Building US food-energy-water security requires avoiding unintended consequences for ecosystems

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Food-energy-water (FEW) systems are increasingly vulnerable to shocks. Repeated floods, worsening droughts, sudden tariffs, and disease outbreaks all underscore the importance of strengthening production systems during a time of rapid global change. However, the laws, regulations, and incentive programs that govern these sectors were often developed in isolation, creating fragmented and lagged responses to previous crises, ineffective governance of FEW security, and unintended effects even when achieving policy goals. Here, we examine the Mississippi River Basin in the Midwest US to illustrate how policies designed to address one challenge had other unanticipated consequences. We argue for a long view of the future that honors the interconnectedness of FEW sectors with ecosystems (FEWE); values non-provisioning ecosystem services; and prioritizes incentives that improve FEW production, farm profitability, and ecosystem health. Now is the time for reassessment of how well FEWE provide security to all humans and the environment, and to support integrated policies that avoid unintended future consequences.

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Society and human well-being depend on food-energy-water (FEW) systems, which are now threatened in unprecedented ways. These threats are exacerbated by the strong connections that exist among FEW systems. Complex linkages and trade-offs between the provisioning aspects of FEW systems and the broader array of ecosystem services they provide determine their security (D'Odorico *et al*. 2018; Bennett *et al*. 2021; Huntington *et al*. 2021). Climate change has brought increased precipitation and large flooding events to some regions, which in turn increases nutrient loading to inland and coastal waters (Van Meter *et al*. 2018). In other regions, prolonged droughts have led to water shortages that reduce crop yield and jeopardize hydropower and aquatic ecosystems (Leng and Hall 2019). Meanwhile, anthropogenic shocks – including trade wars, tariffs, and the COVID-19 pandemic – have produced instability in food and energy markets (Al-Saidi and Hussein 2021). The implications of disruptions to FEW systems for human life are obvious. We argue that innovative, collaborative efforts are necessary to meet the challenges of an uncertain future and avoid abrupt, undesirable changes. In short, FEW systems must become more resilient and also capable of sustaining the ecosystems on which we depend now and in the future.

In a nutshell:

- Previous US policies and incentive programs that govern food-energy-water (FEW) security had unintended negative consequences for ecosystems and the environment
- Policies and technological advances promoted the expansion of cropland area through wetland drainage, increased irrigation, and use of food crops for ethanol production
- As a result, ecosystems have experienced negative impacts, including increased soil erosion and runoff to rivers and streams, and reduced water quality and quantity
- Future policies must take a long view of the future that values natural ecosystems and prioritizes incentives that promote ecosystem health and farm profitability while improving FEW security

How can FEW security be ensured in the face of intensifying shocks and stressors? Solutions must sustain farmers, rural communities, food and bioenergy supplies, and ecosystems, while reducing water and air pollution. Solutions also have to incorporate a long view of the future, be adaptable given unforeseen feedbacks, value natural and semi-natural ecosystems (ie forests, prairies, and wetlands), promote non-provisioning ecosystem services, and acknowledge that historical observations and system responses no longer provide useful analogs for future planning (Milly *et al*. 2008). System change is particularly difficult in the US because of entrenched, bipartisan federal policies that support abundant and inexpensive food despite high social and environmental costs and vulnerabilities. Food and bioenergy production systems and supply chains are optimized for high production and efficiency, which gives them low resilience to disruption (Prokopy *et al*. 2020). Disaster responses – such as crop

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insurance that supports continued corn (*Zea mays*) planting in arid regions, flooded fields, or highly erodible soils – further lock in the vulnerability of FEW systems to future shocks and reduce funding for more strategic mitigation and adaptation. During the COVID-19 pandemic and concurrent trade disputes, federal aid to agriculture was inequitably distributed to larger farms (USDA 2020).

Knowledge of how to achieve FEW security is limited by gaps in understanding of the effectiveness of policies and practices aimed at mitigating the deleterious effects of climate change and unsustainable land management. Strategies for sustaining FEW in the face of change must be tailored regionally to account for heterogeneity in soils, climate, biodiversity, and land use, and consider impacts to farmers, farm workers, and rural communities. Yet it is uncertain how much risk or cost farmers, landowners, and agricultural institutions are willing to absorb to change longstanding practices that impede progress toward attaining FEW security. Short-term policies are problematic if they do not incorporate a long-term view, and short-term incentives that maximize one FEW sector can elicit problems in others (Beekma *et al.* 2021). Here, we focus on the Mississippi River Basin (MRB) to illustrate how previous US policies designed to address one FEW challenge had unanticipated consequences and consequently we offer relevant lessons for achieving FEW security. To move forward, we present strategies for developing innovative policies that not only account for short- and long-term changes and feedbacks but also promote resilience of ecosystems and FEW security.

