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Stakeholder-Driven Policies and Scenarios of Land System Change and Environmental Impacts: A Case Study of Owyhee County, Idaho, United States

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Abstract: While stakeholder-driven approaches have been increasingly used in scenario modeling, previous studies have mostly focused on the qualitative elements, e.g., narratives and policy documents, from the stakeholders, but lack engagement of stakeholders with quantitative inputs. In this study, we conducted workshops with a stakeholder group to integrate the participatory mapping of future policies in the simulation, and to compare the environmental impacts after including the participatory mapping. A land system change model named CLUMondo was used to simulate four scenarios, i.e., Business-As-Usual (BAU), Destroying Resources in Owyhee (DRO), Ecological Conservation (EC), and Managed Recreation (MR), in Owyhee County, Idaho, United States. The InVEST models were used to assess water yield, soil erosion, and wildlife habitat under the four scenarios. The results show that the DRO scenario would decrease shrubland and increased grassland, thus leading to less water yield, more soil erosion, and deteriorated wildlife habitat anticipated through to 2050. On the contrary, the EC and MR scenarios reverse the trend and would improve these ecosystem services over the same time horizon. The stakeholder-driven policies appear to influence the spatial distribution of the land system and ecosystem services. The results help to reach a nuanced understanding of the stakeholder-driven scenarios and highlight the importance of engaging stakeholders in scenario modeling and environmental impact analysis.

Keywords: land change; land systems; ecosystem services; scenario modeling; stakeholder engagement

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1. Introduction

Land systems are outcomes of human–environmental interactions that involve socio-ecological processes altering land use and land cover, land use intensity, and land management [1,2]. Led by the Global Change and Terrestrial Ecosystem and Land Use Land Cover Change (GCTE-LUCC) communities, the early stage of land system science focuses on land use and land cover and their causes and projections, aiming to study the purpose of humans' use of the Earth system's surface and the link to the biophysical subsystem [3]. The LULC work is continued by the Global Land Project (GLP) and makes land system science recognized as a new research field. Beyond land use and land cover, land systems adopt a systematic view, constituting complex and adaptive social and environmental components and their dynamic integrations, interactions, and impacts through land changes [3–5]. Land system changes impact a broad range of ecosystem services, e.g., food, water, biodiversity, and cultural services, which has critical implications for sustainability at the local, regional, and global scales [6–8]. In terms of future land changes and ecological impacts, land systems facilitate their assessment by capturing various underlying determinants in the social-ecological systems (SES), analyzing the causal relationships between the determinants and land conversions to inform future transitions, and utilizing the link between the land and biophysical subsystem to estimate the influences [5]. While the alternative futures of land systems are difficult to capture because of uncertainties in the driving forces and modeling tools used, scenario modeling is widely used as an exploratory approach to simulate hypothetical land changes and their influences on the social and environmental aspects of sustainable development [9–11].

Scenarios are plausible futures depicting how different consistent and coherent storylines might unfold and how relevant components in the system of interest could interact and evolve over time [12,13]. Depending on the frameworks, methods, and objectives, the taxonomy of scenarios varies. One major classification is between exploratory scenarios and anticipatory scenarios, in which the former is built on the past changes and hypothesize if the futures follow or diverge from the trend, and the latter is policy driven to investigate how events or actions envisioned by experts or stakeholders will achieve or avoid certain futures [12,13]. In the empirical studies, the stakeholder-driven policy scenarios are preferred because they could avoid the simplicity in the trend-based scenarios and enhance the plausibility and acceptance compared with the expert-driven scenarios [14–16]. Defined as actors who can affect and/or are affected by a decision, stakeholders can engage in the development of scenarios to co-produce knowledge with scientists through both individual and group perspectives. Participatory approaches have the potential to benefit the scenario development process by providing insights about the mechanisms of the socio-ecological systems that are considered [17–19], improving the perceived credibility and legitimacy of scenarios, and enhancing social learning and stakeholder empowerment towards decision making and adaptation to future changes [20–23]. In terms of land system science, land changes often result in trade-offs and inequal distribution of benefits and detriments among people, places, and with different spatiotemporal distributions and at different scales, which further highlight the importance of engaging stakeholders' values and goals toward developing synergies and identifying solutions [4,5]. For example, Esgalhado et al. find that embedding territorial actors into land system dynamics helps with actions toward sustainable futures in the Mediterranean region [24]. Russeil et al. identify that land availability is the key to food and energy self-sufficiency in small insular places, in which taking farmers' interests into account could enhance the limited potential of only adopting planning policies from the official stakeholders [25].

Stakeholders can participate in the development of scenarios in multiple ways, different levels, and through several phases [26]. Depending on the information required in the analysis, the workflow includes phases of scenario definition, construction of qualitative scenarios by narratives and storylines, translation of qualitative scenarios into quantitative scenarios as numeric rates and spatial maps, analysis and assessment of the scenarios, and one or several iterations of the above processes [11,27]. Although with various definitions, the active collaboration between stakeholders and scientists in one or many of the aforementioned design processes of scenarios and their objectives and challenges is referred to as co-design, in which scientists co-produce knowledge with and serve the end needs of stakeholders [13,28]. Because quantitative scenario construction is generally driven by computational models, this part often proceeds in the absence of stakeholder engagement. Previous studies have intensively focused on how to use and translate qualitative narratives into quantitative scenarios [29–31]. Within the studies that have engaged stakeholders with their quantitative inputs (such as [13,32]), the use of tables or maps generated by the stakeholders are limited to the quantitative scenario development phase but not extended into the scenario analysis and assessment.

In this study, we aim to contribute to the field by using a participatory approach that engages stakeholders with narratives and maps not only in the qualitative and quantitative scenarios developed in our study, but also in the analysis and assessment of environmental impacts. Using a rural agricultural county, Owyhee County in Idaho, United States as an example, we conduct interviews and workshops with the stakeholders to generate scenarios and assess how their participatory mapping of future policies that are hypothetical in the scenarios would affect the environment if implemented. Given that the main socio-economic activities, e.g., ranching and recreation, in the region are built on rangeland landscape [33], the land systems in this study focus on shrubland and grassland cover and management. For the environmental impacts, ecosystem services related to the rangeland landscape and facing pressing challenges associated with land systems change are identified by stakeholders, i.e., water yield, soil erosion, and wildlife habitat. The CLUMondo model is used to simulate the land system scenarios with the spatial policies taken into account [34], and the ecosystem services assessed by corresponding Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) modules [35]. The main research question in this study is in which ways stakeholder-driven policies can improve scenario modeling and impact assessment. The paper is organized as follows: Section 2 describes the study area, data, and methods used; Section 3 illustrates the results regarding the land system scenarios and the environmental impacts; Sections 4 and 5 discuss the contributions and limitations of the approach, respectively; and Section 5 summarizes conclusions.

2. Materials and Methods

2.1. Study Area

Owyhee County is located at the southwestern corner of Idaho, United States (Figure 1) occupying Native American Shoshone-Paiute and Shoshone-Bannock ancestral lands. Composed of rangeland, agricultural land, and forest, the rugged rural landscape is actively used for livestock grazing and farming. The total population was 11,724 in 2020, with Homedale, Marsing, Murphy, and Grand View as its major settlements. In terms of land ownership, 80% of the total area is public land managed by the Bureau of Land Management (BLM), which provides permitted grazing for ranchers to make their operations economically viable [36]. The rural community is concerned about the rapid urbanization in the nearby Treasure Valley (Ada County and Canyon County), in which the population has increased by 68% from 2000 to 2020 [33,37]. Notable concerns have been documented regarding recreationists from Treasure Valley for outdoor activities such as all-terrain vehicle (ATV) riding [33,36,38]. The growing number of visitors is perceived as a threat to the local way of life, social structure, and sense of place that revolve around the traditional farming and ranching livelihoods and relatively unmodified landscape [33,36]. Additionally, the sagebrush ecosystems in the region are threatened by wildfire, climate change, and exotic annual grass (EAG) consisting of invasive grass species such as cheatgrass (*Bromus tectorum*) (Table A1) [39].

2.2. Overall Framework

This study is conducted with a framework that integrates the land system change modeling and ecosystem services modeling [31,40–42]. As shown in Figure 2, the first part builds qualitative scenarios by interviews and workshops with an indicative group of 12 stakeholders representing farmers, landowners, county, state, and federal government, and rangeland associations stakeholders [43]. Four representative scenarios, namely Destroying Resources in Owyhee (DRO), Ecological Conservation (EC), and Managed Recreation (MR), as well as business-as-usual (BAU), are selected and their narratives constructed to reflect the emergent and thematic issues in the study area. These scenarios were adopted because they reflect a set of qualitative scenarios and narratives from the broader study in which this scenario modeling has been developed [43]. By developing alternative futures by the two most critical uncertainties, it also helps to cover a large range of possible end statuses and construct clear, accessible, and replicable scenarios easy to communicate [11,44]. The second part translates the qualitative scenarios into quantitative scenarios in the form of future land system changes by the CLUMondo model. The land systems in 2001, 2011, and 2019 are used to calibrate and validate the model parameters. The calibrated model is then used to simulate projections to the 2050s. The 30-year projection falls within a reasonable range from 10-year to 60-year future simulations in the literature [11,45–47], and enables potential comparison to previous case studies in the nearby region [48]. The last part assesses the ecosystem services under different scenarios by the InVEST model. The annual water yield, sediment delivery ratio, and habitat quality modules are used to evaluate the corresponding ecosystem services.

