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Socio-Ecological Futures: Embedded Solutions for Stakeholder-Driven Alternative Futures

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Abstract: Scenarios of landscape change have the capacity to address spatial and temporal issues, current and future trends, and solutions that increase capacity and/or resilience in social-ecological systems and their networks. In this study, we present a resilience framework for food–energy–water systems and demonstrate it with a case study in Magic Valley, Idaho. We formulated scenarios of change based on stakeholder input (qualitative data), researcher-developed models (quantitative data), and validation of plausibility through impact and indicator evaluation. The stakeholder engagement process identified key issues, critical uncertainties, and plausible and viable solutions to future challenges. Specifically, we analyzed cross-scenario futures and their solutions to address water quality issues in the face of climate change, land-use change conflicts, and population shifts in the region. The process activates stakeholder and research-based models to create geospatial alternative futures and their associated timesteps, with embedded solutions, which broadens and improves conventional scenario-based research. The process intends to provide policy-makers, researchers, and scenario facilitators with a strategic framework to activate solutions temporally with a stakeholder-defined suite of scenarios.

Keywords: alternative futures; scenarios; socio-ecological systems; embedded solutions; stakeholder engagement

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1. Introduction

Landscape-scale social-ecological systems (SES) networks require planning frameworks to explore assumptions from researcher-driven models that often define key issues and plausible solutions from the people of a place [1–3]. In food–energy–water systems, these networks encompass urban and agricultural systems, as well as their interface. Issues such as water quality, water quantity, population growth, agricultural demand, and urban development can have resounding impacts upon a system and its ability to be resilient and adaptive under various circumstances. One approach has been to categorize the circumstances, issues, and challenges into a collection of landscape systems-level responses that can then inform stakeholders on how to best utilize their system. However, local stakeholder groups working in consultation with researchers must validate these responses to meet the needs for stakeholder trust and engagement [4]. Alternative futures research [5] and geodesign [2] have the capacity for addressing this complexity through a formalized and iterative approach applied to complex adaptive management [6,7] of these systems.

Scenarios are depictions and management actions that could hypothetically take place over time, thus altering a given landscape [8]. Scenario-based planning or scenario analysis has been broadly used to define and clarify relationships over time which, in turn, can provide foundations for formulating strategies and solutions [9–11]. Geodesign provides a framework for formulating scenarios that iteratively activate stakeholder assumptions about a place. The incorporation or coupling of scenario-based planning, geodesign, and participatory planning can provide communities with a toolkit for understanding how various changes might occur in the future on a landscape.

In contrast to expert judgment-driven scenario development [12], the development of trust, engagement, and validation of models require many different iterations and model revisions when community feedback is incorporated [4,5,13]. Activation of this trust and engagement requires incremental, strategic, and methodological thinking [14,15] to drive active participation from a stakeholder group for ongoing feedback. Thus, the iterative nature of scenario planning and analysis is crucial to the development of research models driven by stakeholder assumptions. This research intends to demonstrate this concept by providing a representative example of our research workflow throughout the project.

1.1. Current Status of Food, Energy, and Water Systems (FEWS) Research

Food–energy–water systems (FEWS) exemplify complex multiscalar challenges. FEWS nexus research seeks to examine this complexity by addressing various actions or solutions which may occur at a given point in time relevant to impacts of land use [16], urban growth [17], resource management [18], and policy changes for a landscape. However, many of these systems-level examinations rely on cross-sectional evaluations [19] which tend to be limited in understanding nuance over time, how interventions might be applied over time, and/or the implications of not applying an intervention at the optimal time. To address this need for longitudinal thinking, scenario-based approaches have been employed to examine implications of path dependency [20] of a suite of scenarios as they relate to a common trend [21].

1.2. Current Status of Scenario Planning, Alternative Futures, and Geodesign

Scenario analysis is a robust method for dealing with uncertainty [22], both in terms of mechanistic understanding [9] and human endeavors [23]. We can develop scenarios in a number of ways to explore a number of future states, depending on the goal of the project [12]. Normative scenarios can be used to help generate support and coordination for a desired set of future conditions [24], while exploratory scenarios can be used to identify future states under a given set of assumptions [8]. These assumptions can be based on stakeholder input [25], expert knowledge [26], or by data-driven patterns identified using geographic information systems [8,27]. We propose utilizing a combination of the three to generate a complete picture of what resilience might look like for a region. In many cases, scenario analysis focuses on a few key drivers of change to explore future conditions. A more comprehensive approach is to utilize critical uncertainties, the most uncertain and potentially significant forces in a region, to frame multivariate scenarios that explicitly tackle the uncertainty in those forces [28]. This approach is especially robust when combined with spatial models of the scenarios, called alternative futures [26].

Alternative futures (AF) assessments provide a way to explore plausible options for the future of a region or community based on stakeholder assumptions about future trajectories [8]. AF assessments organize, generate, and simulate both qualitative and quantitative data to represent models of change. Plausible trajectories of change are tested through researcher-developed spatially explicit mechanistic models and/or stakeholder-guided assumptions [29,30]. Through various tools and methods of inquiry, the combination of data and assumptions from stakeholder input supports ground-truthing of key uncertainties of environmental change for the near and long-term [10], that will in part come from analytical modeling (as described above). Multivariate scenario narratives are used to describe and relate a series of plausible future actions to a stakeholder advisory group (SAG) who express to what extent the scenarios represent observed reality, with iterations to ensure agreement by both the research team and stakeholders [25,28]. Subsequent sessions aim to validate scenario models for each trajectory of change and develop adaptation strategies that will be spatially represented as a set of alternative futures. Utilizing feedback about future conditions from the stakeholders and experts, a suite of impact models will be developed that help stakeholders understand the implications of each of the future scenarios [10].

Geodesign hinges on the central question, "How do we get from the present state of this geographical study area to the best possible future?" [2]. This iterative process aligns stakeholder input along with landscape analysis, design, and revision through consensus or success metrics. Through a geodesign framework, various scenarios and alternative futures can be established to provide stakeholders, policy-makers, and clients with various permutations of the future established by subject matter experts and stakeholders.

1.3. The Gaps in Current Alternative Futures and Geodesign Projects

Scenarios aim to describe understandings of the future by examining projections driven by computational models; however, many of these models do not represent understandings and needs from local specialists and experts [31]. Scenario-based solutions typically are crafted to meet the needs of a particular group of individuals [32]. Many projects utilize demand to address issues in a reactive sense and having embedded stakeholder input for future simulations of systems-level trends, solutions, and indicators are currently underutilized [31,32]. Within our food–energy–water project, we utilized an input-based conceptual model to develop iterative scenarios of change and developed the associated AF that included stakeholder-driven solutions.

