Spatial interactions among ecosystem services in an urbanizing agricultural watershed

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Understanding spatial distributions, synergies, and tradeoffs of multiple ecosystem services (benefits people derive from ecosystems) remains challenging. We analyzed the supply of 10 ecosystem services for 2006 across a large urbanizing agricultural watershed in the Upper Midwest of the United States, and asked the following: (*i*) Where are areas of high and low supply of individual ecosystem services, and are these areas spatially concordant across services? (*ii*) Where on the landscape are the strongest tradeoffs and synergies among ecosystem services located? (*iii*) For ecosystem service pairs that experience tradeoffs, what distinguishes locations that are "win–win" exceptions from other locations? Spatial patterns of high supply for multiple ecosystem services often were not coincident; locations where six or more services were produced at high levels (upper 20th percentile) occupied only 3.3% of the landscape. Most relationships among ecosystem services were synergies, but tradeoffs occurred between crop production and water quality. Ecosystem services related to water quality and quantity separated into three different groups, indicating that management to sustain freshwater services along with other ecosystem services will not be simple. Despite overall tradeoffs between crop production and water quality, some locations were positive for both, suggesting that tradeoffs are not inevitable everywhere and might be ameliorated in some locations. Overall, we found that different areas of the landscape supplied different suites of ecosystem services, and their lack of spatial concordance suggests the importance of managing over large areas to sustain multiple ecosystem services.

hydrologic services | landscape heterogeneity | sustainability | Wisconsin | Yahara Watershed

Research on ecosystem services—the benefits people obtain from nature—has grown rapidly (1–3), yet understanding of the interactions among multiple ecosystem services across heterogeneous landscapes remains limited (3–5). Ecosystem services may interact in complex ways (6, 7). Synergies arise when multiple services are enhanced simultaneously (4), and tradeoffs occur when the provision of one service is reduced as a consequence of increased use of another (7). Managing spatial relationships among diverse ecosystem services may help to strengthen landscape resilience, but interactions among services and their spatial patterns are not well understood (4). Ecosystem service supply has been mapped at various scales (8–12), and spatial concordance among services has been examined to identify "win–win" opportunities for ecosystem service conservation (13–19). However, few studies have dealt simultaneously with tradeoffs and synergies among a suite of ecosystem services (20–22), and none have done so using spatially explicit analyses. Thus, little is known about where tradeoffs and synergies among ecosystem services are most pronounced. Such information could identify areas of disproportionate importance in a landscape, such as locations where synergies are strong or conflicts among competing services are likely, and spatially target management actions designed to conserve ecosystem services (23).

Ecosystem services related to freshwater (e.g., water supply, surface and groundwater quality, and flood regulation) are of particular concern in agricultural and urban landscapes. These hydrologic services are strongly influenced by the terrestrial landscape (24), and degradation of water resources is often associated with agricultural and urban land use (25–27). Surprisingly few studies have quantified the distribution of key biophysical components of hydrologic services and assessed their relationships with other ecosystem services in regional watersheds, and these studies have focused on a limited set of freshwater services and/or pairwise correlations with other services (19, 24). Research is needed to quantify a range of freshwater services at regional scales and to understand their interactions with other ecosystem services.

Interest in achieving win–win outcomes (in which two or more services are enhanced) through management of ecosystem services is growing (28, 29). Several recent studies have suggested that it is possible to alleviate conflicts among competing services and produce win–win situations through proper interventions or conservation efforts (15, 18, 30, 31). However, these studies considered a limited range of ecosystem services (32), and none has examined win–win exceptions for services that were inversely correlated. Overall, win–wins appear to be uncommon and challenging to attain, and enthusiasm for such outcomes may be outpacing evidence of what is possible and how to achieve them (29). More effort is required to detect win–win outcomes and to evaluate their potential for mitigating tradeoffs and conserving multiple ecosystem services.

