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Scenarios reveal pathways to sustain future ecosystem services in an agricultural landscape

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Abstract. Sustaining food production, water quality, soil retention, flood, and climate regulation in agricultural landscapes is a pressing global challenge given accelerating environmental changes. Scenarios are stories about plausible futures, and scenarios can be integrated with biophysical simulation models to explore quantitatively how the future might unfold. However, few studies have incorporated a wide range of drivers (e.g., climate, land-use, management, population, human diet) in spatially explicit, process-based models to investigate spatial-temporal dynamics and relationships of a portfolio of ecosystem services. Here, we simulated nine ecosystem services (three provisioning and six regulating services) at 220×220 m from 2010 to 2070 under four contrasting scenarios in the 1,345-km^2 Yahara Watershed (Wisconsin, USA) using Agro-IBIS, a dynamic model of terrestrial ecosystem processes, biogeochemistry, water, and energy balance. We asked (1) How does ecosystem service supply vary among alternative future scenarios? (2) Where on the landscape is the provision of ecosystem services most susceptible to future social-ecological changes? (3) Among alternative future scenarios, are relationships (i.e., trade-offs, synergies) among food production, water, and biogeochemical services consistent over time? Our results showed that food production varied substantially with future land-use choices and management, and its trade-offs with water quality and soil retention persisted under most scenarios. However, pathways to mitigate or even reverse such trade-offs through technological advances and sustainable agricultural practices were apparent. Consistent relationships among regulating services were identified across scenarios (e.g., trade-offs of freshwater supply vs. flood and climate regulation, and synergies among water quality, soil retention, and climate regulation), suggesting opportunities and challenges to sustaining these services. In particular, proactive land-use changes and management may buffer water quality against undesirable future climate changes, but changing climate may overwhelm management efforts to sustain freshwater supply and flood regulation. Spatially, changes in ecosystem services were heterogeneous across the landscape, underscoring the power of local actions and fine-scale management. Our research highlights the value of embracing spatial and temporal perspectives in managing ecosystem services and their complex interactions, and provides a system-level understanding for achieving sustainability of the food–water–climate nexus in agricultural landscapes.

Key words: alternative futures; biophysical model; climate change; food production; land-use change; social-ecological systems; sustainability; trade-offs and synergies; water quantity and quality; Wisconsin.

Introduction

Sustaining ecosystem services, such as food, clean water, and climate regulation, is a global priority and the basis on which human welfare depends. Anthropogenic environmental changes (e.g., climate and land-use changes, population growth) are profoundly altering ecosystems from regional to global scales, presenting significant challenges to the sustainability of ecosystem services (Foley et al. 2005, Chapin et al. 2010, Steffen et al. 2015). Globally, the Millennium Ecosystem Assessment provided compelling evidence of ongoing degradation of ecosystem services over the past 50 years and highlighted the importance of combating this adverse trend to avoid unfavorable future trajectories (MEA 2005*a*, Carpenter et al. 2009). The degradation of regulating services is of special concern because it may foreshadow future declines in other services, compromise long-term

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ecosystem resilience, and lead to abrupt changes that take us beyond a safe operating space for humanity (Scheffer et al. 2001, Carpenter et al. 2009, Steffen et al. 2015). In the face of these unprecedented levels of anthropogenic alterations (Ellis 2015), it is vital to understand how multiple drivers of change may reshape the future prospects for ecosystem services.

Anticipating trajectories of future environmental changes and consequences for ecosystem services across heterogeneous landscapes is remarkably challenging and requires long-term thinking (Alcamo 2008, Carpenter et al. 2015). The future entails a high degree of irreducible uncertainty, because historical analogs may be lacking, and interactions, feedbacks, and legacies in social-ecological systems are complex (Folke et al. 2004, Polasky et al. 2011). In other words, current trends could lead to divergent and unpredictable future outcomes. Scenarios have emerged as an effective approach to envisioning how the future of complex social-ecological systems might unfold from existing patterns, drivers, and alternative human choices (Peterson et al. 2003, Raskin 2005). Scenarios are a series of plausible and often contrasting stories (i.e., “narratives”) depicting the future in ways that explicitly incorporate relevant science, societal expectations, and internally consistent assumptions about drivers, relationships, and constraints (Alcamo 2008, Thompson et al. 2012). Scenarios can also be integrated with simulation models to explore a range of potential changes and numerically estimate the likely consequences for the supply of ecosystem services (Alcamo 2008).

Research using scenarios to explore the dynamics and sustainability of social-ecological systems has grown rapidly (Baker et al. 2004, MEA 2005*b*, Schröter et al. 2005, Nelson et al. 2009, Koh and Ghazoul 2010, Palomo et al. 2011, Bateman et al. 2013, Plieninger et al. 2013, Lamarque et al. 2014, Lawler et al. 2014, Byrd et al. 2015, Ruiz-Mallén et al. 2015, Waylen et al. 2015). Recently, Oteros-Rozas et al. (2015) provided a comprehensive synthesis of 23 place-based participatory scenario planning studies worldwide conducted during 2003–2014. It has been increasingly recognized that such place-based, bottom-up scenarios can be especially powerful at engaging stakeholders, encouraging social learning, and fostering decision-makers to explore and achieve sustainable solutions (Oteros-Rozas et al. 2015, Kok et al. 2016). However, among prior scenario studies, integrating social, political, economic, and biophysical storylines from participatory processes with biophysical modeling has been rare for regional social-ecological systems, though it has been done for a number of global scenario exercises (e.g., IPCC 2000, MEA 2005*b*). In addition, most studies thus far have focused on single drivers of environmental change, mostly climate (Bellard et al. 2012, Ntegeka et al. 2014) or land-use (Metzger et al. 2006, Gude et al. 2007, Eigenbrod et al. 2011, Goldstein et al. 2012, Thompson et al. 2016), and a smaller, yet growing, number of studies have simultaneously incorporated multiple drivers of change and their interactions (e.g., Byrd et al. 2015, Fan et al. 2016). In particular, how social factors (e.g., nutrient and land management, economic markets, human population, and diet) drive changes in demand for ecosystem services and biophysical conditions has seldom been considered. Such limitations can be problematic because social, economic, and cultural changes may sometimes overwhelm biophysical drivers of ecosystem services and human welfare (Kriegler et al. 2012, Alexander et al. 2015, Nyborg et al. 2016).

Another body of scenario research uses rich storylines to represent complex economic, political and social dynamics and explore sustainable pathways toward the future (Bohensky et al. 2006, Hanspach et al. 2014). However, these studies tend to be qualitative and have not been developed into quantitative models to estimate the magnitude of changes in ecosystem services. Nevertheless, integrating quantitative models allows for explicitly considering feedbacks and legacies, and exploring surprises that are fundamental in managing sustainability in complex social-ecological systems (Walz et al. 2007, Alcamo 2008). Furthermore, relatively few studies analyze fine-scale spatial patterns and changes in interactions among multiple ecosystem services over decadal time scales. Such detailed spatial-temporal understanding and long-term thinking is a frontier of ecosystem service science and could provide critical information for decision-making and natural resource management toward sustainability in a changing and uncertain future (Bennett 2016).

