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LETTER

Understanding relationships among ecosystem services across spatial scales and over time

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Abstract

Sustaining ecosystem services (ES), mitigating their tradeoffs and avoiding unfavorable future trajectories are pressing social-environmental challenges that require enhanced understanding of their relationships across scales. Current knowledge of ES relationships is often constrained to one spatial scale or one snapshot in time. In this research, we integrated biophysical modeling with future scenarios to examine changes in relationships among eight ES indicators from 2001–2070 across three spatial scales—grid cell, subwatershed, and watershed. We focused on the Yahara Watershed (Wisconsin) in the Midwestern United States—an exemplar for many urbanizing agricultural landscapes. Relationships among ES indicators changed over time; some relationships exhibited high interannual variations (e.g. drainage vs. food production, nitrate leaching vs. net ecosystem exchange) and even reversed signs over time (e.g. perennial grass production vs. phosphorus yield). Robust patterns were detected for relationships among some regulating services (e.g. soil retention vs. water quality) across three spatial scales, but other relationships lacked simple scaling rules. This was especially true for relationships of food production vs. water quality, and drainage vs. number of days with runoff >10 mm, which differed substantially across spatial scales. Our results also showed that local tradeoffs between food production and water quality do not necessarily scale up, so reducing local tradeoffs may be insufficient to mitigate such tradeoffs at the watershed scale. We further synthesized these cross-scale patterns into a typology of factors that could drive changes in ES relationships across scales: (1) effects of biophysical connections, (2) effects of dominant drivers, (3) combined effects of biophysical linkages and dominant drivers, and (4) artificial scale effects, and concluded with management implications. Our study highlights the importance of taking a dynamic perspective and accounting for spatial scales in monitoring and management to sustain future ES.

Introduction

Human activities have substantially transformed our biosphere to promote desirable ecosystem goods and services (ES) (e.g. timber and agricultural products) (Kareiva *et al* 2007, Ellis and Ramankutty 2008, Foley *et al* 2011). Such efforts, while crucial for meeting demands of a growing population, can lead to unintended consequences for other ES that are equally if not more important. For example, the Millennium Ecosystem Assessment revealed that, at the global scale, provisioning services such as crops, livestock, and

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Table 1. Biophysical indicators (and corresponding units) of eight ecosystem services included in this research.

Ecosystem service	Biophysical indicator of ecosystem service	Unit
Provisioning ES		
Crop production	Annual total crop (corn, soybean, wheat) yield	(bu ac^{-1})[b]
Perennial grass production	Annual total forage crops and perennial grass (alfalfa, hay, pasture) yield	kg ha^{-1}
Freshwater supply	Annual total drainage	mm
Regulating ES		
Groundwater quality[a]	Annual total nitrate (NO_3-N) leached at the bottom of soil profile	kg ha^{-1}
Surface-water quality[a]	Annual total phosphorus yield in runoff	kg ha^{-1}
Flood regulation[a]	Annual number of days with runoff >10 mm	days
Climate regulation[a]	Annual net ecosystem exchange (NEE) of carbon	Mg C ha^{-1}
Soil retention[a]	Annual total sediment yield in runoff	t ha^{-1}

[a] Denotes that ecosystem service is quantified using an inverse indicator, where the greater the numeric value of the indicator means the lower the service provided.

[b] 1 bushel/acre = 87 L ha^{-1}.

aquaculture, have been increasing over the past 50 years, whereas most regulating services like disease regulation, water purification, and pollination have been declining (MEA 2005a, Carpenter *et al* 2009). These results are not surprising because ES interact in complex and sometimes nonlinear ways (Bennett *et al* 2009, Koch *et al* 2009, Qiu and Turner 2015), and thus deliberate changes in one ES can simultaneously alter others. The degradation of regulating services raises special concerns from the research and policy communities, because it may compromise long-term ecosystem resilience and lead to changes that take us beyond a safe operating space for humanity (Carpenter *et al* 2009, Steffen *et al* 2015). Hence, it is imperative to understand relationships among ES to sustain multiple services, manage undesirable tradeoffs, and forestall ecological surprises.

Prior research has defined types of ES relationships, and elucidated underpinning mechanisms (Rodríguez *et al* 2006, Bennett *et al* 2009, Cord *et al* 2017). Major relationships include: (1) *tradeoffs*, in which one ES is reduced because of increased use or supply of another; and (2) *synergies*, where multiple ES are enhanced simultaneously. Recent studies also suggested that ES can have constraint effects, where one ES is imposing upper limits on another ES (Hao *et al* 2017). Empirical studies have documented ES relationships across a range of ecosystems and scales (e.g. Raudsepp-Hearne *et al* 2010, Goldstein *et al* 2012, Haines-Young *et al* 2012, Maes *et al* 2012, Qiu and Turner 2013, Howe *et al* 2014, Meacham *et al* 2016, Zheng *et al* 2016). However, two knowledge gaps hamper progress on key research frontiers in ES sustainability. First, ES relationships reported previously were often associated with one particular spatial scale, and only a few studies have explored changes in relationships across different spatial scales (Scholes *et al* 2013, Raudsepp-Hearne and Peterson 2016). Nonetheless, it has been suggested that ES relationships from one spatial scale may not translate to other scales, and simple extrapolation may lead to misinformed actions and unwanted outcomes (Peters *et al* 2006, Costanza *et al* 2007, Anderson *et al* 2009, Holland *et al* 2011, Scholes *et al* 2013). Second, many empirical studies have focused on snapshots in time and not considered temporal changes. However, other studies have highlighted dynamic nature of ES and their interactions (MEA 2005b, Qiu *et al* 2018, Renard *et al* 2015, Tomscha and Gergel 2016, Spake *et al* 2017).

Scale and the search for scaling laws in biological and ecological systems has long intrigued scientists (Allen and Starr 1982, O'Neill 1986, Wiens 1989, Levin 1992, Whittaker 1999, Gardner *et al* 2001, Wu 2004, Wu *et al* 2006, Sims *et al* 2008). One common issue is the mismatch between scales of ecological processes and human observations and management (Schneider 2001, Scholes 2017), and whether and how observed ecological phenomenon can be scaled (Wu *et al* 2006). Scale mismatches are especially problematic for ES research because the production, distribution, and management of ES are determined by myriad social-ecological processes and structures, each with distinct scales (Cumming *et al* 2006, Andersson *et al* 2015, Raudsepp-Hearne and Peterson 2016). In addition, ES provision may be affected by processes operating at different spatial and temporal scales, leading to complex cross-scale interactions (Heffernan *et al* 2014, Rose *et al* 2017). Although it is often assumed that ES and their relationships vary across scales, quantitatively testing this assumption with multiple ES is rare. Such empirical evidence is needed to test expectations and elucidate mechanisms underlying changes in ES relationships across scales of analysis. It could also improve the capacity to predict critical ES changes (Clark *et al* 2001), and sustainably manage multiple ES.

In this study, we quantified spatial-temporal dynamics of a portfolio of food, water, and biogeochemical ES (table 1) in an urbanizing agricultural landscape (Yahara Watershed, Wisconsin, USA), and analyzed changes in ES relationships. We then synthesized a typology of why ES relationships may vary across scales, and exemplified this typology with our results. Detailed study region description can be found in supplementary materials (SM) available at stacks.iop.org/ERL/13/054020/mmedia. ES were estimated from 2001−2070 using process-based simulation models under four plausible future scenarios that varied in social, political, economic and biophysical drivers

(Carpenter *et al* 2015, Booth *et al* 2016). The use of scenarios and gridded model simulations allowed us to analyze long-term changes in ES relationships and test whether spatial scale of analysis matters over a wide range of future social-environmental conditions.

