at the Central Plains Experimental Range: Collaborative Adaptive Rangeland Management. *J. Environ. Qual.* **2024**, *53*, 904–912. [CrossRef]
33. Clark, P.E.; Woodruff, C.D.; Hedrick, A.R.; Hardegree, S.P.; Flerchinger, G.N. The LTAR Grazing Land Common Experiment at the Great Basin. *J. Environ. Qual.* **2024**, *53*, 861–868. [CrossRef]
34. Shipley, J.R.; Frei, E.R.; Bergamini, A.; Boch, S.; Schulz, T.; Ginzler, C.; Barandun, M.; Bebi, P.; Bolliger, J.; Bollmann, K.; et al. Agricultural Practices and Biodiversity: Conservation Policies for Semi-Natural Grasslands in Europe. *Curr. Biol.* **2024**, *34*, R753–R761. [CrossRef] [PubMed]
35. Starrs, P.F. Transhumance as Antidote for Modern Sedentary Stock Raising. *Rangel. Ecol. Manag.* **2018**, *71*, 592–602. [CrossRef]
36. Wilmer, H.; Taylor, J.B.; Macon, D.; Reeves, M.C.; Wilson, C.S.; Beck, J.M.; Strong, N.K. Loss of Seasonal Ranges Reshapes Transhumant Adaptive Capacity: Thirty-Five Years at the US Sheep Experiment Station. *Agric. Hum. Values* **2024**, *42*, 545–563. [CrossRef]
37. Finch, T.; Day, B.H.; Massimino, D.; Redhead, J.W.; Field, R.H.; Balmford, A.; Green, R.E. Evaluating Spatially Explicit Sharing-sparing Scenarios for Multiple Environmental Outcomes. *J. Appl. Ecol.* **2020**, *58*, 655–666. [CrossRef]
38. Lusiana, B.; van Noordwijk, M.; Cadisch, G. Land Sparing or Sharing? Exploring Livestock Fodder Options in Combination with Land Use Zoning and Consequences for Livelihoods and Net Carbon Stocks Using the FALLOW Model. *Agric. Ecosyst. Environ.* **2012**, *159*, 145–160. [CrossRef]
39. Mosley, J.C.; Fidel, J.; Hunter, H.E.; Husby, P.O.; Kay, C.E.; Mundinger, J.G.; Yonk, R.M. An Ecological Assessment of the Northern Yellowstone Range: Introduction to the Special Issue. *Rangelands* **2018**, *40*, 173–176. [CrossRef]
40. Haggerty, J.H.; Epstein, K.; Stone, M.; Cross, P.C. Land Use Diversification and Intensification on Elk Winter Range in Greater Yellowstone: Framework and Agenda for Social-Ecological Research. *Rangel. Ecol. Manag.* **2018**, *71*, 171–174. [CrossRef]
41. Derner, J.D.; Augustine, D.J. Adaptive Management for Drought on Rangelands. *Rangelands* **2016**, *38*, 211–215. [CrossRef]
42. Huntsinger, L.; Forero, L.C.; Sulak, A. Transhumance and Pastoralist Resilience in the Western United States. *Pastoralism* **2010**, *1*, 29.

43. Gulliford, A. *The Woolly West: Colorado's Hidden History of Sheepscapes*; Texas A&M University Press: College Station, TX, USA, 2018; Volume 44, ISBN 1-62349-653-5.
44. Sando, L.C. Sheep Country in Three Western American Localities: Place Identity, Landscape, Community and Family. Ph.D. Thesis, Montana State University, Bozeman, MT, USA, 2018.