AF analysis [8] examines projections based on stakeholder inputs as well as modeling efforts. However, there is a current gap in the understanding, utility, and appropriateness of embedding solutions within each iteration of a model [33]. We propose that design-based input per scenario and AF representation is needed to properly engage stakeholders and capture their input in complex FEW systems [34].

Geodesign [2] and scenario projects seek to answer key issues in landscapes by addressing solutions. However, model parameterization typically does not change within each iteration or alignment with stakeholder understandings [31,32,35]. As inputs are disseminated to experts or stakeholders, solutions are often limited in effectiveness because stakeholders may not have input on solutions or have a comprehensive understanding of how each may operate within a specific scenario. Current projects utilizing the geodesign framework limit research input through models depending on time constraints and other probabilistic limiting factors in research such as consistency in modeling capacity and degree of development [27], coupling stakeholder input [34], and relevant parameterization of concatenating qualitative and quantitative data.

1.3.1. Longitudinal Assessment of Effectiveness

Mixed-methods approaches for planning FEWS and SES system-level understandings are often accompanied by combining consistent performance indicators across scales and time [34]. Geodesign offers an iterative approach to build in stakeholder feedback through "Impact Models" [2]. However, research-based model parameterization of scenarios becomes limited due to a lack of mechanisms for revising scenarios. Using the stakeholder engagement process over a multi-year project explicitly developed and maintained trust in the research and the project outcomes [34,36,37]. Iteratively coupling models (climate models, water balance models, and land use and land cover models) at various phases within the process is key to this process.

Alternative futures typically builds in research-based assumptions about future trajectories of change with stakeholder input [36]; however, decision-making, in terms of scenario-specific solutions, is rarely integrated within the process. Scenario and future depictions typically occur at the end of the process to demonstrate how stakeholder notions of the future were combined with modeling approaches. These outputs within the process (Figure 1) evoke explicit feedback about land use and land cover change in the future.

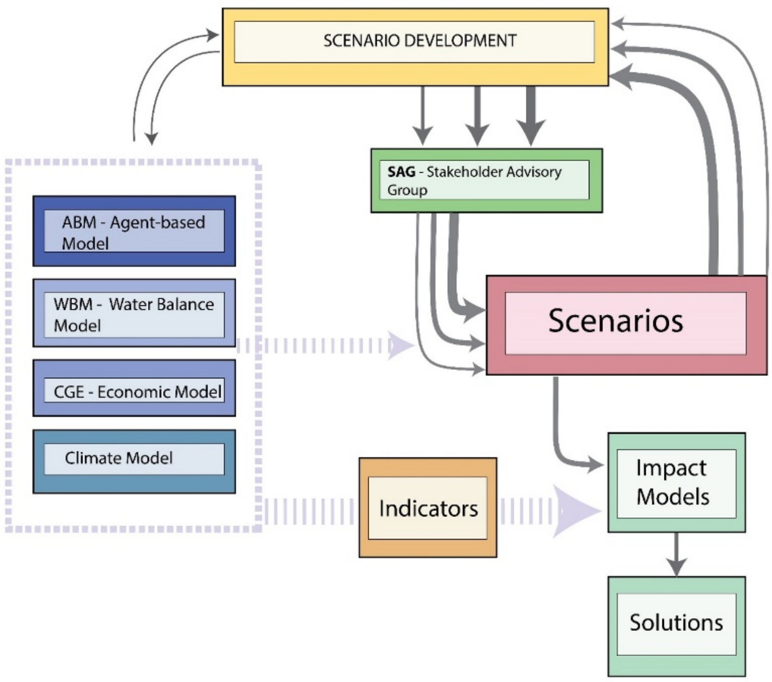

Figure 1. Conceptual diagram showing coupling of impact models, stakeholder input, scenario development, and evaluative indicators for representing alternative futures.

1.3.2. Applicability for Futures Development and Scenarios

Providing an operational framework, as well as a workflow for SES management, along with a coupled-modeling approach can provide interoperability of functional, strategic, and operational logistics for scenario depiction [34]. Following a framework can ensure iterative consistency for each AF, as well as improve the dissemination of stakeholder representations over space and time. Tools such as our framework (Figure 1) have the capacity to address issues at multiple scales as well as various co-dependent systems [31,34].

1.4. Addressing Solutions for Change

Solutions are typically a hindsight cast once scenarios and futures are developed, thus providing a prescriptive set of means to address issues [29,34,38]. FEWS nexus-based projects often model solutions at scales relevant to researchers utilizing data, but may not provide a feasible result to stakeholders. For example, stakeholders may seek structural and policy solutions at the municipal scale; however, computational models may only evoke solutions relevant to the scale addressed by the model [4,39–41]. Our research demonstrates a process to address the following research question: How can solutions be embedded within a geodesign framework across scenarios?

InFEWS Resilience Framework

Our collective approach operationalized and instituted the InFEWS Resilience Framework building from the conceptual approach to coupled approaches (Figure 1). This framework provides a scaffolding for organizing, coupling, and formulating stakeholder input into spatiotemporal quantitative models and future representations (Figure 2). The models illustrate and define key differences in the scenarios presented through a suite of indicators. That is, the framework uses input from stakeholders combined with research team data to (a) assess current food, energy, and water issues and uncertainties, (b) define and establish anticipatory scenarios, (c) evaluate the scenarios with standardized metrics, and (d) revise the scenarios with embedded solutions provided through feedback from the SAG.