Materials and methods

Quantifying spatial-temporal dynamics of ES

We quantified indicators of eight ES at 220 × 220 m spatial resolution using simulation results from an integrated spatially explicit model—Agro-IBIS (Agroecosystem Integrated BIosphere Simulator) (Foley *et al* 1996, Kucharik *et al* 2000, Kucharik 2003). Selected indicators capture key ecological processes that underlie production/condition of each ES (table 1). For example, we used drainage as an indicator for freshwater supply, because drainage is critical for replenishing aquifers that are the primary freshwater sources in this region. Nitrate leaching and phosphorus yield were used as (inverse) indicators for water quality, because (1) nitrate is the most ubiquitous contaminant of groundwater with detrimental impacts on human health, and (2) phosphorus from agricultural or urban runoffs is the major threat to surface-water quality, especially in agriculture-dominated watersheds (Qiu and Turner 2013).

Agro-IBIS is a process-based model that simulates continuous dynamics of terrestrial ecosystem processes, biogeochemistry, water and energy balances, and has been calibrated and validated extensively for performance in natural and managed systems in the Midwestern United States (Donner and Kucharik 2003, Kucharik and Twine 2007, Motew and Kucharik 2013). In this research, we used an updated version of Agro-IBIS that included newly developed phosphorus and sediment modules (Motew *et al* 2017). Watershed-scale phosphorus, sediment, and streamflow processes were calibrated and evaluated against historical data with satisfactory performance (Soylu *et al* 2014, Zipper *et al* 2015, Motew *et al* 2017).

We performed simulations from 2001−2070, where 2001−2010 was considered as the baseline for comparison, and 2011−2070 were simulated under four scenarios that contrasted in social, political, economic and biophysical drivers (Carpenter *et al* 2015, Booth *et al* 2016, Wardropper *et al* 2016). Complete scenario narratives are available at Yahara2070.org. A brief synopsis of driving questions, climate and land-use drivers for each scenario is provided below:

- **Accelerated Innovation (AI)**—'What if we prioritized technological solutions to our environmental changes?' is the driving question in AI. Booming green- and bio-technology increases population and urban footprints, and major efficiencies are gained in agriculture. This scenario has the least extreme climate change, characterized by more frequent heavy rainfall events and warming of ~2 °C by 2070.
- **Abandonment and Renewal (AR)**—'What if we are not prepared for escalating environmental changes?' is the major question in AR. AR explores consequences due to societal unpreparedness for climate changes, where a series of catastrophic events in 2030s reduces the watershed population >90%, causing farmland abandonment, urban deterioration and increased natural vegetation. This scenario has the most extreme climate change, with flooding and extreme heat during the 2030s and warming of 5.5 °C.
- **Connected Communities (CC)**–'What if, collectively, we shifted our values towards community and sustainability?' is the overarching theme of CC. Urban footprint shrinks due to increased urban density and conversion of turf grass to restored prairies and urban farms. Diet shifts lead to transitions from row-crops to a mix of pasture, vegetables and fruits, and small grains. Climate change in CC is intermediate between AR and AI, with heavy rainfall events and drought increasing in frequency and 3.5 °C warming.
- **Nested Watersheds (NW)**–'What if we reform how we govern freshwater resources to better protect them?' is the salient feature of NW. In NW, governance is centered on national water and food securities. Urban lands remain relatively constant, but tax disincentives for intensive agriculture reduce row-crops and promote practices that support clean and sufficient water. This scenario has comparable climate change to CC, with more frequent precipitation extremes and 4 °C warming.

Scenarios offer a range of social-environmental conditions to test whether and how scale matters for ES relationships. Based on scenario narratives, we produced spatial-temporal changes of major drivers (climate, land use/cover, nutrients) (Booth *et al* 2016). These drivers were spatially-explicit and temporally dynamic, and were input into Agro-IBIS to simulate long-term ES dynamics (Qiu *et al* 2018). All scenario drivers were detailed in Booth *et al* (2016), and here we highlighted land use/cover and climate in SM. This work differs from and builds upon prior foundational work referenced above by analyzing changes in ES relationships across scales.

Analytical framework

Relationships among ES indicators were analyzed at three spatial scales—grid-cell, subwatershed, and watershed (figure 1) using pairwise correlations. We chose pairwise correlations because they allow for analyzing temporal changes in ES relationships and facilitate comparisons across spatial scales. Since there are 28 possible ES pairs, we limited our analyses to a subset of 12 that were previously reported as prominent tradeoffs or synergies in agricultural landscapes (Power 2010, Qiu and Turner 2013). At the grid-cell scale (figure 1(*a*)), we generated a random sample of