45. Smit, B.; Wandel, J. Adaptation, Adaptive Capacity and Vulnerability. *Glob. Environ. Change* **2006**, *16*, 282–292. [CrossRef]
46. Semplici, G.; Haider, L.J.; Unks, R.; Mohamed, T.S.; Simula, G.; Tsering, P.; Maru, N.; Pappagallo, L.; Taye, M. Relational Resiliences: Reflections from Pastoralism across the World. *Ecosyst. People* **2024**, *20*, 2396928. [CrossRef]
47. Hendrickson, A.W. A Paradigm Shift in Use and Management of United States Public Lands for Livestock Grazing. *Anim. Front.* **2015**, *5*, 36–42.
48. Lynch, H.J.; Hodge, S.; Albert, C.; Dunham, M. The Greater Yellowstone Ecosystem: Challenges for Regional Ecosystem Management. *Environ. Manag.* **2008**, *41*, 820–833. [CrossRef]
49. Berger, J.; Cain, S.L. Reproductive Synchrony in Brucellosis-Exposed Bison in the Southern Greater Yellowstone Ecosystem and in Noninfected Populations. *Conserv. Biol.* **1999**, *13*, 357–366. [CrossRef]
50. Frank, D.A.; McNaughton, S.J.; Tracy, B.F. The Ecology of the Earth's Grazing Ecosystems. *BioScience* **1998**, *48*, 513–521.
51. Frank, D.A.; McNaughton, S.J. Evidence for the Promotion of Aboveground Grassland Production by Native Large Herbivores in Yellowstone National Park. *Oecologia* **1993**, *96*, 157–161.
52. Kilpatrick, A.M.; Gillin, C.M.; Daszak, P. Wildlife–Livestock Conflict: The Risk of Pathogen Transmission from Bison to Cattle Outside Yellowstone National Park. *J. Appl. Ecol.* **2009**, *46*, 476–485.
53. Knapp, A.K.; Blair, J.M.; Briggs, J.M.; Collins, S.L.; Hartnett, D.C.; Johnson, L.C.; Towne, E.G. The Keystone Role of Bison in North American Tallgrass Prairie. *BioScience* **1999**, *49*, 39–50. [CrossRef]
54. Anderson, R.M.; Charnley, S.; Martin, J.V.; Epstein, K. Large, Rugged and Remote: The Challenge of Wolf–Livestock Coexistence on Federal Lands in the American West. *People Nat.* **2024**, 1–13. [CrossRef]
55. Carlson, S.C.; Dietsch, A.M.; Slagle, K.M.; Bruskotter, J.T. The VIPs of Wolf Conservation: How Values, Identity, and Place Shape Attitudes toward Wolves in the United States. *Front. Ecol. Evol.* **2020**, *8*, 6. [CrossRef]
56. Ripple, W.J.; Beschta, R.L. Wolves, Elk, Willows, and Trophic Cascades in the Upper Gallatin Range of Southwestern Montana, USA. *For. Ecol. Manag.* **2004**, *200*, 161–181. [CrossRef]
57. Montana Department of Livestock. Livestock Loss Board. 2025. Available online: https://liv.mt.gov/Attached-Agency-Boards/Livestock-Loss-Board/index (accessed on 30 January 2025).
58. Carpenter, T.E.; Coggins, V.L.; McCarthy, C.; O'Brien, C.S.; O'Brien, J.M.; Schommer, T.J. A Spatial Risk Assessment of Bighorn Sheep Extirpation by Grazing Domestic Sheep on Public Lands. *Prev. Vet. Med.* **2014**, *114*, 3–10. [CrossRef] [PubMed]