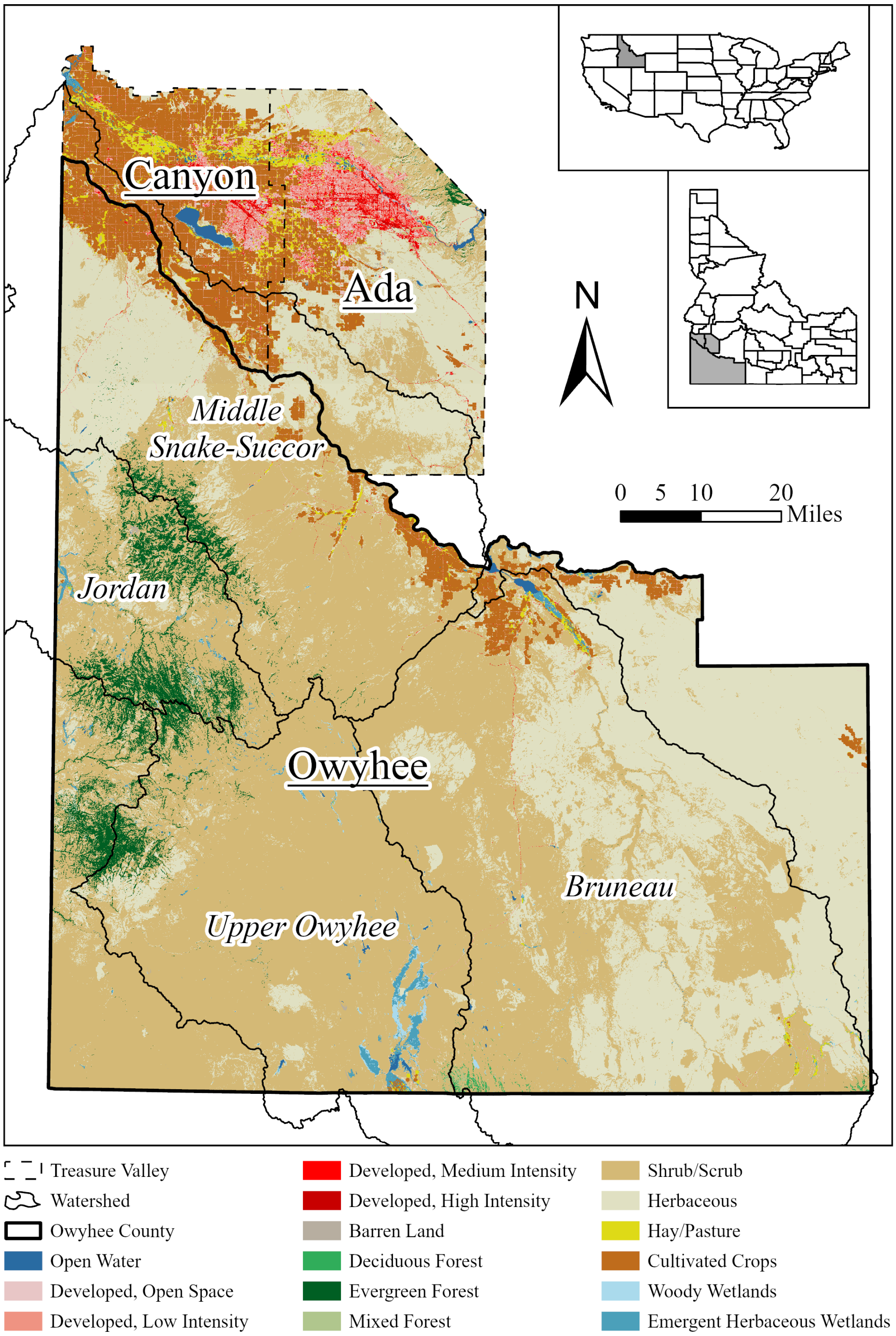

Figure 1. Location of Owyhee County, Idaho, United States.

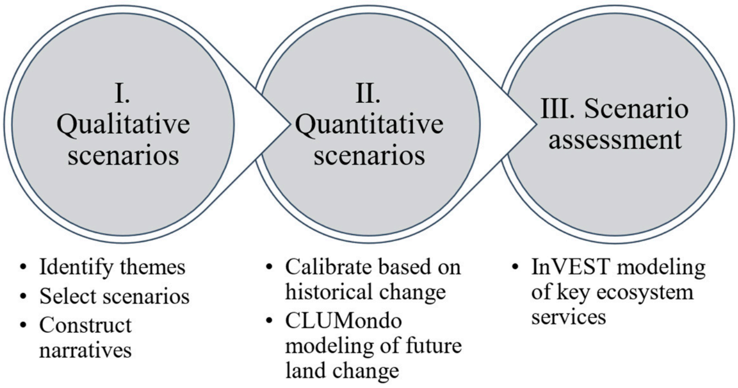

Figure 2. Overall framework of this study.

2.3. Qualitative Scenarios

Starting as a focus group in 2018, local stakeholders from various backgrounds and occupations were recruited and to discuss significant social and ecological issues in the study area [43]. Virtual interviews were then conducted to identify desirable and undesirable futures, drivers of change, actors and actions, and potential outcomes with the stakeholders. Those elements were organized and voted on through an online Delphi survey, of which the aim is to use a series of questionnaires to gather and aggregate the group's response to and assessment of the elements [49,50]. The top three scenarios of interest are Destroying Resources in Owyhee (DRO), Ecological Conservation (EC), and Managed Recreation (MR). These three scenarios, as well as the business-as-usual (BAU) scenario, align with the two dimensions of conservation and recreation (Figure 3). In a series of online workshops from 2020 to 2023, the historical trends, scenario storylines and narratives, spatial policies, and future landscape change models were discussed by the stakeholders and researchers (see Appendix A for narratives) [43].

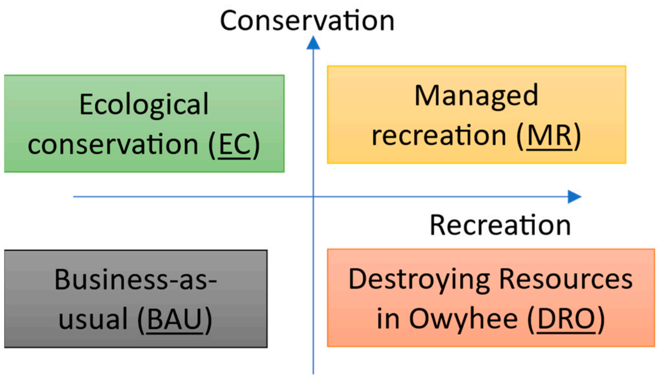

Figure 3. Scenarios aligning two dimensions of conservation and recreation.

2.4. Land System Scenarios by CLUMondo

A relatively new approach, named CLUMondo, is used to model future land system change in the scenarios [34]. This method was selected because it is capable of integrating land use cover, land use intensity, and land use management into simulation, and is increasingly used in studies at the global, regional, and local scales [44,45,51–56]. The approach starts with the classification of the land system by multiple data sources, thus enabling it to model "many-to-many" demand–supply relationships of goods or services provided by land [57]. Based on the scenarios in this study, we identified four goods or services of focus, i.e., urban, sagebrush, exotic annual grass (EAG), and agricultural land.

The locational suitability of the different land systems represented under each scenario are then estimated by binominal logistic regressions using biophysical and socio-economic factors as the independent variables [1]. Eight factors are selected after multi-collinearity analysis (Table A2). The goodness-of-fit of the regression is measured by the Area Under Curve (AUC) value, for which values above 0.9 indicate an excellent accuracy, good accuracy for values between 0.8 and 0.9, fair accuracy between 0.7 and 0.8, and values below 0.7 means a poor accuracy (Table A3) [58].