We studied the production, spatial distribution, and interactions among multiple provisioning, regulating, and cultural ecosystem services in the Yahara Watershed, Wisconsin (Fig. S1). This largely agricultural watershed drains 1,336 km^2 and includes five major lakes. Presettlement vegetation was a mix of prairie and savanna vegetation (33) that was converted to agriculture during the mid-1800s. Farms are currently dominated by corn, soybeans, and dairy, but the watershed also includes a densely populated urban area (Madison, WI) and remnant native vegetation. The Yahara Watershed typifies many agricultural landscapes in the Midwest, making it an ideal microcosm of the larger region (34). We used empirical estimates and spatially explicit models to quantify and map indicators of supply of 10 ecosystem services (Table 1) at 30-m spatial resolution for 2006, the most recent year for which data were available for all services. We asked three questions: (*i*) Where are areas of high and low supply of individual ecosystem services, and are these areas spatially concordant across services? (*ii*) Where on the landscape are the strongest tradeoffs and synergies among ecosystem services located? (*iii*) For ecosystem service pairs that experience tradeoffs, what distinguishes locations that are win-win exceptions from other locations? We assessed the degree of spatial congruence of the upper and lowest 20th percentile (by area) of each service to identify "hotspots" and "coldspots" of

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Table 1. Ecosystem services, biophysical indicators, median, and range for 10 ecosystem services quantified and mapped for the Yahara Watershed, Wisconsin, for the year 2006

Ecosystem service	Biophysical indicator	Estimated values for 2006
Provisioning services		
Crop production	Expected annual crop yield	0 (0–57.6 bushel/y)
Pasture production	Expected annual forage yield	0 (0–2.2 animal unit mo/y)
Freshwater supply	Annual groundwater recharge	41.7 (0–126.0 cm/y)
Regulating services		
Carbon storage	Amount of carbon stored	70.9 (0–192.3 Mg/ha)
Groundwater quality	Probability of groundwater nitrate concentration >3.0 mg/L	0.5 (0–1.0; unitless)
Surface water quality	Annual phosphorus loading	0.1 (0–0.6 kg/ha)
Soil retention	Annual sediment yield	0.01 (0–1.0 t/ha)
Flood regulation	Flood regulation capacity	67.9 (0–100; unitless)
Cultural services		
Forest recreation	Recreation score	0 (0–100; unitless)
Hunting recreation	Recreation score	0 (0–100; unitless)

See *SI Text* and Fig. S2 for details and validation of estimates.

multiple service delivery. Hotspots were defined as locations containing six or more services in the upper 20th percentile and coldspots as locations with six or more services in the lowest 20th percentile. No area on the landscape can have high or low supply of all 10 services, and some services are mutually exclusive based on land-cover class; six services represented a majority that allowed all land-cover types to provide multiple services (*SI Text*). We used factor analysis to identify tradeoffs and synergies among the 10 services based on a random sample of 1,000 points. Factor scores were mapped to identify locales with the most pronounced synergies and tradeoffs across the landscape. We identified win–win exceptions from ecosystem service tradeoffs by multicriteria analysis and used backward logistic regression model to explore biophysical and social factors that distinguish these win–win areas. Please see *Materials and Methods* and *SI Text* for further details.

Results

Production of individual ecosystem services varied substantially across the landscape (Table 1, Fig. 1) and showed distinct