Unintended consequences of previous US policies

FEW systems and ecosystems are governed by a complex network of governmental, civil society, and private-sector organizations. However, laws, regulations, markets, and incentive programs for these sectors have often been developed in separate silos without accounting for unintended and undesirable consequences of production systems. Although citizens have a clear interest in long-term environmental sustainability, their lack of organized power contributes to weak representation in the decision-making process. As a consequence, a disproportionate amount of federal funding has enhanced agricultural production without sufficient resources to prevent ecosystem deterioration.

Failure to target multiple FEW goals simultaneously through coordinated policies has inadvertently created new FEW challenges. Historical FEW goals that have dominated US policy and landscapes include increased crop and livestock production, energy independence, clean and reliable water supply, and reduced flood risk. Often spurred by public urgency in the face of crisis, these goals were usually targeted with separate policies. Increased crop and livestock production – a problematic and oversimplified proxy of food security when disconnected from food accessibility and crop-to-food energy losses – has been supported and subsidized by the federal government through policies related to water, erosion, and reducing farm income variability (agricultural drainage, irrigation, soil conservation, crop insurance, and flood insurance). However, a shift from highly diversified farms that focused on both crop and livestock production to increased specialization during the past century has contributed to fewer and larger farms that are dependent on substantial agrochemical inputs. The goal of energy independence has shaped agricultural landscapes via policies that support corn ethanol production primarily through transportation fuel volume mandates (Lark *et al.* 2015; Hochman and Zilberman 2018; Hoekman *et al.* 2018). A clean and reliable water supply has been codified in federal policy mainly through the Clean Water Act but also through environmental protection legislation. Finally, there is a long history of federal policies and support for flood risk reduction practices and infrastructure that is driven by legislation such as the Flood Control Act of 1944 and the Flood Insurance Act of 1968. While these goals may have been laid out for individual policies and connected with an urgent public demand, their complex interactions have led to numerous unintended consequences and a non-integrated approach to FEW challenges.

We highlight three examples of well-intentioned but one-dimensional US policy approaches that spawned subsequent challenges. We draw them from the MRB, a region that includes much of the Corn Belt (a broad section of the US Midwest featuring high corn production), which is critical to FEW security but threatened by increasing system shocks (Figure 1). The MRB is an exceptional example of both the vulnerabilities and opportunities related to FEW, biodiversity, and ecosystem security. The MRB is the world's third largest watershed, with its namesake river supplying water to ~50 cities and 18 million people while providing other ecosystem services to 91 million residents and many others around the world (Manson *et al.* 2021). While occupying only 43% of the total continental US (CONUS) land area, the MRB produces 86% of US corn for grain, 83% of soybeans (*Glycine max*), 73% of rice (*Oryza sativa*), and 58% of wheat (*Triticum* spp) (Table 1; USDA-NASS 2020). However, the expansion of agricultural land has come at a high cost to natural wetlands; since the time of European settlement through the mid-1980s, the conterminous US as a whole and parts of the MRB have lost 53% and more than 85%, respectively, of their original wetland area (Dahl and Allord 1997; Dahl 2011). The amount of nitrogen and phosphorus fertilizers applied in the MRB are 65% of the total applications in the CONUS, while manure nitrogen and manure phosphorus are 57% and 60%, respectively, of the CONUS total (Table 1; Falcone 2021). Annual groundwater withdrawals for irrigation constitute 45% of the CONUS total (Table 1; Dieter *et al.* 2018). Meanwhile, the MRB also supports rich but declining biodiversity; for example, the region is a migration corridor for nearly half of North America's birds and supports at least 150 fish species (USACE 2004). Although a land of plenty, the demands placed upon the MRB are not without challenges that render it vulnerable to shocks and stressors. One notable and persistent issue is hypoxia in the