In the simulation, CLUMondo allocates the land system in each grid with the highest transitional potential that sums the locational suitability, the conversion resistance, and the competitive advantage. The conversion resistance is a proxy for the conversion cost, ranging from 0 to 1. The higher the value is, the more difficult for a land system, e.g., high capital investment land such as urban settlement, to convert from one to another, which indicates a lower conversion elasticity. Because of the "many-to-many" supply–demand relationships, the competitive advantage is used to construct a priority hierarchy determining the conversion order of land systems to fulfill each specific demand. Before the allocation, a binary conversion matrix is also checked to determine if such conversion is possible or allowed. The determination of these conversion settings is based on expert knowledge, literature review, and model accuracy validation (Tables A4–A6).

The simulation performance is evaluated by the location accuracy and the pattern accuracy (Table A7) [46,47]. The location accuracy contains the Figure of Merit's components, i.e., (a) misses, (b) hits, (c) wrong hits, (d) false alarms, and (e) correct rejections, as well as the well-predicted performance (WPP) and overall model performance (OMP). The OMP measures the ratio of hits and correct rejections in all pixels, i.e., $(b+e)/(a+b+c+d+e)$, and the WPP measures the ratio of hits and correct rejections in all pixels except misses and wrong hits, i.e., $(b+e)/(b+d+e)$ [59]. The pattern accuracy is based on the fuzzy inference system (FIS) statistic using the Map Comparison Kit [60]. The changes from 2001 to 2011 are used to calibrate the parameters and the changes from 2011 to 2019 are used to validate.

A notable feature of CLUMondo is the capability to utilize spatial policies in terms of restrictions and/or locational preferences in the model. The restrictions limit changes in areas considering spatial policies, tenure status, or other restrictions, in the form of forbidding either any land system changes or conversions among specific land systems. Previous studies that use spatial policies in CLUMondo are mainly researcher driven, and use nature reserves [41,61,62], ecologically important areas [53], or government planning [42,46,47] as restricted areas in the simulation, but lack stakeholder engagement in deciding where and how to implement the policies. Spatial policies could also take the form of locational preferences that increase or decrease the transition potential of land systems not captured by the locational suitability, which was rarely used in the previous CLUMondo studies [34].

In the online workshops from 2020 to 2023, we used ArcGIS GeoPlanner version 3.6 alongside the stakeholder advisory group (SAG) to depict the area for conservation/restoration (SAG-1) and the area with less resilience due to wildfire and recreation (SAG-2). GeoPlanner is a web-based geodesign and scenario planning application by ESRI.Inc and emerged as a useful tool to co-design scenarios with the stakeholders to support knowledge co-production and communication [12,28,48,63]. In addition to the stakeholder inputs, we use information about the areas with low level Resilience and Resistance (R&R) to wildfire and cheatgrass (RES-1), as well as the areas with wildfire risk and recreational influences (RES-2), to build locational preferences for grassland and shrubland in the scenarios, reflecting how climate change (RCP 8.5 is adopted to reflect an extreme condition) and anthropogenic activities could impact future land system changes (Table 1; See Appendix A for details). By including both restrictive and preferential policies, the flexibility of scenario modeling is strengthened by taking more impact factors in the socio-ecological systems into account that are not captured by suitability analysis or simply implementing restrictions in the land systems change.

Table 1. Stakeholder and researcher policies used in the scenarios.

Scenario	Restriction	Locational Preference	
		Grassland	Shrubland
BAU	-	RES-1	-
DRO	SAG-1	SAG-2; RES-1; RES-2	-
EC	-	RES-1	SAG-1; SAG-2; RES-2
MR	-	SAG-2; RES-1; RES-2	SAG-1

2.5. Assessment of Ecosystem Services by InVEST

The InVEST model suite is widely used to integrate and assess the impacts of land use and land cover change (LULC) [64]. It is capable of evaluating the provisioning, regulating, and supporting of ecosystem services under future scenarios [65–70]. In the integration with CLUMondo, the water yield, sediment retention, habitat quality, nutrient retention, and carbon storage and sequestration ecosystem services have been the most evaluated in previous studies, of which the first three are the focus of this study [41,42,55,58,62,71]. The quantification of water yield, sediment transport, and habitat quality in CLUMondo is based on raster analysis and is described here for each ecosystem service indicator.

The realized water yield on pixel x, $Y\prime_x$, is calculated by water yield, Y_x, minus the water consumption, WC_x:

$$Y'_x = Y_x - WC_x \tag{1}$$

$$Y_x = \left(1 - \frac{AET_x}{Pr_x}\right) \cdot Pr_x \tag{2}$$

$$\frac{AET_x}{Pr_x} = 1 + \frac{PET_x}{Pr_x} - \left(1 + \left(\frac{PET_x}{Pr_x}\right)^{\omega}\right)^{\frac{1}{\omega}} \tag{3}$$

$$PET_x = Kc \cdot ETo_x \tag{4}$$

$$\omega_x = Z \cdot \frac{AWC_x}{Pr_x} + 1.25 \tag{5}$$

in which WC_x is determined by the water consumption coefficient associated with LULC, Pr_x is the annual precipitation, AET_x is the annual actual evapotranspiration estimated by the Budyko curve [72], PET_x is the potential evapotranspiration, ω is a non-physical parameter [73], ETo_x is the reference evapotranspiration, Kc is the vegetation evapotranspiration coefficient, Z is a seasonality factor [74], and AWC_x is the plant available water content.

In the sediment model, the sediment export, sed_export_x, is calculated by the product of the soil loss from the Universal Soil Loss Equation (USLE) and a sediment delivery ratio (SDR) that determines the proportion of fine sediment deposited into the stream [75]:

$$USLE_x = R_x \cdot K_x \cdot LS_x \cdot C_x \cdot P_x \tag{6}$$

$$SDR_x = \frac{SDR_{Max}}{1 + \exp\left(\frac{IC_0 - IC_x}{k_b}\right)} \tag{7}$$

$$sed\_export_x = USLE_x \cdot SDR_x \tag{8}$$

in which $USLE_x$ is the potential average annual soil loss for pixel x, R_x is the rainfall erosivity factor [76], K_x is the soil erodibility factor [77], LS_x is the slope length–gradient factor [35], C_x is the land cover-management factor, P_x is the supporting practice factor [35], SDR_{Max} is the maximum theoretical SDR with a default value of 0.8, IC_x is an index of connectivity [78], IC_0 and k_b are calibration parameters defining the shape of the sigmoid function, SDR-IC [79].

The habitat quality model is based on the LULC maps and the threats to habitat, and estimates the extent of habitat, vegetation types across landscape, and their degradation state. It contains four factors, i.e., each threat's relative impact, the relative sensitivity of each habitat type to each threat, the distance between habitats and threat sources, and the degree of protection of land:

$$Q_{xj} = H_j \left(1 - \frac{D_{xj}^z}{D_{xj}^z + k^z} \right) \tag{9}$$

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{w_r}{\sum_{r=1}^{R} w_r} \right) r_j i_{rxy} \beta_x S_{jr} \tag{10}$$

$$i_{rxj} = 1 - \left(\frac{d_{xy}}{d_{r\ max}} \right) \quad if\ linear \tag{11}$$

$$i_{rxj} = \exp\left(-\left(\frac{2.99}{d_{r\ max}} \right) d_{xy} \right) \quad if\ exponential \tag{12}$$

where Q_{xj} is the habitat quality of LULC j in grid cell x, H_j is habitat suitability, z is a normalized constant, k is the half-saturation constant, D_{xj} is the total threat level, r represents each threat, Y_r is the set of grid cells on r's raster map, w_r is the relative effect of each threat, β_x is the level of accessibility, S_{jr} is the relative sensitivity of each LULC to each threat, i_{rxy} is the impact of threat r from grid cell y to grid cell x following either linear or exponential distance decay, d_{xy} is the distance between x and y, and d_{rmax} is the maximum effective distance of r's reach across space. The inputs for the habitat quality model, as well as the water yield model and the sediment retention model, are listed in Table A8.

3. Results

3.1. Land Systems and Rates of Change in Scenarios

To build land systems in the region, land cover from the National Land Cover Database (NLCD) in 2001, 2011, and 2019 is reclassified into seven land systems and rescaled to 90 m resolution. The supply of urban and agricultural land is based on that resolution and the supply of sagebrush and EAG are calculated by their ratio in the shrubland and the grassland (Table 2) [80,81].

Table 2. Percent cover of land system and its supply of goods and services.

Code	Land System	NLCD Class	Percent Cover	Goods and Services *			
				Urban	Sagebrush	EAG	Ag Area
0	Water	Open Water; Woody/Emergent Herbaceous Wetlands	1.32%	-	-	-	-
1	Urban	Developed, Open Space; Developed Low/Medium/High Intensity	0.05%	0.810	-	-	-
2	Barren	Barren Land	0.04%	-	-	-	-
3	Forest	Deciduous/Evergreen/Mixed Forest	3.98%	-	-	-	-
4	Shrubland	Shrub/Scrub	59.68%	-	0.083	0.121	-
5	Grassland	Grassland/Herbaceous	31.54%	-	0.029	0.236	-
7	Ag land	Pasture/Hay; Cultivated Crops	3.39%	-	-	-	0.810

* Unit: hectare per 90 m by 90 m pixel.