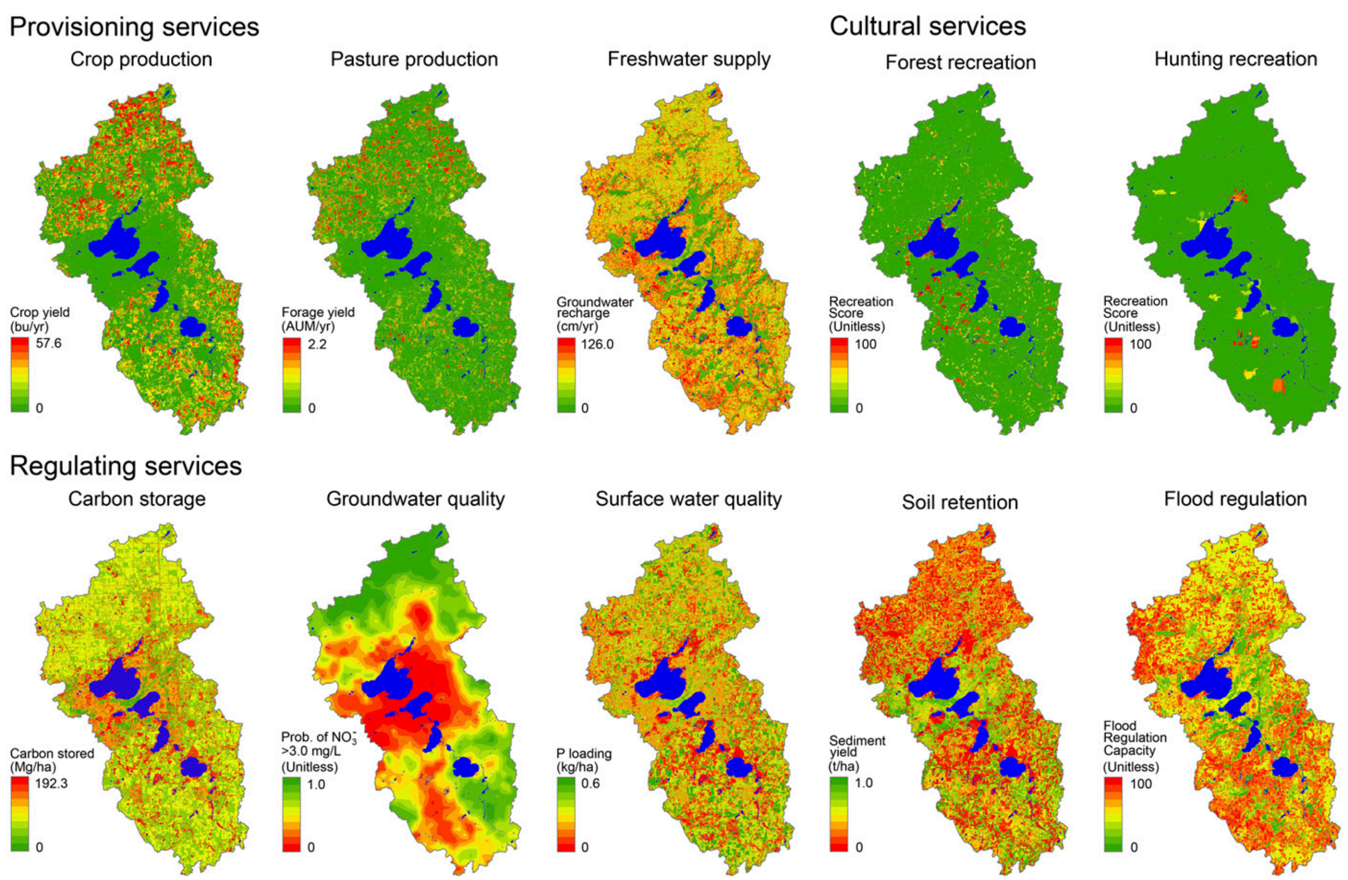

Fig. 1. Spatial distributions of 10 ecosystem services in the Yahara Watershed, Wisconsin, for 2006. Red indicates areas with high supply and green indicates low supply of ecosystem services.

geographic distributions that were spatially aggregated (all Moran's $I > 0.39$, $P < 0.001$). For descriptive statistics and cumulative frequency distributions (CFDs) for each service, please see *SI Text*, Table S1, and Fig. S3. Areas of high ecosystem service production often were not spatially concordant among different services (Fig. 2). Hotspots occupied only 3.3% of the landscape (Fig. 2*B* and Fig. S4) and frequently coincided with nature preserves, wildlife areas, parks, and riparian zones. Half of the landscape produced high values of one or no ecosystem service; these locations were primarily croplands or developed lands. Coldspots occupied 24.5% of the landscape (Fig. 2*D* and Fig. S4) and coincided with croplands, roads, and urban areas. Spatially, hotspots were few in number and small in size (patch density = 3.1 km^{-2}, area-weighted mean patch size = 12 ha), whereas coldspots were more numerous and larger in size (patch density = 10.2 km^{-2}, area-weighted mean patch size = 1,594 ha). The cohesion index was also greater for coldspots (98.1%) than for hotspots (84.1%), indicating greater connectivity among coldspots.