59. Castaing-Taylor, L. *Sweetgrass*; Cinema Guild: New York, NY, USA, 2009.
60. Sage, A.H.; Hillis, V.; Graves, R.A.; Burnham, M.; Carter, N.H. Paths of Coexistence: Spatially Predicting Acceptance of Grizzly Bears along Key Movement Corridors. *Biol. Conserv.* **2022**, *266*, 109468. [CrossRef]
61. Smith, A.P.; Sundstrom, A.; Burnham, M. Understanding Diverse Perspectives on Grizzly–Livestock Conflict and Conflict-reduction Tools across Southwest Montana Ranching Communities. *J. Wildl. Manag.* **2024**, *89*, e22709. [CrossRef]
62. Doherty, K.; Maestas, J.; Remington, T.; Naugle, D.; Boyd, C.; Wiechman, L.; Bedrosian, G.; Cahill, M.; Coates, P.; Crist, M. State of the Sagebrush: Implementing the Sagebrush Conservation Design to Save a Biome. *Rangel. Ecol. Manag.* **2024**, *97*, 1–11. [CrossRef]
63. Hilty, J.A.; Chester, C.C.; Wright, P.A.; Zenkewich, K. Uniting Hearts and Lands: Advancing Conservation and Restoration across the Yellowstone to Yukon Region. *Front. Conserv. Sci.* **2024**, *4*, 1264460.
64. Naugle, D.E.; Maestas, J.D.; Morford, S.L.; Smith, J.T.; Mueller, K.R.; Griffiths, T.; Heater, T. From a Bird to a Biome: Exploring the Sage Grouse Initiative's Role in Defending and Growing Sagebrush Core Areas. *Rangel. Ecol. Manag.* **2024**, *97*, 115–122.
65. van Eeden, L.M.; Bogezi, C.; Leng, D.; Marzluff, J.M.; Wirsing, A.J.; Rabotyagov, S. Public Willingness to Pay for Gray Wolf Conservation That Could Support a Rancher-Led Wolf-Livestock Coexistence Program. *Biol. Conserv.* **2021**, *260*, 109226.
66. Whiting, J.C.; Bleich, V.C.; Bowyer, R.T.; Epps, C.W. Restoration of Bighorn Sheep: History, Successes, and Remaining Conservation Issues. *Front. Ecol. Evol.* **2023**, *11*, 1083350. [CrossRef]
67. Robbins, P. The Politics of Barstool Biology: Environmental Knowledge and Power in Greater Northern Yellowstone. *Geoforum* **2006**, *37*, 185–199. [CrossRef]
68. Brunson, M.; Huntsinger, L. Ranching as a Conservation Strategy: Can Old Ranchers Save The New West? *Rangel. Ecol. Manag.* **2008**, *61*, 137–147. [CrossRef]
69. Swette, B.; Lambin, E.F. Institutional Changes Drive Land Use Transitions on Rangelands: The Case of Grazing on Public Lands in the American West. *Glob. Environ. Change* **2021**, *66*, 102220. [CrossRef]
70. Lawson, M. *Is Rural America Really Doing So Badly?* Headwaters Economics: Bozeman, MT, USA, 2020; p. 18.
71. McIntyre, K.B.; Schultz, C.A. Facilitating Collaboration in Forest Management: Assessing the Benefits of Collaborative Policy Innovations. *Land Use Policy* **2020**, *96*, 104683. [CrossRef]

72. Gardezi, M. The Role of Living Labs in Cultivating Inclusive and Responsible Innovation in Precision Agriculture. *Agric. Syst.* **2024**, *216*, 103908. [CrossRef]
73. McPhee, C.; Bancerz, M.; Mambrini-Doudet, M.; Chrétien, F.; Huyghe, C.; Gracia-Garza, J. The Defining Characteristics of Agroecosystem Living Labs. *Sustainability* **2021**, *13*, 1718. [CrossRef]
74. Brymer, A.L.B.; Holbrook, J.D.; Niemeyer, R.J.; Suazo, A.A.; Wulfhorst, J.; Vierling, K.T.; Newingham, B.A.; Link, T.E.; Rachlow, J.L. A Social-Ecological Impact Assessment for Public Lands Management: Application of a Conceptual and Methodological Framework. *Ecol. Soc.* **2016**, *21*, 9. [CrossRef]
75. Dollerschell, K.D.; Tanaka, J.A.; Maczko, K.A.; Wulff, S.S. Evaluating Nonfee Grazing Permit Costs on Federal and Private Lands. *Rangel. Ecol. Manag.* **2024**, *92*, 138–145. [CrossRef]
76. Greene, C.; Wilmer, H.; Ferguson, D.B.; Crimmins, M.A.; McClaran, M.P. Using Scale and Human Agency to Frame Ranchers' Discussions about Socio-Ecological Change and Resilience. *J. Rural Stud.* **2022**, *96*, 217–226. [CrossRef]
77. Seefeldt, S.S.; Laycock, W. The United States Sheep Experiment Station: Shedding Light on Rangeland Ecosystems. *Rangelands* **2006**, *28*, 30–35.