The rates of change in each scenario are based on the historical trends (Table A1) and match the scenarios' narratives (Table 3). In the BAU scenario, the rates of sagebrush and EAG are equal to the trend from 2011 to 2019 to reflect the continuing retreat of sagebrush because of an increase in human activities such as agriculture and recreation, as well as wildfire, climate, and EAG expansion caused by anthropogenic activities. The rates of change in urban and agricultural land are set to match a longer trend in the last two decades from 2001 to 2019. Given the BAU scenario's extrapolatory nature solely depending on the historical trends, the following results focus and report on the latter three anticipatory scenarios, i.e., DRO, EC, and MR, driven by both stakeholders and researchers. In the DRO scenario, the radical rates from 2001 to 2011 are chosen, indicating a worse situation with a more rapid decrease in sagebrush and a more rapid increase in EAG. The urban growth rate increases up to 1.5%; The growth of agricultural land is tuned down to 0.2%, because of the disturbance from recreational activities.

Table 3. Annual rate of change in each scenario.

Scenario	Urban	Sagebrush	EAG	Ag Land
BAU	0.85%	−0.35%	0.25%	0.30%
DRO	1.50%	−0.65%	0.65%	0.20%
EC	0.50%	0.50%	−0.45%	0.30%
MR	1.00%	0.35%	−0.25%	0.40%

On the contrary, the trends for sagebrush and EAG are reversed in the EC scenario, but not high enough to match with the DRO scenario because the proposed restoration requires investment: medium levels from 2001 to 2019 are chosen. The urban land grows less rapidly concerning the impacts to the environment and the growth rate of agricultural land is equal to the BAU scenario to maintain the rural community's culture. In the MR scenario, the trends of sagebrush and EAG are reversed against the level of the BAU scenario, as more ethical recreational activities occur, and efforts are devoted to conserving and restoring. The urban land increases by 1% and agricultural land by 0.4%, as a balance among agriculture and recreation is achieved and the rural community prospers.

3.2. Model Performance of CLUMondo and InVEST

The locational suitability results show good performance, with the Area Under Curve (AUC) averaging at 0.85 and values ranging from 0.64 to 0.96 (Table A3). The regression of urban, forest, shrubland, and agricultural land demonstrated has an excellent accuracy, of above 0.9. The accuracy of grassland is fair with the AUC value at 0.78, because its occurrence is also decided by the wildfire locations, which is counted as the locational preference in CLUMondo for the historical and future simulations. The barren land has the lowest AUC value at 0.64, which is due to its small count of observations in the area and randomness in spatial distribution.

The CLUMondo results suggest that the model achieves a high location accuracy in predicting the land system changes from 2001 to 2011, with the well-predicted performance (WPP) value at 97% and the overall model performance (OMP) value at 95% (Table A7). The pattern accuracy indicates that the model simulates patches of change with relatively high accuracy, based on the fuzzy inference system (FIS) value of 78%. The results also show a decayed accuracy when the calibrated model is applied to the period from 2011 to 2019, which is common in land change simulations [47,82].

The performance of InVEST modules depends on the data availability of the observations. The water yield model is validated against the flow rate observations for twenty years from 2000 to 2019 in the Bruneau River basin in the region. After applying the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) to calibrate the Z parameter and the evapotranspiration coefficients of shrubland and grassland [83], the Kling–Gupta Efficiency (KGE) and Nash–Sutcliffe Efficiency (NSE) values obtained were 0.67 and 0.47, respectively [84,85]. The sediment model is validated by the only available data in 2000 from the Total Maximum Daily Load (TMDL) report by the Idaho Department of Environmental Quality. It achieves the same export value as 702.61 mg/L after calibrating the k_b parameter and the cover-management factor of the shrubland and grassland by the NSGA-II algorithm. The habitat quality model is derived from the land systems maps so it depends on the accuracy of the CLUMondo model analyzed above.

3.3. Comparison of Land System Scenarios

As shown by the flows of land systems (Figure 4), the conversion in the DRO scenario mainly happens between the shrubland and the grassland, accounting for 39.1% of the shrubland in 2019 (465.6 thousand hectares, Kha hereafter). In the meantime, 37% and 1.5% of forest in 2019 (29.5 Kha and 1.2 Kha, respectively) are converted to shrubland and grassland in the DRO scenario. The changes towards grassland and shrubland from shrubland and forest indicate a degradation of rangeland vegetation environment under the DRO scenario. The agricultural land has the inflow as 0.2% of the shrubland (2.6 Kha) and 0.3% of the grassland (1.7 Kha) in 2019, and the outflow to the urban land as 0.7% of its area (0.4 Kha) in 2019, contributing solely to the source of new urban area in the DRO scenario. The expansion of urban and agricultural land further puts pressure on the environment in addition to the dynamics of vegetation.

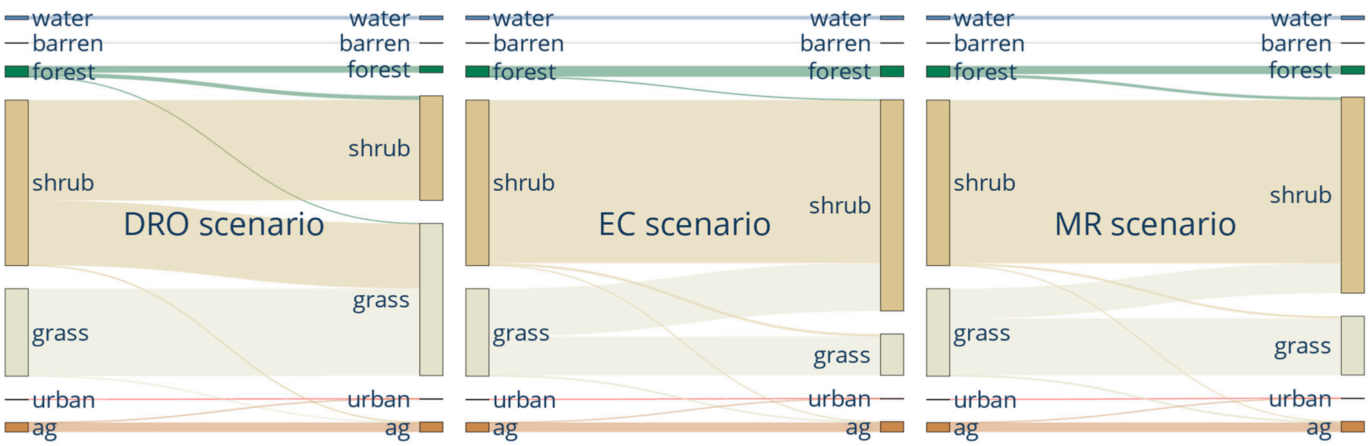

Figure 4. Land system flows from 2019 to 2049 in the scenarios by Sankey diagram.

For the EC scenario, the trend of conversion is reversed compared to the DRO scenario, indicating a conservation purpose of this scenario. A total of 54.7% of the grassland in 2019 (344.3 Kha) is converted to shrubland, and only 1.5% of the shrubland in 2019 (17.6 Kha) is converted to grassland. The outflow of the forest only happens to the shrubland, accounting for 2.5% of the forest in 2019 (2.0 Kha). The inflow of the agricultural land relies more on the grassland (0.9% or 5.7 Kha) rather than the shrubland (0.1% or 0.6 Kha), and the outflow of the agricultural land to the urban land (0.2% or 0.1 Kha) is less compared to the DRO scenario (0.7% or 0.4 Kha).

The MR scenario represents a balance between the DRO scenario and the EC scenario. A total of 34.1% of the grassland in 2019 (214.4 Kha) is converted to shrubland, while 1.3% of the shrubland in 2019 (16.0 Kha) is converted to grassland. A total of 26.4% of the forest in 2019 (21.0 Kha) is converted to shrubland. The inflow of the agricultural land is more evident than the other two scenarios to ensure a 0.4% annual growth rate, causing 1.2% of the grassland in 2019 (7.5 Kha) and 0.1% of the shrubland (0.7 Kha) to be converted. The outflow of the agricultural land to the urban land (0.4% or 0.3 Kha) is between that of the DRO scenario (0.7% or 0.4 Kha) and the EC scenario (0.2% or 0.1 Kha), echoing the balanced trend in the MR scenario.