In this study, we investigated how the provision and interaction of a portfolio of diverse food, water, and biogeochemical-related services (Table 1) play out under plausible future scenarios. We focused on the Yahara Watershed in southern Wisconsin, USA, a microcosm for many urbanizing agricultural landscapes in the midwestern United States and similar regions globally, to address three research questions: (1) How does ecosystem service supply vary among alternative future scenarios? (2) Where on the landscape is the provision of ecosystem services most susceptible to future social-ecological changes? (3) Among alternative future scenarios, are relationships (i.e., trade-offs, synergies) among food production, water and biogeochemical services consistent over time?

Materials and Methods

Study area

The Yahara Watershed (Wisconsin, USA) drains 1,345 km^2 and includes five major lakes (Appendix S1: Fig. S1). The region’s climate is humid continental and exhibits strong seasonal and interannual variations. Influenced by the last glaciation, the topography of the watershed is generally flat with gentle hills and shallow depressions. Soils are primarily composed of Mollisols and Alfisols that support productive agriculture. Presettlement

Table 1. List of nine ecosystem services in the Yahara Watershed (Wisconsin, USA), projected at 220 × 220 m spatial resolution across four future scenarios from 2010 to 2070, with corresponding biophysical indicators and units.

Ecosystem service	Biophysical indicator	Unit
Provisioning		
Crop production	Annual total crop (corn, soybean, wheat) yield	bushels/acre†
Perennial grass production	Annual total forage crops and perennial grass (alfalfa, hay, pasture) yield	kg/ha
Freshwater supply	Annual total drainage of groundwater	mm
Regulating		
Groundwater quality	Annual total nitrate (NO_3-N) leached at the bottom of soil profile	kg/ha
Surface-water quality	Annual total phosphorus yield in runoff	kg/ha
Flood regulation	Annual number of days with runoff >10 mm	d
Net ecosystem exchange	Annual net ecosystem exchange (NEE)	Mg C/ha
Soil carbon storage	Total soil carbon stored in upper 1 m	Mg C/ha
Soil retention	Annual total sediment yield in runoff	Mg/ha

†1 bushel/acre = 87 L/ha.

vegetation was a mix of prairie and oak savanna (Curtis 1959) that was converted to agriculture beginning in the mid-1800s. Farms are currently dominated by corn, soybean and dairy for meeting domestic and global demands. Similar to many other agricultural landscapes, this watershed is experiencing increased urbanization with a densely populated urban core (Madison, the state capital of Wisconsin) and adjoining suburban areas and towns, along with scattered remnants of native vegetation. The mosaic of different land-uses makes for a complex social-ecological environment that interacts strongly with water (Carpenter et al. 2007). Current and anticipated future challenges in the watershed include striking a balance between farmland preservation and urban growth, increasing agricultural production while improving water quality, and managing flood risk with increasing impervious surface areas and increasing frequency of high rainfall events (Gillon et al. 2015). Nonetheless, how these challenges and drivers of change will interact to determine the sustainability of this social-ecological system remains highly uncertain.

Scenario development

During 2001–2014, four plausible and contrasting future scenarios were developed to explore alternative social-political options for human action and socio-economic development for the Yahara Watershed (Carpenter et al. 2015). Major steps of scenario development included (1) extracting archetypal drivers from the global scenario literature; (2) eliciting perspectives on the future of the watershed through interviews and workshops with diverse watershed residents and stakeholders; and (3) condensing participants' views and potential trajectories of change into a small number of scenarios. Synopses of the four scenarios are shown in Table 2 that capture key social-ecological changes of the Yahara Watershed from 2010 to 2070. For complete narratives and art illustrations of the scenarios see University of Wisconsin-Madison (2014). Details on scenario development and storylines were presented in Carpenter et al. (2015). Booth et al. (2016) demonstrated the translation of qualitative storylines of each scenario into key quantitative drivers (e.g., climate, land use/cover, nutrients) consistent with scenario narratives using an iterative process. These drivers were spatially explicit (i.e., 220 × 220 m grid-cell determined by the model) and temporally dynamic (i.e., daily time step for climate, annual time-step for land use/cover and nutrients), and were directly input into a process-based biophysical model (Motew et al. 2017) to simulate the long-term dynamics of ecosystem services. This paper differs from and builds upon prior foundational work by integrating the rich scenario narratives with biophysical modeling to quantitatively analyze spatial-temporal changes in the provision of nine ecosystem services and their complex relationships under alternative future pathways.

Quantifying ecosystem services

We quantified biophysical indicators for nine ecosystem services (including three provisioning and six regulating services; Table 1) at 220 × 220 m spatial resolution using an integrated spatially explicit model: Agro-IBIS (Agroecosystem Integrated Biosphere Simulator; Foley

Table 2. Key factor and synopses of the four alternative future scenarios.

Factor	Accelerated innovation	Abandonment and renewal	Connected communities	Nested watersheds
Key factor	Technology	Inaction	Values	Government
Synopsis	Massive growth in green technology	Disaster leads to reorganization	Shift in values toward sustainability	Government interventions to maintain ecosystem services

Note: Detailed descriptions of scenarios can be found in Carpenter et al. (2015).

et al. 1996, Kucharik et al. 2000, Kucharik 2003, Motew et al. 2017). Selected indicators capture key ecological processes that underlie the production or condition of each service (Qiu and Turner 2013). Agro-IBIS simulates continuous dynamics of terrestrial ecosystem processes, biogeochemistry, water and energy balance, and has been calibrated and validated extensively for performance in both natural and managed systems in the U.S. Midwest (Donner and Kucharik 2003, Kucharik and Twine 2007, Motew and Kucharik 2013), including recent studies focusing on subsurface water dynamics and agricultural production in the Yahara Watershed (Soylu et al. 2014, Zipper et al. 2015). We used an updated version of Agro-IBIS that included newly developed phosphorus and sediment modules; watershed-scale phosphorus, sediment, and streamflow processes were carefully calibrated and evaluated against historical data with satisfactory performance (Motew et al. 2017).

Analyzing ecosystem service changes and interactions

To analyze future ecosystem services (question 1), we computed annual summaries for the watershed by summing or averaging (depending on the service) biophysical outputs across all grid cells, and then plotted each indicator against time for each scenario. We computed five-year moving averages of annual values to remove noise and highlight trends over time. We chose five years as the moving window size because it sufficiently removed fine-scale noise without over-smoothing major trends. Net changes in biophysical indicators between the averaged first decade (i.e., 2001–2010 as the baseline) and last decade (2061–2070) of simulation results were calculated for all scenarios. Decadal average results were chosen to assess net change to avoid arbitrariness of selecting a specific year for comparison. To identify locations most susceptible to future social-ecological changes (question 2), we performed overlay analysis to calculate net changes of indicators between the averaged last and first decade of simulation at the 220 × 220-m grid-cell scale. To analyze relationships among pairs of ecosystem services (question 3), we first calculated mean values of indicators at the watershed scale at five-year intervals (i.e., 2011–2015, 2016–2020, …, 2066–2070), and then plotted each pair of service indicators in a two-dimensional space with the 2001–2010 averages as baselines for comparison (Fig. 1). We used five-year intervals to strike a balance between removing high inter-annual variations and depicting fine-scale temporal dynamics of ecosystem services. Synergies are suggested if both services increase over time (Fig. 1; quadrat I), and trade-offs are suggested if one service increases as the other decreases (quadrat II, III). If both decline, lose-lose outcomes are suggested (quadrat IV). Because there are a large number of possible pairwise combinations, we limited this analysis to a subset of ecosystem service pairs focused on food production and vital regulating services. All analyses were performed in R statistical software version 3.3.1 (R Core Team 2016).