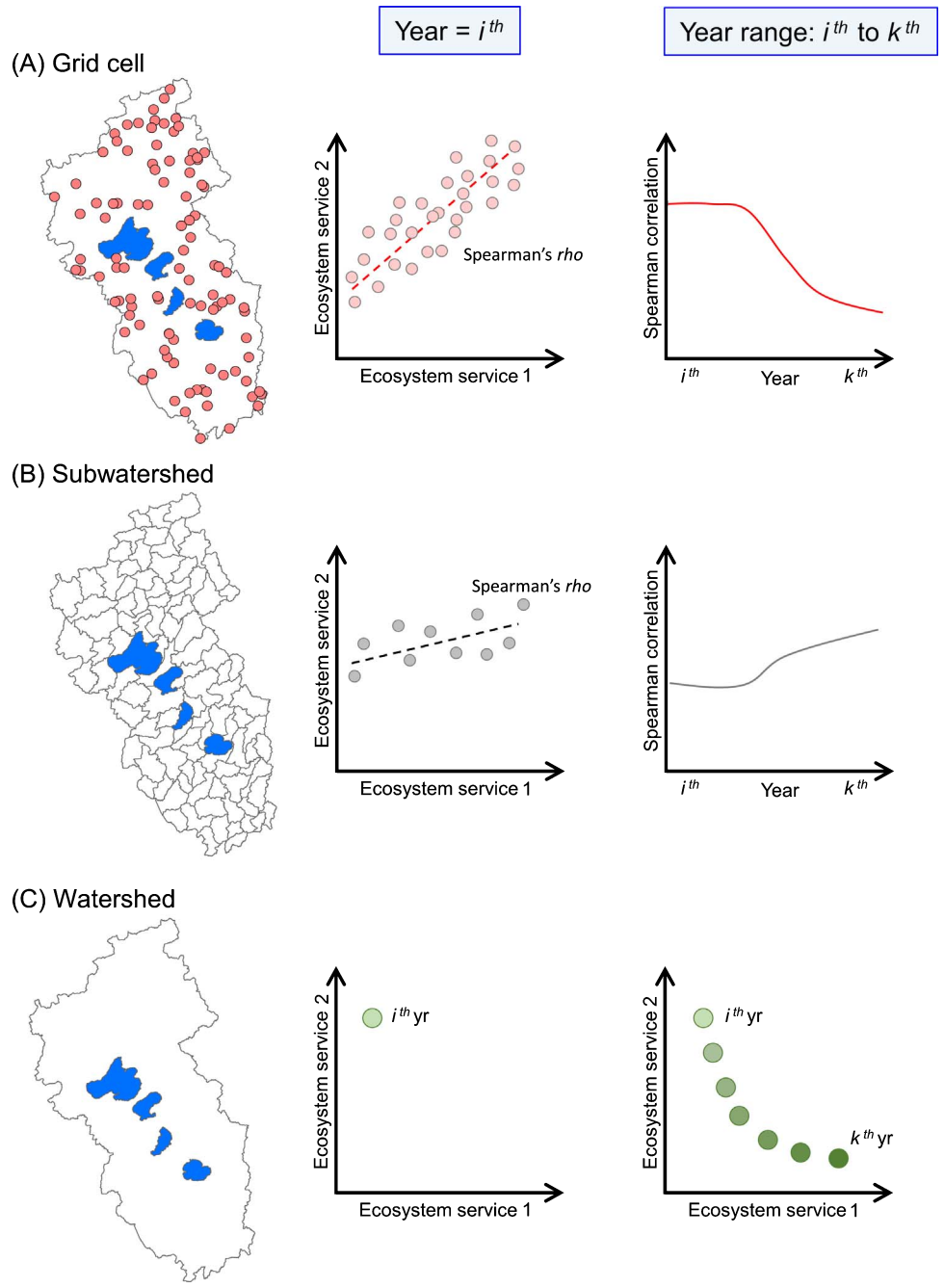

Figure 1. Analytical framework for examining relationships among ecosystem services across three spatial scales: (*A*) grid-cell; (*B*) subwatershed; and (*C*) watershed, over 2001−2070 period. Panel *A* shows relationships among paired ecosystems services calculated annually based on a random sample of 220 × 220 m grid cells across the landscape; correlation coefficients were then plotted against time to demonstrate temporal dynamics of relationships. In panel *B*, relationships among paired ecosystem services were calculated annually at the subwatershed scales, and then plotted against time. Panel *C* shows emergent relationships between paired ecosystem services at the watershed scale as they evolve over time, and the color gradient from lightest to darkest represents the time dimension from 2001−2070. The middle column represents the determination of ecosystem service relationships for a given year, and the third column represents the dynamics of ecosystem service relationships over a time period.

3000 grid-cells across the landscape, and extracted estimates of ES indicators for each cell following Qiu and Turner (2013). We then computed pairwise Spearman correlations annually based on randomly sampled cells, and plotted correlation coefficients over time. At the subwatershed scale (figure 1(*b*)), we computed ES indicators at 100 second-order subwatersheds (Qiu and Turner 2015) annually by summing or averaging (depending on the ES) biophysical outputs, and then calculated pairwise Spearman correlation coefficients and plotted over time. At the watershed scale (figure 1(*c*)), we first summed or averaged (depending on the ES) the ES indicators annually and calculated watershed means at 5 year intervals (i.e. 2011−2015, 2016–2020 ... 2066−2070), then plotted each pair of ES indicators in a two-dimensional space with time color-coded. Synergies are suggested if both ES increase over time, and tradeoffs are indicated if one ES increases

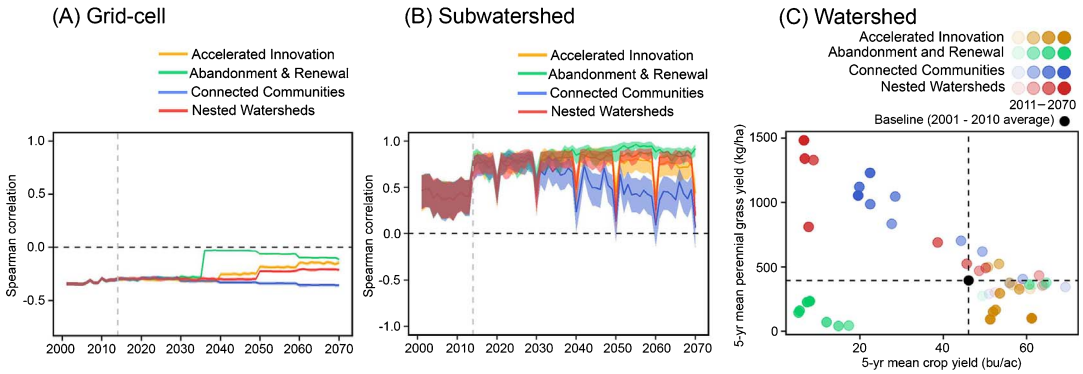

Figure 2. Changes in relationships between crop and perennial grass production across three spatial scales (*A*) grid-cell, (*B*) subwatershed, and (*C*) watershed from 2001–2070 under four future scenarios. Scenarios were color-coded in panels *A* and *B*, with thick color lines as Spearman correlation coefficient and color ribbons as 95% confidence interval, on the basis of bootstrap approach with 1000 iterations. Panel *C* shows temporal changes in the indicators of crop and perennial grass production, calculated at the watershed scale at 5 year intervals (i.e. 2011–2015, 2016–2020...2066–2070). For a given scenario (colored circle), the gradient from 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.

as the other decreases. Such an approach can analyze emergent landscape dynamics of ES relationships at the watershed scale (Qiu *et al* 2018). All analyses were performed in R statistical software 3.3.1 (R Core Team 2016).

Results

Crop and perennial grass production showed consistent negative relationships over time at the grid-cell scale, but were positively correlated at the subwatershed scale (figure 2). At the watershed level, crop production again showed tradeoffs with perennial grass production in all scenarios, except for AR in which crop and perennial grass production both declined.

Persistent tradeoffs between crop production and water quality were found at grid-cell and subwatershed scales across all scenarios, indicated by positive correlations of crop yield with nitrate leaching and phosphorus yield (inverse indicators of water quality) (figures 3(*a*) and (*c*) and 4(*a*) and (*c*)). At the watershed scale, crop production—water quality tradeoffs appeared in three scenarios (figures 5(*a*) and (*c*)), but not in AI where synergies emerged over time. Interestingly, tradeoffs between crop production and water quality at the grid-cell scale diminished over time under two scenarios (NW and AR); nevertheless, also in these two scenarios, such tradeoffs persisted and intensified at the watershed scale. On the other hand, crop production—water quality tradeoffs intensified over time in AI scenario at the grid-cell scale, but such tradeoffs were not evident at watershed scale. For relationships between crop production and drainage (indicator of freshwater supply), no clear patterns were detected across all spatial scales (figures 3(*e*), 4(*e*) and 5(*e*)). Their relationships shifted between positive and negative over time with large interannual variations in all scenarios.

Consistent tradeoffs between perennial grass production and groundwater quality were found at grid-cell and subwatershed scales under all scenarios (figures 3(*b*) and 4(*b*)), indicated by positive correlations between grass yield and nitrate leaching. However, at the watershed scale, this tradeoff appeared in only two scenarios (figure 5(*b*)). In NW and CC, synergies emerged over time between perennial grass production and groundwater quality; interestingly, also in NW and CC, tradeoffs between these two ES intensified at the grid-cell scale (figure 3(*b*)). Tradeoffs between perennial grass production and surface-water quality were evident at grid-cell and subwatershed scales at the start of the simulation period, indicated by positive associations between grass and phosphorus yields (figures 3(*d*) and 4(*d*)). However, such tradeoffs declined over time in most scenarios. At the watershed scale, perennial grass production and surface-water quality were related as synergies in two scenarios (NW and CC), but as tradeoffs in the other two (figure 5(*d*)). Similar to crop production, relationships between perennial grass production and drainage were highly variable with large interannual variations at all spatial scales (figures 3(*f*), 4(*f*) and 5(*f*)).

