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A Framework for Tracing Social–Ecological Trajectories and Traps in Intensive Agricultural Landscapes

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Abstract: Charting trajectories toward sustainable agricultural development is an important goal at the food–energy–water–ecosystem services (FEWES) nexus of agricultural landscapes. Social–ecological adaptation and transformation are two broad strategies for adjusting and resetting the trajectories of productive FEWES nexuses toward sustainable futures. In some cases, financial incentives, technological innovations, and/or subsidies associated with the short-term optimization of a small number of resources create and strengthen unsustainable feedbacks between social and ecological entities at the FEWES nexus. These feedbacks form the basis of rigidity traps, which impede adaptation and transformation by locking FEWES nexuses into unsustainable trajectories characterized by control, stability, and efficiency, but also an inability to adapt to disturbances or changing conditions. To escape and avoid rigidity traps and enable sustainability-focused adaptation and transformation, a foundational understanding of FEWES nexuses and their unique trajectories and traps is required. We present a framework for tracing trajectories and traps at the FEWES nexuses of intensive agricultural landscapes. Framework implementation in a case study reveals feedbacks characteristic of rigidity traps, as well as opportunities for modifying and dissolving them. Such place-based understanding could inform sustainable agricultural development at the FEWES nexus of intensive agricultural landscapes worldwide.

Keywords: agriculture; feedbacks; governance; management; resilience; rigidity; social–ecological systems; sustainable agricultural development

1. Introduction

The pursuit of sustainable agricultural development aims to ensure that current and future human demands for vital ecosystem services can be satisfied without severe ecological degradation [1]. In the context of resilience thinking [2], two broad strategies for adjusting and resetting the trajectories of social–ecological systems (SES) toward sustainable futures are adaptation and transformation [3]. Social–ecological adaptation involves actively (i.e., intentionally) or passively (i.e., unintentionally) adjusting in anticipation of or response to perturbations or changing conditions, so that a SES maintains its characteristic structures and functions. Meanwhile, transformations are exemplified by intentional, human-driven changes in structures and functions (i.e., crossing a threshold, collapsing, and reorganizing in a new state), generally to foster a change from an undesirable SES state to one that is perceived as more desirable. Human agency in initiating and guiding SES state shifts is a hallmark of transformations that differentiates them from other state shifts [4]. In the resilience literature, the practices of adaptive management [5] and adaptive governance [6] are promoted for intentional SES adaptation, while the emerging practice of transformative governance is promoted for intentional SES transformation [7].

The food–energy–water–ecosystem services (FEWES) nexus [8] is a SES arena where adaptations and transformations important for sustainable development take place (Table 1). Geographically, FEWES nexuses are nested within SES, which are nested within individual or multiple landscapes. In agricultural systems, food, energy, and water are individual resources; however, their interactions as components of the FEWES nexus are also important (e.g., crop irrigation for food production). The ecosystem services component broadens the scope of the FEWES nexus beyond agricultural systems per se to include resources that people obtain directly from ecological systems (e.g., recreation) and to recognize the ultimate dependence of agricultural systems on ecological systems (e.g., crop yields depend on soil health).

Table 1. Glossary of terms.

Trap Type	Definition
Causal loop diagram	A tool for visualizing relationships among system variables and external factors [9].
FEWES nexus	Interactions and interdependencies among the resources of food, energy, and water, as well as additional ecosystem services that people draw directly from ecosystems and which support the flows of resources to people [8].
Intensive agriculture	Areas devoted exclusively to agricultural production, with a high degree of specialization for a small number of agricultural commodities through high levels of external inputs [10].
Process-tracing	An analytical technique from the social sciences that uses empirical evidence from case studies to explore causal relationships among variables [11]. Minimalist or systems versions may be adopted, according to baseline understanding and information available. Theory-building or theory-testing versions may also be adopted, according to study objectives.
Rigidity trap	A SES trap in which a low degree of flexibility (i.e., adaptive capacity) prevents adaptation to changing conditions or novel disturbances [12].
Scenario planning	The practice of considering alternative, plausible futures in situations in which there is a high level of uncertainty and low level of control over a focal variable or system [13].

People obtain resources (e.g., food and fresh water) for meeting basic needs at the FEWES nexus, but often at the long-term expense of supporting (e.g., soil health and photosynthesis) and regulating (e.g., climate and nutrient cycling) ecosystem services. The degradation of supporting and regulating ecosystem services threatens the availability of basic resources over the long-term [14]. Despite the clear connections among different FEWES components, there has been a tendency to research and manage individual components in isolation, with insufficient consideration of tradeoffs. For a more sustainable FEWES future, better integration of FEWES components is necessary. In addition to integration of components, adaptation and transformation of FEWES nexuses may be necessary for making and keeping them sustainable amidst global change.