Results

Variation in future ecosystem services among scenarios

Biophysical indicators of food, water, and biogeochemical services at the watershed scale varied substantially among scenarios (Figs. 2, 3). Some service indicators (e.g., phosphorus yield) changed in similar directions in

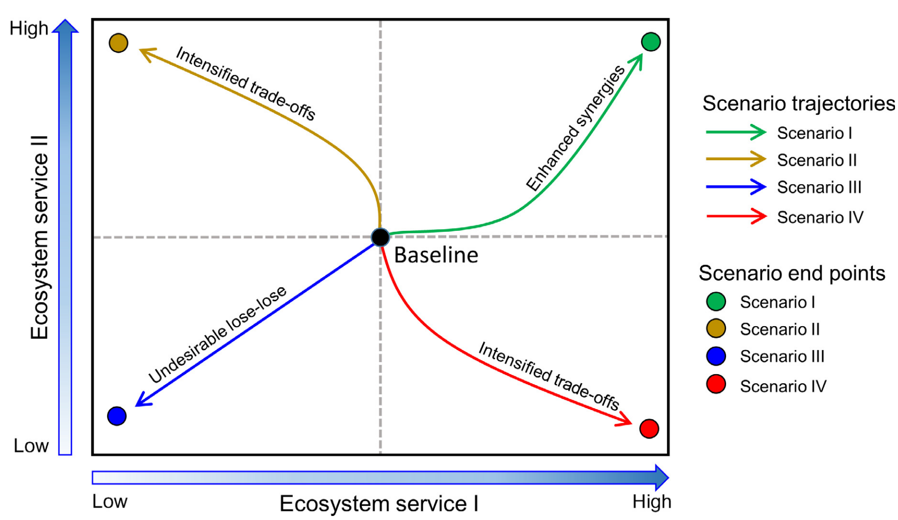


Fig. 1. Hypothetical diagram illustrating relationships (i.e., synergies, trade-offs, and lose-lose) between paired ecosystem services as they evolve from current to the future. Different colors correspond to alternative scenarios: colored circles represent estimates of ecosystem services at the end point, and colored lines show the trajectories of changes from the baseline (shown as a solid black circle) to the end point. Note that the four scenarios shown here are illustrative examples, not necessarily corresponding to the four scenarios simulated for our study. [Color figure can be viewed at wileyonlinelibrary.com]

all scenarios, while others diverged considerably. Relative to the baseline condition (2001–2010 average), crop production in the last decade (2061–2070) of simulation declined substantially (−54% to −83%) in three scenarios and increased (22%) in one. Changes in perennial grass production also varied qualitatively among scenarios, declining in two scenarios and increasing by a factor of 1.9 and 2.6 in the other two. Drainage, a proxy for freshwater supply, showed consistent declines (−9% to −35%) among all scenarios. Nitrate leaching decreased (−19% to −53%), and phosphorus yield in runoff also declined (−21% to −54%) depending on the scenario, indicating improved water quality. The number of days with runoff >10 mm increased from 44% to 104% in three scenarios (signifying reduced flood regulation), but declined by −22% in one. Net ecosystem exchange (NEE) declined from −11% to −69% across all scenarios, indicating enhanced capacity of ecosystems to uptake atmospheric CO_2 and thus regulate climate. Soil carbon storage changed minimally (1–5%) among scenarios. However, such changes may not be negligible because soil carbon is the largest terrestrial pool, and even with a small percent increase, absolute values may exceed NEE. Sediment yield declined (−28% to −62%) in three scenarios and showed almost no change in one. It is noteworthy that although averaged decadal changes are highlighted here, there was substantial inter-annual variability and sometimes changes (e.g., phosphorus and sediment yield) were not monotonic (Fig. 2).

Where are changes in ecosystem services most apparent?

Spatial patterns of change in ecosystem service indicators were heterogeneous and differed by service and scenario (Fig. 4). Most changes in crop and perennial grass production occurred where agricultural lands were converted to other land covers (Figs. 4A, B; Appendix S1: Fig. S1). Most declines in drainage were found in newly-developed urban areas or where forests (which have high evapotranspiration) expanded, in concert with warmer temperatures and lower precipitation (Fig. 4C). Declines of nitrate leaching and phosphorus yield were most pronounced in historically agriculture-dominated locations (i.e., substantial nutrient applications and build-up in

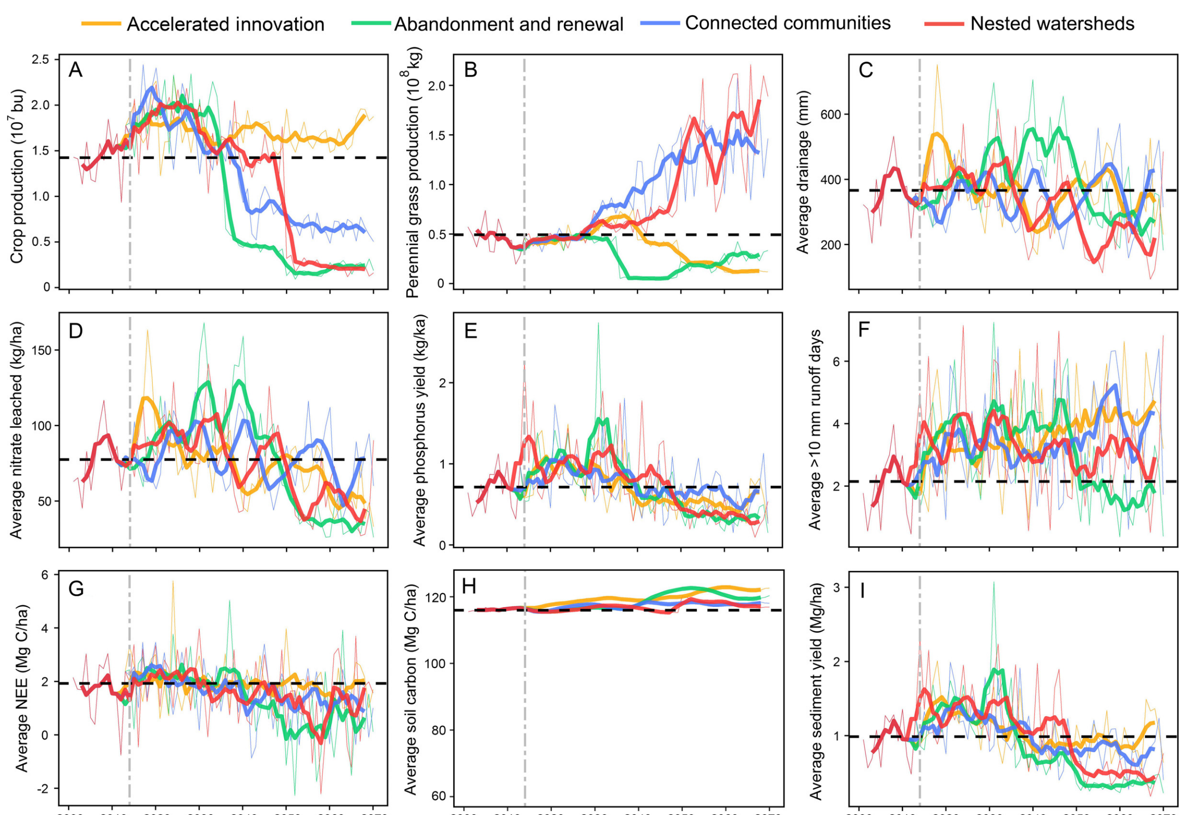


FIG. 2. Simulated changes in nine ecosystem service indicators from 2001 to 2070 at the watershed scale under four future scenarios. Black dashed horizontal lines are the baseline estimates of 2001–2010 average. Colored thin lines indicate annual changes in the biophysical indicator of each service under future scenarios, and colored thick lines are 5-yr moving averages used to demonstrate a general trend over time. NEE, net ecosystem exchange; 1 bushel = 35.24 L [Color figure can be viewed at wileyonlinelibrary.com]