78. Wulfhorst, J.D.; Rimbey, N.; Darden, T. Sharing the Rangelands, Competing for Sense of Place. *Am. Behav. Sci.* **2006**, *50*, 166–186. [CrossRef]
79. Butler, W.H. Collaboration at Arm's Length: Navigating Agency Engagement in Landscape-Scale Ecological Restoration Collaboratives. *J. For.* **2013**, *111*, 395–403. [CrossRef]
80. Holling, C.S. Resilience and Stability of Ecological Systems. *Annu. Rev. Ecol. Syst.* **1973**, *4*, 1–23. [CrossRef]
81. Wilmer, H.; Derner, J.D.; Fernández-Giménez, M.E.; Briske, D.D.; Augustine, D.J.; Porensky, L.M. Collaborative Adaptive Rangeland Management Fosters Management-Science Partnerships. *Rangel. Ecol. Manag.* **2018**, *71*, 646–657. [CrossRef]
82. Mendez, V.E.; Bacon, C.M.; Cohen, R. Agroecology as a Transdisciplinary, Participatory, and Action-Oriented Approach. *Agroecol. Sustain. Food Syst.* **2013**, *37*, 3–18. [CrossRef]
83. Ferguson, D.B.; Meadow, A.M.; Huntington, H.P. Making a Difference: Planning for Engaged Participation in Environmental Research. *Environ. Manag.* **2022**, *69*, 227–243.
84. Knapp, C.N.; Reid, R.S.; Fernández-Giménez, M.E.; Klein, J.A.; Galvin, K.A. Placing Transdisciplinarity in Context: A Review of Approaches to Connect Scholars, Society and Action. *Sustainability* **2019**, *11*, 4899. [CrossRef]
85. Tengo, M.; Hill, R.; Malmer, P.; Raymond, C.M.; Spierenburg, M.; Danielsen, F.; Elmqvist, T.; Folke, C. Weaving Knowledge Systems in IPBES, CBD and beyond—Lessons Learned for Sustainability. *Curr. Opin. Environ. Sustain.* **2017**, *26–27*, 17–25. [CrossRef]
86. Tengo, M.; Brondizio, E.S.; Elmqvist, T.; Malmer, P.; Spierenburg, M. Connecting Diverse Knowledge Systems for Enhanced Ecosystem Governance: The Multiple Evidence Base Approach. *AMBIO* **2014**, *43*, 579–591. [CrossRef]
87. Silva, J.A.; Mosimane, A. "How Could I Live Here and Not Be a Member?": Economic versus Social Drivers of Participation in Namibian Conservation Programs. *Hum. Ecol.* **2014**, *42*, 183–197. [CrossRef]
88. Tengo, M.; Austin, B.J.; Danielsen, F.; Fernández-Llamazares, Á. Creating Synergies between Citizen Science and Indigenous and Local Knowledge. *BioScience* **2021**, *71*, 503–518. [PubMed]
89. Fernandez-Gimenez, M.E.; Augustine, D.J.; Porensky, L.M.; Wilmer, H.; Derner, J.D.; Briske, D.D.; Stewart, M.O. Complexity Fosters Learning in Collaborative Adaptive Management. *Ecol. Soc.* **2019**, *24*, 29. [CrossRef]
90. Gunderson, L.; Light, S.S. Adaptive Management and Adaptive Governance in the Everglades Ecosystem. *Policy Sci.* **2006**, *39*, 323–334.