For relationships among water and biogeochemical ES, our results demonstrated consistent negative relationships between drainage and number of days with runoff >10 mm (inverse indicator of flood regulation) at grid-cell and subwatershed scales (figures 6(*a*) and 7(*a*)), but positive relationships at the watershed scale (figure 8(*a*)). However, relationships of drainage vs. nitrate leaching, nitrate leaching vs. phosphorus yield, and phosphorus vs. sediment yield remained consistently positive across all spatial scales (figures 6(*b*)–(*d*), 7(*b*)–(*d*) and 8(*b*)–(*d*)). Even though the strength of these positive relationships declined over time under certain scenarios at grid-cell or subwatershed scales, their strong positive relationships at the watershed scale were maintained. In addition, consistent

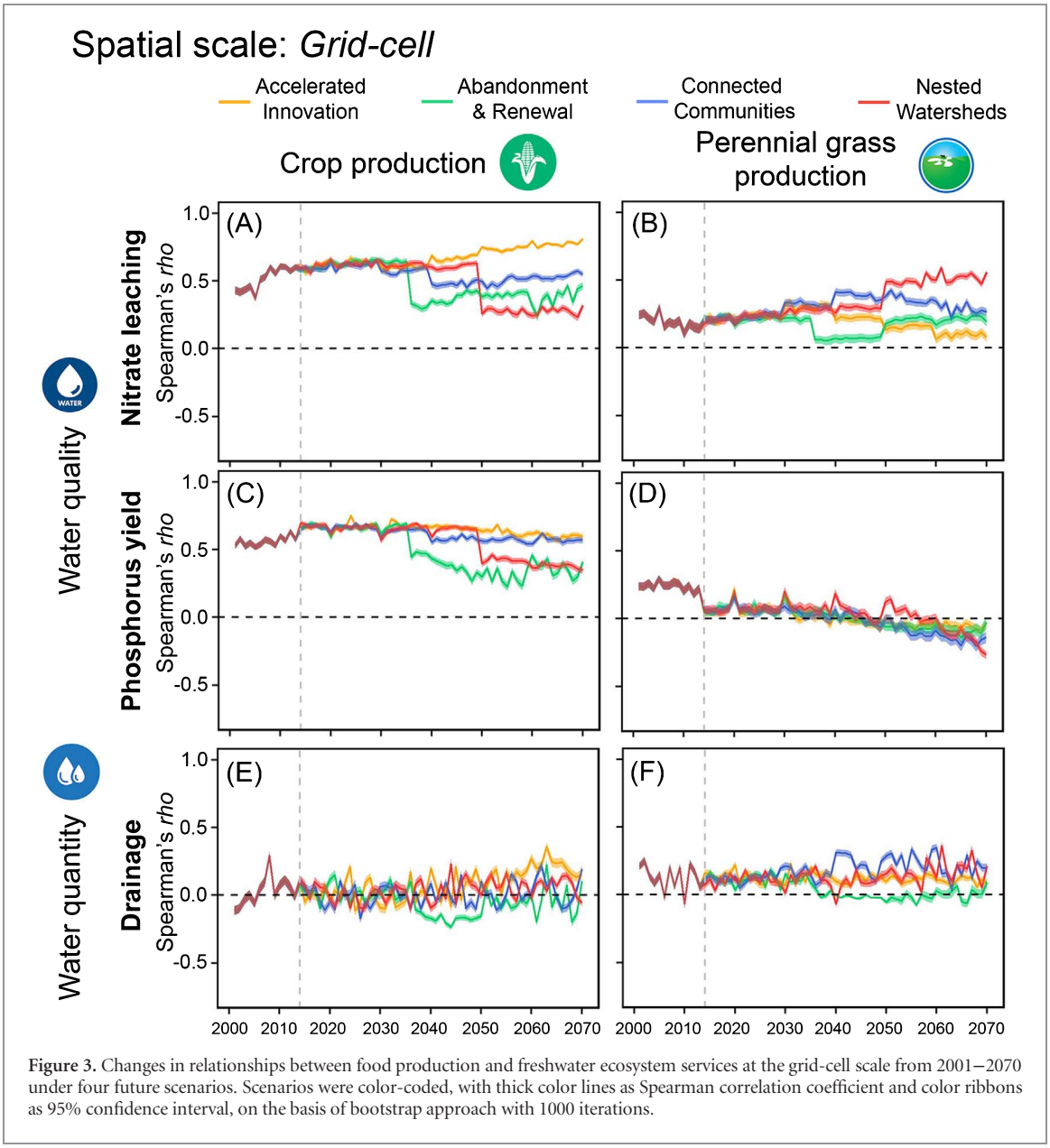

Figure 3. Changes in relationships between food production and freshwater ecosystem services at the grid-cell scale from 2001–2070 under four future scenarios. Scenarios were color-coded, with thick color lines as Spearman correlation coefficient and color ribbons as 95% confidence interval, on the basis of bootstrap approach with 1000 iterations.

positive relationships (albeit with large interannual variations) were found between nitrate leaching and net ecosystem exchange (NEE; inverse indicator of climate regulation) across three spatial scales under most scenarios (figures 6(*e*), 7(*e*) and 8(*e*)). Similarly, relationships between phosphorus yield and NEE remained positive across all spatial scales for most simulation periods under all scenarios (figure 6(*f*), 7(*f*) and 8(*f*)).

Discussion

Managing multiple ES sustainably requires improved understanding of scale-dependent relationships. Our research integrated state-of-the-art biophysical modeling with scenarios to test consistency of relationships for eight ES over a 70 year period under a range of social-ecological changes. Most ES relationships were not static over time, with large interannual variations or sudden changes for certain pairs of ES. While relationships among some regulating services were robust across spatial scales (e.g. water quality vs. soil retention), others varied substantially. Relationships between food production and water quality were inconsistent across scales: local relationships did not apply at broader scales, and sometimes had opposite patterns. Our results suggest caution when extrapolating ES relationships from one scale to another, and underscore the importance of accounting for spatial and temporal scales in monitoring and managing multiple ES (Sun *et al* 2016, Spake *et al* 2017).

A typology of ES relationships across spatial scales

Bennett *et al* (2009) suggested two mechanisms for ES relationships: (1) interactions among ES, and (2) effects of dominant drivers on multiple ES. Such typologies were instrumental and used to identify linkages between biodiversity and ES (e.g. Ricketts *et al* 2016). Based on earlier research and our findings,