For soil retention, surface water quality, and groundwater quality, we also evaluated coldspots by using a complementary approach in which ecological thresholds were used to map areas where levels were undesirable or unacceptable (see *SI Text* for details). The resulting maps revealed that thresholds were exceeded for soil retention, surface water quality, and groundwater quality in 28.5%, 8.0%, and 20.7% of the watershed, respectively (Fig. S5 *A–C*). When using these maps of threshold-based estimates along with the lowest 20th percentile maps of the other seven services to identify coldspots among all 10 services, coldspots occupied 23.4% of the landscape, similar to the maps based on the lowest 20th percentiles, and spatial patterns were nearly identical (Fig. S5 *D* and *E*).

Three distinct groups of ecosystem services were identified by factor analysis, which revealed synergies and tradeoffs among the

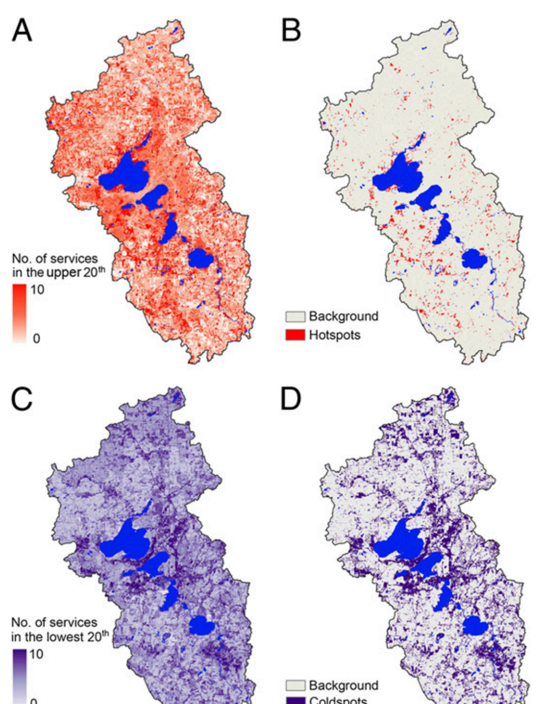

Fig. 2. Maps of hotspots and coldspots for delivery of multiple ecosystem services: (*A*) number of ecosystem services in the upper 20th percentile, (*B*) hotspots where six or more services were in the upper 20th percentile, (*C*) number of ecosystem services in the lowest 20th percentile, and (*D*) coldspots where six or more services were in the lowest 20th percentile.

10 services (Table 2). The first factor ("forest and water synergies") identified positive relationships among four services, of which three were regulating services (carbon storage, surface water quality, and soil retention) and one was a cultural service (forest recreation). The second factor ("pasture and water synergies") identified positive relationships among two provisioning services (pasture production and freshwater supply) and a regulating service (flood regulation). The third factor ("crop and water quality tradeoffs") identified tradeoffs between a provisioning service (crop yield) and two regulating services (ground and surface water quality). One service (hunting) remained independent (all factor loadings <0.30). The four hydrologic services (freshwater supply, surface and groundwater quality, flood regulation) were distributed among the three orthogonal factors (Table 2).

The spatial patterns of synergies and tradeoffs among ecosystem services were complex (Fig. 3). The strongest forest and water synergies were patchy, widely scattered (Fig. 3*A*), and concentrated primarily in forests, woody wetlands, grasslands, and remnant prairies. Some of these areas were adjacent to aquatic ecosystems and likely functioned as buffers for retaining nutrients and sediment. The most pronounced pasture and water synergies were situated on lands dominated by perennial grasses or hay crops, such as alfalfa (Fig. 3*B*). These areas supplied forage for a large number of animal units while providing groundwater recharge and flood regulation services. The strongest tradeoffs between crop production and water quality were found in the most productive and intensively managed croplands (Fig. 3*C*), where high crop yield was associated with greater phosphorus and nitrogen supply and thus reduced water quality.