In some instances, financial incentives, technological innovations, and/or subsidies associated with the consistent and efficient maximization of a small number of provisioning ecosystem services encourage the creation and strengthening of maladaptive, amplifying (i.e., self-reinforcing) feedbacks between social and ecological entities at the FEWES nexus [15]. These feedbacks can lock FEWES nexuses into unsustainable trajectories characterized by short-term control, stability, and efficiency, but also the inability to withstand or adapt to novel disturbances and/or changing conditions (i.e., inflexibility, low adaptive capacity), and therefore, long-term vulnerability to large-scale collapse (i.e., undesirable, unintentional state shifts) [16]. Such phenomena are investigated as rigidity traps in the resilience literature [12].

As an example, rigidity traps can develop at the FEWES nexus when financial profits associated with high crop yields incentivize intensive cultivation, which decreases soil productivity and necessitates the application of synthetic fertilizer in order to maintain high yields. Here, a fast variable (i.e., annual crop yield) and slow variable (i.e., soil productivity) are decoupled through the utilization of efficient technologies (i.e., synthetic fertilizers). In other words, a natural negative (i.e., stabilizing) feedback between soil productivity and annual yield is rerouted. Although FEWES nexuses in such pathways may be stable and efficient in crop production over the short-term, they also become increasingly vulnerable over the long-term as their dependence on fertilizer inputs increases. This is especially true if optimization of yield for a specific crop causes a decrease in system diversity, because when conditions change (e.g., the region becomes climatically unsuitable for dominant crops) or disturbances occur (e.g., fertilizer costs rise), the FEWES nexus is left with few options for remaining economically viable. In other words, short-term stability is achieved but at the expense of long-term sustainability [12].

Rigidity traps are a major obstacle for sustainable agricultural development because they entrench FEWES nexuses in unsustainable pathways and increase their vulnerabilities to changing conditions and disturbances, which they are increasingly likely to experience over longer time periods. Rigidity traps may also impede the integration of FEWES components in more sustainable management approaches. Even when there is awareness of the negative consequences associated with optimizing for a single ecosystem service, human actors in rigidity traps tend to be unwilling or unable to make changes necessary for escaping traps and reducing vulnerability [17,18]. This inability or unwillingness to change (i.e., path-dependency) presents a major challenge to sustainability-focused adaptation and transformation because both rely on human agency. There has been relatively little exploration into how different FEWES components might be integrated or how the trajectories of FEWES nexuses might be adjusted (i.e., adapted) or reset (i.e., transformed) toward more sustainable futures in the face of rigidity traps.

To avoid and escape rigidity traps and enable FEWES integration, adaptation, and transformation, an understanding of the focal FEWES nexus, its developmental trajectory, and trap(s) along that trajectory is fundamental. Such understanding could be used to target certain valuable or problematic interactions or feedbacks related to the sustainability and/or flexibility of the FEWES nexus, in order to help escape traps, adapt, and/or transform. In this study, we present and apply a framework for tracing social–ecological trajectories and traps at the FEWES nexuses of intensive agricultural landscapes with the tools of process-tracing, causal loop diagramming, and scenario planning. Collectively, these tools can be used to increase understanding of: the current nexus trajectory, what led to the current nexus trajectory, and plausible future nexus trajectories. Such understanding could inform sustainable agricultural development strategies at the FEWES nexuses of intensive agricultural landscapes worldwide.

2. Materials and Methods

Our framework uses the tools of process-tracing, casual loop diagramming, and scenario planning to examine causal relationships within individual FEWES components (i.e., food, energy, water, and ecosystem services) and then integrates them for broader understanding. For demonstrative purposes, we apply the framework at the FEWES nexus of the Central Platte Natural Resource District (CPNRD), an intensive agricultural watershed in the Platte River Basin (PRB) of the American Great Plains (Figure 1). Here, intensive agriculture refers to areas devoted exclusively to crop production, with specialization for grain yields through high levels of external inputs.

2.1. Focal FEWES Nexus

The CPNRD extends for several hundred kilometers west-to-east on the north and south sides of the Platte River in the State of Nebraska, U.S.A. (Figure 1). Rocky Mountain snowmelt feeds the North Platte and South Platte Rivers in the States of Wyoming and Colorado, which along with a number of smaller tributaries, join to form the main stretch of the Platte River in Nebraska [19]. Prior to Euro-American settlement, the Platte was a non-channelized, braided prairie river, with seasonal ebbs and flows and other periodic flow fluctuations of high variance [20]. However, the Platte has been extensively modified by human activity since the early 20th century, and is now dammed, has more regulated flows, and has banks and sandbars stabilized by trees and aquatic vegetation [19,21].

The once grass-dominated lowlands and uplands of the CPNRD are now utilized for crop and livestock production. Economically important crops include maize (*Zea mays*) and soybeans (*Glycine max*). Large proportions of maize grain produced in the region are used for livestock feed and the production of starch-based ethanol. Cattle production in the CPNRD occurs in rangelands and feedlots. In addition to being important for agriculture, the CPNRD provides important habitat for a number of resident and migratory aquatic and terrestrial species, several of which are federally endangered and protected [19,21]. Finally, aquatic and terrestrial areas provide people with recreational opportunities (e.g., hunting, fishing, and camping), as well as other cultural ecosystem services. The CPNRD has a relatively sparse human population with few major cities.