The spatial distribution of land systems between 2019 and the four scenarios in 2049 are shown in Figure 5. The results with and without spatial policies from the SAG are illustrated, which reveals the nuance that is not captured by the numerical results from the land system flows in the scenarios. In the DRO scenario, the provision of sagebrush decreases while the amount of EAG increases. As a result, the shrubland along the agricultural area to the central northern area and the eastern part of the region is replaced by the grassland. But without the conservation policy boundary based on the SAG inputs and narratives, the replacement also occurs in southwestern Owyhee, which includes the areas of concern in the region because of the presence of water and wetland, as well as the tribal land in the areas. The implementation of the policy in the scenario potentially impedes those transitions.

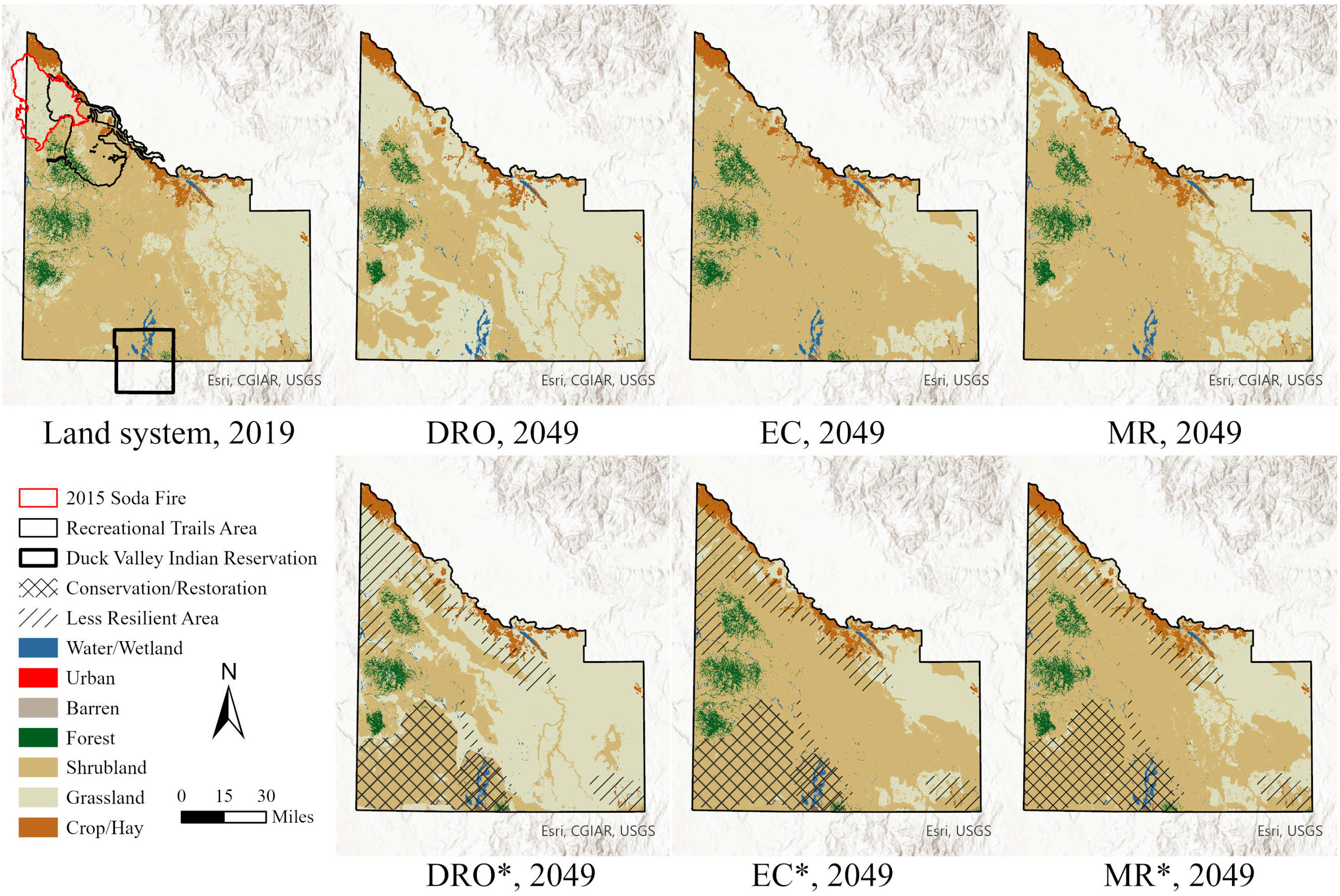

Figure 5. The spatial distribution of land systems between 2019 and four scenarios in 2049 (scenarios with asterisk include SAG policies).

In the EC scenario and the MR scenario, the trend is reversed and results in the restoration from grassland to shrubland in the southeastern part of the county, as well as the northern part, which used to be the 2015 Soda Fire site. The less resilient area depicted by the stakeholders influences the restoration of shrubland by leaving part of the intensively used recreational area in central northern Owyhee unchanged and even with expanded grassland. Compared with the DRO scenario, the conservation policy in the EC scenario and the MR scenario shows little impact on the spatial distribution, because the shrubland persists in its restriction area. Overall, the impact of the resilient area in the EC scenario and the MR scenario is less evident than that of the conservation and restoration policy boundary, since the former is a "soft" and preferential policy while the latter is a "hard" and restrictive one.

3.4. Comparison of Environmental Impacts

The overall changes in ecosystem services under the four scenarios are listed in Table 4. In terms of water yield, the impact of climate change is more significant than the one of land systems change. Water yield per year increases by 16.2%, from 23.11 mm to 26.86 mm if the current land systems are sustained until the mid-21st century. It is due to the increased precipitation that buffers the rising air temperature and evapotranspiration [86]. In terms of land systems under the current climate condition, the DRO scenario leads to a decrease of 0.12 mm, or 0.52% of the current water yield, while the EC scenario and the MR scenario result in an increase of water yield by 1.23 mm (5.29%) and 1.56 mm (6.73%), respectively.

Table 4. Ecosystem services change under four scenarios from 2019 to 2049.

Ecosystem Services	Climate	2019	DRO	EC	MR
Water yield, mm/year	2000–2020	23.11	22.99	24.34	24.67
Water yield, mm/year	2040–2060	26.86	26.63	28.23	28.59
Sediment export, thousand ton/year	2000–2020	1.21	1.33	1.17	1.19
Sediment export, thousand ton/year	2040–2060	1.36	1.50	1.32	1.34
Habitat quality, unitless score	-	0.893	0.856	0.909	0.897

For the sediment exported, the impact of climate change is negative since more precipitation means higher rainfall erosivity and more sediment runoff. The sediment export to the streams increases by 12.46% from 1.21 thousand tons (Kton, hereafter) per year to 1.36 Kton to the mid-21st century. If we assume the current climate conditions are unchanged, the DRO scenario has an increase of sediment export by 9.95% to 1.33 Kton per year, while the EC scenario and the MR scenario have a decrease of sediment export by 3.26% to 1.17 Kton per year and by 1.43% to 1.19 Kton per year, respectively.

Habitat quality is counted as a relative level of unitless score, in which a higher and closer to unity value (1.0) indicates a better quality. The impact of the DRO scenario is evident as the score decreases to 0.856 from 0.893 in the current land systems. Not surprisingly, with more sagebrush as the favorable habitat, the EC scenario increases the score by 0.016 to 0.909 and the MR scenario by 0.004 to 0.897.

The spatial distribution of environmental impacts is shown in Table 5 by the four major basins, i.e., Upper Owyhee (UO), Bruneau River (BR), Middle Snake-Succor (MSS), and Jordan (JO). Given that the impact assessment in the InVEST modules are land driven and the land systems in the EC and MR scenarios show relatively small difference (Figure 5), the difference between the scenario with (marked by asterisk) and without stakeholder policy is illustrated by the DRO scenario. For the water yield ecosystem service, the BR basin benefits the most from the EC scenario and the MR scenario because of the restoration of the shrubland in the basin (Figure 5), of which the water yield increases by 10.42% and 9.37% under the two scenarios, respectively. It is followed by the MSS basin, the JO basin, and the UO basin, by 9.01%, 2.72%, and 1.63% under the EC scenario, and by 9.11%, 5.80%, and 3.68% under the MR scenario. Under the DRO scenario, the spatial policy conserves the shrubland in the UO basin but leaves the BR basin, as well as the MSS basin and the JO basin, more likely to convert shrubland to grassland, to keep the same rates of change for different land systems. As a result, the change in water yield in the UO basin increases from −2.01% to −1.85%, but in the BR basin, change in water yield decreases from −4.98% to −11.52%, followed by 2.18% to −1.52% in the MSS basin and by 6.23% to 5.41% in the JO basin.