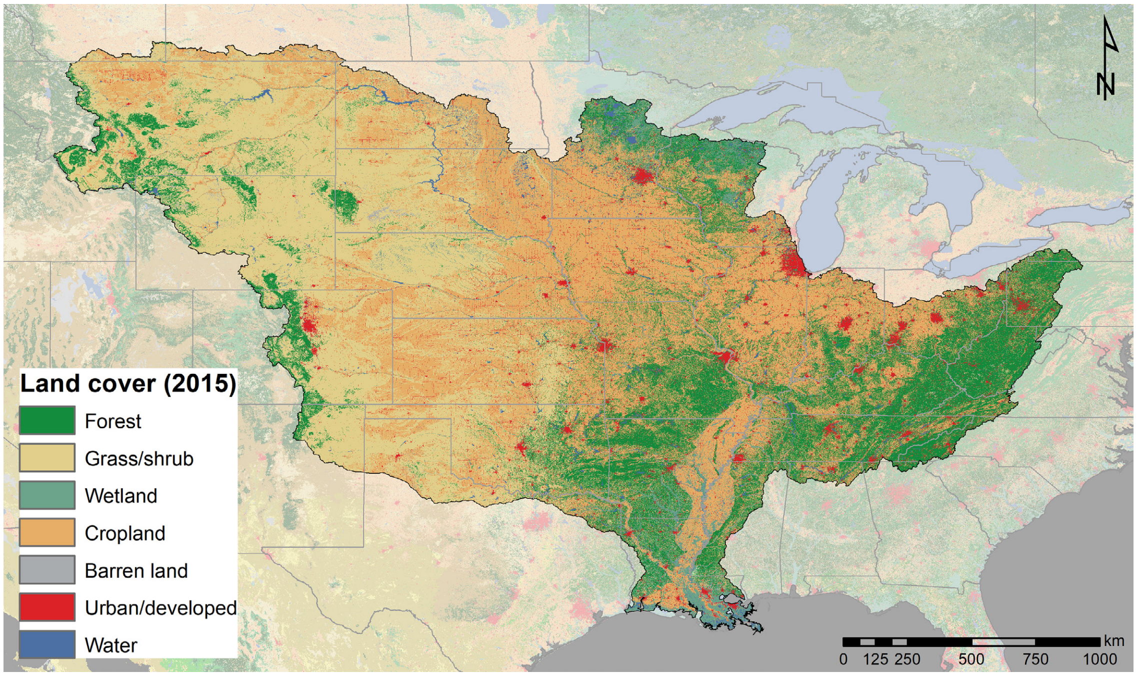

Figure 1. Mississippi River Basin (MRB) land cover in 2015.

northern Gulf of Mexico, which is caused primarily by excessive nitrogen runoff from the Basin's extensive agricultural lands (Donner and Kucharik 2008).

Wetland drainage expanded cropland but reduced water quality

In the mid-19th century, large segments of the MRB's formerly glaciated and poorly drained landscape – containing prairie and wetlands – were too wet for row crop agriculture. The goals of the federal government to bolster the agricultural economy and feed a growing population led to policies that provided technical and financial support for draining wetlands for crop production, beginning with the Swamp Land Acts of 1849, 1850, and 1860 (Figure 2; Jenkins *et al*. 2003). These policies, which coincided with a period of rapid westward migration, allowed state governments to assume control of federal lands if they agreed to drain and convert the land to other uses, like agriculture. This initiated broad-scale intensive landscape and hydrologic changes in segments of the MRB, whereby 60–80% of the original wetland area was lost between 1780 and the 1980s, and approximately 80% of those wetlands were converted to agricultural lands (Jenkins *et al*. 2003).

The end of federal support for drainage resulted from a shift in attitudes toward environmental and water quality protection in the 1960s and 1970s, as the impacts of drainage on aquatic diversity/habitats, flood regulation, and nutrient transport became more apparent (Dahl and Allord 1997; Blann *et al*. 2009; Evenson *et al*. 2018). Today, drainage is viewed as a primary driver of water quality and ecosystem degradation through loss of biodiversity, increased flood risk, perturbation of natural carbon cycling, and higher transport rates of excessive land-applied nitrogen from soils to waterways (Brinson and Eckles 2011). Thus, a clear tension exists between the legacy of a historical federal policy goal of improved food security through drainage and the more recently codified goal of clean water (Figure 2).

Groundwater irrigation increased food production but also increased fossil-fuel use and decreased water supply

Increasing national food security goals drove federal support for the development of groundwater-supplied irrigation, which was followed by water sustainability concerns due to depleted aquifers and streams. At first, the federal government encouraged westward migration and agricultural expansion into the Great Plains through passage of the Timber Culture Act of 1873 and the Desert Land Act of 1877, both of which promised an expanded ownership title to settlers for more land area: if trees were planted (Timber Culture Act) or if landowners irrigated their land using simple irrigation ditches (Desert Land Act) (Figure 2; Opie *et al*. 2018).

The federal role in the development of groundwater irrigation began with federally funded studies and surveys of the western US and Great Plains in the 1880s, and included crude estimates of available groundwater (Rusinek 1987). Eventually, drought in the 1930s, farm mechanization, advances in pump and center pivot technologies, rural electrification, and enhanced understanding of groundwater flow systems created a "perfect storm" to fuel a boom in

Table 1. Statistics for the Mississippi River Basin (MRB) relative to the continental US (CONUS)