Despite tradeoffs between crop production and water quality services, there were areas where both could be high (i.e., win–win exceptions; Fig. 4). These locations were not common, occupying only 2.4% of the landscape, with patch sizes ranging from 0.09 to 9.9 ha. However, these areas could be distinguished from other locations. The occurrence of win–win exceptions was positively associated with the amount of adjacent wetlands, depth to water table, and soil silt content, and negatively associated with slope, soil erodibility, soil permeability, and distance to stream (Table 3; Hosmer and Lemeshow test $\chi^2 = 5.6$, df = 8, $P = 0.69$).

Discussion

We identified synergies and tradeoffs among ecosystem services and described complex spatial distributions of these services, their spatial congruence, and their interactions in the Yahara Watershed. Variation in the degree of spatial concordance of different ecosystem services, particularly those related to freshwater, suggests that many services will not be good surrogates for others and underlines the importance of managing spatial relationships among multiple ecosystem services (4). The spatial heterogeneity of ecosystem services and their interactions indicates that sustainability of ecosystem service production will require regional-scale management that accounts for the geographic position and spatial distribution of services (23, 35, 36).

The rareness of hotspots on the landscape indicates that it is difficult to obtain high supply of multiple services from the same area. Nonetheless, at 3.3% of the landscape, hotspots occupied an area greater than 40 km^2 and may represent conservation priorities; the loss or degradation of these sites could cause multiple services to decline. Hotspots also may be disproportionately important because these areas of high multifunctional supply of services often coincide with higher species and functional diversity, as suggested by Lavorel et al. (11). Coldspots were even more common and often represented areas that maximized the provision of one or few services. Coldspots may be useful in demarcating areas of concern (e.g., where ecological thresholds are exceeded) for which intervention or restoration may be especially beneficial. The distinct spatial patterns of hotspots and coldspots suggest landscape-scale tradeoffs, as all locations cannot

Table 2. Loading of ecosystem service estimates on each of three orthogonal axes derived from factor analysis (with varimax rotation) of 10 ecosystem services, on the basis of 1,000 random points within the Yahara Watershed

Ecosystem service	Factor 1: Forest and water synergies	Factor 2: Pasture and water synergies	Factor 3: Crop and water quality tradeoffs
Carbon storage	**0.65**	0.00	−0.13
Surface water quality	**0.60**	0.22	**−0.43**
Forest recreation	**0.49**	0.06	0.01
Soil retention	**0.41**	0.10	−0.01
Flood regulation	0.31	**0.59**	0.19
Pasture production	−0.02	**0.56**	−0.14
Freshwater supply	0.26	**0.47**	0.29
Crop production	−0.12	−0.26	**0.53**
Groundwater quality	−0.01	−0.06	**−0.36**
Hunting recreation	0.10	−0.15	−0.29

Factor loadings ≥0.35 are shown in bold.

be expected to produce all services. Most of the landscape (~70%) contributed high supply of one, two, or no services, and a low supply of three to five services (Fig. S4). Thus, producing all services will require an area large enough to encompass the spatial heterogeneity in service supply.

We detected both synergies and tradeoffs among ecosystem services. The forest and water synergies were consistent with those reported in other studies (e.g., ref. 21) and suggested suites of services that may be enhanced (or reduced) simultaneously. For example, other studies have found that afforestation, wetland restoration, and practices that increase riparian-zone vegetation have the potential to increase carbon storage, soil retention, surface water quality, and forest recreation simultaneously (e.g., refs. 24, 37). Similarly, conversion of forest or native vegetation to other land-cover classes may reduce this whole group of services. The pasture and water synergies were consistent with known hydrologic benefits of perennial crops (35). Compared with annual crops, deep-rooted perennial forage crops can increase water infiltration, reduce runoff, and attenuate peak flow, thereby enhancing recharge and mitigating flooding (24, 38, 39). If properly managed, perennial bioenergy crops might produce similar synergies with freshwater ecosystem services while supplying energy rather than animal units (40).