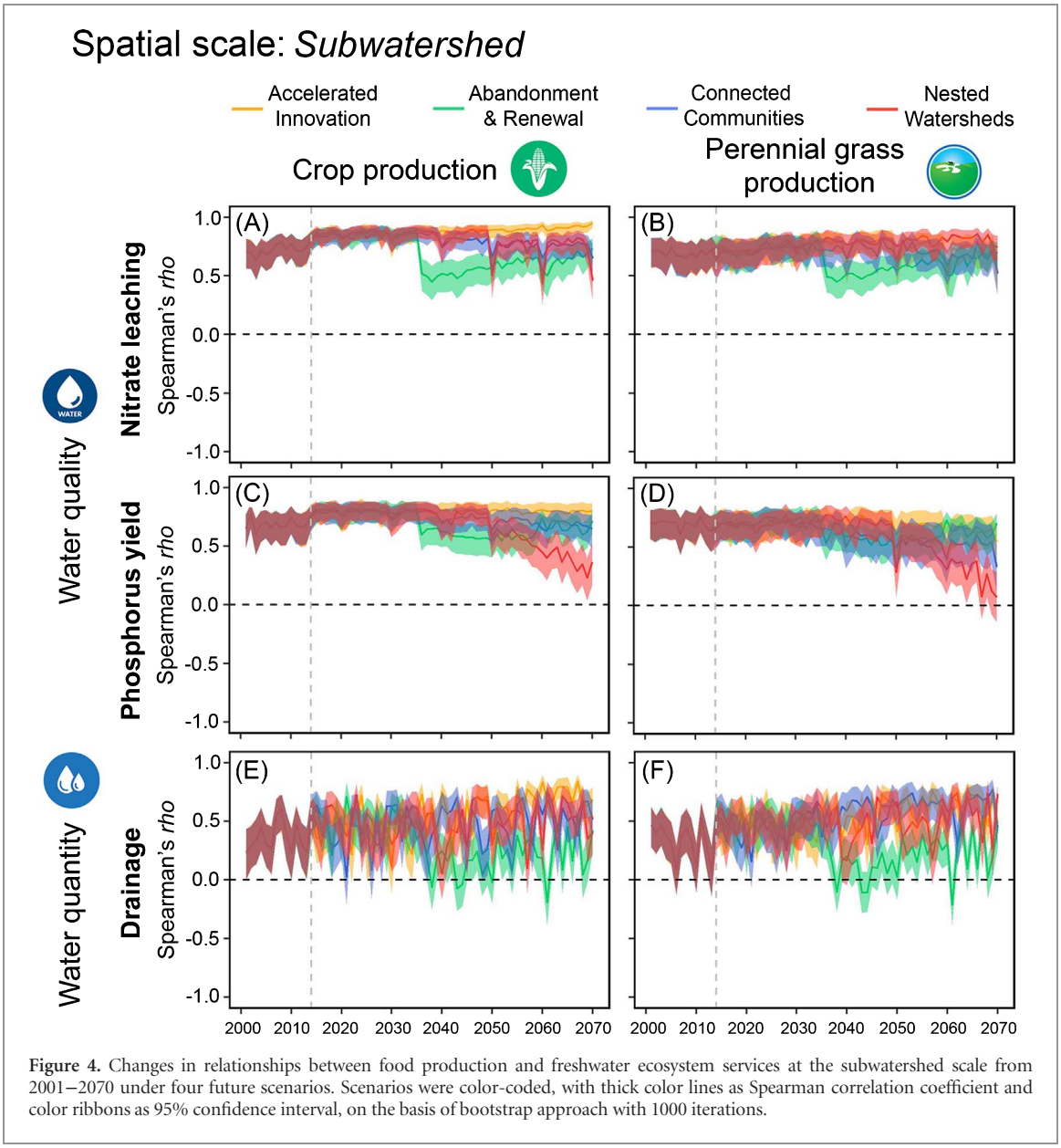

Figure 4. Changes in relationships between food production and freshwater ecosystem services at the subwatershed scale from 2001–2070 under four future scenarios. Scenarios were color-coded, with thick color lines as Spearman correlation coefficient and color ribbons as 95% confidence interval, on the basis of bootstrap approach with 1000 iterations.

we proposed four possible explanations of why ES relationships may differ across scales (figure 9): (1) effects of biophysical connections; (2) effects of dominant drivers; (3) combined effects of biophysical linkages and dominant drivers; (4) artificial scale effects. We then exemplified and substantiated this typology with our results.

Effects of biophysical connections. ES relationships can result from their biophysical connections (i.e. level of ES 1 affects level of ES 2, or vice versa) (figure 9(*a*)). Changing scales of analysis may enhance, reverse or diminish apparent relationships among ES, because biophysical connections underlying interactions among ecological processes and services can be scale-dependent (e.g. scale-dependence of pollinator-plant interactions; García and Chacoff 2007).

Our results showed that relationships among certain water and biogeochemical ES were consistent and predictable across scales (figures 5–7). Positive relationships of drainage vs. nitrate leaching, and phosphorus yield vs. sediment yield are associated with biophysical processes that link these ES at all spatial scales (figure 9(*a*); biophysical connections remain unchanged across scales). Consistent relationships between drainage and nitrate leaching across scales suggest inherent tradeoffs of freshwater supply and groundwater quality, and thus challenges to enhance these freshwater ES together. This result corresponds well with findings from other studies (e.g. Nangia *et al* 2008, Carlson *et al* 2011). Consistent synergies between surface-water quality and soil retention suggest opportunities to co-manage these two ES simultaneously at different spatial scales. Another example of this typology is consistent synergies between climate regulation and water quality across spatial scales, which are also due to that biophysical connections underlying these two ES remain unchanged across scales (figure 9(*a*)). Specifically, increased carbon uptake means higher net

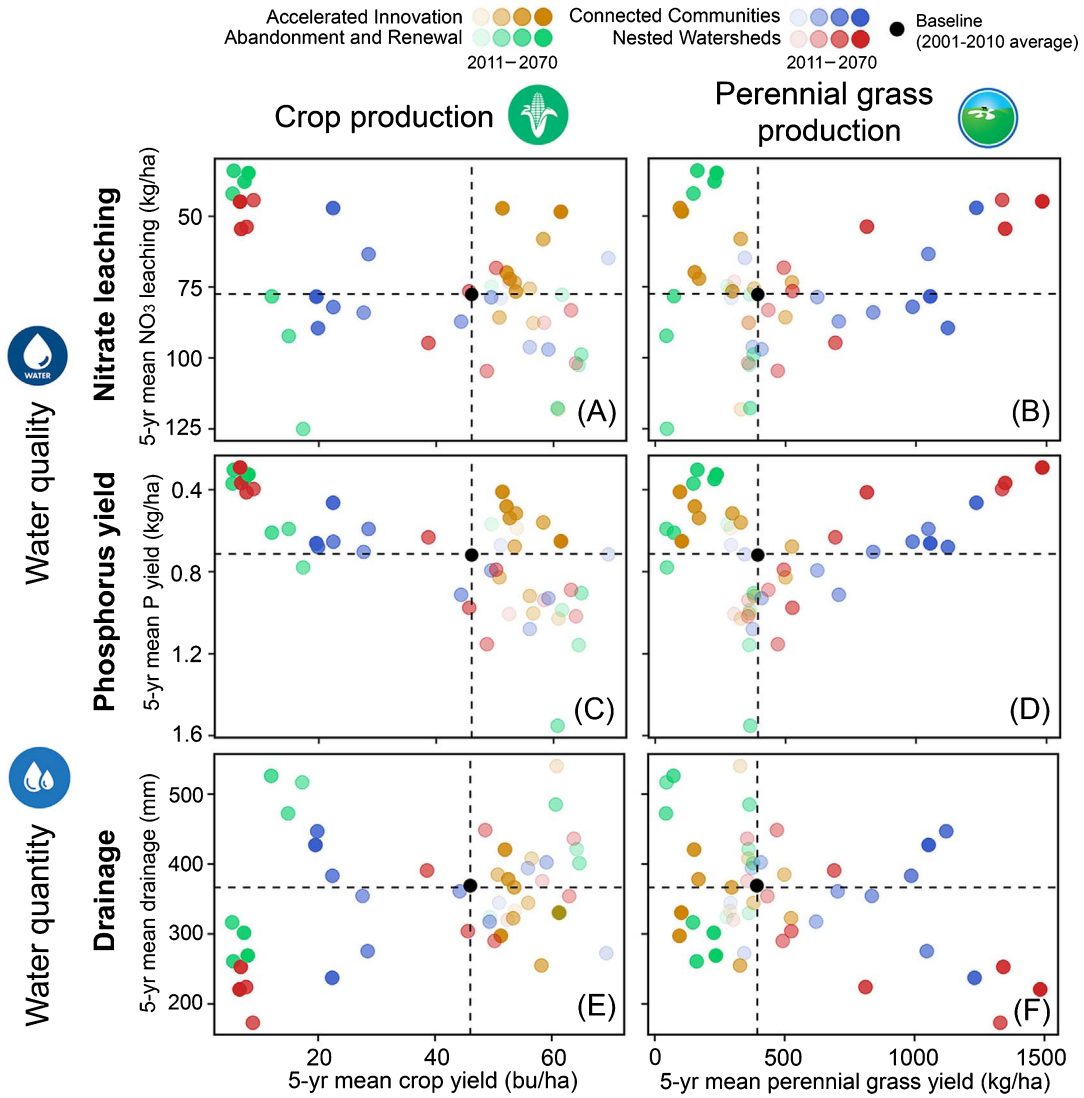

Figure 5. Changes in relationships between food production and freshwater ecosystem services at the watershed scale from 2001–2070 under four future scenarios. Scenarios were color-coded, and temporal changes in the indicators of paired ecosystem services were calculated at the watershed scale at 5 year intervals (i.e. 2011–2015, 2016–2020...2066–2070). For a given scenario (colored circle), the gradient from 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. Please note that *y*-axes were reversed for ecosystem services quantified using inverse indicators (i.e. the higher the indicator, the lower the provision of service, such as nitrate leaching and phosphorus yield).

primary production and more nutrient uptake from soils, thereby reducing the risk of nutrient losses (e.g. nitrate from the root zone, and phosphorus from soils). Other studies also revealed similar synergies between carbon storage/sequestration and water quality at varied scales (Raudsepp-Hearne *et al* 2010, Holland *et al* 2011, Turner *et al* 2014).