A rain shadow effect from the Rocky Mountains creates a west-to-east precipitation gradient across the CPNRD and surrounding PRB. In much of the CPRND, water availability is a limiting factor for crop productivity; therefore, groundwater irrigation is common [22]. Prevalent irrigation methods include gravity (i.e., furrow), center-pivots, and drip irrigation systems. Dryland (i.e., no irrigation) is also common. The Platte River and its tributaries provide surface water for crop irrigation and human consumption, and recently documented hydrological connections between rivers/streams and groundwater from the High Plains Aquifer [23] means that the rivers and streams also support—and are affected by—groundwater withdrawals for irrigation, industry, and human consumption. Surface water and groundwater withdrawals are currently regulated by state and local governmental agencies. In Nebraska, the Department of Natural Resources manages surface water at the state-level, while Natural Resource Districts (NRD) manage groundwater at the watershed-level. Hydrological connectivity between surface water and groundwater requires collaborations among agencies in water management. The official recognition of groundwater–surface water connectivity [23] was established in 2004, following a sustained drought.

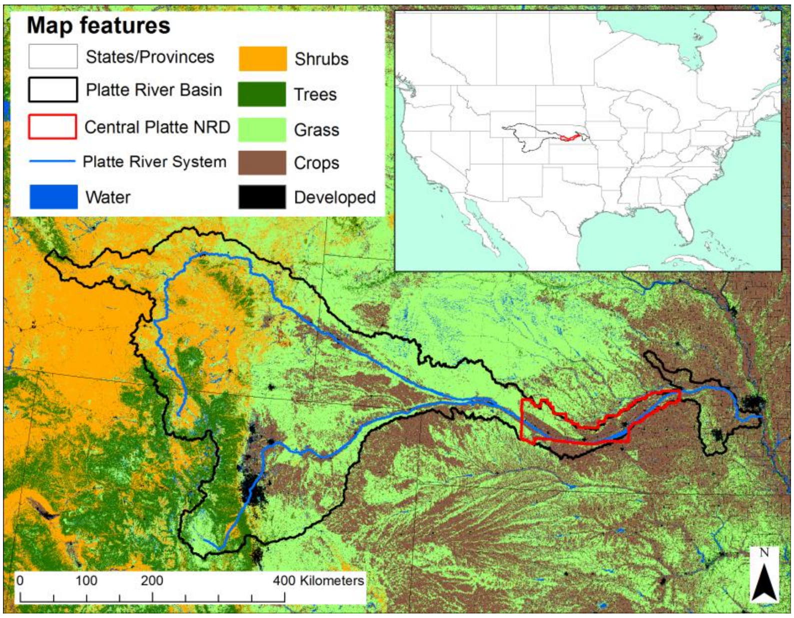

Figure 1. Landcover data in the Central Platte Natural Resource District in the Platte River Basin of the American Great Plains. Landcover data was obtained from the National Land Cover Dataset [24] and reclassified.

The FEWES nexus of the CPNRD is important for its production of and effects on a number of provisioning, supporting, regulating, and cultural ecosystem services. Although the flows of ecosystem services to human populations in the CPNRD are currently relatively stable, the FEWES nexus may exist in a rigidity trap(s) and be vulnerable to collapse in the long-term. Commercial agricultural production in the CPNRD may also be largely unsustainable because of its high degree of reliance on external inputs and erosion of supporting and regulating ecosystem services. We apply our framework for tracing social–ecological trajectories and traps at the CPNRD FEWES nexus, in order to increase understanding of its past, present, and potential futures.

2.2. Process-Tracing

Process-tracing is a technique that uses empirical evidence from case studies to evaluate causal relationships among variables [25]. Process-tracing may take several different forms, each of which are more or less appropriate, depending on study objectives and baseline understanding of the research subject. When understanding and information are limited, a minimalist version of process-tracing is used to test fundamental assumptions and hypotheses about among-variable relationships and to lay a foundation for in-depth future examinations. A systems version of process-tracing goes into greater detail in examining the specifics of causal relationships. In addition to minimalist versus systems versions, either theory-building (i.e., inductive) or theory-testing (i.e., deductive) approaches to process-tracing may be adopted, also according to baseline understanding and study objectives [11]. Process-tracing does not involve simply speculating about relationships between causes and outcomes; rather, it formally links causes to outcomes through specific mechanisms. This necessitates gathering accurate information on specific outcomes, mechanisms, and causes related to the phenomenon at hand.