	MRB	% of CONUS
Human population (2020)	90,706,289	27.5
Total area (ha × 10^6)	573.1	43.2
Total cropland (2017, ha × 10^6)	109.5	68.3
Total agricultural land (2017, ha × 10^6)	202.1	59.3
Total wetland and surface-water area (2017, ha × 10^6)	23.5	52.7
Crop production (2017, million metric tons [MMT])		
Corn (*Zea mays*) grain	321.2	85.6
Corn silage	48.2	44.1
Soybean (*Glycine max*)	98.7	83.3
Wheat (*Triticum* spp)	28.3	58.2
Rice (*Oryza sativa*)	5.8	72.9
Alfalfa (*Medicago sativa*)	24.0	48.6
Nutrients applied (2017, MMT)		
Fertilizer nitrogen (N)	8.449	65.3
Fertilizer phosphorus (P)	1.330	65.4
Manure N	3.802	57.0
Manure P	1.181	59.6
Water use (2015)		
Irrigation, groundwater withdrawals, fresh (megaliters/day)	98,237	45.4
Irrigation, total ha irrigated	12,664,000	49.3
Total groundwater withdrawals, fresh (megaliters/day)	127,585	41.0
Total surface-water withdrawals, fresh (megaliters/day)	316,590	42.3
Animal population (2017, × 10^6)		
Beef cows	20.1	63.8
Milk cows	2.97	31.7
All cattle	58.1	62.2
Hogs/pigs	54.6	79.1

Notes: Human population data from Manson *et al*. (2021); cropland area and production and animal population data from USDA-NASS (2020); wetland surface-water area from Dahl (2011); manure and fertilizer applications from Falcone (2021); irrigation and water withdrawal data from Dieter *et al*. (2018).

irrigation development in the 1940s and 1950s (Kepfield 1993; Opie *et al*. 2018) that lasted for several decades (Watson 2020) (Figure 2). Although federal and state governments did not fund construction of groundwater irrigation systems directly, they did play a crucial supporting role in both rural electrification (through implementation of New Deal programs) and improved understanding of groundwater behavior (Kepfield 1993).

Watson (2020) suggested that the increased availability and abundance of cheap natural gas in the Great Plains streamlined the transformation of this arid region into a non-renewable landscape. The combination of using a non-renewable energy source (natural gas) to extract another non-renewable resource (water) gave farmers the necessary means to break the ecological barriers to producing bountiful crop yields (Opie *et al*. 2018; Watson 2020). However, expansion of groundwater irrigation led to almost immediate declines in water levels in portions of the Ogallala Aquifer in the 1950s, which continued through the 1970s. The state of Nebraska responded by passing the Nebraska Groundwater Management Act in 1975, signaling the beginning of an era in which more efficient irrigation systems were developed and implemented, as well as a new role for the federal government in support of these emerging technologies. However, these shifts led to the paradoxical phenomenon of expanding irrigation area and increased water withdrawals (Pfeiffer and Lin 2014), which further increased energy use and farmer expenses due to declining well yields attributed to declining water tables. Water withdrawals can also reduce surface-water flow and streamflow, negatively impacting riparian habitats (Figure 2; Scanlon *et al*. 2012). Therefore, the push to substantially increase crop production in the Great Plains through irrigation has contributed to an unsustainable rate of water withdrawals, with unintended consequences for other ecosystems.

The Renewable Fuel Standard increased energy independence (possibly) but reduced water quality

Federal subsidization of corn ethanol is a prime example of a conflict between FEW security goals (Figure 2). Approximately 40% of the US corn crop is used to produce ethanol (Hoekman *et al*. 2018), and another major fraction goes to livestock feed; only a small portion is actually consumed by humans (Moore *et al*. 2014). The Energy Policy Act of 2002 established a Renewable Fuel Standard (RFS) and mandated an increasing minimum volume of ethanol be blended with gasoline each year (Bracmort 2020). Goals included increased US energy independence and reduced greenhouse-gas (GHG) emissions to combat climate change. The volume mandate was subsequently increased in 2005 and 2007 and established a target of 36 billion gallons of liquid biofuels by 2022. The RFS was also designed to help promote adoption of more advanced or cellulosic biofuels after 2015 (Moore *et al*. 2014), but that shift has yet to occur. In 2020, the total amount of renewable fuel produced in the US was 20.09 billion gallons, but only 590 million gallons (2.9%) was cellulosic biofuel (EPA 2020).

In the years following RFS establishment, several studies have documented the shortcomings of this policy and the unintended impacts on water, energy, ecosystems, and people. The RFS was reported to contribute to substantial changes in commodity prices and a shift in land use (Anderson and Coble 2010) toward more marginal lands, with subsequent negative impacts on water quality (Donner