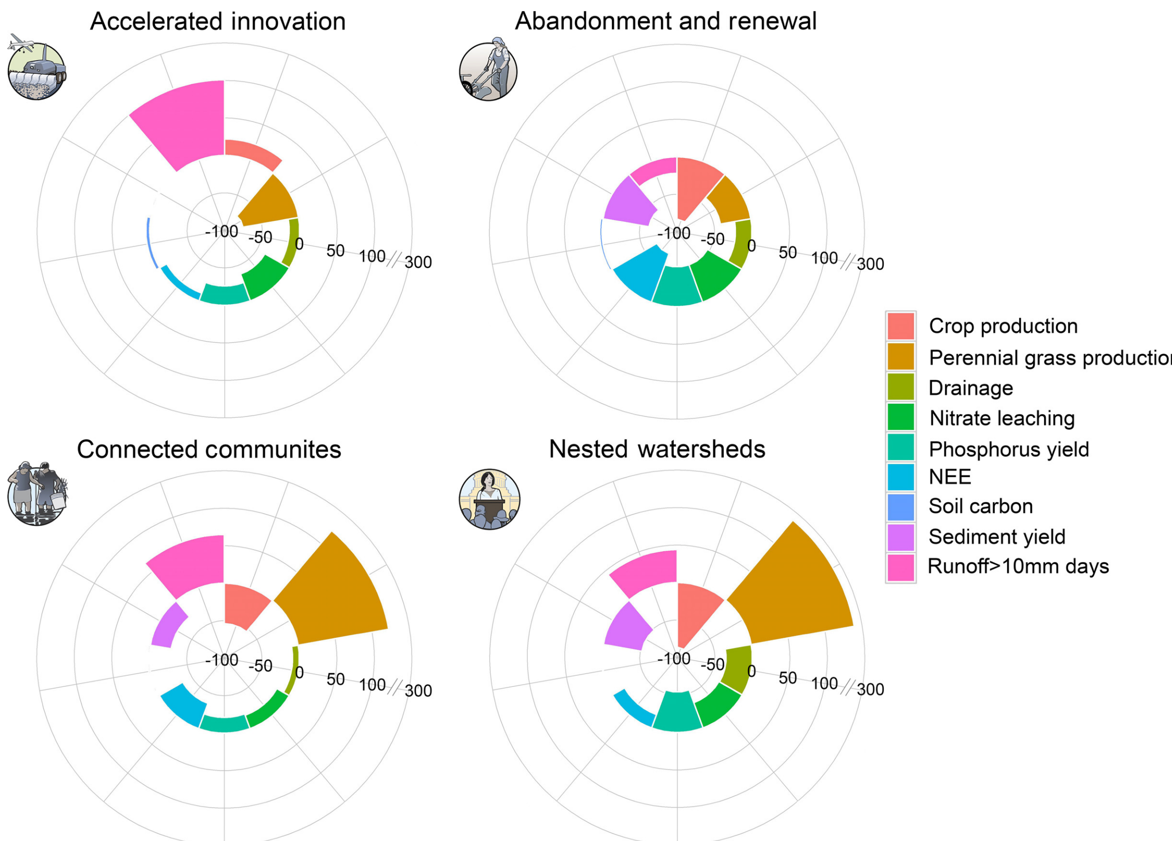


FIG. 3. Percent changes in the biophysical indicators of nine ecosystem services between the averaged last (i.e., 2061–2070) and first decade (i.e., 2001–2010) of simulation under alternative future scenarios. Numbers on the radial axes denote percent changes. Graphic icons are illustrations of each scenario by John S. Miller (Gray Jay Graphics: http://www.grayjaygraphics.com). [Color figure can be viewed at wileyonlinelibrary.com]

the soils) that were converted to other land covers such as perennial grasses and natural vegetation (Fig. 4D, E). Changes in land use and management in such areas had the most potential to reduce nutrient exports and improve water quality. Surprisingly, most increases in nitrate leaching and phosphorus yield were found where intensive farming like corn transitioned toward small-scale farms (e.g., fruits/vegetables, small grains) that have much lower nutrient uptake by crops but still require moderate nutrient inputs. In tandem, this suggests that both nutrient applications and soil nutrient legacies must be reduced to enhance water quality (Van Meter et al. 2016). Spatially, most increases in the number of days with runoff >10 mm were found in highly impervious urban areas (including areas that became developed) across all scenarios (Fig. 4F), and increases were greater in scenarios with high precipitation. Changes in NEE were highly variable across the landscape (Fig. 4G). Increased CO_2 uptake (i.e., decreased NEE) was found in restored forests, wetlands, and perennial grasslands, whereas reduced CO_2 uptake spatially aligned with areas of intensive cropping. Changes in soil carbon illustrated long-term shifts in terrestrial carbon storage (Fig. 4H). While changes in soil carbon at the watershed level were minimal among all scenarios, spatial variations were notable (~ −100% to 100% relative to the baseline), with most declines occurring in agriculture-dominated lands (Fig. 4H). Changes in sediment yield also showed large spatial variations, with most declines in perennial crops, grasslands or restored natural vegetation (Fig. 4I).

Relationships among ecosystem services across scenarios

Relationships between food production and services related to water and biogeochemical cycles evolved over time and varied among scenarios (Fig. 5). As time progressed, crop production increased with nitrate leaching and phosphorus yield at the beginning of simulation across all scenarios, and then diverged. In Accelerated Innovation, increased crop production toward the 2060s was accompanied by large declines in nitrate leaching and phosphorus yield, suggesting that watershed trade-offs between crop production and water quality diminished over time and shifted toward synergies (Fig. 5A, B). In Nested Watersheds and Abandonment and