Our framework accommodates the use of different forms of process-tracing to increase understanding of among-variable relationships in the past and present of different FEWES components. In other words, process-tracing is used to examine causal relationships within individual food, energy, water, and ecosystem services components of the focal FEWES nexus separately. When the understanding of and information regarding the focal FEWES nexus is limited, a theory-building and minimalist form of process-tracing should be adopted, whereas a theory-testing and/or systems form of process-building should be adopted when there is a higher level of understanding and information.

For the CPNRD FEWES nexus, sets of causes, mechanisms, and outcomes related to past and present processes in each of the four FEWES components were obtained from scientific literature and our own understanding of the CPNRD. Recent scientific studies on the PRB, which encompasses the CPNRD, were Birgé et al. [19], Nemec et al. [21], and Zipper et al. [22]. Our version of process-tracing is minimalist and theory-building (i.e., inductive). Process-tracing is applied to the watershed scale of organization.

2.3. Causal Loop Diagramming

Causal loop diagrams are tools used to represent interactions among system entities and how entities and interactions are affected by external factors [9,26]. In regard to rigidity traps, causal loop diagrams may be particularly useful for identifying social–ecological feedbacks that encourage and discourage rigidity traps, as well as the influences of different forms of context (e.g., spatial, historical, and socioeconomic) on rigidity traps and feedbacks. In essence, causal loop diagrams can increase system-level understanding by examining relationships among diverse processes.

Our framework uses causal loop diagramming to represent FEWES nexus characteristics, which include interactions and feedbacks. The results of process-tracing (Section 2.2) form the basis of causal loop diagrams. Relationships among the causes, mechanisms, and outcomes of different processes are established in causal loop diagrams, as are the influences of context variables. The direction of effects among different causes, mechanisms, and outcomes can be represented with directional arrows, which produces a perceptual model of the FEWES nexus—or mathematical relationships—which produces a conceptual model of the FEWES nexus [27]. Following construction of the causal loop diagram, it can be inspected for social–ecological feedbacks, which may broadly be labeled as positive (i.e., amplifying) or negative (i.e., stabilizing).

For the CPNRD FEWES nexus, we used the results of process-tracing (Section 3.1) as the basis for causal loop diagram development. In addition to directionally connecting various causes, mechanisms, and outcomes associated with processes in each of the four FEWES components, we explored the influences of several external (i.e., context) variables. Information for diagram construction was drawn from Birgé et al. [19], Nemec et al. [21], and Zipper et al. [22], as well as our baseline understanding of the CPNRD. Following construction of the causal loop diagram, we visually inspected it for social–ecological feedbacks and labeled each feedback as positive or negative.

2.4. Scenario Planning

Scenario planning is a tool used to envision and prepare for future changes under conditions of high uncertainty and low control [13]. The goal of scenario planning is not to forecast the most likely version of the future, but rather to consider alternative, plausible futures, none of which are likely to fully represent the true future, but each of which contain potentially relevant aspects of and uncertainties over it.

Our framework applies scenario planning to the envisioning of alternative, plausible FEWES nexus trajectories, applying understanding of past and present trajectories gained through process-tracing and causal loop diagramming, as well as projecting changes it may experience in the future. In particular, the framework considers how the intentional alteration of social–ecological interactions and feedbacks could adjust or reset the trajectory of the FEWES nexus. Beyond the alteration of existing interactions and feedbacks, scenarios could be used to identify opportunities for the establishment of novel feedbacks. Causal loop diagram results (Section 3.2) can be analyzed and even reconstructed (i.e., rewired [28]) around altered or novel interactions and feedbacks to indicate the effects of feedback alteration or establishment on other FEWES elements.

For the CPNRD FEWES nexus, we developed two scenarios of future trajectories: (1) Climate Adaptation and (2) Perennial Transformation. The Climate Adaptation Scenario focuses on the alteration of existing social–ecological feedbacks for increased resilience to the agricultural effects of climate change [29], whereas the Perennial Transformation Scenario involves the transformation of the CPNRD FEWES nexus from producing food [30] and bioenergy [31] from perennial instead of annual crops. Each scenario focused primarily on a feedback(s) identified in the causal loop diagram (Section 3.2).

3. Results

3.1. CPNRD FEWES Processes

We traced two processes in each of the four components of the CPNRD FEWES nexus, which resulted in a total of eight traced processes (Table 2). Each process was broken into a cause, one or more mechanisms associated with the cause, and a resulting outcome(s). Processes in the food component are associated with the outcomes of high grain production—and the high degree of consistency in that production—that characterizes the current CPNRD FEWES nexus. Energy processes involve the production of bioenergy (i.e., starch-based ethanol) and increased mechanization in farming. Water-based processes are associated with groundwater levels, surface water flows, and groundwater nitrification. Finally, ecosystem service processes are tied to wildlife habitat and soil health as cultural and supporting ecosystem services, respectively.

Table 2. Selected causes, mechanisms, and outcomes in each of the components of the food–energy–water–ecosystem services nexus of the Central Platte Natural Resource District watershed.