Surprisingly, the only tradeoff among the 10 ecosystem services we quantified was between crop production and water quality. This tradeoff is common in agricultural landscapes and exemplifies a recognized conflict between provisioning and regulating services in production landscapes (41, 42). Regulating services underpin the sustained supply of other essential services and are critical to maintain resilience of production systems (7, 20). Hence, this type of tradeoff implies a compromise between current and future needs (43). Environmental externalities that increase food supply at the expense of regulating services such as water purification may undermine the resilience of agricultural landscapes and the ecosystem services they provide.

Concerns about eutrophication, drinking water pollution, and flood regulation are manifest in many agricultural landscapes. Our analyses revealed that freshwater ecosystem services separated among three distinct groups of ecosystem services that were generally supplied at different places in the landscape. These complex spatial relationships indicate that optimizing freshwater supply, ground and surface water quality, and flood regulation in an agricultural landscape will not be simple; there is no "silver bullet" for managing water sustainability. Individual services will require different strategies, and management to sustain the suite of hydrologic services must conserve places on the landscape that supply each service. The pasture and water synergies imply opportunities for enhancing flood regulation and freshwater supply by promoting perennial crops. Enhanced surface water quality should be associated with management practices that reduce soil erosion. Surface and groundwater quality both had positive loadings on the same factor, indicating that they may respond similarly to the same drivers and/or that one may directly influence the other. Our analysis cannot disentangle

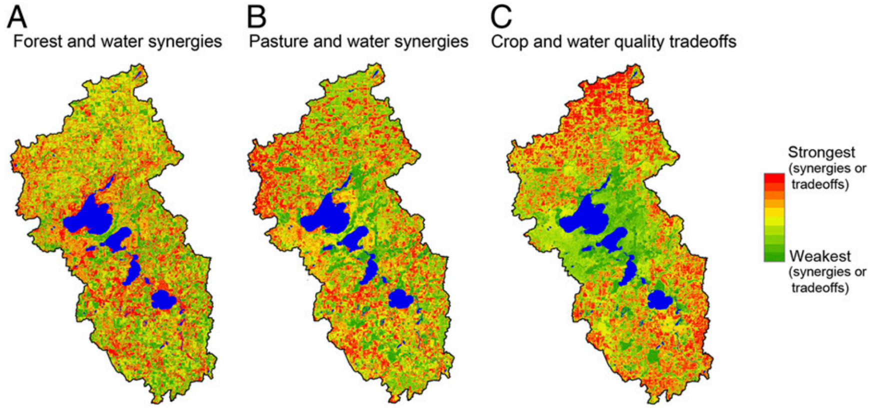

Fig. 3. Spatial patterns of three factor scores represent the synergies and tradeoffs among ecosystem services: (*A*) Factor 1, forest and water synergies. Red represents areas where carbon storage, surface water quality, forest recreation, and soil retention are high, whereas green represents areas where all these services are low. (*B*) Factor 2, pasture and water synergies. Red represents locations where pasture production, flood regulation, and freshwater supply are all high, whereas green represents locations where all these services are low. (*C*) Factor 3, crop and water quality tradeoffs. Red represents where crop production is high, and surface and ground water quality are both low.

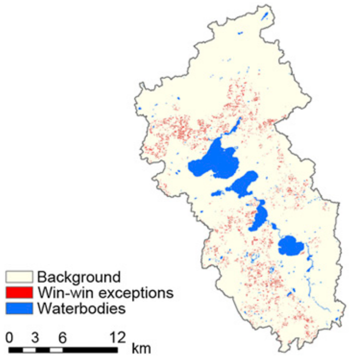

Fig. 4. Spatial pattern of win–win exceptions to the tradeoff between crop yield and water quality. The win–win exceptions had high crop yield and high-level surface and groundwater services.

cause and effect, but the results suggest that it would be prudent to consider surface and groundwater as an integrated hydrological and biogeochemical continuum for ecosystem service management (44, 45). An enhanced understanding of how ecosystem services interact and an awareness of tradeoffs and opportunities for synergies will improve the ability to sustainably manage landscapes for joint supply of water resources and other ecosystem services.