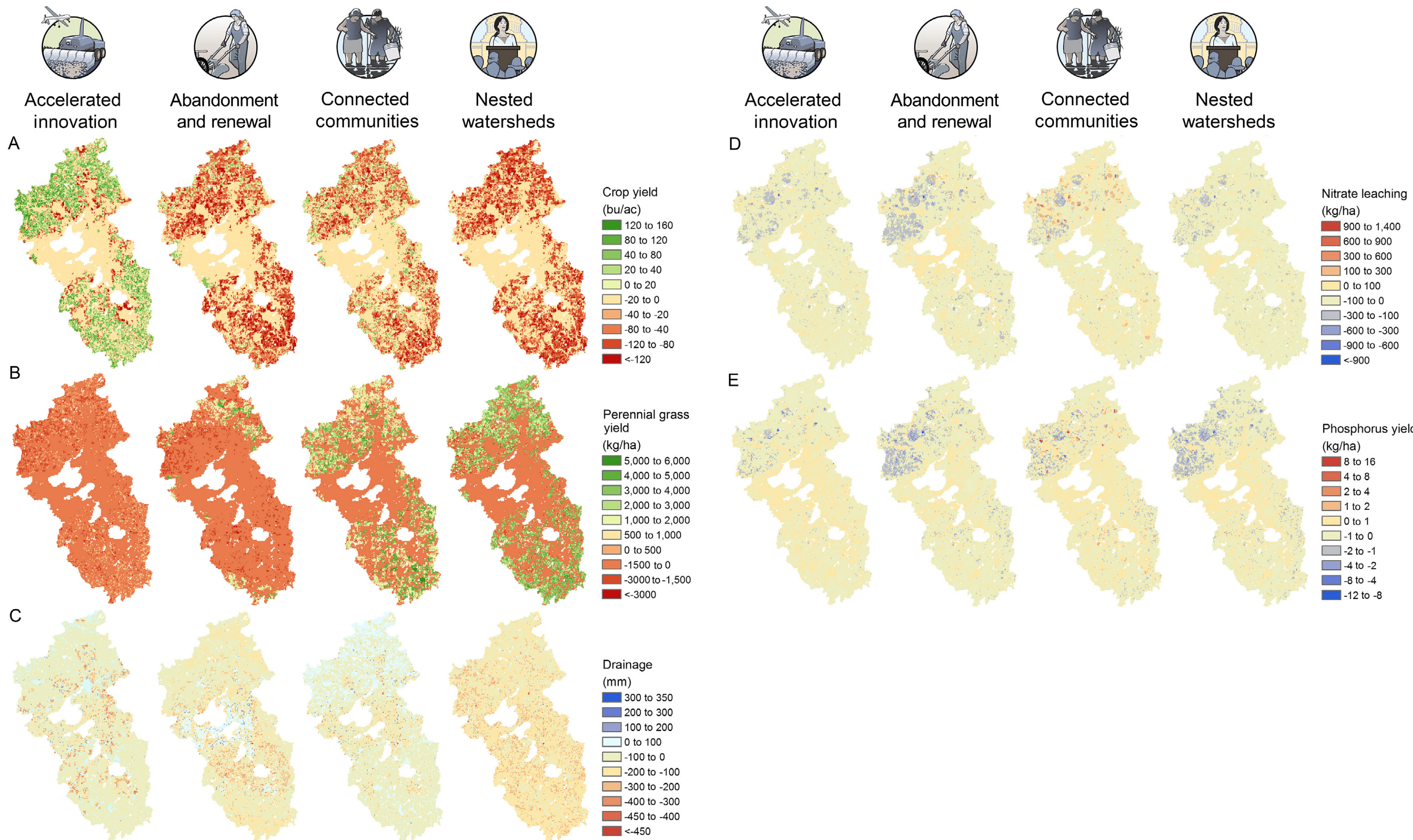


FIG. 4. Spatial patterns of changes in biophysical indicators of ecosystem services between the averaged last (i.e., 2061–2070) and first decade (i.e., 2001–2010) of simulation under alternative future scenarios. Green or blue colors indicate overall increases in the provision of ecosystem services and red color indicates declines in service supply. Graphic icons at the top are illustrations of each scenario by John Miller (Gray Jay Art Technical). 1 bushel/acre = 87 L/ha.