The spatial pattern of the environmental impact is similar when applied to the sediment exported. The change in sediment export is the most evident in the BR basin under the EC scenario and the MR scenario, by −13.98% and −13.78% respectively, compared to the rate of −3.60% and −0.47% in the UO basin, −0.96% and 0.99% in the JO basin, and 4.57% and 7.69% in the MSS basin. The increase in sediment yield in the MSS basin under the EC scenario and MR scenario is due to the larger increase in the two scenarios (Table 3) and the location of new agricultural land is mainly in the MSS basin (Figure 5), thus leading to more sediment being exported. The difference between the DRO scenario with and without spatial policy is more significant in terms of the sediment exported. The change of sediment export in the UO basin decreases from 26.79% to 5.36% when the conservation policy is implemented. On the contrary, the change of sediment export in the BR basin increases from 2.42% to 13.55%, followed by the MSS basin from 10.63% to 20.36%, and the JO basin from 3.65% to 4.54%.

Table 5. Spatial distribution of environmental impacts under future scenarios.

Ecosystem Services	Basin	2019	DRO	DRO *	EC	MR
Water yield, mm/year	UO	19.13	18.75	18.78	19.44	19.84
	BR	11.08	10.53	9.80	12.23	12.12
	MSS	26.65	27.23	26.25	29.05	29.08
	JO	92.77	98.56	97.79	95.30	98.15
Sediment export, ton/year	UO	302	292	309	343	260
	BR	241	262	267	291	252
	MSS	73	78	93	77	71
	JO	566	571	587	592	561
Habitat quality, unitless score	UO	0.897	0.860	0.846	0.922	0.909
	BR	0.850	0.825	0.818	0.854	0.840
	MSS	0.982	0.933	0.962	0.988	0.985
	JO	0.976	0.972	0.967	0.983	0.983

* The DRO scenario with spatial policies by SAG.

The pattern persists for the change in habitat quality in the four basins. The change in the BR basin is 0.028 and 0.014 in the EC scenario and MR scenario, respectively, compared to 0.007 and 0.006 in the JO basin, 0.006 and 0.003 in the UO basin, and 0.006 and −0.011 in the MSS basin because of more agricultural land as the source of threat. The implementation of the conservation policy in the DRO scenario mitigates the change of habitat quality score from −0.050 in the DRO scenario without the policy to −0.020 in the UO basin, while the change of score decreases from −0.041 to −0.057 in the BR basin, from −0.029 to −0.037 in the MSS basin, and from −0.005 to −0.010 in the JO basin.

4. Discussion

This study uses stakeholder-driven spatial policies to simulate scenarios of land systems' change and their environmental impacts. It contributes to the literature by engaging stakeholders in a more thorough way that integrates participatory mapping in the assessment phase of scenario development [20]. Differing from the conventional computational modeling of quantitative scenarios solely driven by the scientists, this study uses spatial policies that integrate the inputs from both the stakeholders and the researchers in the simulations of future land systems and the assessment of their environmental impacts. Other studies suggest that, through a bottom-up approach, the participation of stakeholders facilitates the perception and understanding of land use and landscape planning and their environmental impacts [87–89]. Prior research also suggests that collaboration between stakeholders and researchers is beneficial to the process of co-design and co-production of scenarios and knowledge [28,90].

In this study, the mapping inputs from the stakeholders reflect their perspective on how landscape changes under different scenarios. The less resilient area matches with the previous fire site and intensively used recreational areas in the region, indicating that stakeholders view wildfire and recreational activities as the drivers for the EAG expansion and sagebrush retreat. The conservation boundary covers the southwestern part of Owyhee County and includes the Duck Valley Indian Reservation, showing the importance of those areas from the stakeholders' perspective (Figure 5). These areas also coincide with the view of researchers and the regional planning, echoing the concept of co-design and co-production. For example, the less resilient area from the stakeholders overlaps with the high burn probability areas and the low resilience and resistance areas based on soil characteristics and wildfire (Figure A1). The conservation area includes wilderness area and a designated scenic river by the Bureau of Land Management (BLM) (Figure A2).

As shown in Figure 5 and the latter half of Section 3.3, model simulations have different land system changes in the future scenarios, both with and without stakeholder inputs, which also show the utility of working separately with the scenarios involving restrictive spatial policies, on the one hand, and preferential spatial policies, on the other. The restrictive policy, which is conservation in essence, has evident influence in the simulation by keeping the current land systems unchanged, while the preferential policy, which is additive to the locational suitability of land systems, provides modification that is less significant in the simulation (Figure 5). The environmental impacts from the land systems change match with the narratives from the stakeholders as well as the broader socio-ecological processes in the region [91], with degradation of freshwater and habitat ecosystem services in the DRO scenario and mitigated ones in the EC and MR scenarios under climate change (Table 4). More importantly, the stakeholder inputs also have an influence on the spatial distribution of environmental impacts, as shown in the comparison of the DRO and the DRO* columns in Table 5. As shown in Section 3, the scenarios, as well as the spatial policies, lead to diverse trends of ecosystem services in the four major basins in Owyhee County, which further highlight the importance of investigating the spatial heterogenous effects and trade-offs in the potential policies [42].

The strength of CLUMondo is showcased in this study, i.e., to consider land use cover, land use intensity, and land use management simultaneously in the model [34]. It enables the many-to-many demand–supply relationship to be included by linking multiple goods and services with multiple land systems. The linkages should be considered as regionally specific to the study area, which reflects the needs and practices of the local community within a context of either an urban [46,47], agricultural [52,58], or generic landscape [6,45]. Given that Owyhee County is a semi-arid rural landscape and the invasive grass species and sagebrush are the focus of local people, the relevant goods and services are selected and calculated for each land system (Table 2). In addition to the definition of land systems, the selection of ecosystem services for impact analysis and divisions for spatial heterogeneity and policy effects should also be regionally specific and determined by both the researchers and stakeholders. The change of the EAG and sagebrush, as well as the consequences for ecosystem services, reveals the dynamics in the rangeland landscape, which further provide evidence for the building of middle-range theories of land system change in similar ecoregions in the form of contextual generalization of the phenomena [92].

The study provides implications for sustainability in the region and potential application to other case studies. In summary, the results depict a potentially worsening situation in the DRO scenario for stakeholders where the decline of shrubland and the increase of grassland is dominant. On the contrary, the EC scenario reverses this trend, and the MR scenario achieves a middle ground between the two scenarios. For the ecosystem services of interest, water yield in the DRO scenario decreases while the EC and MR scenario exhibit increased water yield because of different rates of change for shrubland and grassland. Similar patterns are observed for the sediment export retention and habitat quality scores. It is notable that the MR scenario has equal if not slightly better performance in ecosystem services compared to the EC scenario, with a lesser rate of change in shrubland and grassland, and a higher level of urban and agricultural land expansion. It implies that the environment could be improved without radical change in the landscape to support the traditional farming and ranching livelihood in the region or other similar rangeland landscapes, while ensuring sustainable development of the local communities.

5. Limitations

There are several uncertainties, limitations, and corresponding future directions in both the scenario development and scenario modeling processes. Firstly, the translation from the narratives to the rates of change in each scenario depends on the historical trends (Tables 3 and A1). It suffices as an exploratory approach on how scenarios differ in the direction of conservation and exploitation of the landscape, but the trend is fixed at the end year and a linear growth rate is assumed. Future studies could investigate uncertain rates of land system change and non-linear temporal trends because of local, regional, and global changes and initiatives [12,45]. Second, the stakeholder-driven policies could be improved by recursive validation and refinement with the stakeholders. The workshop was held virtually due to COVID-19, which provides flexibility to use the online platforms but also limits in-depth communications and engagement. Future studies could also combine the stakeholder-driven policies with government planning and policies and embed them within both local and global scenario contexts [46,47,71]. Thirdly, the tele-coupling relationship between SES in different places and its influence deserve more investigation [93–95]. In this study, land systems and ecosystem services in Owyhee County are impacted by the flow of people from the Treasure Valley. The current urbanization in the Treasure Valley is characterized by a double-digit population growth, in-fill and compaction of urban land, and increase and decrease of farmland in Canyon County and Ada County, respectively [37,96]. The spillover effects will become more evident if the trend is sustained. Future studies should explicitly take the scenarios of tele-coupled SES into account instead of implicitly including them in the narratives and rates of change for the in situ scenarios. Lastly, while the simulation achieves relatively high-performance metrics in both CLUMondo and InVEST (See Section 3.1), the models and data used are not free of uncertainties and limitations. The land change model is calibrated and validated by two historical periods, but a decline of performance is observed from the calibration period to the validation period. Although common in the previous land change studies [46,47], it implies non-linear changes in the land system that are difficult to capture within the existing toolbox. A relevant example is that, depending on the direction of climate change, sagebrush will face additional stress from the expansion of invasive grass species, which will strengthen or weaken the feedback loops among EAG, climate warming, and wildfires, thus leading to accelerated or decelerate rates of change in land systems and environment impacts [39,80,97]. The land use data from NLCD has an overall accuracy of 91% [98]. As one of the key inputs, the historical and future climate data have errors and uncertainties after developing and projecting site observations to a spatial dataset [99]. Both models are sensitive to the parameter settings and further add uncertainties on top of the data inputs [34,100,101]. Future studies could seek and adopt data with higher spatial and temporal resolution, assemble and compare multiple land and environmental change models, assess and communicate the model uncertainties and limitations with the stakeholders in the scenario development processes.