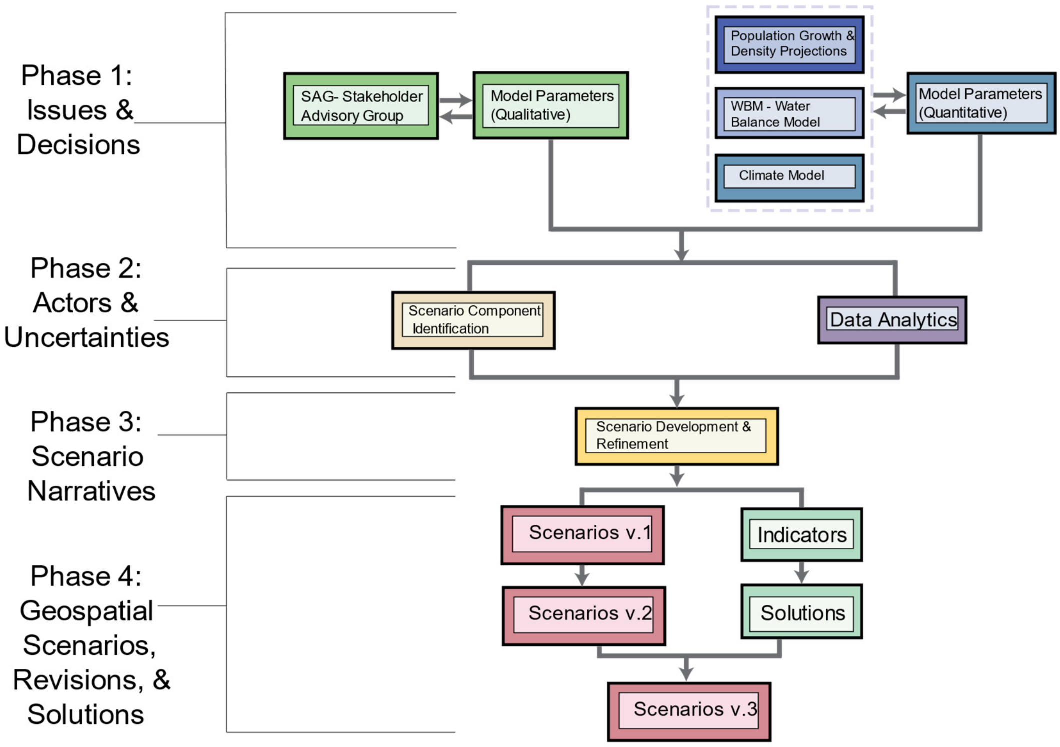

Figure 2. The InFEWS Resilience Framework linking the characterization of issues and decisions to a description of actors and uncertainties, to the development of scenario narratives, and to geospatial scenarios.

We apply our InFEWS Resilience Framework to the Magic Valley of Idaho, USA as a case study of how to embed solutions into geodesign scenarios and AF.

2. Methods

2.1. Study Area: Magic Valley Idaho

Magic Valley (Figure 3) located in the southern part of the state of Idaho, is composed of 9 counties totaling approximately 7.5 million acres. As of 2017, the U.S. Census Bureau [42] reported Idaho to be the fastest growing state in the U.S. by population at a 6.9% growth rate. Dairy production is also a major commodity in Magic Valley, as well as the agriculture that supports dairies. Due to population growth, stresses on agricultural lands have increased over the past decade. Uncertainties about the future have led to local concern about land management decisions and their impacts upon the current and future production of food from the system.

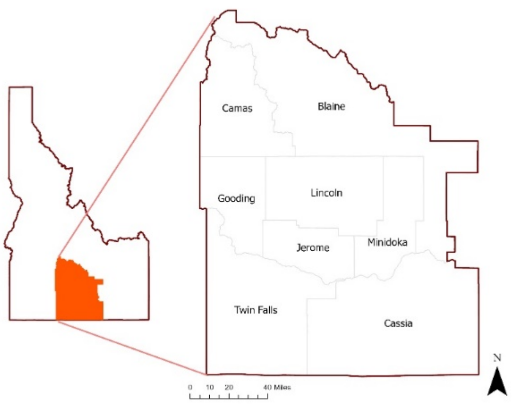

Figure 3. Location map of Magic Valley within Idaho including counties within the region.

Magic Valley is a complex socio-ecological system (SES), as issues within the region often lack definition, understanding, and organization across the many stakeholders. Issues such as land use conflict, water quality, and water quantity concerns contribute to this complexity [43]. Complex systems require complex organizational frameworks, guided by local stakeholder input, to assess, analyze, define, evaluate, and revise possible trajectories of change for the future [2,44]. In order to demonstrate stakeholder interests, assumptions, and various solutions about the future, we utilized the geodesign [2] approach but adapted it to formulate the InFEWS (Innovations at the Nexus of Food, Energy, and Water Systems) Resilience Framework.

2.2. Stakeholder Advisory Group Definition and Membership

Our research team assembled a SAG to help better understand the region and guide development through the InFEWS Resilience Framework. The SAG was comprised of food processing representatives, water governance organizations, canal companies, municipal water engineers, a dairy industry group, indigenous representatives, farmers, and ranchers who understood the opportunities represented by this research. Stakeholders were largely identified and selected through snowball sampling [34] and vetted through the local University of Idaho extension office. SAG members directly worked with the research team to determine the most effective solutions and policy interventions necessary to optimize the FEW system for each scenario. Stakeholders initially weighed in by defining roles, identifying key actors, and weighing their input via decision-making [34,36]. The duties of the SAG members were

- Participation in working meetings to be held once per year, typically in the fall (2017–2020), where members directly interacted with the research team;
- Participation (in person or by teleconference) in the "all-hands" meeting once per year, typically in the spring (2017–2020);
- Participation in quarterly reviews of progress reports from the research team and provision of suggestions for ways in which the research team could better address the needs of the SAG but also to provide bespoke revisions to scenario development.

2.3. Phase 1: Issues and Decisions

The first phase of the InFEWS SAG workshops was to define our initial conceptualization of the SES system issues and actions, framed as "issues and decisions" (Figure 2), for Idaho's Magic Valley. System conceptualization [45,46] was established at this stage by the presentation of a conceptual workflow to frame key assumptions, actors, decisions, and their connections. This conceptual workflow provided transparency for reporting and stakeholder engagement as we intended the project to be model-informed, but not model-driven. Stakeholders were asked to identify past and present drivers of change as well as crucial issues and decisions that they anticipated would shape the regions' social-ecological systems. Within this phase, researchers established ancillary data preparation in response to SAG input. Data-driven models, backed by stakeholder assumptions, provided the means to establish future research questions and project deliverables [12]. Because that initial conceptualization of stakeholder-defined issues was qualitative and anticipatory, researchers interpreted key issues from stakeholder responses into "key forcings" to identify instrumented data and initial parameterization of models [34,36].

2.4. Phase 2: Actors and Uncertainties

After reporting back to the stakeholders and refinement of key issues and decisions, "key actors" and "critical uncertainties" [10,28] were defined by the SAG. The goal of the workshops was to identify (a) "actors", as decision-makers with the most agency in influencing the FEW system, and (b) establish "critical uncertainties" which are defined as the key biophysical and social issues that are hardest to predict, but are most likely to profoundly change the region. Researchers ranked "actors and uncertainties" with stakeholder feedback to provide inputs for integrated model parameterization. The following table presents an example of critical uncertainties linked to actors for two key questions concerning uncertainty explored with the SAG (Table 1).

Table 1. Example of stakeholder-derived actor/critical uncertainty matrix for Magic Valley food, energy, and water systems. Note: positive numbers suggest a benefit to the actor, while negative numbers suggest a cost to the actor.