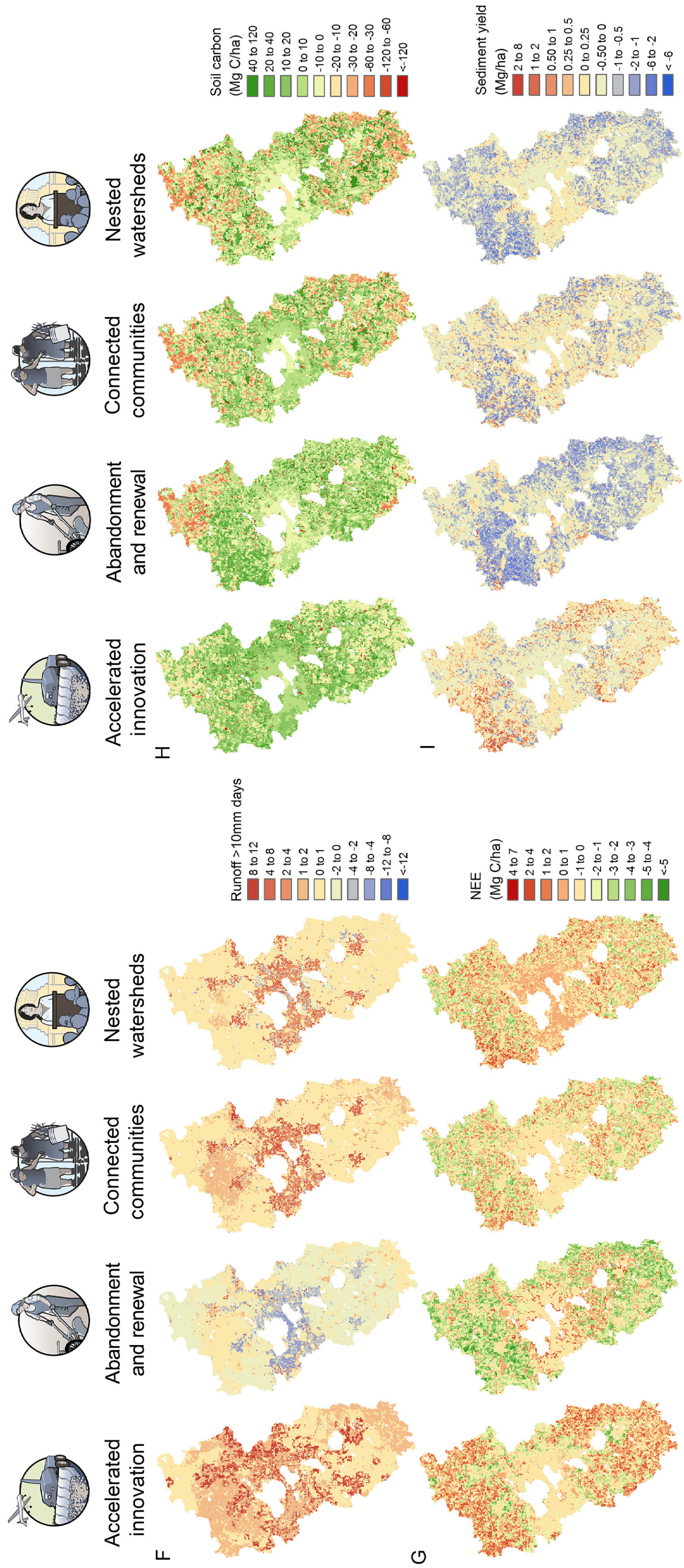


FIG. 4. Continued

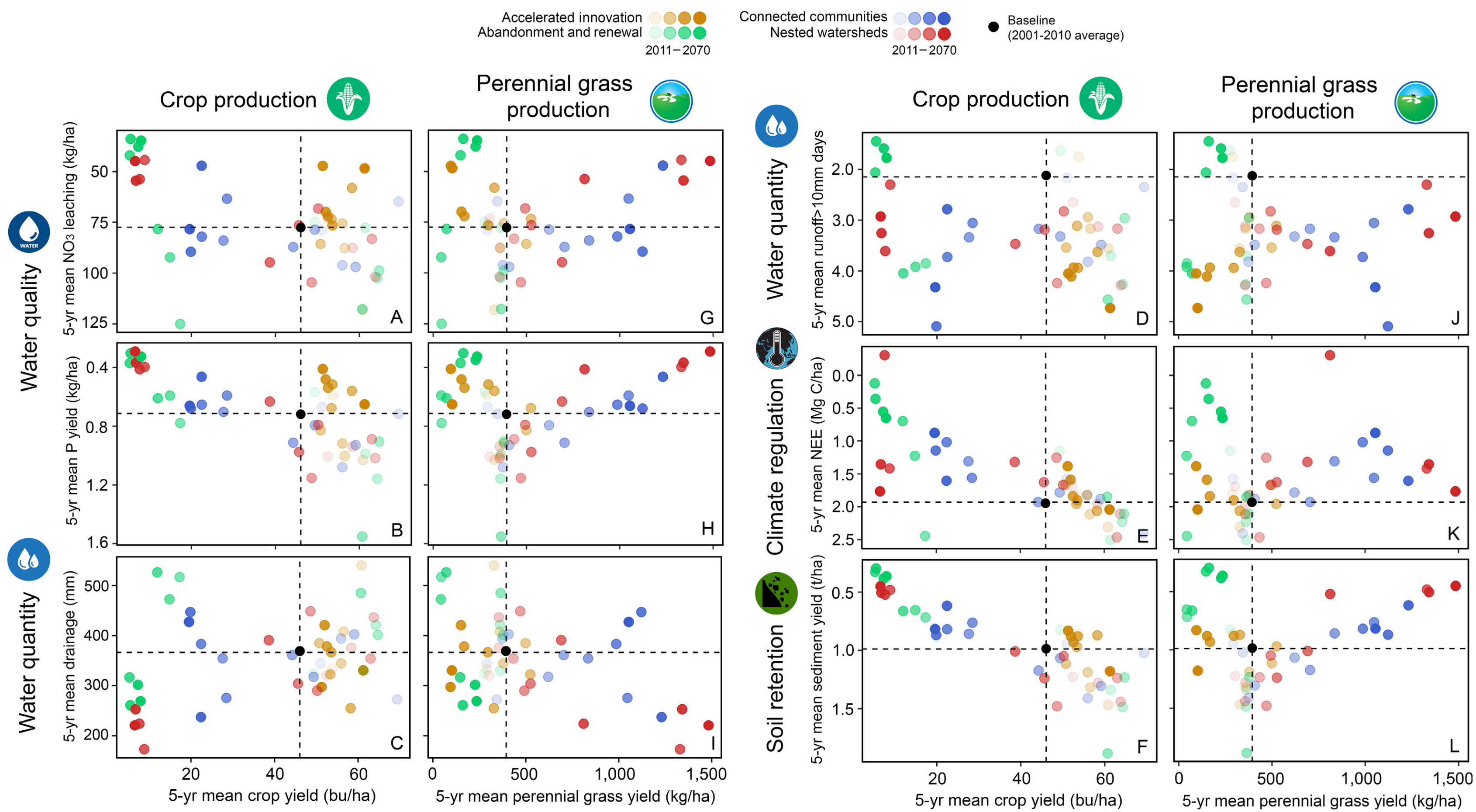


FIG. 5. Temporal changes in the indicators of paired food production vs. water and biogeochemical services. Indicators of ecosystem services were calculated at the watershed scale at 5-yr intervals (i.e., 2011–2015, 2016–2020, …, 2066–2070). For a given scenario (colored circles), the gradient from the lightest to darkest represents the time dimension from 2011–2015 to 2066–2070. Solid black circles are the baseline estimates (averaged 2001–2010) for comparison. Note that the *y*-axes were reversed for services quantified using inverse indicators (i.e., the higher the value, the lower the provision of service, such as nitrate leaching and phosphorus yield) so that the results are consistent with Fig. 1 where quadrat I denotes synergies, quadrats II and IV trade-offs, and quadrat III lose-lose outcomes.

Renewal, such trade-offs persisted through time but shifted toward improved water quality at the expense of crop production. In Connected Communities, water quality did not improve substantially, even though crop production declined. For water quantity, no general pattern between crop production and drainage was found in Accelerated Innovation. However, strong trade-offs and lose-lose outcomes developed in the other three scenarios toward the last decade of simulation (Fig. 5C). Relationships between crop production and flood regulation (indicated by inverse of number of days with runoff >10 mm) were manifested as trade-offs in Accelerated Innovation and Abandonment and Renewal. These trade-offs were intensified and transitioned to lose-lose outcomes in Nested Watersheds and Connected Communities (Fig. 5D). Relationships between crop production and climate regulation (quantified as the inverse of NEE) were variable in Accelerated Innovation, but persistent trade-offs were present in other three scenarios toward the 2060s (Fig. 5E). Patterns of crop production with sediment yield were almost identical to that with phosphorus yield (Fig. 5F), because phosphorus and sediment transport processes are linked.

Patterns of perennial grass production, another vital food and bioenergy service, differed from crop production. In two scenarios, as watershed-level perennial grass production increased, nitrate leaching and phosphorus yield declined (i.e., perennial-grass–water-quality synergies); but trade-offs appeared in the other two scenarios (Figs. 5G, H). Relationships between perennial grass production and drainage were highly variable in three scenarios, but showed as trade-offs in Nested Watersheds (Fig. 5I). Over time, both perennial grass production and number of days with runoff >10 mm increased in two scenarios (i.e., Nested Watersheds, and Connected Communities), indicating perennial-grass–flood-regulation trade-offs. Such trade-offs persisted in Abandonment and Renewal, but shifted toward the opposite direction (Fig. 5J). Nonetheless, in Accelerated Innovation, both perennial grass production and flood regulation declined (i.e., lose-lose outcomes). Moreover, perennial grass production increased as NEE declined (i.e., perennial-grass–climate-regulation synergies) in Nested Watersheds and Connected Communities, but progressed as trade-offs in the other two scenarios (Fig. 5L). Patterns of perennial grass production and sediment yield were almost identical to those of phosphorus yield (Fig. 5M).

In contrast, relationships among water and biogeochemical services were more predictable and consistent. Across contrasting future scenarios, watershed-level changes in drainage over time were positively associated with changes in the number of days with runoff >10 mm and nitrate leaching (Fig. 6A, B). Relationships between drainage and NEE were highly variable in all scenarios (Fig. 6C). Changes in nitrate leaching and phosphorus yield increased initially and then declined in all scenarios (Fig. 6D), and a similar pattern was found for changes in phosphorus and sediment yield (Fig. 6E). Further, watershed-level changes in nitrate leaching and phosphorus yield were overall positively associated with NEE across most scenarios, albeit with magnitudes and rates of change differing by scenarios (Fig. 6F, G). Lastly, watershed-level changes in NEE were also positively associated with sediment yield across the scenarios (Fig. 6G), with initial increases and then declines toward the 2060s.