Effects of dominant drivers. ES relationships can result from effects of dominant drivers that simultaneously control multiple ES (figure 9(*b*)). Yet it is possible that the magnitude of driver effects or kind of dominant drivers change across scales, thus altering ES relationships. For example, prior research has revealed that dominant controlling abiotic factors for ecosystem processes such as nutrient transport, decomposition, and carbon and nitrogen dynamics, differ across spatial scales (Jones *et al* 2006, Manzoni and Porporato 2009, Bradford *et al* 2014).

Our results showed that relationships between food production and water quality differed across spatial scales. Persistent tradeoffs at grid-cell and subwatershed scales are likely due to local effects of dominant drivers—nutrient and manure applications—at small spatial scales (Motew *et al* 2017). However, at the watershed scale, such tradeoffs can be mitigated or even shift to synergies, reflecting cumulative effects of multiple dominant drivers acting in concert at large spatial scales (figure 9(*b*); dominant drivers changed across scales). Specifically, proactive management and land-use transitions, technological advances, and less extreme climate changes can interact to reduce nutrient application, increase plant nutrient

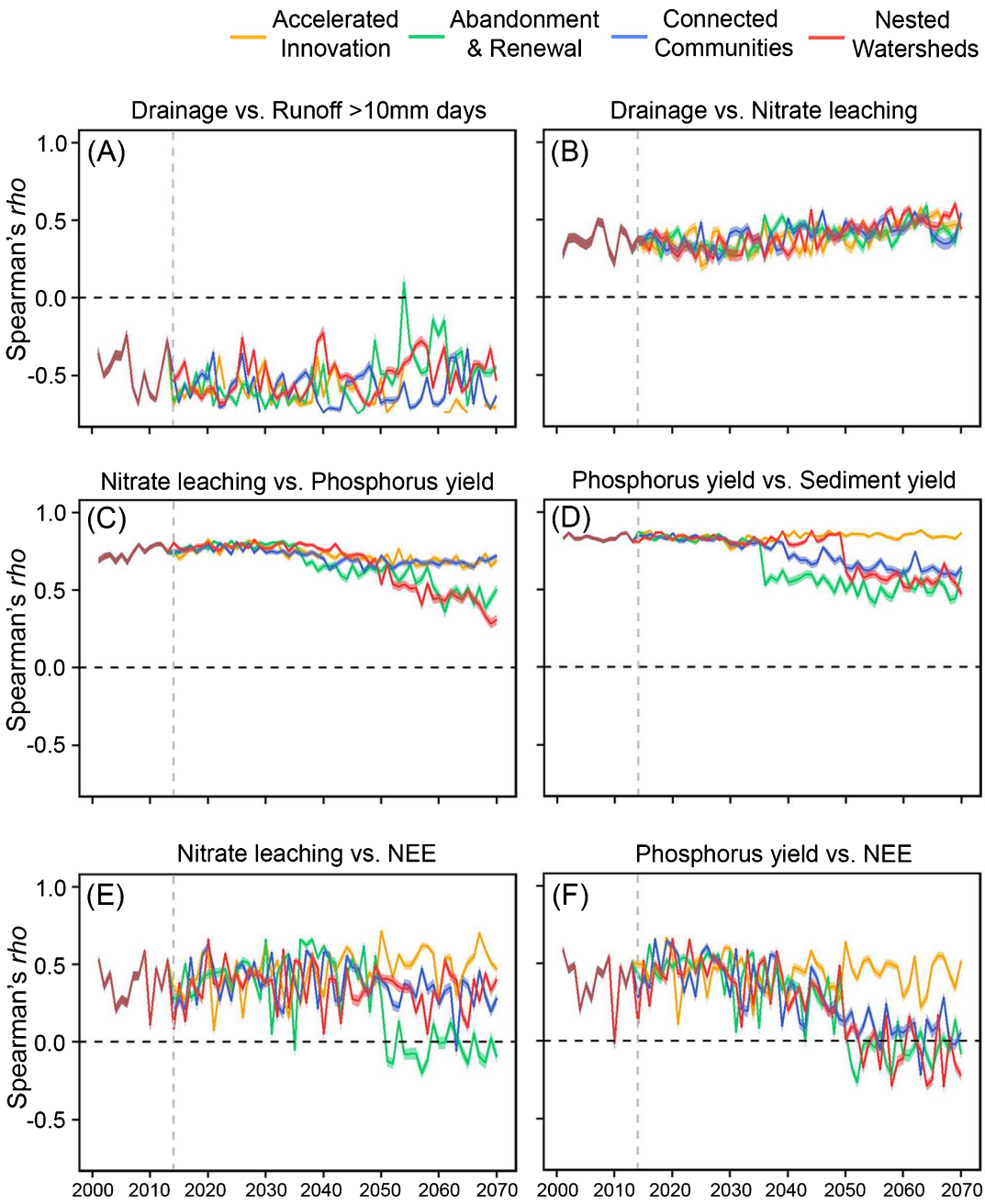

Figure 6. Changes in relationships among water and biogeochemical services at the grid-cell scale from 2001–2070 under four future scenarios. Scenarios were color-coded, with thick color lines as Spearman correlation coefficient and color ribbons as 95% confidence interval, on the basis of bootstrap approach with 1000 iterations.

uptake, mitigate nutrient loss, and thus reduce tradeoffs of food production and water quality (Randall *et al* 1997, McIsaac *et al* 2010, Asbjornsen *et al* 2014). While consistent with prior research that identified local tradeoffs of food production and water quality (Raudsepp-Hearne *et al* 2010, Qiu and Turner 2013), our simulated results provided further evidence that this well-recognized local tradeoff can be alleviated at broad spatial scales. However, our results also suggested that reducing local tradeoffs between crop production and water quality may be insufficient to mitigate their tradeoffs at larger scales where climate effects are dominant (Carpenter *et al* 2017).

On the other hand, dominant drivers of ES relationships could also remain unaltered across scales (figure 9(*b*)), as evidenced by relationships between drainage and food production that were highly variable with large interannual variations. Consistent patterns between these two ES likely reflect the fact that climate remains the dominant driver across scales. Additionally, the tight coupling of nitrate leaching vs. phosphorus yield is likely associated with applied nutrients and manure that contain high levels of