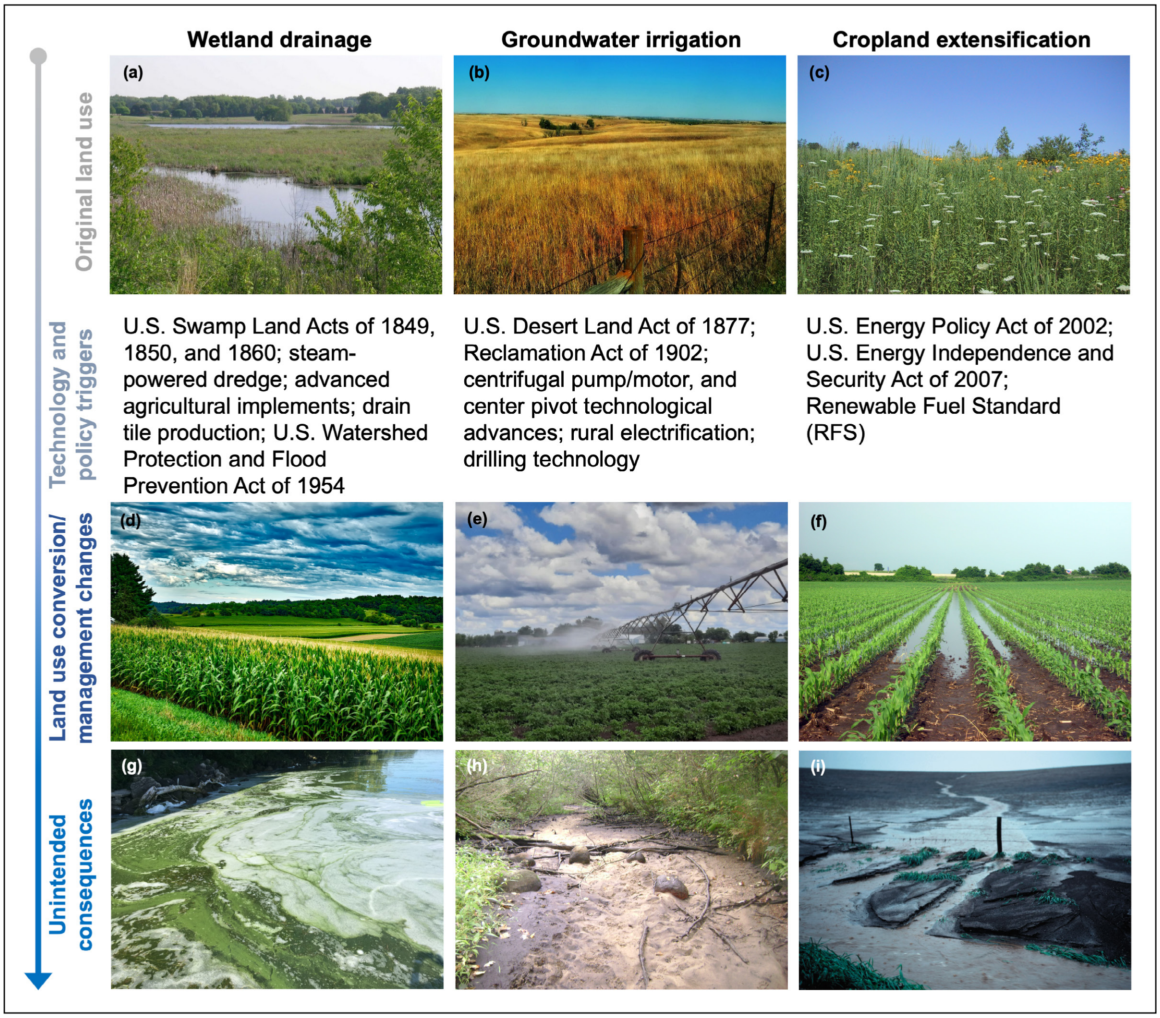

Figure 2. Land-use change and unintended consequences in the MRB. Technological and policy-based triggers (text beneath images in top row) that promoted wetland drainage, groundwater extraction for irrigation, and use of food crops for biofuel within a symbolic (a) wetland, (b) grassland, and (c) land enrolled in the Conservation Reserve Program (CRP), respectively. These triggers led to (d) increased row crop area after wetland drainage, (e) widespread use of groundwater irrigation, and (f) conversion of CRP to corn on marginal land. Unintended consequences include (g) algal blooms; (h) dry rivers and streams, and lower groundwater tables; and (i) increased soil erosion and runoff. Image credits: (f) S Zipper, (g) E Stanley, and (h) Center for Watershed Science and Education (University of Wisconsin–Extension).

and Kucharik 2008) and wildlife (Lark *et al.* 2020). While US energy independence has been enhanced during the period of the RFS, this has largely been due to increased US natural gas and oil production (Harris *et al.* 2018). Many have also argued that related reductions in GHG emissions have been overestimated, and that the impact of the RFS, and in particular corn grain ethanol, on climate change has in fact been minimal (Hochman and Zilberman 2018). Life-cycle assessments of carbon accounting associated with US corn ethanol production continue to be debated in the scientific literature given large uncertainties, particularly with indirect land-use change, and in some cases suggest that carbon costs may exceed gains (Spawn-Lee *et al.* 2021). In addition, the RFS-driven expansion of corn acreage at the expense of US Department of Agriculture's Conservation Reserve Program land and other ecosystems (Lark *et al.* 2015; Hoekman *et al.* 2018) has led to an increase in corn prices, soil erosion, and nutrient losses, contributing to downstream degradation of water quality and hypoxic events in the Gulf of Mexico (Figure 2; Lark *et al.* 2022). Given that its benefits to FEW systems remain unclear, active debate concerning the RFS continues today, as policy makers consider conflicting goals and constituencies and increasing uncertainty about future demand for transportation fuels due to increasing adoption of electric vehicles.