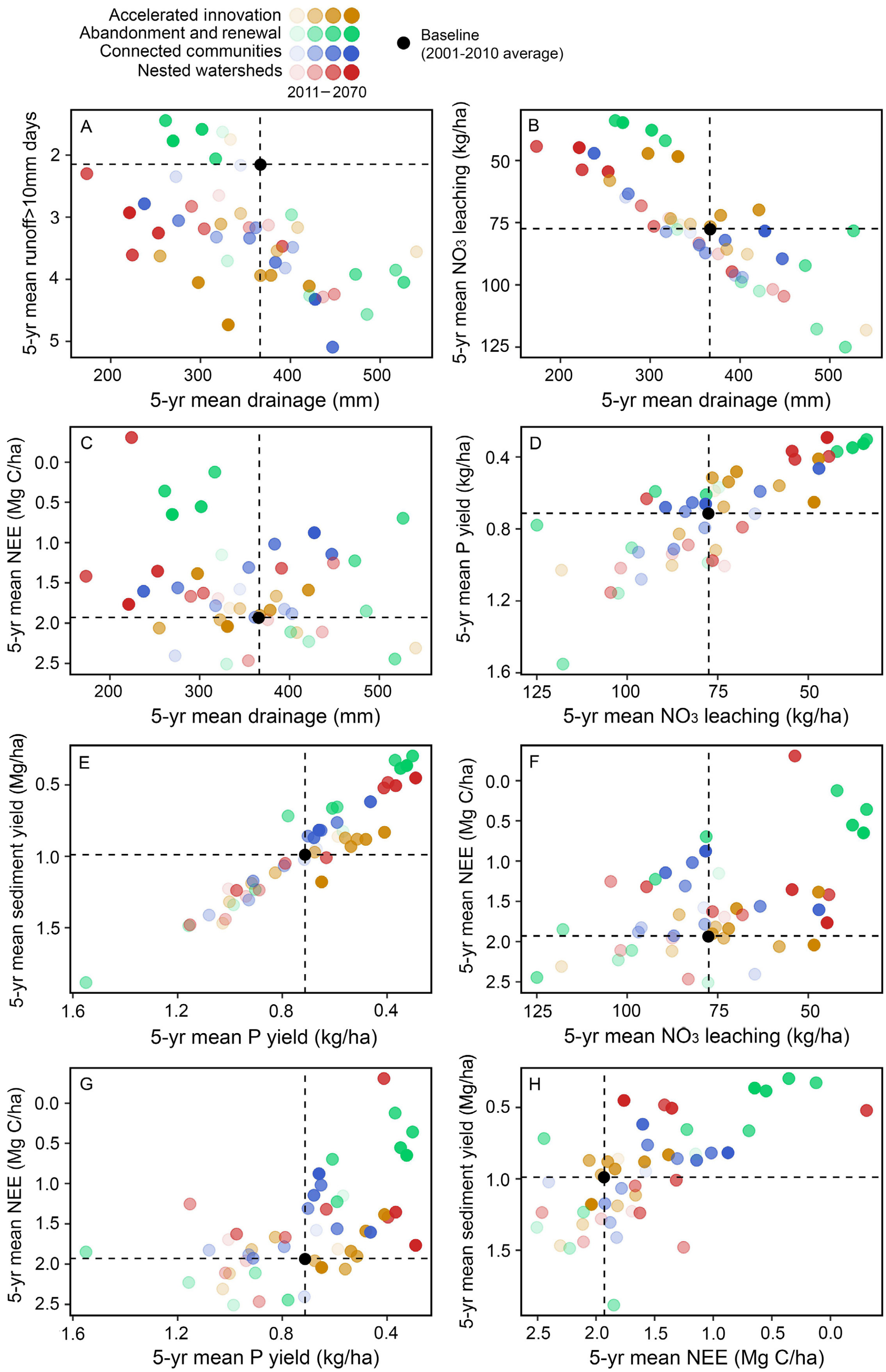
Discussion

Our research integrated qualitative scenarios with quantitative biophysical models to investigate food, water, and biogeochemical services and their interactions in an agricultural watershed. Food production responded to future land-use choices and management and, in most scenarios, showed trade-offs with water quality and soil retention. However, opportunities existed to mitigate such trade-offs through technological advances and sustainable agricultural practices. Consistent relationships among regulating services were identified across scenarios (e.g., trade-offs of freshwater supply vs. flood and climate regulation, synergies among water quality, soil retention, and climate regulation), highlighting opportunities and obstacles for sustainable management. Our findings also suggested that future climate changes may overwhelm land use/cover effects in sustaining freshwater supply and flood regulation. For water quality, however, land-use changes and management could mitigate climate change impacts. Spatially, changes in ecosystem services were heterogeneous on the landscape, underscoring the power of local actions in managing future ecosystem services.

Future trajectories of food production

Future land-use choices and management strongly alter food production. Increased crop production in Accelerated Innovation (where cropland declined) reflected the role of technology (e.g., genetic modification) and management (e.g., precision agriculture) in enhancing nutrient-use efficiency and closing yield gaps (Tester and Langridge 2010, Mueller et al. 2012). Increased atmospheric CO_2

Fig. 6. Temporal changes in the indicators of paired water and biogeochemical services. Indicators of ecosystem services were calculated at the watershed scale at 5-yr intervals (i.e., 2011–2015, 2016–2020, . . ., 2066–2070). For a given scenario (colored circles), the gradient from the lightest to darkest represents the time dimension from 2011–2015 to 2066–2070. Solid black circles are the baseline estimates (averaged 2001–2010) for comparison. Note that the *x*- or *y*-axes were reversed for services quantified using inverse indicators (i.e., the higher the indicator, the lower the provision of service, such as nitrate leaching and phosphorus yield) so that the results are consistent with Fig. 1 where quadrat I denotes synergies, quadrats II and IV trade-offs, and quadrat III lose-lose outcomes.



Accelerated innovation
Abandonment and renewal
Connected communities
Nested watersheds
2011–2070
Baseline
(2001-2010 average)
A
5-yr mean runoff>10mm days
5-yr mean drainage (mm)
B
5-yr mean NO3 leaching (kg/ha)
5-yr mean drainage (mm)
C
5-yr mean NEE (Mg C/ha)
5-yr mean drainage (mm)
D
5-yr mean P yield (kg/ha)
5-yr mean NO3 leaching (kg/ha)
E
5-yr mean sediment yield (Mg/ha)
5-yr mean P yield (kg/ha)
F
5-yr mean NEE (Mg C/ha)
5-yr mean NO3 leaching (kg/ha)
G
5-yr mean NEE (Mg C/ha)
5-yr mean P yield (kg/ha)
H
5-yr mean sediment yield (Mg/ha)
5-yr mean NEE (Mg C/ha)

levels (Appendix S1: Fig. S2) and farmer adaptation to increased growing degree days through shifting planting dates and hybrids in all scenarios can also boost yields (Kucharik et al. 2000, Long et al. 2006, Lobell and Field 2007). Reduced crop production results from agricultural abandonment (Abandonment and Renewal), shifts toward less consumptive lifestyles (Connected Communities), and farm regulations and biofuel investments (Nested Watersheds). Similarly, increased perennial grass production occurred in two scenarios with more lands devoted to forage crops and grasses for environmental concerns (Appendix S1: Fig. S1). Moderate-to-high increases in temperature and CO_2 level in these two scenarios also enhance grass productivity, especially when the grasses are C_3 plants. It is important to note that crop and grass production are intermediate indicators of food provision, because most crops and grasses in this watershed are not directly consumed, but rather used for producing meat, dairy products, or biofuels.