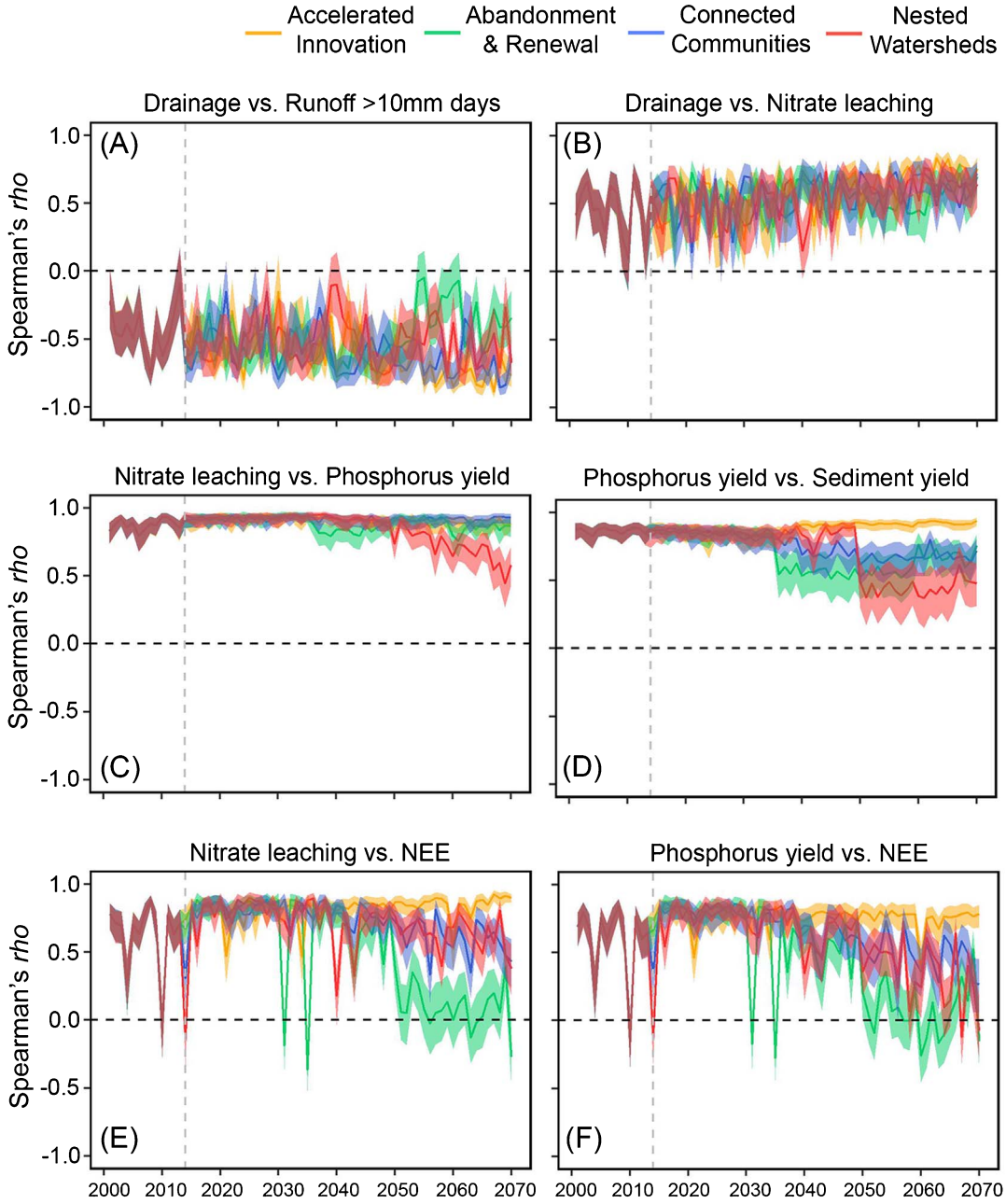

Figure 7. Changes in relationships among water and biogeochemical services at the subwatershed scale from 2001–2070 under four future scenarios. Scenarios were color-coded, with thick color lines as Spearman correlation coefficient and color ribbons as 95% confidence interval, on the basis of bootstrap approach with 1000 iterations.

both nutrients, and precipitation as the primary control (figure 9(*b*)); dominant drivers remain unchanged across scales). Consistent synergies between surface- and groundwater quality indicators highlight the importance of considering surface and groundwater as an integrated hydrological and biogeochemical continuum for enhancing management effectiveness across scales (e.g. leveraging water polices and landscape management to improve both surface- and groundwater) (Qiu and Turner 2015, Qiu *et al* 2017).

Combined effects of biophysical linkages and dominant drivers. Changing scales can alter dominant drivers as well as biophysical linkages of ES, thus affecting their relationships. Relationships between drainage and number of days with runoff >10 mm shifted from negative at local scales to positive at the watershed scale (figures 5–7), reflecting combined effects of biophysical linkages and dominant drivers (figure 9(*c*)). Specifically, at grid-cell and subwatershed scales, biophysical processes of runoff-infiltration partitioning drive negative relationships between drainage and extreme runoff days on a yearly basis (i.e. areas with more infiltration necessarily had less runoff, and vice versa) (Craig *et al* 2010); whereas

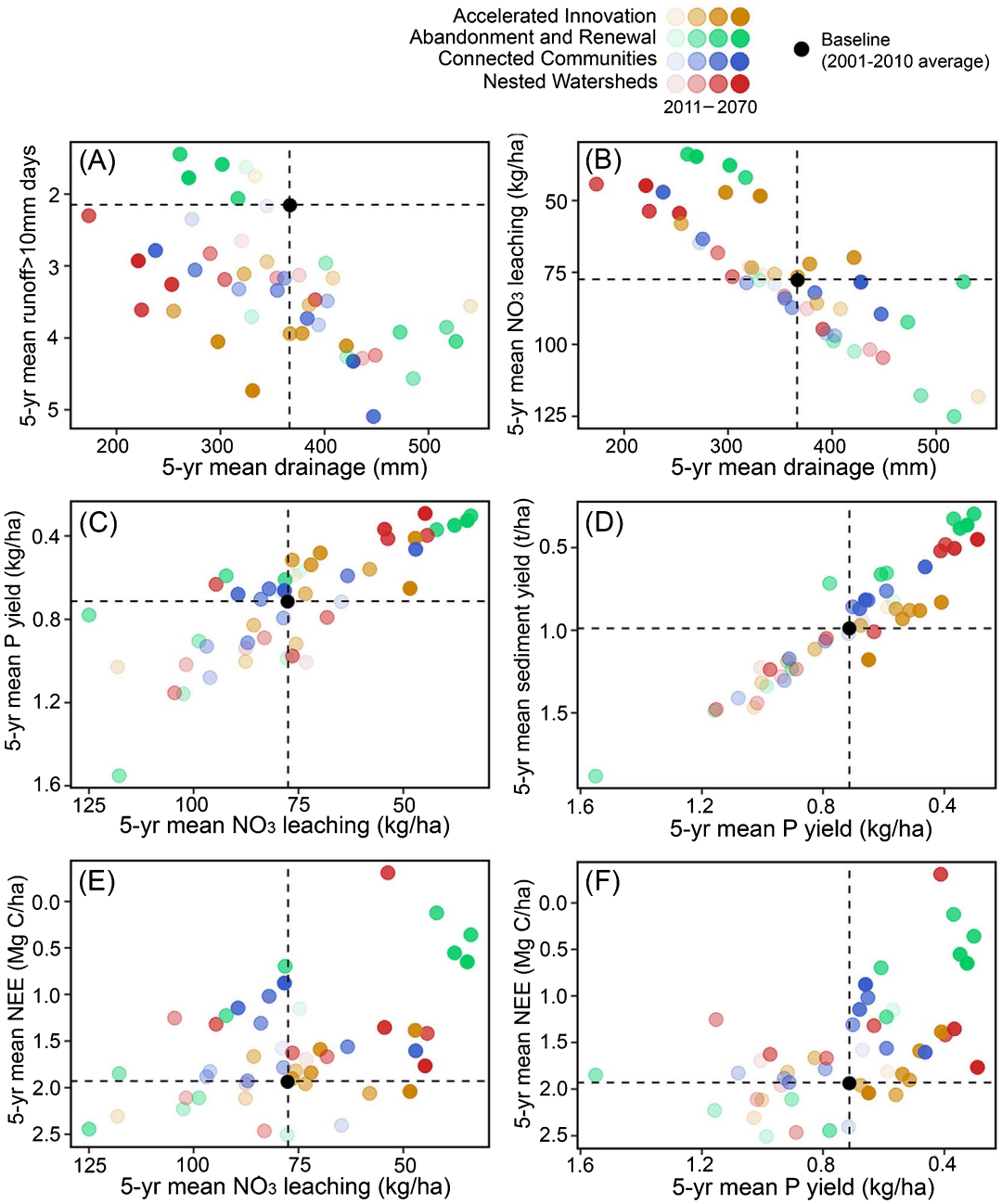

Figure 8. Changes in relationships among water and biogeochemical services at the watershed scale from 2001–2070 under four future scenarios. Scenarios were color-coded, and temporal changes in the indicators of paired services were calculated at the watershed scale at 5 year intervals (i.e. 2011–2015, 2016–2020…2066–2070). For a given scenario (colored circle), the gradient from 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. Please note that *y*-axes were reversed for services quantified using inverse indicators.

at the watershed scale when many years are considered, precipitation emerges as the dominant driver of their positive relationships (i.e. more precipitation led to more water available for both drainage and runoff).