91. Rist, L.; Felton, A.; Samuelsson, L.; Sandström, C.; Rosvall, O. A New Paradigm for Adaptive Management. *Ecol. Soc.* **2013**, *18*, 63.
92. Lubell, M.; Pozzi, T.; Heikkila, T.; Gerlak, A.K.; Rittelmeyer, P. Learning in Polycentric Governance: Insights from the California Delta Science Enterprise. *Policy Stud. J.* **2024**, *53*, 7–28. [CrossRef]
93. Daniels, S.E.; Walker, G.B. *Working Through Environmental Conflict: The Collaborative Learning Approach*; Praeger: Westport, CT, USA, 2001.
94. Doig, I. *Dancing at Rascal Fair*; Perennial Library: New York, NY, USA, 1987.
95. Spiegal, S.; Bestelmeyer, B.T.; Archer, D.W.; Augustine, D.J.; Boughton, E.H.; Boughton, R.K.; Cavigelli, M.A.; Clark, P.E.; Derner, J.D.; Duncan, E.W. Evaluating Strategies for Sustainable Intensification of US Agriculture through the Long-Term Agroecosystem Research Network. *Environ. Res. Lett.* **2018**, *13*, 034031. [CrossRef]
96. Ingalls, M.L.; Kohout, A.; Stedman, R.C. When Places Collide: Power, Conflict and Meaning at Malheur. *Sustain. Sci.* **2019**, *14*, 625–638. [CrossRef]
97. Reed, J.; Barlow, J.; Carmenta, R.; van Vianen, J.; Sunderland, T. Engaging Multiple Stakeholders to Reconcile Climate, Conservation and Development Objectives in Tropical Landscapes. *Biol. Conserv.* **2019**, *238*, 108229. [CrossRef]
98. Reed, M.S.; Graves, A.; Dandy, N.; Posthumus, H.; Hubacek, K.; Morris, J.; Prell, C.; Quinn, C.H.; Stringer, L.C. Who's in and Why? A Typology of Stakeholder Analysis Methods for Natural Resource Management. *J. Environ. Manag.* **2009**, *90*, 1933–1949.

99. Reed, M.S.; Vella, S.; Challies, E.; De Vente, J.; Frewer, L.; Hohenwallner-Ries, D.; Huber, T.; Neumann, R.K.; Oughton, E.A.; Sidoli del Ceno, J. A Theory of Participation: What Makes Stakeholder and Public Engagement in Environmental Management Work? *Restor. Ecol.* **2018**, *26*, S7–S17.
100. Handcock, M.S.; Gile, K.J. Comment: On the Concept of Snowball Sampling. *Sociol. Methodol.* **2011**, *41*, 367–371. [PubMed]
101. Charmaz, K. *Constructing Grounded Theory: A Practical Guide Through Qualitative Analysis*; Sage: Thousand Oaks, CA, USA, 2006; ISBN 1-4462-0040-X.
102. Nowell, L.S.; Norris, J.M.; White, D.E.; Moules, N.J. Thematic Analysis: Striving to Meet the Trustworthiness Criteria. *Int. J. Qual. Methods* **2017**, *16*, 1–13. [CrossRef]
103. Ragin, C.C. The Logic of Qualitative Comparative Analysis. *Int. Rev. Soc. Hist.* **1998**, *43*, 105–124.
104. Harniss, R.O.; Murray, R.B. 30 Years of Vegetal Change Following Burning of Sagebrush-Grass Range. *Rangel. Ecol. Manag. Range Manag. Arch.* **1973**, *26*, 322–325.