ACTORS	**UNCERTAINTY: Will There Be Sufficient Water Supply for Demand?**	
	Increase or decrease in Uncertainty	Scaled impact on Actor's Agency (−5 is significant inhibitor, +5 is a significant facility)
Irrigated Agriculture	Increase in water supply	+4
	Decrease in water supply	−4
Idaho State Legislature	Increase in water supply	+1
	Decrease in water supply	−5
Municipalities and Local Governments	Increase in water supply	+4
	Decrease in water supply	−3
Economic Development Entities	Increase in water supply	+5
	Decrease in water supply	−5
CAFOs	Increase in water supply	+3
	Decrease in water supply	−4

2.5. Phase 3: Scenario Narratives

At this point in the process, stakeholder input was compiled and organized into explorative scenario narratives [10]. These narratives were compiled from stakeholder-driven ranked decisions from actors, key critical uncertainties, and trends within the region. Key points (Table 2) of each scenario were delivered to stakeholders for input and revision. The grouping of scenarios into a descriptive format allowed stakeholders to examine prospective possibilities of future change [47]. Through a storyline format, scenario narratives represent combined stakeholder and researcher understanding, allowing stakeholders to explore plausible alternative futures (AF) [28]. Furthermore, the scenario narratives activate previous outputs (actors, uncertainties, issues, and decisions) from SAG workshops to reinforce stakeholder trust [4]. Summaries of the scenario narratives are presented in Table 2.

Table 2. Summary narratives for the six stakeholder-derived scenarios for Magic Valley, Idaho food–energy–water systems for 2019–2050.

Scenario	**Key Points of Narrative**
1. Business as Usual	Water supply remains consistent but demand increases; food prices and demand are high thus agriculture is given an economic advantage over other land uses; water quality regulations increase; residential land uses increase at a moderate rate.
2. The Courts Call	Shorter water years; tribes renegotiate leases; limited water supply rendering crops unsustainable; regional population grows slightly; increased temperatures; reduced water supply.
3. Locavore	Wetter conditions; more residential development; in-migration increases population substantially; high costs of fuel drive need for local agriculture; clean water and food production defined as "highest and best use".
4. Population Boom	Water supply is stable without drought; substantial population growth drives an increase in residential demand and water use; water quality regulations increase to support the increase.
5. Megadrought	Increased drought; increase in residential water demand; a large proportion of irrigated agriculture is decommissioned; regulations are tightened.
6. Happy Valley	Low drought conditions; food production increase; increase in aquifer recharge; sustainable urban development achieved.

2.6. Phase 4: Geospatial Scenarios, Revisions, and Solutions

In Phase 4, the first draft depictions of AFs were incorporated into geophysical models. Permutations of climate models, a water balance model [48] and land use and land cover (LULC) models were interlinked and, driven by scenario narratives, were crafted into AF depictions for decadal timesteps from the years 2020 to 2050. Through iteration, researchers aligned variables and stakeholder input as conditions for a coupled-modeling approach (Figure 2) to refine scenarios for Magic Valley. Model outputs were used as an instrument to guide research-based scenario revisions from the stakeholder group's input.

2.6.1. Climate Model

We assembled a suite of historical climate forcing trends required for running the water balance model at appropriate spatial resolutions (1.54 square miles) using the gridded meteorological dataset of Abatzoglu [49]. Scenarios of future climate were down-scaled for the study area through 2100. However, we evaluated the credibility of different climate models to capture aspects of drought [50] that helped us identify a more appropriate set of models of future conditions.

Climate models were derived from future climate projection data in terms of Representative Concentration Pathways (RCPs). The "High Emissions Scenario (RCP 8.5)" represents a future pathway similar to a business-as-usual continuation of current emissions. The "Low Emissions Scenario (RCP 4.5)" considers curtailment of greenhouse gas emissions through mitigation efforts [51].

Researchers defined and retrofitted previously hindcasted models and future projections of change with a multifaceted approach. Specifically, models were chosen to (a) explore the variability around the "mean" model for the region and (b) best match each scenario narrative. These models were validated by stakeholders and climate conditions were set for each scenario.

2.6.2. Water Balance Model

The research team applied a water balance model (WBM) to represent the hydrogeologic setting incorporating the SAG's robust understanding of the system [52]. WBM is a rasterized, process-based hydrologic model that comprehensively accounts for human alterations and interactions with the hydrologic cycle. Projected future climate predictions were used along with revisions to the land cover data to create indicators of water constraints. Two indicators were used for validation with stakeholders: (a) a water availability indicator that described unmet water demand, and (b) violations of the Swan Falls Agreement. This legal agreement mandates a specific river flow regime based on day-of-the-year flow leaving the basin [48].

2.6.3. Land Use and Land Cover Models

Land use and land cover change models were generated to reflect the spatial allocation of three key indicators of importance to our stakeholders. Those included population, dairy production, and crop production.

Three trends for population growth were modeled to reflect assumptions from the SAG workshops. Upper and lower bounds of parabolic, linear, and geometric confidence intervals were used to represent ranges of incremental percent increase over decadal timesteps. These ranges were applied to geospatial population density maps (Figure 4) using dasymetric modeling [53].

The Magic Valley contributes the majority of Idaho's milk production (currently 74.8% of total milk herd), meaning the current demand for silage, primarily corn and alfalfa, requires substantial tracts of irrigated agriculture to support this system [54]. Calculations of total dairy cattle and associated supporting acreage were generated for each scenario based on narrative trends, research-based calculations, and stakeholder input [54]. As outputs, these representative values to total dairy cattle (head of cattle) populations per each scenario were utilized as scenario performance indicators as well as parameters for agricultural fodder allocation and proportion with a Cropland Data Layer (CDL).

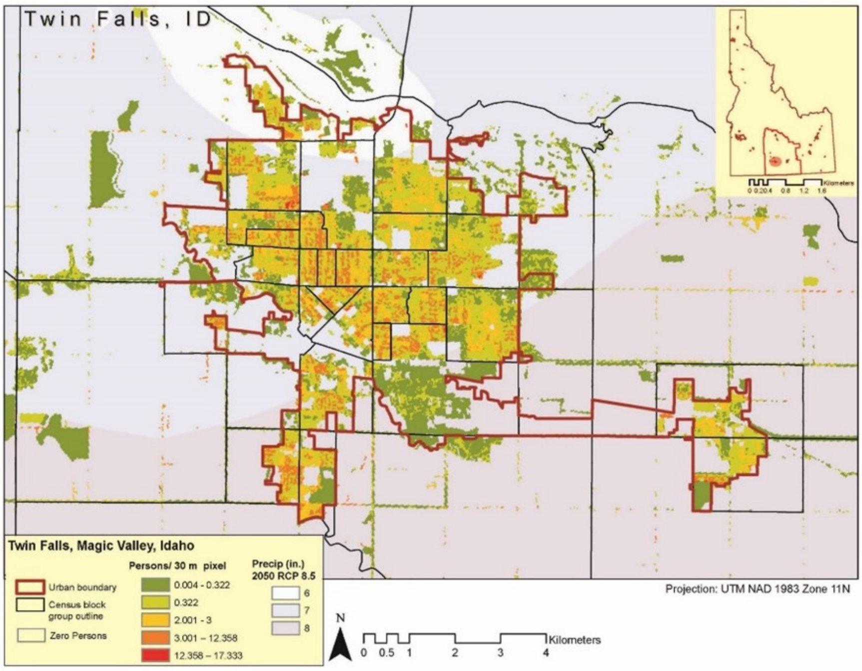

Figure 4. Example of population growth projection for Magic Valley, Idaho under the Megadrought scenario showing a map of 2050 population density and 2050 precipitation distribution.