Policies that created "win–wins" for food and water security are rare

Historical examples of "win–wins" for food and water security from federal policies do exist but are uncommon. However, the federal response during the Dust Bowl era of the 1930s enhanced both crop production and water security by promoting conservation practices that reduced soil erosion in places like the Driftless Area of southwestern Wisconsin, which was devastated by soil erosion and flooding but subsequently reinvigorated through soil conservation (Potter 1991). While Euro-American settlement in the mid-1800s led to widespread conversion of prairie and forest to row crops and pasture throughout the Corn Belt, the Driftless Area was the center of some of the most devastating consequences due to its steep topography. Scientists began to study the problem of soil erosion in the 1910s, but conservation practice implementation lagged until federally supported experimental research was initiated in the 1930s, which created a base of knowledge for practitioners and conservation agents to utilize. Equipped with evidence-based science from local farms, the federal government was then able to facilitate widespread implementation of such practices as contour strip cropping and terracing using the enormous labor resources of the Depression-era Civilian Conservation Corps. Although progress has regressed somewhat in the region due to land-use change (Hart 2008), the RFS, and increasing frequency of heavy rainfall events, this region offers an instructive example of the positive outcomes that can result when federal policy considers dual goals (such as food production and water/ecosystem security).

How to move forward

Previous adaptive management of individual FEW components – while responsive to immediate needs – has failed to build long-term resilience of FEW systems. Future policy making must consider these systems' integrated responses in a changing environment and feedbacks across scales to sustain FEW systems and their portfolio of ecosystem services (Figure 3). Changing drivers, shifting land use, fluctuating resource stocks, and technological advances ensure that solutions of the past, as well as those currently under development, will not last forever. We must continually aim to reduce trade-offs, which can be fostered by building multifunctional agricultural landscapes (Kremen and Merenlender 2018).

Sustaining food production and a broad portfolio of ecosystem services in the face of systemic shocks will require both strategic solutions and the will to implement them at scales that matter. Single parcels of land cannot "do it all", but strategies that combine land sparing and land sharing can minimize trade-offs (Tscharntke *et al.* 2012; Kremen and Merenlender 2018). In the following sections, we offer ideas to help guide the creation of innovative policies that account for short-term and long-term changes and feedbacks to promote enhanced resilience of ecosystems and FEW security.

Principle #1: value and promote the importance of non-provisioning ecosystem services and the connection of natural and semi-natural ecosystems to FEW

Many changes are needed to achieve success for FEW and ecosystems. We suggest starting by recognizing these systems as FEWE, to acknowledge the interconnectedness of FEW provisioning services with broader ecosystems (Figure 3). We must incorporate other natural ecosystems to create increased diversity, adaptability, and complexity in landscapes to achieve FEW security and other environmental goals. Retaining and restoring semi-natural ecosystems and the biodiversity they support ensures that