Future trajectories of water and biogeochemical services

Declining freshwater supply and flood regulation in most scenarios highlights challenges to sustaining water quantity, and suggests that correctives (e.g., improving water use efficiency and stormwater management) may be needed. Reduced drainage (freshwater supply proxy) was partially due to rising temperature and evapotranspiration (Appendix S1: Figs. S2a, S3a) that exceeded effects of increased precipitation. Expansion of urban areas can also reduce infiltration and drainage (Arnold and Gibbons 1996). The highest decline in drainage occurred in Nested Watersheds with considerable increases in temperature and least increases in precipitation, even though urban lands declined (Appendix S1: Figs. S1, S2). Hence, results for Nested Watersheds suggest that future climate changes may overwhelm land-use/cover effects on freshwater supply. Number of days with runoff >10 mm (flood regulation proxy) increased in most scenarios, consistent with historical analyses (1916–2015) for this watershed (Usinowicz et al. 2016). Extreme runoff was likely driven by increased frequency of heavy rainfall events in most scenarios (Appendix S1: Fig. S4), especially when extreme rainfall exceeds soil moisture storage capacity (Berghuijs et al. 2016). In particular, in Abandonment and Renewal, number of days with runoff >10 mm increased by ~15% from 2035 to 2048, when even massive increases in natural covers in the same period did not counter extreme rainfall events (Appendix S1: Figs. S1, S4), reinforcing the dominance of climate over land use/cover on water quantity services.

Declines in nitrate leaching, phosphorus and sediment yield in most scenarios suggest that water quality and soil retention can be improved through diverse pathways. Declines of nitrate leaching and phosphorus yield were due to combined effects of reduced fertilizer and manure application (Kronvang et al. 2005, Schoumans et al. 2014), along with reduced drainage, in all scenarios (Appendix S1: Fig. S5). Decreased nutrient input could be achieved through improved technology and management to enhance nutrient-use efficiency (in Accelerated Innovation; Fageria and Baligar 2005), or conversions of intensive row crops (in other scenarios). Decreased sediment yield in nearly all scenarios was attributable to reduced croplands with soils susceptible to erosion and restoration of natural ecosystems. Another important finding is that phosphorus and sediment yield decreased in three scenarios even with increased surface runoff (Appendix S1: Fig. S3b), suggesting that land-use and management could buffer the watershed from future declines in surface-water quality even as climate changes.

Decreased NEE together with increased soil carbon (albeit minimal) in all scenarios increased the watershed's contribution to climate regulation, although the watershed is a very small contributor to global trends. Increased carbon storage is associated with increased natural covers, which may act as carbon sinks (Twine and Kucharik 2009). Rising temperature and CO_2 levels in all scenarios also enhanced net primary productivity, especially if water was not limiting (Nemani et al. 2003). Changes in soil carbon storage were slow and minimal even after 60 years; thus, a long-term perspective is needed for managing soil carbon in agriculture-dominated landscapes.

Implications of spatial variations of ecosystem service changes

Substantial spatial variations of ecosystem service changes occurred across the landscape and differed among scenarios. Such heterogeneity likely resulted from prevailing spatial patterns in human drivers and geophysical properties, in conjunction with different assumptions of each scenario. This large spatial variability has several implications: (1) a particular service could either increase or decrease at a given location depending on future pathways, underscoring the power of local actions and fine-scale management; (2) it is critical to identify areas most susceptible to future social-ecological changes to maximize benefits of management using, for example, spatially explicit land-use planning (Bateman et al. 2013, Qiu and Turner 2015) or spatially targeted policy applications (Qiu et al. 2017); (3) most locales showed increases in some services but declines in others (rarely increases for all), indicating the persistence of spatial trade-offs (Rodríguez et al. 2006, Qiu and Turner 2013) and need to account for these interactions in future landscape management; (4) watershed-level changes could mask geographic variations, which may be much greater in magnitude (e.g., soil carbon) or differ in direction from watershed changes. Understanding causes and mechanisms for changes in distinct locations or areas of disproportionate importance could shed light on how to manage lands for improving services at fine-scales, so as to lead to cumulative effects at the watershed scale.

Trade-offs and synergies among food, water and biogeochemical services

Our research explored how trade-offs and synergies among multiple ecosystem services evolved over time. Not surprising, trade-offs between food production and regulating services (e.g., water quality, soil retention) persisted in several scenarios. Such common trade-offs in agricultural landscapes, however, can be alleviated and transitioned to novel synergies: (1) technological and agricultural practice improvements in Accelerated Innovation led to enhanced crop production, water quality and soil retention, when future climate change was not drastic; (2) crop choices also mattered, and conversion from intensive row crops to perennial grasses and forage crops in Nested Watersheds and Connected Communities helped achieve a balanced supply of grass production, improved water quality and soil retention under moderate climate changes. Nonetheless, enhancing food production and climate regulation concurrently remains challenging (West et al. 2010), especially for annual cropping systems that are frequently harvested, and can lead to minimal carbon accumulation if residues are not returned to the soil. Yet pathways exist to mitigate such trade-offs, whereby perennial grass production can be maintained with climate regulation. Other studies also suggested the potentials of technology and sustainable agricultural practices as solutions to reconcile food with regulating services to achieve long-term agricultural sustainability (Tilman et al. 2002, Foley et al. 2011, Werling et al. 2014). Our research provides insights into whether, when and how these goals can be achieved altogether. Moreover, our results showed that sustaining food and water quantity can be difficult; future changes will likely result in significant trade-offs or even lose-lose outcomes across a range of scenarios examined. This also suggests the need to consider groundwater feedbacks between land-use change and agricultural productivity (Zipper et al. 2017). Collectively, our research highlights importance of acknowledging challenges in future management of ecosystem services, and exploring innovative strategies to mitigating their trade-offs.

Relationships among water and biogeochemical services were consistent across scenarios, suggesting opportunities and challenges coexist for management. Such consistency likely resulted from biophysical mechanisms that underpin relationships among indicators of ecosystem services. Trade-offs between freshwater supply and flood regulation differ from synergies reported in Qiu and Turner (2013), mostly due to differing timespans and spatial scales of analysis. Qiu and Turner (2013) focused on a single year with a fixed precipitation amount, and thus runoff-infiltration partitioning drives synergies at the grid-cell scale (i.e., at individual grid cells, those with more infiltration necessarily had less runoff, and vice versa; Craig et al. 2010); whereas in this study, precipitation changed over time and dominated the trade-offs between freshwater supply and flood regulation at the watershed scale (i.e., more precipitation led to more water for recharge and runoff). Trade-offs also persisted between freshwater supply and groundwater quality, indicating challenges of managing for water sustainability. Potential trade-offs between freshwater supply and climate regulation were found in two scenarios featuring large increases in natural covers, reflecting carbon–water trade-offs as a result of climate and land-use changes (Jackson et al. 2005, Kim et al. 2016). Consistent with the snapshot estimates in Qiu and Turner (2013) and similar to other studies (Maes et al. 2012, Thompson et al. 2016), persistent synergies were found among indicators of surface- and ground-water quality, soil retention, and climate regulation, highlighting opportunities to co-manage and enhance these essential regulating services together in the future.

Conclusions

Understanding how to feed a growing population while sustaining land, water, and climate in a rapidly changing and uncertain future remains challenging but critical for research and policy communities. Our research demonstrates pathways to balance food, water, and vital regulating services in agricultural landscapes, identifies which services are likely to experience future declines, and reveals when and how trade-offs and synergies among ecosystem services might be altered by future social-ecological changes. Further understanding of the relative effects of multiple drivers of change, the role of climate variability and extreme events, and important feedback and potential legacy effects on ecosystem services (e.g., Ziter et al. 2017) will be fruitful avenues for future research. The knowledge gained in the Yahara Watershed will be relevant for managing Midwestern agricultural landscapes or other human-watershed systems experiencing similar stresses for sustaining diverse ecosystem services and ensuring human wellbeing in the future.

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Supporting Information

Additional supporting information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.1633/full

Data Availability

Data available from Figshare: https://doi.org/10.6084/m9.figshare.5405275.v1