The predominant land cover for the Magic Valley is agriculture, on which the economy is heavily dependent. The main crops grown throughout the region consist of alfalfa, silage corn, and wheat which provide for interregional dairy production. The region is listed as 49% dairy-related agriculture, 28% commercial agriculture, and 23% developed areas. Due to this dominance of agricultural lands in the region, the 2019 Cropland Data Layer (CDL) [55] raster dataset was used for the land-use model and baseline condition for AF to represent proportions of decadal change through 2050 per each scenario. Operating as decision units [56], the rasters were altered based on iterative scenario-specific SAG feedback and organized within decadal timesteps per scenario (i.e., increases or decreases in types of crops).

2.6.4. Indicators Selection

Within the geodesign process, indicators (otherwise known as "evaluation models") are used to compare scenarios of change based on metrics defined by the stakeholders and researchers [2]. The set of performance indicators was determined by researchers and validated by stakeholders [34]. The indicators serve as a metric to compare and analyze scenarios outputs. The indicators are listed as follows:

- Total human population (number of people);
- Dairy cow count (number of cattle);
- Total agricultural (area in acres);
- Agriculture supporting dairies (area in acres);
- Total non-dairy-based agriculture (area in acres);
- Total urban area (area in acres);
- Fallow/grazing land (area in acres).

2.6.5. Solutions

Feedback from the stakeholder group was used to calibrate and refine spatially explicit representations of the coupled AF vis-à-vis the coupled biophysical models. Through workshop platforms, this process worked to refine stakeholder-driven understandings and uncertainties concerning the SES through mapping tools (Figure 5) [57]. Upon completion of the revised scenarios (Figure 2, Phase 4, Scenarios v.2), the futures were used to guide the final iteration of the scenarios with embedded solutions. A suite of solutions was identified through research conducted by the team and brainstorming with stakeholders. These solutions were prioritized by stakeholders and they identified probable time periods for their adoption. These futures and solutions were the foundation of impact and indicator analysis using ESRI's Geoplanner [58] and ESRI's ArcGIS Pro.

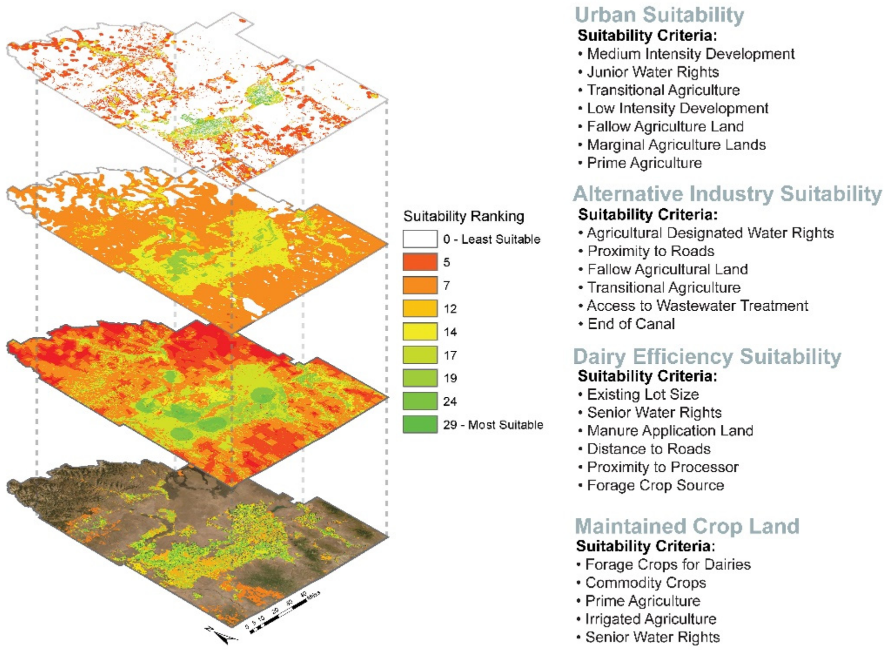

Figure 5. Spatial suitability indices and criteria to support scenario evaluation.

Integrated solutions for each scenario were developed into the "InFEWS Atlas" (see Supplementary Materials). The master list of solutions allowed researchers and stakeholders to highlight relevant solutions per scenario to be analyzed in the magnitude of impact at different levels of change.

3. Results

3.1. Phases 1, 2, and 3

The "Issues and Decisions" workshop (November of 2017) allowed stakeholders, representing multiple industries and interests, to co-develop a set of issues and decisions that will be facing the region in the future (2050). The stakeholders first brainstormed issues and decisions and then prioritized the top five. Some examples of the issues included "water availability" and "water quality", whereas decisions included "Should prior appropriation change?" or "Should co-ops be adopted?" The data from stakeholder input was used to identify past and present drivers of change in the region's SES, focus research conducted by the research team, and inform model input.

Following the development and ranking of the issues and decisions, the SAG identified actors that would be impacted by those issues and decisions in either a positive or negative manner. Uncertainties were then compiled and vetted through the SAG. These were not only essential for the scenario narrative process but also aided in the development of indicators for the region. The following uncertainties were developed and ranked by the stakeholder group and subsequently used to support the development of the scenario narratives:

- Will there be sufficient water supply for demand?
- Will water regulations change?
- Will allocation of resources impact growth?
- Will the highest and best use (HBU) be the driver for change?
- Will agriculture be used as a national security tool?

Scenario narratives were produced to vary the multiple issues and uncertainties identified by the SAG into plausible AFs and supported by research and data on the issues and uncertainties (population growth over time, for example), when available. Varying only a few (three or four) for each scenario provides an opportunity for stakeholders to process AFs without becoming overwhelmed as they would be if all ranges of each variable were modified, as is the case in most simulation-style scenarios. The narratives were iterated with stakeholders and researcher input and revised based on the input. The research team iterated the narratives up until the final year of the project to ensure any changes in stakeholder perceptions and understanding of the system were accurately reflected. For examples of the narratives please see Table 2 and refer to the Supplementary Materials section for a more detailed description.