Component	Cause	Mechanism(s)	Outcome(s)
Food	Financial profits	Intensive cultivation	High grain production
Food	Financial profits	Fertilization + Pesticide application + Irrigation	Sustained high grain yield
Energy	Bioenergy mandates	Financial subsidization	Sustained ethanol production
Energy	Mechanization	Efficient production	Decreased labor demand
Water	High crop water use	Irrigation	Decreased ground/surface water
Water	Fertilizer application	Nitrification	Unsafe drinking water
Ecosystem services	Financial profits	Conversion to crops	Reduced wildlife habitat
Ecosystem services	Intensive cultivation	Erosion + Soil carbon loss	Soil degradation

We also identified four external factors associated with the historical and geographical context of the CPNRD FEWES nexus and identified the process each external factor was most closely associated with (Table 3). Drought is a relatively common form of natural disturbance in the CPNRD and surrounding Great Plains; however, it stresses availability of groundwater and surface water for crop irrigation and human consumption [22]. Conservation incentives—such as payments for converting erodible cropland soils to perennial grassland under the Conservation Reserve Program—drive land use change decisions and affect the quality and quantity of habitat for grassland-dependent species. Irrigation regulations are established at the state- and watershed-levels of organization. Specifically, NRDs regulate groundwater withdrawals within watersheds and the DNR regulates surface water flows within the State of Nebraska. Finally, the Endangered Species Act mandates that minimum surface water flows necessary for providing habitat for the piping plover (*Charadrius melodus*), interior least tern (*Sterna antillarum athalassos*), whooping crane (*Grus americana*) and pallid sturgeon (*Scaphirhynchus albus*)—all of which are currently listed as federally endangered or threatened—be maintained in the Platte River at certain times each year. This means that groundwater and surface water withdrawals may be restricted in order to ensure the provision of sufficient habitat for these endangered and threatened species.

Table 3. External factors at food–energy–water–ecosystem services (FEWES) nexus of the Central Platte Natural Resource District watershed and the FEWES process it influences.

External Factor	Process Influenced
Drought	Crop water use–Irrigation–Ground/surface water
Endangered Species Act	Financial profits–Conversion to crops–Wildlife habitat
Conservation incentives	Financial profits–Land use change–Wildlife habitat area change
Irrigation regulations	Crop water use–Irrigation–Ground/surface water

3.2. CPNRD FEWES Diagram

The current trajectory of the CPNRD FEWES nexus is characterized by interactions among various FEWES processes (Figure 2). An influential positive social–ecological feedback is evident between intensive cultivation, sustained high grain yields, and financial profits (Figure 3). This feedback makes farming profitable and results in the production of large quantities of food. However, this feedback does not exist in isolation—a number of additional social–ecological feedbacks have effects on the profitability of grain production within the CPNRD.

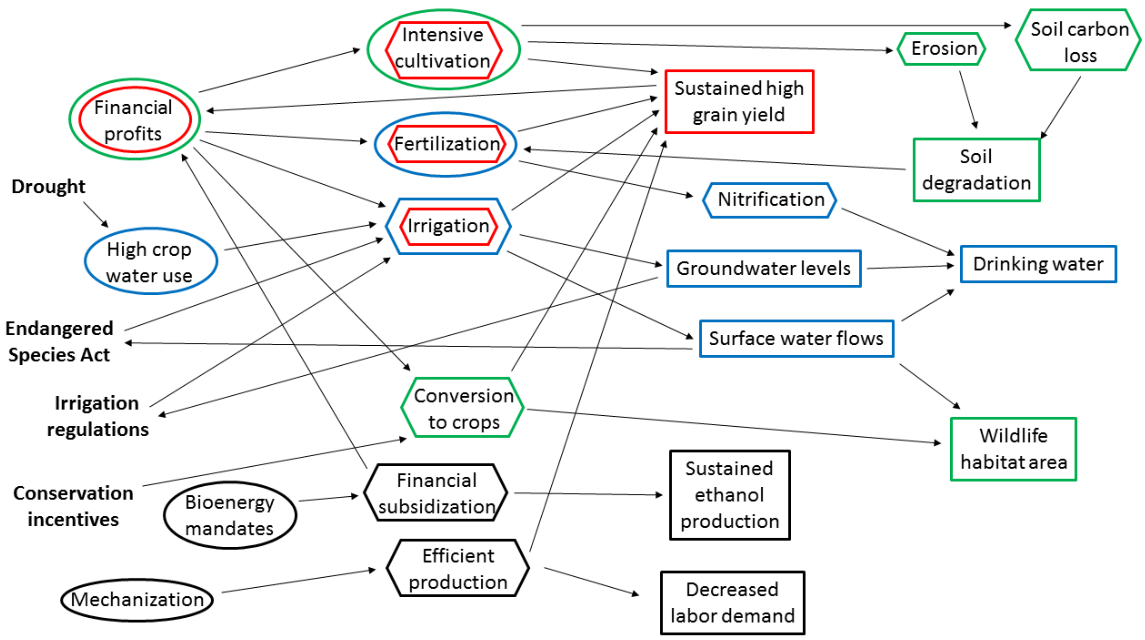

Figure 2. Causal loop diagram of the food (red)—energy (black)—water (blue)—ecosystem services (green) nexus of the Central Platte Natural Resource District composed of causes (oval frames), mechanisms (hexagon frames), outcomes (rectangle frames), and external factors (no frames).