Artificial scale effects. ES relationships can also change due to artificial scale effects (figure 9(*d*)), e.g. from simple alterations to spatial resolution and/or extent of analysis (Wu 2004). Our study showed that crop and perennial grass production were negatively correlated at the grid-cell scale (i.e. at a given time, a pixel of land can be devoted to either crop or perennial grass, but not both), while both can be achieved at a larger spatial scale (e.g. subwatershed) via a mix of land uses. Such scale effects due to spatial extent of analysis may often be manifested through mutual exclusivity of resources (e.g. land use/cover) dominating ES provision which vary across scales. While our example is related to ES dependent on land, this artificial scale effect could broadly apply to ES dominated by other resources (e.g. water) whose mutual exclusivity changes across scales.

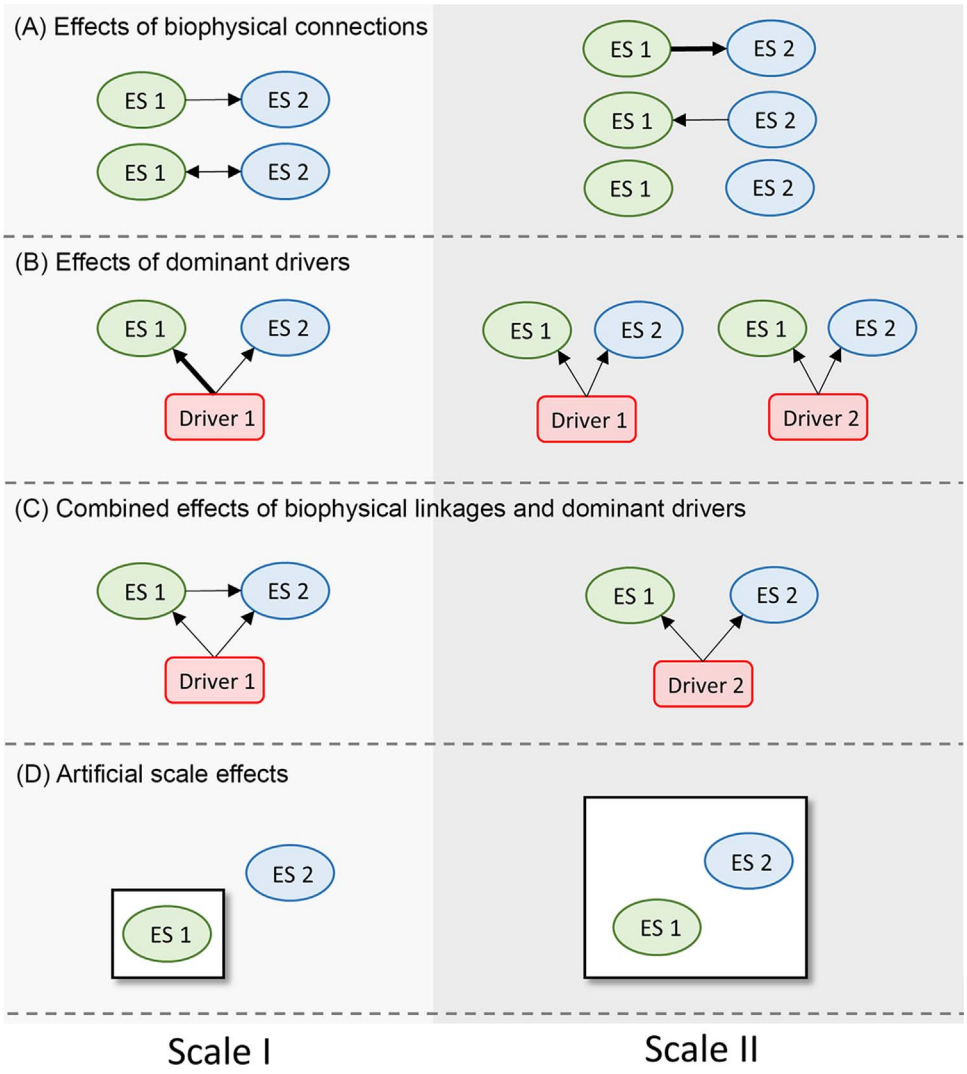

Figure 9. Conceptual diagram illustrating the typology through which changes in scales may alter ecosystem service relationships: (*A*) Effects of biophysical connections, where the strength, magnitude and direction of connections that underlie the relationships among services may change from one scale to another; (*B*) Effects of dominant drivers, where shifting scales could alter either the magnitude or kinds of drivers in effect, and thus affect relationships among services; (*C*) Combined effects of biophysical linkages and dominant drivers; (*D*) Artificial scale effects, where relationships among services may change across scales as a result of simple alterations to spatial resolution and/or extent of analysis. Please note that the examples demonstrated here are for illustrative purposes and not an exhaustive list of all possible changes.

Temporal dynamics of ES relationships

Temporal dynamics of ES relationships reflected responses to social-environmental changes (figures S1–S2) entailed in each scenario (Qiu *et al* 2018) that can shape the provision and interactions of ES. Changes in relationships can be abrupt with high interannual variations (e.g. drainage vs. food production, drainage vs. number of days with runoff >10 mm). Abrupt changes in ES relationships seemed to align well with timing of substantial alterations in land cover and associated management (figures S1–S2). High interannual variability, on the other hand, is possibly associated with weather effects. Some ES relationships diverged among scenarios; e.g. at grid-cell and subwatershed scales, the strength of tradeoffs between crop production and water quality increased in certain scenarios but declined in others. Sometimes, the nature of relationships could even be reversed; e.g. perennial grass production—surface-water quality tradeoffs shifted to synergies towards the end of the simulation.

Management and policy implications

Our research provides management and policy implications. First, management at one spatial scale do not necessarily produce similar synergies or tradeoffs at other scales. Although robust patterns exist for relationships among certain regulating services, not all have simple scaling rules. This is especially true for relationships between food production and water quality, where local changes in relationships do not necessarily scale up to watershed where a different set of drivers are operating (figures 3–5). Hence, field-specific management practices (e.g. nutrient or stormwater management) to reduce local tradeoffs might not be sufficient to mitigate such tradeoffs at

the landscape scale (Arabi *et al* 2006, Ahiablame *et al* 2012). Rather, managers and decision-makers need to consider the drivers, social-ecological complexities, and mechanisms of ES dynamics that are appropriate to scales of watersheds. In the event of data and time constraints, our results did provide initial documentation to managers on which ES might be robust and predictable across scales, and which ones are likely to be sensitive to changes in spatial scales. For example, synergies among water quality, soil retention and climate regulation ES across scales suggest that management and policy responses (e.g. afforestation, cover crops, conservation tillage) at different scales may lead to similar synergistic outcomes.

Time also plays an important role. Analyzing ES relationships at a single time, as in earlier studies, would emphasize effects of spatial variability of drivers (e.g. land use/cover, management practices), but overlook effects of drivers whose temporal variations play a more critical role (e.g. precipitation). As social-environmental conditions change, ES tradeoffs and synergies may also vary in their magnitude and directions. Hence, timely assessment and monitoring of ES and their relationships are needed, and can help avoid surprising tradeoffs and take advantage of emerging synergies. It also points to the necessity to leverage long-term monitoring programs (e.g. Long-Term Ecological Research, National Ecological Observation Network, and Critical Zone Observatories in the United States) for ES research. Such long-term and extensive efforts could reveal how ES relationships change over time, what factors drive their dynamics, and any time lags or legacy effects to better guide management strategies for sustaining multiple ES.

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