3.2. Phase 4

3.2.1. Climate Scenarios Utilized

Climate models systematically underestimated regional drought severity as defined by prolonged precipitation shortfalls. This emphasizes the importance of using output from bias-corrected and down-scaled climate models in assessing future landscape resilience for water-limited or dependent ecosystems and economies. Six scenarios (Figure 6) were selected for scenario model coupling and discussion with the stakeholder group to account for the possibility that drought severity was still underrepresented in the existing model results, we synthesized a millennial-scale drought dataset using reanalysis data for the period of the 1920s drought, and then scaled all results to seasonal temperatures expected from down-scaled climate models until 2050 [49,59].

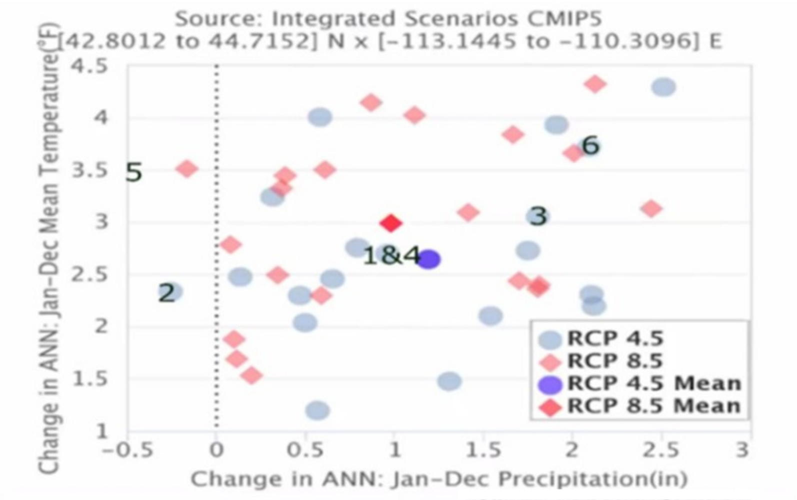

Figure 6. Climate model variability, according to changes in temperature and precipitation, for the models that perform best in the region, separated by RCP 4.5 (blue and purple) and RCP 8.5 (pink and red). We identified a selection of climate models to capture the range in annual temperature and annual precipitation projection variability to be used in each of the six scenarios for Magic Valley, Idaho 2019–2050. Scenarios (identified by numbers 1–5 on the graph, see Tables 2 and 3) were assigned to models that best aligned with the stakeholder-defined narrative.

Table 3. Scenarios associated with each climate model.

	Scenarios, Models Used and RCP Values
Scenario	**Model and RCP Value**
Business as Usual	Can-ESM2 (RCP 4.5)
The Courts Call	MIROC5 (RCP 4.5)
Locavore	CNRM-CM5 (RCP 4.5)
Population Boom	CNRM-CM5 (RCP 4.5)
Megadrought	MIROC5 (RCP 8.5)
Happy Valley	CNRM-CM5 (RCP 4.5)

3.2.2. Water Balance Model Scenarios

The WBM results demonstrated the variability and nuance for spatially explicit and temporal solutions needed within each scenario. Socio-hydrological system interventions included water conservation, alternative cropping patterns, domestic metering of wells, urban water savings, land use and land cover change, water reuse strategies, and drought-resistant crops introduced within the land use and land cover models. Figure 7 provides an example of spatiotemporal WBM outputs with integrated solutions for the "Megadrought" scenario.

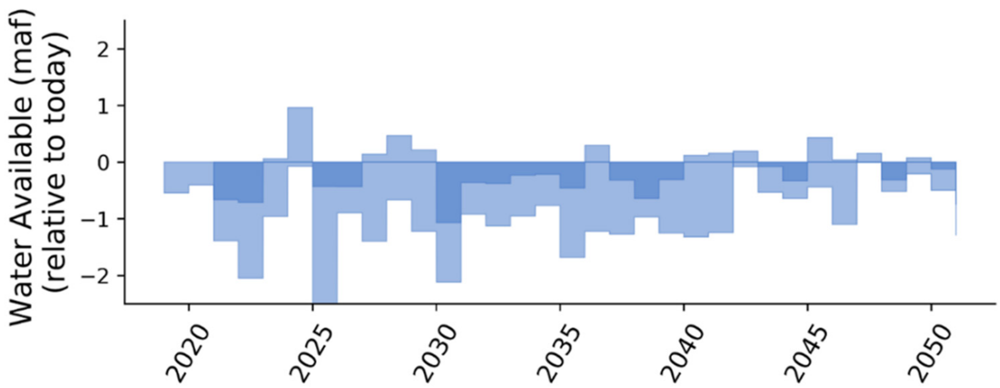

Figure 7. Megadrought scenario water availability diagram.

3.2.3. Land Use and Land Cover Change

In parallel with the revision of narratives, the researcher team finalized spatial models that aligned with input and data recommendations derived from the SAG workshops. Defined by land-use suitability, population growth, climate models, and water balance modeling, land use and land cover change models were generated to reflect issues, decisions, and uncertainties that varied with each scenario narrative identified with the SAG.

Upper and lower bounds of parabolic, linear, and geometric confidence intervals were used to represent ranges of an incremental percent increase in the human population over decadal timesteps. These ranges were applied to geospatial density maps across the region using dasymetric analysis [53]. Results inferred geospatial patterns of urban growth which were vetted by stakeholders and, in turn, used to locate the growth trends of the study area per implications of each scenario. Figure 8 demonstrates these trends applied to specific scenarios aligned with stakeholder understandings.

Dairy cow projections (Table 4) increased and decreased based on each scenario's narrative and set of hydrologic, climatic, and land use assumptions. Stakeholders validated iterative results, identified more reliable data, and helped define the hypothetical upper (carrying capacity) and lower bounds and location of dairy cows within the region.