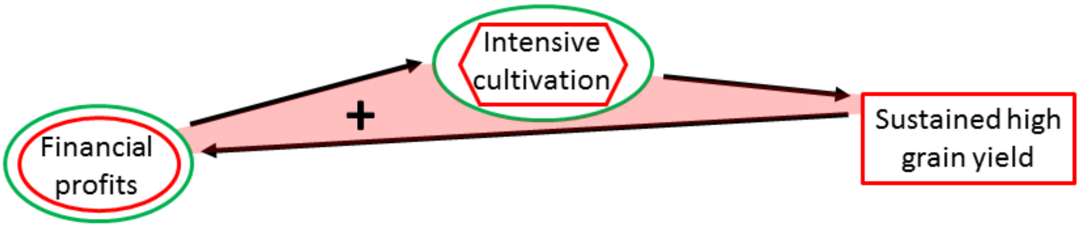

Figure 3. Positive (amplifying) feedback between financial profit, intensive cultivation, and sustained high grain yield at the food (red)—energy (black)—water (blue)—ecosystem services (green) nexus of the Central Platte Natural Resource District, composed of causes (oval frames), mechanisms (hexagon frames), and outcomes (rectangle frames).

A positive feedback between intensive cultivation, soil degradation, synthetic fertilizer application, and the maintenance of high yields is evident (Figure 4). Because it results in soil degradation (i.e., slow ecological variable) and an increased dependence on fertilizer inputs to maintain annual financial profits (i.e., fast social variable), the feedback could form the basis of a strong rigidity trap. Outside of the feedback itself, the long-term effect of annual fertilizer application is groundwater nitrification—a phenomenon with increasing relevance to agroecosystems and human health at broader scales [32].

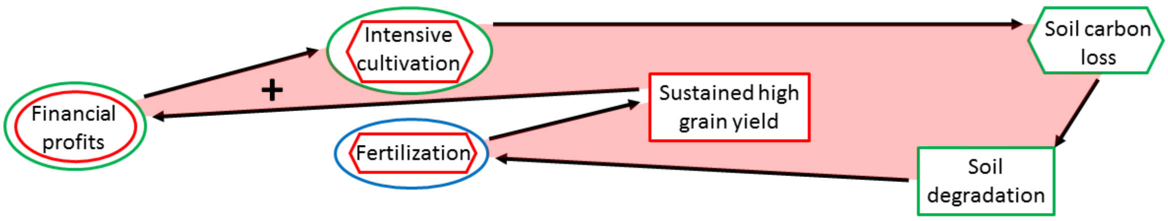

Figure 4. Positive (amplifying) feedback between intensive cultivation, soil degradation, fertilizer application, and sustained high grain yield at the food (red)—energy (black)—water (blue)—ecosystem services (green) nexus of the Central Platte Natural Resource District, composed of causes (oval frames), mechanisms (hexagon frames), and outcomes (rectangle frames).

There are both positive and negative feedbacks associated with crop irrigation at the CPNRD FEWES nexus (Figure 5). A positive feedback is apparent between irrigation, sustained high grain yields, and financial profits. However, this feedback is counteracted by two negative feedbacks associated with the external factors of irrigation regulations and enforcement of the Endangered Species Act. In short, restrictions on groundwater withdrawals for irrigation are enforced when irrigation results in a decrease in groundwater levels, and restrictions on surface water withdrawals for irrigation are enforced when irrigation results in decreases in habitat area for endangered species in the Platte River. Although the dependence on irrigation for sustained high yields may also form the basis of a rigidity trap, the stabilizing effects of external factors likely limit the degree to which it can strengthen and negatively affect the availability of irrigation water over the long-term. Hydrologic connectivity between groundwater and surface water in the CPNRD means that these negative feedbacks interact to manage groundwater levels and surface water flows for continued availability.