6. Conclusions

Using CLUMondo and InVEST, this study integrates stakeholder-driven policies in the scenario modeling of land system changes and environmental impact assessment. In this case study of a rural landscape in Owyhee County, Idaho, four scenarios, namely BAU, DRO, EC, and MR, show different trends of provision of sagebrush, EAG, urban, and agricultural land. While the DRO scenario has an increasing area of grassland from the shrubland and forest, the EC and MR scenarios reverse the trend. The distribution of the land system changes is altered if the spatial policies are adopted, of which the level depends on whether the policy is restrictive or preferential. The assessment of ecosystem services change in the scenarios matches with the trend of land systems, in which the DRO scenario has degraded water yield, sediment retention, and habitat quality, while the EC and MR scenarios are beneficial for these services. The spatially heterogeneous influence of the environmental impacts is shown by comparing the changes in four watersheds in the region. The conservation policy improves the ecosystem services in the basin where the policy is implemented but shows trade-offs with other basins to keep the overall rates of change. This study helps to reach a more nuanced understanding of landscape change and environmental impacts in the future and highlights the importance of engaging stakeholders in more robust ways in each of the scenario development phases.

These findings expand our knowledge of the way in which co-designed land use change scenarios are generated, iterated, and quantified [8,11,12], and, notably, how plausible future change is articulated from a socio-ecological system perspective [12,20,31]. The four alternative futures co-designed in the Owyhee case-study exemplify both the use of computational modeling of land system changes (e.g., CLUMondo to map shrubland and grassland distributions within scenarios and policies in Figure 5) and the analysis of trade-offs in multiple ecosystem services (e.g., InVEST results on the gain and loss of ecosystem services among major basins under different scenarios in Table 5) that extends the critical need to understand rapid change in ecosystem service provisioning, e.g., regional water resources [86]. In addition, the approach used here both builds from, and advances, evolving best practices in stakeholder engagement for food, energy, and water systems science [12,14,28] by elaborating on how iterative computational modeling can be used in support of co-production of knowledge when an explicit and stakeholder-engaged framework is used.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of the University of Idaho (protocol code 19-053 approved on 21 February 2019 and amended on 7 July 2021).

Informed Consent Statement: All subjects gave their informed consent.

Data Availability Statement: The data could be accessed by https://github.com/huan7515/CLUMondo (accessed on 2 January 2024).

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Appendix A

I. Scenario narratives (see [43])

Destroying Resources in Owyhee (DRO): As Treasure Valley has experienced continued population growth, the need for and interest in various types of recreation have increased beyond the capacity for services and support from management agencies. For decades, swaths of recreators have inundated surrounding regions of Treasure Valley, including areas within the Owyhee region. Campsites have exceeded their capacity and impromptu motorized and non-motorized trails have become the norm, with no enforcement or mitigation from management agencies. Various year-round recreational uses (consumptive and non-consumptive) have caused a wide range of impacts, including soil erosion, intractable conflicts between recreators and rangeland managers, and destruction of wildlife habitat. By 2050, riparian areas in close proximity to trails will be impacted by humans, leading to further eroded stream banks, destroyed springs, and loss of riparian vegetation. Unmonitored and unauthorized camps further impact wildlife access to riparian areas. With excessive heat and decreased precipitation events, fire extent and severity has grown, leading to widespread invasion of weeds such as cheatgrass overtaking and replacing native flora. Resentment and conflict increase and create a barrier for cooperative solutions.

Ecological Conservation (EC): Increased heat and wildfire events continue within the Owyhee region, but collaborative efforts to manage and restore habitat have also increased and involve landowners, local citizens, NGOs, county, state, and federal agencies. The Bureau of Land Management is successful in developing methods that reduce the amount of invasive grass species affecting the area and improving approaches to fire risk. By 2050, efforts such as the Cheatgrass Challenge and the Soda Fire restoration, will have led to proactive management of invasive grass species and the localized success of these efforts will have led to increased trust in management agencies and collaborative approaches Effective management of recreation (i.e., motorized vs. non-motorized access) will have also reduced wildfire risk and overcrowding. Increased cooperation among users helps mitigate impacts on wildlife habitat. Due to incremental restoration practices, habitat availability has increased for species such as big sagebrush, redband trout, mule deer, pronghorn, greater sage grouse, and bighorn sheep. Similarly, there are increases in conditions for viable salmon habitat envisioning and increasing the potential for salmon restoration. Sagebrush, riparian areas, and meadow restoration have been successful and reflect increases in biodiversity. Due to these impacts, the local economy thrives as recreationists not only visit the area but aid in stewardship to support restoration and protection of habitat.

Managed Recreation (MR): With droves of recreators from Treasure Valley and other neighboring communities, the Owyhee region has seen an uptick in use on private and public land. The Owyhees' local communities have been seen as "gateways" providing services for local communities, thus providing a revenue stream supporting infrastructure. Revenue has been generated through the support of state and county wide initiatives. In an effort to control increased recreation, regulations and improved infrastructure have been managed through the planning of designated areas of use to prevent trespassing. Along with population growth and increases in infrastructure (limited but impactful), fire risk has also become an issue, in particular along highways and roadways. Outreach and education efforts conducted by Bureau of Land Management (BLM), Idaho department of lands, and the tribal community have continued to inform visitors of fire and invasive risk. Strict regulations for motorized and non-motorized vehicle use are also enforced by Idaho Fish and Game (IDFG), tribes, and the county sheriff's office to control the spread of wildfires and detrimental issues on habitat and private land uses.

II. Appendix tables

Table A1. Historical trends of goods and services in Owyhee.

Decennial Change	From 2001 to 2011	From 2011 to 2019	From 2001 to 2019
Urban	9.40%	6.81%	8.54%
Sagebrush	−6.37%	−3.41%	−4.96%
EAG	6.31%	2.46%	4.67%
Ag land	4.06%	2.08%	3.22%

Table A2. Independent variables in the suitability analysis.

Abbreviation	Category	Variable	Description	Source
slope	Environmental	Slope (degree)	Calculated from elevation.	USDA NRCS
precip	Environmental	Precipitation (mm)	The 30 year normal annual precipitation, in milimeter.	PRISM Climate Group
popDen	Socioeconomic	Population density (1 k/km^2)	Calculated by census block population in 2010.	U.S. Census Bureau
mktAcc	Socioeconomic	Market accessibility (index from 0 to 1)	Access to national and international markets.	[86]
soilDep	Soil characteristics	Soil depth (cm)	Extracted from gNATSGO.	USDA NRCS
awc	Soil characteristics	Available water capacity (fraction)	Extracted from gNATSGO.	USDA NRCS
distUrban	Proximity	Distance to urban (km)	Calculated by distance to city/CDP in 2020.	U.S. Census Bureau
distRiver	Proximity	Distance to river (km)	Calculated by distance to rivers.	USGS

Table A3. Logistic regression results of the suitability analysis.

Coefficient *	Water	Urban	Barren	Forest	Shrub	Grass	Ag. Land
Constant	−5.7371	−5.4721	−9.5705	−5.2821	3.4438	−2.2986	2.1014
slope	−0.5075	−0.1594	-	0.0695	0.0024	−0.0029	−0.7561
precip	0.0028	-	0.0017	0.0109	−0.0002	−0.0067	−0.0126
popDen	−15.6612	10.1253	-	−4381.2422	−144.3840	−79.6714	−1.9413
mktAcc	1.4526	4.5171	8.4771	−1.5294	−0.4009	−2.0504	6.2921
soilDep	0.0431	-	0.0199	−0.0085	−0.0174	0.0011	-
awc	−3.2564	-	−20.4530	−15.7942	−20.5207	23.8600	11.7380
distUrban	−0.0056	−0.0323	-	-	0.0104	-	−0.0447
distRiver	−0.0271	−0.0800	0.0574	−0.0611	0.0281	0.0048	−0.0703
AUC	0.8319	0.9075	0.6363	0.9636	0.9012	0.7842	0.9610

* Backward stepwise variable selection is conducted to exclude the driving factors with p-value less than 0.05 in each logistic regression.

Table A4. Conversion resistance of land systems.

Land System	Water	Urban	Barren	Forest	Shrub	Grass	Ag Land
Value	0.7	0.75	0.6	0.65	0.5	0.4	0.7

Table A5. Land use conversion priority matrix.