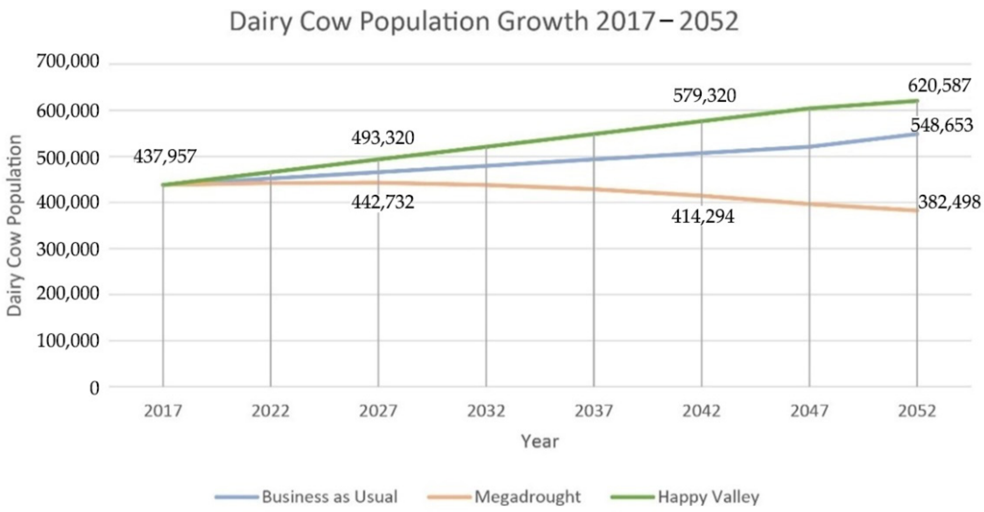

Figure 8. Milk cow population growth projections for each county in Magic Valley, Idaho 2017–2052.

Table 4. Projections for human population change in Magic Valley, Idaho 2020–2050.

	Population at Each Decadal Timestep			
Scenario	**2020**	**2030**	**2040**	**2050**
Low Growth (Megadrought, Locavore)	207,327	224,100	242,500	261,000
Moderate Growth (Business as Usual, The Courts Call)	207,327	240,400	264,100	302,400
High Growth (Population Boom, Happy Valley)	207,327	313,100	374,600	435,200

Modeled cropland results indicate variability and change across the entire scenario suite. Within the "Megadrought" scenario (Figure 9), prominent areas for dairy-based agriculture production steadily decreased across timesteps, and dairy cow count rapidly responds to this reduction in agricultural yields. Similarly, drought-resilient crop types are introduced to sustain the remaining dairy cow demand.

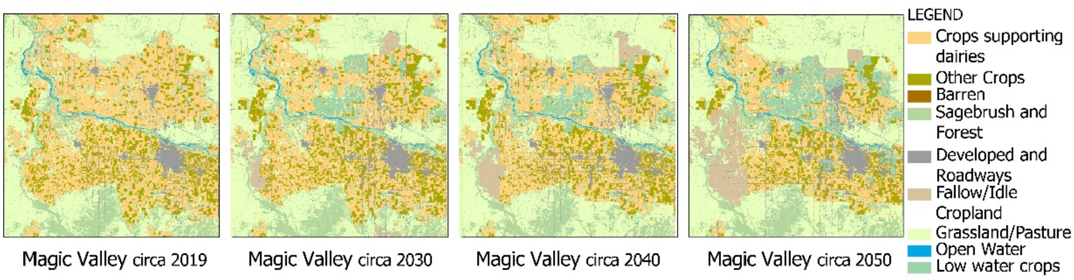

Figure 9. Land use and land cover alternative future example. This image illustrates land use and land cover change for the Megadrought scenario from 2019 to 2050 in decadal timesteps for Magic Valley in a "Megadrought" scenario. The figure demonstrates a large portion of agricultural land converting to either "fallow or Idaho cropland" or "low water crops" within this scenario.

3.3. Solutions

Multiple solutions were identified by the research team and vetted by the SAG. Results indicate that stakeholders were able to identify solutions that were temporally sensitive (Figure 10). Each solution, per each scenario, was geared toward adapting to or mitigating an undesirable change. Once a solution was identified, the biophysical models were rerun to capture and assess the impacts of that solution.

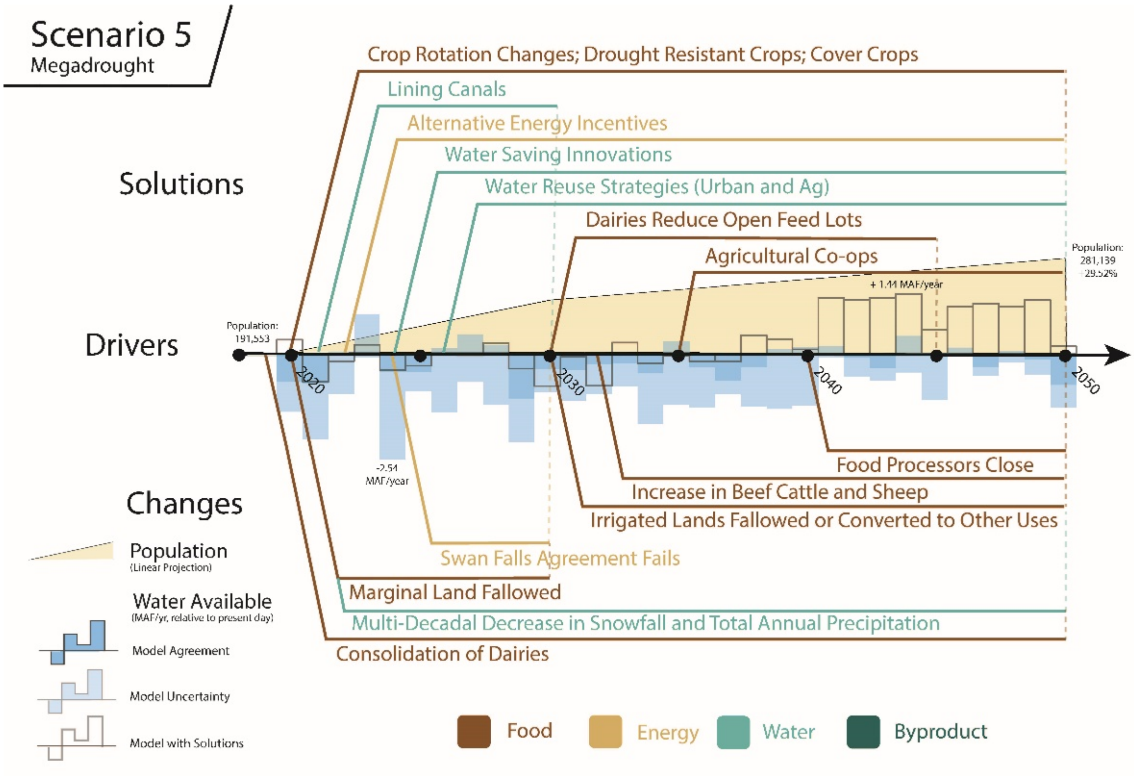

Figure 10. Example of the "Megadrought" scenario showing projections of key drivers of change, the projected impacts of those changes, and superposition of a sequence of stakeholder-developed interventions on the landscape, for 2019–2050 for Magic Valley, Idaho. Specifically, this figure shows how solutions line up with specific drivers (social and biophysical). For solutions that impact water availability, hollow bar charts represent the impact.