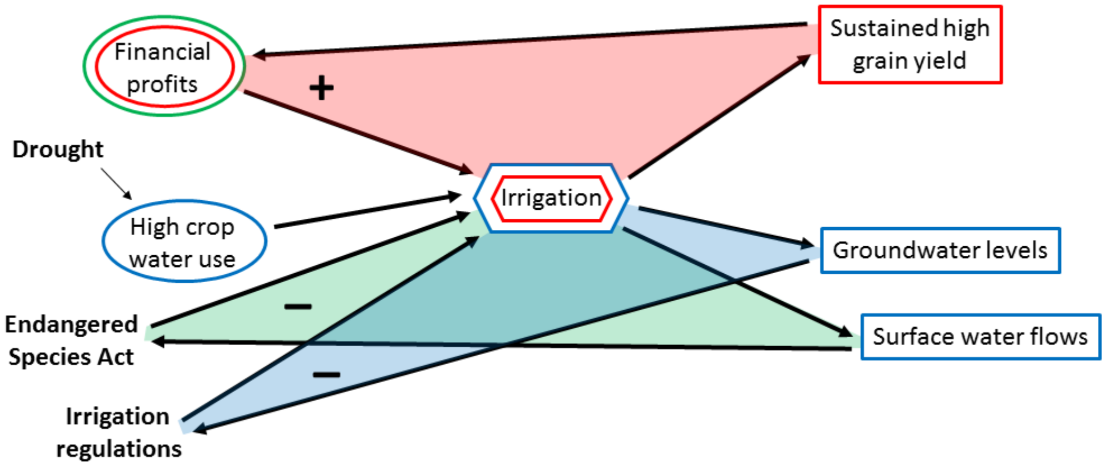

Figure 5. Three interacting feedbacks related to irrigation at the food (red)—energy (black)—water (blue)—ecosystem services (green) nexus of the Central Platte Natural Resource District, composed of causes (oval frames), mechanisms (hexagon frames), outcomes (rectangle frames), and external factors (no frames). A positive (amplifying) feedback exists between irrigation, sustained high grain yield, and financial profits; a negative (stabilizing) feedback exists between irrigation, groundwater levels, and irrigation regulations; and a negative feedback exists between irrigation, surface water flows, and the Endangered Species Act.

3.3. CPNRD FEWES Scenarios

In the Climate Adaptation Scenario, the CPNRD FEWES nexus was intentionally adapted in response to effects of increasing temperatures and altered precipitation patterns consistent with regional climate change projections. These adaptations primarily targeted social–ecological feedbacks associated with irrigation (Figure 5). Adaptations entailed adopting more drought-tolerant crop varieties and more sustainable irrigation technologies. Although crop irrigation continued to be a contributing factor to sustained high grain yields, the positive feedback between irrigation, sustained high grain yield, and financial profits was substantially weakened by the cultivation of drought-tolerant crops. Similarly, the adoption of more sustainable irrigation technologies decreased the frequency of instances in which irrigation regulations and the Endangered Species Act were required to restrict groundwater and surface water irrigation withdrawals. Therefore, although the negative feedbacks between irrigation, groundwater levels, and irrigation regulations, and between irrigation, surface water flows, and the Endangered Species Act remained in place, they had less of an effect on sustained high grain yields and financial profits because of the decreased dependency of sustained high grain yields on irrigation.

In the Perennial Transformation Scenario, the CPNRD FEWES nexus was transformed by the replacement of annual food and bioenergy crops with perennial species. Although this transformation affected the entire FEWES nexus, it had a particularly noticeable effect on the social–ecological feedback associated with annual synthetic fertilizer application (Figure 5). Because perennial crops may be capable of reducing or reversing soil degradation by minimizing soil erosion and sequestering carbon, the dependency of the FEWES nexus on the annual application of synthetic fertilizers substantially decreased. More broadly, the replacement of annual with perennial crops decreased financial incentives associated with intensive cultivation. Because perennial crops also tend to be more drought tolerant than annual crops, the adoption of perennial crops also decreased the dependency of the CPNRD FEWES nexus on irrigation [33], with similar effects on irrigation-associated social–ecological feedbacks as in the Climate Adaptation Scenario. Finally, the adoption of perennial crops increased habitat for grassland-dependent species [34].

4. Discussion

Social–ecological interactions and tradeoffs with consequences for sustainable agricultural development occur at the FEWES nexuses of agricultural landscapes worldwide; however, productive and efficient FEWES nexuses can get caught in rigidity traps, which make them unsustainable, inflexible, and vulnerable in the face of disturbances or changing conditions [12]. Rigidity traps are undergirded by maladaptive feedbacks between the social and ecological entities at the FEWES nexus. Adaptation- and transformation-focused landscape management and governance are needed to create more sustainable FEWES futures [3]; however, rigidity traps impede intentional adaptation and transformation. Understanding of FEWES nexuses and their unique social–ecological trajectories, feedbacks, and traps is foundational for escaping rigidity traps and enabling sustainability-focused adaptation and transformation.

We presented a framework for tracing social–ecological trajectories and traps at the FEWES nexus of intensive agricultural landscapes and applied it at the FEWES nexus of the CPNRD watershed of the PRB in the American Great Plains. Our framework combines the tools of process-tracing, causal loop diagramming, and scenario planning to increase understanding of: (1) The current nexus trajectory; (2) What led to the current nexus trajectory; and (3) Plausible future nexus trajectories. In doing so, our framework caters to the assertion that rigidity traps and related social–ecological traps are processes that can be best overcome through explicit consideration and targeting of their underlying feedbacks [15].