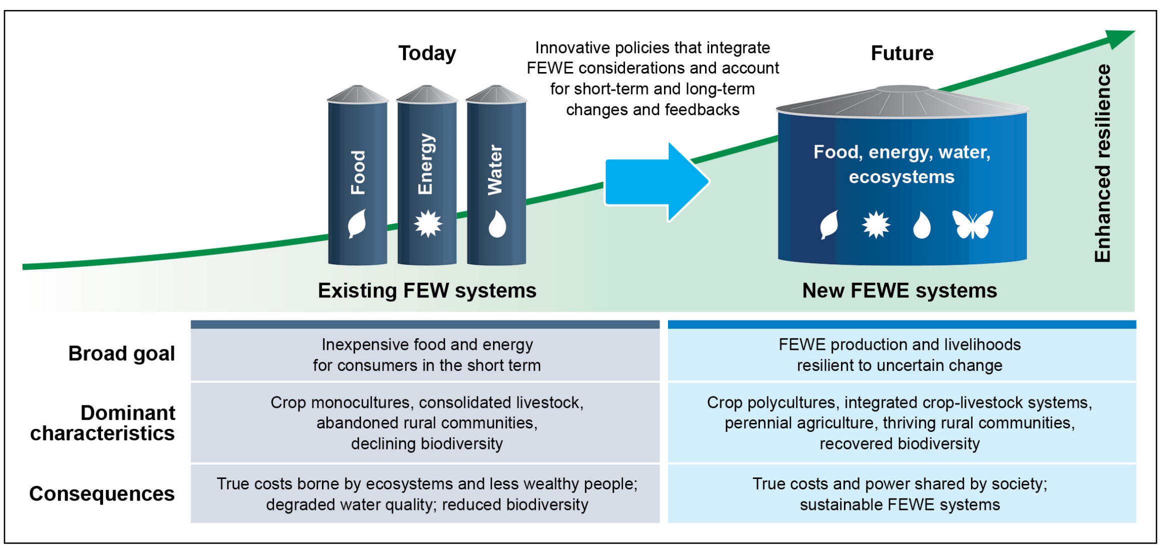

Figure 3. Transition needed to enhance food-energy-water (FEW) security and resilience given the increasing frequency and intensification of shocks and stressors. How adaptive management is currently applied separately to existing FEW components (left column) is compared to future integrated planning approaches that account for the interconnectedness of the FEW components with one another as well as with ecosystems (right column). Rows compare the goals, dominant characteristics, and consequences of each type of management approach. Achieving this transition will require innovative policies that not only account for bidirectional feedbacks along with short-term and long-term changes but also eliminate unintended (often predictable) negative consequences.

agricultural landscapes will have the capacity to adapt to more rapid environmental change (Tscharntke *et al.* 2012, 2021; Duru *et al.* 2015).

Forests, grasslands, wetlands, and riparian buffers sustain biodiversity and provide myriad benefits in agricultural landscapes (Tscharntke *et al.* 2012). Incorporating perennial grass cropping systems offers advantages (Figure 3) from field to landscape scales, such as support for insect predators and native birds (Werling *et al.* 2014). Perennial cropping systems work to increase soil carbon sequestration and reduce nutrient runoff into waterways. Incorporating diverse prairie strips to catchments dominated by fields of corn and soybeans reduces total water runoff, increases soil and phosphorus retention, and enhances pollinator abundance (Schulte *et al.* 2017). When placed appropriately, semi-natural elements decrease soil erosion, nitrogen leaching, and phosphorus export without adversely affecting crop production (Galpern *et al.* 2020). More complex agricultural landscapes also enhance aesthetics and support diversity of insectivorous birds and natural enemies, which suppress agricultural pests and boost crop yields (Haan *et al.* 2020). Semi-natural ecosystems supply critical hydrologic services, with riparian buffers mitigating nutrient runoff (Cole *et al.* 2020) and depressional wetlands storing water and reducing flooding downstream. We strongly endorse calls to maintain agricultural landscape mosaics that include diverse vegetation types to sustain biodiversity and FEW systems (Kremen and Merenlender 2018; Tscharntke *et al.* 2021).

Principle #2: identify "keystone locations" and create solutions that are tailored yet scalable

With more recent advances in geospatial information science, trade-offs can continue to be minimized by identifying "keystone locations" of ecological and cultural importance, where converting relatively little cropland to semi-natural elements will yield disproportionate benefits to social–ecological systems (Cuerrier *et al.* 2015; Lepofsky *et al.* 2017). For example, shifting from annual to perennial cropping systems or rotational grazing in areas of low crop yield and high erosive potential can maintain food production goals and enhance many ecosystem services (Asbjornsen *et al.* 2014; Robertson *et al.* 2014). Where intensive annual cropping systems are maintained, practices like drainage water recycling can mitigate nutrient losses to surface waters and groundwater, and address the negative impacts of flooding and drought on food and energy production (Reinhart *et al.* 2019). To achieve success, however, local solutions must lead to positive impacts at the larger watershed scale and beyond, and account for a changing climate (Roland *et al.* 2022). Identifying solutions and locations to implement them must also incorporate Indigenous and local knowledge (Lam *et al.* 2020).

Principle #3: take a long view and prioritize incentives that improve FEW production, farm profitability, and ecosystem health

Climate change dictates that future planning must account for more frequent and intense flooding and drought events, as well as associated economic shocks (IPCC 2022). However, current capacity to react to concurrent or sequential (compounding) shocks is especially limited. Historical analogs no longer serve as reliable guides (Milly *et al.* 2008), and of equal consequence, society's ongoing recalibration of what is "normal" (ie shifting baselines) can mask the magnitude of changes already underway (Moore *et al.* 2019). Instead, embracing flexibility and adaptability, along with employing state-of-the-art methods like numerical models and scenarios that take a long view (Campbell *et al.* 2022), will allow society to plan for outside-the-box surprises, novel futures, and unintended consequences. Crop insurance reforms would incentivize farmers to adopt conservation and diversification practices that reduce the risk of loss in dry and wet years. A more holistic approach that prioritizes financial incentives and commitments for improvements in ecosystem health will increase FEWE security.