3.4. Cross-Scenario Comparison

Using a consistent set of indicators, we see strong inter-scenario variability (Figure 11), allowing for cross-scenario comparison of potential solutions and impacts to the region.

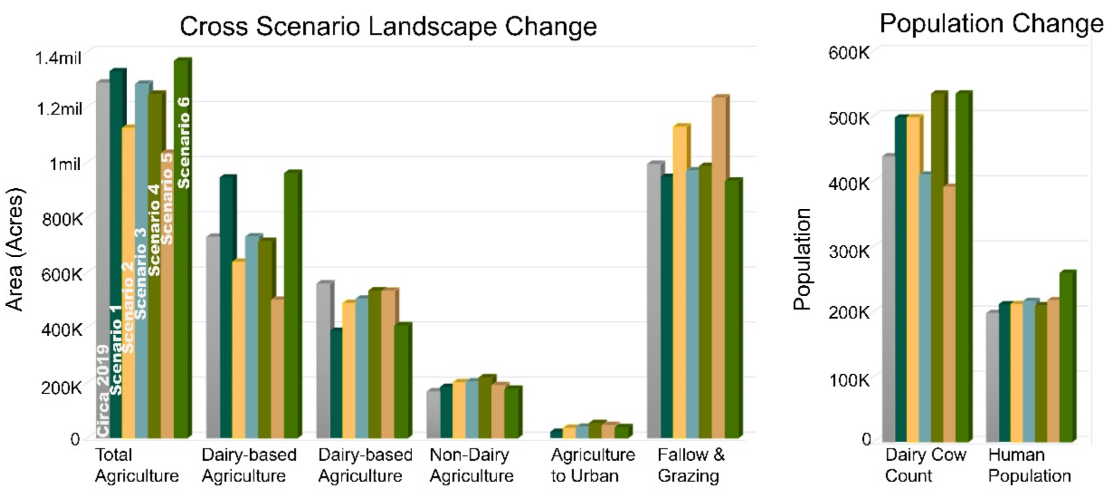

Figure 11. Comparison of projected land use land cover change and human population change for the six stakeholder-developed scenarios for Magic Valley, Idaho 2019–2050.

4. Discussion

4.1. Expanding Geodesign Frameworks from Stakeholder-Informed to Stakeholder-Directed

This project demonstrates an expansion of the geodesign framework [2] from a stakeholder-informed to a stakeholder-directed approach [4,5,8,12]. The sequence of representation, process, evaluation, change, impact, and decision models are successively and iteratively developed, assessed, and refined by stakeholders for their communities. Furthermore, an implication of the development of scenarios in this way is the relinquishment of control by the researcher and the acknowledgment of the necessity to be continually adaptive to new knowledge and understandings brought by stakeholders.

The Magic Valley case study demonstrates the wide array of stakeholder perspectives that can define and potentially confine stakeholder-based scenarios and alternative futures. We were able to explore incremental and plausible future trajectories of change defined by a set of scenarios, with embedded solutions defined for each scenario. Model coupling and inferences made to define spatiotemporal solutions into scenarios required a robust framework based on knowledge and ground-truthing from a local stakeholder group. In the Magic Valley, Idaho case study the SAG was crucial throughout the entire methodological approach (Figures 1 and 2) for co-developing [34] the six alternative futures and solutions through multiple iterations, renditions, and representations.

4.2. Transparency through Feedback

Feedback from stakeholders was used to calibrate and refine spatially explicit representations of biophysical models. This iterative process was successful in the refinement of the final scenario models. These models then provided a foundation for impact and indicator analysis using geospatial tools through the InFEWS Atlas which was presented to stakeholders and is available to future researchers and interested parties. The InFEWS Atlas operates as a platform for audiences with our research process, methodologies, and illustrated geospatial futures for Magic Valley Idaho (see Supplementary Materials section).

We found that the geodesign framework is flexible to deducing a suite of solutions early in the scenario development process and can be distilled into a set of spatiotemporal viable solutions. An organizational framework, such as the InFEWS Resilience Framework, can offer a formalized methodology to address crucial components for the production of stakeholder-defined scenarios. Importantly, the way the framework was implemented with the SAG in the Magic Valley case study leads to ownership of the process and outcomes by the stakeholders, and consequently, a greater likelihood that the solutions designed during the process can be implemented by the communities it was meant to serve.

4.3. Transferability for Resilience

From this research, it can be inferred that scenario depictions, coupled biophysical models, and stakeholder engagement have the capacity and ability to facilitate: 1. understanding of a system as a coupled socio-economic and biophysical system; 2. anticipating future issues and uncertainties within the system; 3. creating a suite of available solutions, and identifying possible time periods or events that would trigger the adoption of the solution even before an issue arises. This framework increases the resilience of communities by allowing them to anticipate, plan, and find solutions beforehand. It also increases the human capital of the region.

5. Conclusions

Integration of models to produce scenarios of change requires many different factors for processing and representation to evoke stakeholder engagement. A "predict-then-act" [40] resilience-based framework for anticipatory scenarios can address key issues in agrarian landscapes by denoting a range of plausible solutions vis-à-vis uncertainties identified within the geodesign process [2]. Plausible and viable solutions to enhance SES change under biophysical variability require early integration into models, stakeholder workshops, scenario construction, and solution adoption from local decision-makers. This also requires researchers to be receptive to new ideas and knowledge from stakeholders and a willingness to adapt the process as it unfolds.

As highlighted in the discussion, providing research-based outputs and scenario depictions vetted through a stakeholder group can impact the conceptualization of future trajectories of change. As a limiting factor, stakeholder input throughout similar processes may be specifically focused on impacts for key sectors and perceptions of actors' sense of agency due to implied biases. Embedding solutions within these modeled futures demonstrate researcher and stakeholder characterization of resilient nexus-based FEWS dynamics.

However, there are some limitations with our approach and assumptions around future-oriented solutions. Embedded solutions may not directly address the stressors identified in each scenario; nonetheless, we made an attempt to define or determine the potential magnitude and impact of future shifts in regional and national externalities on resource and land-use policy. Similarly, addressing low-intervention, high-reward strategies, and solutions (i.e., best management practices) per each scenario requires further research. However, within our process, only viable solutions, as identified by our SAG, were proposed. Finally, furthering scenario-based research for food–energy–water system dynamics is subject to challenges in stakeholder engagement and modeling capacity; however, initial solution-oriented frameworks could be an important addition to future FEWS research.

Supplementary Materials: The following supporting information can be accessed at: https://the-infews-atlas-magic-valley-idaho-alternative-futures-uidaho.hub.arcgis.com/ (accessed on 23 February 2022).

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