Although our framework does not contain a specific set of steps for weakening maladaptive feedbacks or escaping rigidity traps, it can be used to generate the FEWES- and trap-specific understanding for doing so. In other words, our framework alone cannot be used to escape rigidity traps, but it can be used to pinpoint the social–ecological feedbacks responsible for forming the trap and imaging alternative futures associated with feedback-modification. Adaptive management [5], adaptive governance [6], and transformative governance [7] are practices from the resilience literature that could be used to intentionally adapt and transform FEWES nexuses caught in rigidity traps. By targeting certain feedbacks for sustainability-focused management and governance, the path-dependency associated with rigidity traps may be overcome, and our framework provides the understanding necessary for doing so.

In addition to avoiding and overcoming rigidity traps, our framework can be used to encourage the integration of FEWES components in management and governance. The process-tracing phase of our framework focuses on place-based causal relationships in individual FEWES components, and the causal loop diagramming phase of the framework considers how processes in different components relate to one another and how they are influenced by various external factors. Although we only applied our framework at a single (i.e., watershed) scale, it could be used to increase understanding of FEWES nexus trajectories and traps within and across additional scales of organization. In light of the cross-scale organization of SES and their FEWES nexuses, cross-scale tradeoffs in the production of ecosystem services [35], and the potential for development of multi-scale rigidity traps [36], cross-scale assessments could generate insights for avoiding and escaping rigidity traps, adaptation, and transformation.

The application of our framework to the FEWES nexus of the CPNRD revealed several maladaptive social–ecological feedbacks characteristic of rigidity traps. These included a positive feedback between intensive cultivation, sustained high grain yields, and financial profits (Figure 3), and a positive feedback between intensive cultivation, soil degradation, annual fertilizer application, and high sustained grain yields (Figure 4). In addition to soil degradation, a negative consequence of the fertilizer feedback is the nitrification of groundwater and surface water, which decreases the quality of human drinking water. A positive feedback between irrigation, high sustained grain yields, and increased financial profits was evidenced; however, the amplification of this feedback and its negative effects on groundwater levels and surface water flows were stabilized by interacting negative feedbacks associated with irrigation regulations and the Endangered Species Act (Figure 5). Adaptation- and transformation-based approaches to agricultural management and governance may target these feedbacks to avoid and escape rigidity traps and promote more sustainable FEWES futures. FEWES adaptation and transformation in the CPNRD could take a number of forms. Our scenarios explore the potential for drought-tolerant annual crops and sustainable technologies to adapt the FEWES nexus to climate change, and the potential of the replacement of annual crops with perennial crops to transform it. Although the CPNRD is consistently productive in the short-term, its long-term sustainability may be compromised by its rigidity, especially amidst the pressures of global change.

Instead of focusing on the production of a single commodity under ideal conditions, a resilience-based perspective instead seeks to guarantee production over a wide array of conditions [37]. A resilience focus also recognizes and acknowledges that a system may be resilient, and sustainable, but may not be desirable. The CPNRD is in a desirable state, socially and economically, as one of the most productive agricultural landscapes on the planet. However, it has not withstood an extensive test of time—the intensive irrigation that characterizes much of the landscapes has slowly developed over the past 50 years. This ecological aspect of the CPNRD is undesirable, and considerable financial and land resources are devoted to remediating damage to the river system resulting from actions meant to increase predictability and usability of Platte River waters for humanity, especially for agriculture. To avoid and mitigate the potential long-term declines or collapse, management and governance must continue to learn about the sources and feedbacks of resilience in the CPNRD to enable improvements in management and governance and to allow for transformation, should the need occur.

The implementation of our framework could assist managers in the CPNRD and similar intensive agricultural landscapes in identifying influential social–ecological feedbacks and rigidity traps, and adapting and transforming FEWES nexuses for more sustainable futures. Managing for increased diversity in agricultural commodities and land use within and across scales is another means by which the CPNRD could increase adaptability and flexibility moving forward; however, this might only be accomplished through a combination of external subsidies (e.g., temporary price supports) and internal momentum (e.g., shifting public perceptions). The high degree of uncertainty over future events and their consequences means that proactive and reactive adaptation and transformation are valuable for establishing and maintaining desirable, sustainable, and resilient trajectories for FEWES nexuses.

It is important to note that rigidity traps are only one subset of SES traps that may occur at the FEWES nexus. For example, persistent poverty traps plague the FEWES nexuses of landscapes worldwide [38]. Our framework and others could be customized for poverty traps, according to recommendations for doing so in the resilience and development literatures. Awareness of social–ecological traps and management and governance processes for encountering them adaptively are a critical step towards the sustainable management of agricultural landscapes and the circumvention of negative consequences that may occur when entire landscapes catastrophically fail due to the slow changes and detrimental social–ecological feedbacks. Such exercises are not purely academic. For example, the CPNRD FEWES nexus collapsed fewer than 100 years ago in the event known as the dust bowl [39], which serves as a cautionary lesson for the management of agricultural systems globally.

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