Solutions to FEWE security challenges must also improve the livelihoods of farm operators, workers, their families, and others who have been negatively affected by biophysical shocks and stressors, along with economic and political changes (Carlisle *et al.* 2019; Wezel *et al.* 2020). This requires a shift from the goal of maximizing production toward ensuring farmer profitability through lower inputs and public conservation incentives (Figure 3). Such assistance must also better support underserved farmers and farm workers to ensure more diversity among those making choices for FEWE. Better coordination and power sharing at the nexus of FEWE governance could enable more balanced financial investments and integrated governing networks that protect ecosystems and increase production simultaneously (Pahl-Wostl 2019). Reorienting incentives to create new market opportunities and rethinking governmental programs that make environmental conservation and ecosystem preservation inherent in FEWE systems, and not dependent solely on separate government support, can help to sustain economic livelihoods and enhance FEWE security.

Conclusions

Now is the time for major reassessment of how well FEWE systems provide security to all humans and the environment. Recent repeated flooding events, prolonged drought in the western US and Great Plains, and the COVID-19 pandemic have highlighted the vulnerability of FEWE systems to shocks. Despite persistent warnings and previous shocks that sparked short-term conversations, fragmented and lagged responses to crises have not produced the transformations needed to protect farmers, supply chains, and rural communities, and to enhance ecosystem resilience. Rather, they have underscored the perils of ineffective governance and acting too late. The absence of a consistent, coherent response to a global challenge like COVID-19 should be a warning. People's and institutions' willingness to act during key moments of change should be harnessed when bad memories and socioeconomic wounds are fresh.

The dominant focus on increasing food production without considering interconnected energy, water, and ecological systems has had too many negative consequences (Foley *et al*. 2011). Rural communities have been abandoned, biodiversity has declined, and water quality has degraded, with the true costs borne by ecosystems and underserved communities. Society can only benefit by internalizing the true costs of more resilient and adaptive FEWE systems. Expansion of integrated crop–livestock systems, crop polycultures, and perennial agriculture can help ecosystems recover, increase diversity, and reduce the impact of price volatility and climate change to farmer livelihoods (Duru *et al*. 2015). A multilevel, scalable approach that fosters transformational management changes can improve the public benefits that food, water, ecosystems, and biodiversity provide. In parallel, stakeholders and decision makers must work toward creating novel integrated policies that protect and sustain FEW systems and eliminate unintended but predictable negative consequences for ecosystems.

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Data Availability Statement

No data were collected for this study.

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FrontiersEcoPics

A native parrot as an invasive plant controller

Generalist psittacines (parrots) can adjust to anthropogenic ecosystems by taking advantage of novel opportunities therein, such as by feeding on introduced plant species (*Wilson J Ornithol* 2008; doi.org/10.1676/07-038.1). In the city of Ilha Solteira (within the state of São Paulo, Brazil), a native blue-and-yellow macaw (*Ara ararauna*) – shown here – consumes flower buds of the African tulip tree (*Spathodea campanulata*) to access the calyx water, which is rich in amino acids. Such behavior, considered a dietary innovation (*Ornitol Neotrop* 2015; doi.org/10.58843/ornneo.v26i2.27), is a case of florivory of a non-native plant by a native animal. Florivory diminishes plant fitness by decreasing, and even eliminating, the chances that fruits and seeds will form (*New Phytol* 2021; doi.org/10.1111/nph.17670).

According to the IUCN's Global Invasive Species Database, the African tulip tree is ranked 88 out of "100 of the World's Worst Invasive Alien Species" (https://bit.ly/3ZvinOX). Outside of its native range in West Africa, the tree can degrade tropical ecosystems not only by altering habitat structure and ecological processes but also by reducing biodiversity (*Anthr Sci* 2022; doi.org/10.1007/s44177-021-00004-y).

Notably, macaws' florivory provides some degree of biological control, which could be high given that the birds en masse can consume more than 100 flower buds in a single feeding bout lasting only a few minutes. Indeed, since 2014 (when the macaws discovered this food resource), we have rarely observed nearby African tulip trees bearing fruit and thus seeds, thereby limiting daughter plant recruitment.

Evidence of only one instance of florivory is portrayed here. Nevertheless, as a generalist, the blue-and-yellow macaw feeds on the reproductive structures of several nonnative plant species in developed areas (*Ornitol Neotrop* 2018; doi.org/10.58843/ornneo.v29i1.363), which if otherwise left undisturbed would facilitate invasion (*Landscape Ecol* 2011; doi.org/10.1007/s10980-011-9585-3). Can macaws prevent, reduce, or delay the likelihood of invasive plant species spreading across the anthropogenic tropical landscape?

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