105. Laycock, W.A.; Buchanan, H.; Krueger, W.C. Three Methods of Determining Diet, Utilization, and Trampling Damage on Sheep Ranges. *J. Range Manag.* **1972**, *25*, 352. [CrossRef]
106. Moffet, C.A.; Taylor, J.B.; Booth, D.T. Postfire Shrub Cover Dynamics: A 70-Year Fire Chronosequence in Mountain Big Sagebrush Communities. *J. Arid Environ.* **2015**, *114*, 116–123.
107. Ahlering, M.A.; Kazanski, C.; Lendrum, P.E.; Borrelli, P.; Burnidge, W.; Clark, L.; Ellis, C.; Gadzia, K.; Gelbard, J.; Gennet, S. A Synthesis of Ranch-Level Sustainability Indicators for Land Managers and to Communicate across the US Beef Supply Chain. *Rangel. Ecol. Manag.* **2021**, *79*, 217–230.
108. Maestre, F.T.; Le Bagousse-Pinguet, Y.; Delgado-Baquerizo, M.; Eldridge, D.J.; Saiz, H.; Berdugo, M.; Gozalo, B.; Ochoa, V.; Guirado, E.; García-Gómez, M. Grazing and Ecosystem Service Delivery in Global Drylands. *Science* **2022**, *378*, 915–920.
109. Augustine, D.J.; Derner, J.D.; Fernández-Giménez, M.E.; Porensky, L.M.; Wilmer, H.; Briske, D.J. Adaptive, Multipaddock Rotational Grazing Management: A Ranch-Scale Assessment of Effects on Vegetation and Livestock Performance in Semiarid Rangeland. *Rangel. Ecol. Manag.* **2020**, *73*, 796–810. [CrossRef]
110. Smart, A.J.; Harmoney, K.; Scasta, J.D.; Stephenson, M.B.; Volesky, J.D.; Vermeire, L.T.; Mosley, J.C.; Sedivec, K.; Meehan, M.; Haigh, T. Critical Decision Dates for Drought Management in Central and Northern Great Plains Rangelands. *Rangel. Ecol. Manag.* **2021**, *78*, 191–200. [CrossRef]
111. Spiegal, S.; Webb, N.P.; Boughton, E.H.; Boughton, R.K.; Brymer, A.L.B.; Clark, P.E.; Collins, C.H.; Hoover, D.L.; Kaplan, N.; McCord, S.E. Measuring the Social and Ecological Performance of Agricultural Innovations on Rangelands: Progress and Plans for an Indicator Framework in the LTAR Network. *Rangelands* **2022**, *44*, 334–344.
112. Organ, J.F.; Geist, V.; Mahoney, S.P.; Williams, S.; Krausman, P.R.; Batcheller, G.R.; Decker, T.A.; Carmichael, R.; Nanjappa, P.; Regan, R.; et al. The North American model of wildlife conservation. In *The Wildlife Society Technical Review*; The Wildlife Society: Bethesda, MD, USA, 2012; Volume 12.
113. Headwaters Economics. *Rural Capacity Map*; Headwaters Economics: Bozeman, MT, USA, 2020.
114. Epstein, K.; Haggerty, J.H.; Gosnell, H. With, Not for, Money: Ranch Management Trajectories of the Super-Rich in Greater Yellowstone. *Ann. Am. Assoc. Geogr.* **2024**, *112*, 432–448. [CrossRef]
115. Epstein, K.; Wood, D.J.A.; Roemer, K.; Currey, B.; Duff, H.; Gay, J.D.; Goemann, H.M.; Loewen, S.; Milligan, M.C.; Wendt, J.A.F.; et al. Toward an Urgent yet Deliberate Conservation Strategy: Sustaining Social-Ecological Systems in Rangelands of the Northern Great Plains, Montana. *Ecol. Soc.* **2021**, *26*, 10. [CrossRef]
116. Phelps, D.; Kelly, D. A Call for Collaboration: Linking Local and Non-Local Rangeland Communities to Build Resilience. *Rangel. J.* **2020**, *42*, 265–275.