Code	Class	Urban	Sagebrush	EAG	Ag Area
0	Water	0	0	0	0
1	Urban	1	0	0	0
2	Barren	0	0	0	0
3	Forest	0	0	0	0
4	Shrubland	0	2	1	0
5	Grassland	0	1	2	0
7	Ag. land	0	0	0	1

Table A6. Allowed conversion matrix.

Code	Class	Water	Urban	Barren	Forest	Shrub	Grass	Ag. Land
0	Water	1	0	0	0	0	0	0
1	Urban	0	1	0	0	0	0	0
2	Barren	0	0	1	0	0	0	0
3	Forest	0	0	0	1	1	1	0
4	Shrubland	0	0	0	1	1	1	1
5	Grassland	0	0	0	0	1	1	1
7	Ag. land	0	1	0	0	0	0	1

Table A7. Location accuracy and pattern accuracy in 2011 and 2019.

Year	Location Accuracy							Pattern Accuracy
	Misses	Hits	Wrong Hits	False Alarms	Correct Rejections	WPP	OMP	FIS
2011	2.43	8.72	0.01	2.75	86.09	97.18	94.81	78.14
2019	3.20	5.86	0.04	5.60	85.30	94.21	91.16	64.44

Table A8. Data source for the InVEST modules.

Module	Data	Label	Source	Description
Annual water yield	Annual precipitation	Pr	PRISM; MACA	Historical data from the PRISM climate group, Oregon State University; future data from MACA dataset [102].
	Available water content	AWC	STATSGO	The fraction of water in soil that is available to plants.
	Z parameter	Z	Calibration	The empirical constant typically ranges from 1 to 30.
	Evapotranspiration coefficient	Kc	Literature; Calibration	Initial data from the literature [66,103].
	Reference evapotranspiration	Et_o	PRISM; MACA	Calculated by the modified Hargreaves method [104].
	Water consumption	WC	National Water-Use Science Project	Calculated by the county scale report [105].
Sediment export	Rainfall erosivity	R	PRISM; MACA	Calculated by precipitation [76].
	Soil erodibility	K	STATSGO	Soil's susceptibility to detachment and transport by rainfall.
	Slope length–gradient factor	LS	NRCS	Calculated by terrain factors extracted from elevation [35].
	Cover-management factor	C	Literature; Calibration	Initial data from the literature [106,107].
	Support practice factor	P	Literature	Values from the literature [106,107].
	Maximum sediment retention ratio	SDR_{max}	Literature	Set to default value, 0.8 [79].
	Calibration parameter	IC_0	Literature	Set to default value, 0.5 [79].
	Calibration parameter	k_b	Literature; Calibration	Initial data from the literature [79].
Habitat quality	Habitat suitability	H	Literature	Values from the literature [108–110].
	Relative sensitivity of LULC to threat	S	Literature	Values from the literature [108–110].
	Relative effect of threat	w	Literature	Values from the literature [108–110].
	Maximum effective distance of threat	$d_{r\ max}$	Literature	Values from the literature [108–110].

III. Spatial policies in the scenarios

To reflect the risk of wildfire and climate warming, the current fire probability is increased based on the projection to the mid-century in RCP8.5 [111,112]. Then, the mean probability is calculated in the low Resilience and Resistance (R&R) areas and used as the locational preference for grassland in four scenarios [113] (Figure A1).

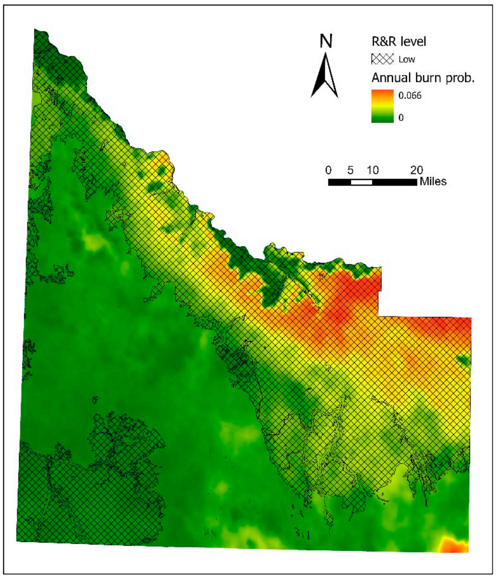

Figure A1. Annual probability of wildfire and the low Resilience and Resistance (R&R) area.

In addition to the Resilience and Resistance (R&R) that is based on the soil conditions, the recreational sites from Idaho Bureau of Land Management (BLM) and Recreation Information Database (RIDB), motorized trails for ATVs and motorcycle from BLM, scenic rivers and creeks within the wilderness areas, Owyhee Uplands Backcountry Byway (also known as the Mud Flat Road), and recreational and fire risk areas depicted by SAG are also considered less resilient to fire and of low resistance to invasive grass species (Figure A2).

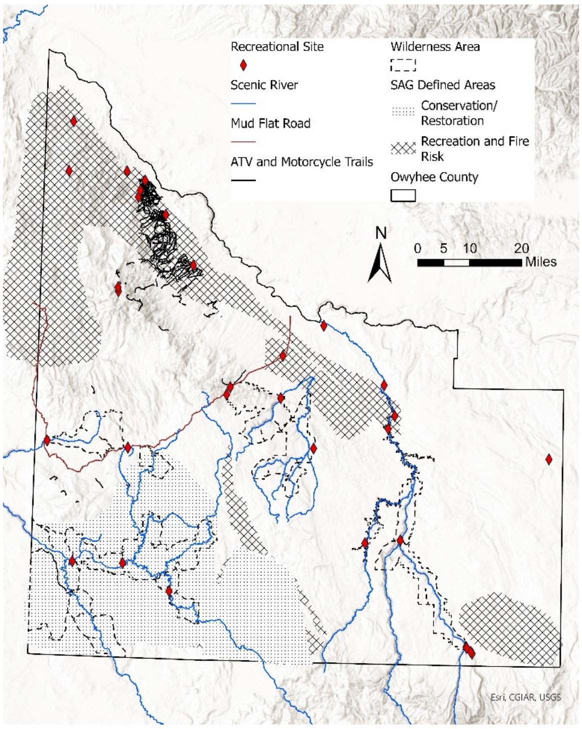

Figure A2. Additional low Resilience and Resistance (R&R) area.

Low Resilience and Resistance (R&R) areas are used for locational preference of grassland in all future scenarios to indicate the impact of wildfire and climate warming (RES-1 and Low R&R under locational preference for grassland column in Tables 1 and A9, respectively). After the calculation mentioned above, the weight is set as 0.18 for the probability of burning at least once in 10 yr period. In DRO, the recreational and fire risk zones by the stakeholders, 45 m riparian buffer (the buffer size is chosen as 45 m (~150 ft) that falls into the range discussed in the literature and federal and state regulations [114–116]) around scenic rivers in the wilderness areas, 90 m buffer (impacts from the motorized trails for ATVs and OHVs are on soil, vegetation, and wildlife. The spatial extent of the impacts depends on the issues and ranges from 25 m for vegetation change to 100 m for soil erosion and wildlife habitat and to miles as noise traveling in open landscape to wildlife [117–121]. The impact zone is set as 90 m to each side of the motorized trails to focus on the impacts to soil and habitat) around motorized trails and the Mud Flat Road, and an 800 m buffer (recreational sites are points of interest from RIDB and BLM recreational sites that are used for ATV/OHV staging, trail access, boat launch, and picnic/camping. The impact buffer is set to be 0.5 mile (~10 min walk or ~15 min hike)) around recreational sites is included as the locational preference of grassland (RES-2 and Rec. and Fire areas by researchers under locational preference for shrubland in Tables 1 and A9, respectively). The restoration/conservation areas by SAG are considered to have no change in the DRO scenario as a restriction for conservation.

In the EC scenario, the restoration/conservation areas, as well as the recreational and fire risk zones in the DRO scenario, are used as the locational preference for shrubland as an effort for restoration, invasive species removal, and fire risk mitigation. The weight for such preference is set as 0.5, which is the high and low end of established probability by the seeding and seedling transplant approaches [122]. As compared to the DRO scenario, the riparian buffer is not included in grassland preference in EC and the buffer size for trails and recreational sites are halved because of education and outreach for recreation ethics. The weight for shrubland preference in restoration/conservation areas is 0.25, which is the high and low end of established probability by the passive and seeding approaches [122].

Table A9. Spatial policies used in the scenarios.

Scenario	Restriction	Locational Preference	
		Grassland	Shrubland
BAU	-	Low R&R	-
DRO	Restoration/Conservation area defined by SAG	Low R&R; Rec. and Fire area by SAG and researchers	-
EC	-	Low R&R	Restoration/Conservation area defined by SAG; Rec. and Fire area by SAG and researchers
MR	-	Low R&R; Rec. and Fire area by SAG and researchers	Restoration/Conservation area defined by SAG

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