117. Burns, A.; Wilmer, H.; Miller, R.S.; Clark, P.E.; Taylor, J.B. Precision Animal Husbandry: Using Artificial Intelligence for Camera Traps to Optimize Animal Production and Management Decision Support Systems. *Anim. Front.* **2024**, *14*, 68–71. [CrossRef]
118. Clark, P.E.; Porter, B.A.; Pellant, M.; Dyer, K.; Norton, T.P. Evaluating the Efficacy of Targeted Cattle Grazing for Fuel Break Creation and Maintenance. *Rangel. Ecol. Manag.* **2023**, *89*, 69–86. [CrossRef]
119. Davies, K.W.; Bates, J.D. Native Perennial Forb Variation between Mountain Big Sagebrush and Wyoming Big Sagebrush Plant Communities. *Environ. Manag.* **2010**, *46*, 452–458. [CrossRef]
120. Seefeldt, S.S.; Germino, M.; DiCristina, K. Prescribed Fires in *Artemisia tridentata* ssp. *vaseyana* Steppe Have Minor and Transient Effects on Vegetation Cover and Composition. *Appl. Veg. Sci.* **2007**, *10*, 249–256.
121. Derner, J.; Augustine, D.J.; Briske, D.; Wilmer, H.; Porensky, L.; Fernández-Giménez, M.E.; Peck, D.P.; Ritten, J. Can Collaborative Adaptive Management Improve Cattle Production in Multipaddock Grazing Systems? *Rangel. Ecol. Manag.* **2021**, *75*, 1–8. [CrossRef]
122. Karrasch, L.; Grothmann, T.; Michel, T.; Wesselow, M.; Wolter, H.; Unger, A.; Wegner, A.; Giebels, D.; Siebenhüner, B. Integrating Knowledge within and between Knowledge Types in Transdisciplinary Sustainability Research: Seven Case Studies and an Indicator Framework. *Environ. Sci. Policy* **2022**, *131*, 14–25. [CrossRef]

123. Ghorbani, M.; Azadi, H. A Social-Relational Approach for Analyzing Trust and Collaboration Networks as Preconditions for Rangeland Comanagement. *Rangel. Ecol. Manag.* **2021**, *75*, 170–184. [CrossRef]
124. Emery, M.R.; Pierce, A.R. Interrupting the Telos: Locating Subsistence in Contemporary US Forests. *Environ. Plan. Econ. Space* **2005**, *37*, 981–993. [CrossRef]
125. Lewis, L.W. Envisioning Knowledge Exchange in a Gift Economy. *Prospects* **2024**, *54*, 433–439.
126. Clark, P.E.; Chigbrow, J.; Johnson, D.E.; Larson, L.L.; Nielson, R.M.; Louhaichi, M.; Roland, T.; Williams, J. Predicting Spatial Risk of Wolf-Cattle Encounters and Depredation. *Rangel. Ecol. Manag.* **2020**, *73*, 30–52. [CrossRef]
127. Hillis, V.; Berry, K.A.; Swette, B.; Aslan, C.; Barry, S.; Porensky, L.M. Unlikely Alliances and Their Implications for Resource Management in the American West. *Environ. Res. Lett.* **2020**, *15*, 045002. [CrossRef]
128. Leopold, A. *A Sand County Almanac, and Sketches Here and There*; Oxford University Press: New York, NY, USA, 1949.
129. Galtung, J. *Conflict Transformation by Peaceful Means (the Transcend Method): Participants Manual [and] Trainers Manual*; United Nations Disaster Management Training Programme: Geneva, Switzerland, 2000.
130. Ritten, J.; Fernández-Giménez, M.E.; Pritchett, J.; Kachergis, E.; Hibbs, W. Using State and Transition Models to Show Economic Interdependence of Ecological Sites at the Ranch Level. *Rangel. Ecol. Manag.* **2017**, *70*, 666–674. [CrossRef]

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