Our study attempts to empirically explore win–win exceptions to conflicting services. The existence of win–win exceptions supports prior suggestions that tradeoffs between agricultural production and other services are not inevitable at all locations (38), and our findings suggest where these might be achieved. Crop yield and water quality could both be high in areas with flat topography, less erodible soil, high water-holding capacity, and a deeper water table, conditions that promote plant growth and environmental filtration (e.g., nutrients and contaminants absorption) in soil and root systems (24). Win–win exceptions also had more adjoining wetlands, which trap sediment and remove nutrients from runoff (46, 47), and were closer to streams, where riparian vegetation also filters nutrients (48, 49). Surprisingly, the management factors included in our analysis were not important for distinguishing win–win areas. However, we only considered variables for which continuous spatial data were available in the watershed, and other unmeasured factors or practices (e.g., no-till agriculture, manure digesters) could enhance win–win opportunities. More research is needed to determine the degree to which tradeoffs can be mitigated, and whether the likelihood of win–win outcomes can be increased.

This study has presented an innovative spatially explicit approach for analyzing interactions among multiple ecosystem services and identifying where in the landscape tradeoffs and synergies are most pronounced. We analyzed ecosystem services at fine scales and accounted for landscape heterogeneity in the delivery and relationships among services, contributing to an emerging literature on ecosystem services at landscape scales (11, 18, 23, 50). Relationships observed among services may be a function of the scale at which they are assessed (20), and results could differ if the extent or grain of analysis was changed. The analytic framework could be applied in different regions or other types of landscapes, and it also could be used to explore changes in ecosystem services given alternative future scenarios. Our results also may contribute to improved management of agricultural landscapes for sustainable provision of freshwater and other diverse ecosystem services. Different areas of the landscape supplied different suites of ecosystem services, and their lack of spatial concordance underscores the importance of managing over large areas to sustain multiple ecosystem services.

Materials and Methods

Ten ecosystem services that included provisioning, regulating, and cultural services (Table 1) were quantified and mapped at 30-m spatial resolution for the terrestrial landscape of the Yahara Watershed. Ecosystem services were selected based on their importance to this region and the availability of spatial data. Because many services cannot be measured directly and land cover is a poor proxy (51), we used biophysical indicators for each service (Table 1). All services were quantified using data for 2006 or as close as possible to this date. For most ecosystem services, accuracy was assessed by comparing our estimates with field measurements or census data for this region. Full details on data sources, methods and accuracy assessment for ecosystem service quantification are provided in *SI Text*, Table S2, and Fig. S2.

All data were imported into ArcGIS 10.0 [Environmental Systems Research Institute (ESRI)] for representation, data manipulation, and analysis. We standardized each service to a scale ranging from zero to one and transformed biophysical indicators as necessary so that higher values corresponded to greater supply of services. We calculated summary statistics (Table S1) and plotted CFDs of the biophysical indicator values for each service on the basis of 30-m grid cells (Fig. S3). The degree of spatial clustering of each service was evaluated using Moran's *I*.

Hotspots and coldspots of multiple service supply were identified by overlaying and summing maps of the upper and lowest 20th percentile (by area) of each service (Fig. S3). However, there were two exceptions. First, if >20% (but <80%) of the landscape provided no supply for a given service (e.g., crop production, soil retention; Fig. 1, Fig. S3), we computed the upper 20th percentile directly from the CFD and considered areas of zero service as within the lowest 20th percentile. Second, if <20% of the landscape could potentially provide a certain service (e.g., forest and hunting recreation; Fig. 1, Fig. S3), we considered all areas that produced the service as falling within the upper 20th percentile, and all areas with zero service as within the lowest 20th percentile. Three of the 10 services quantified (soil retention, surface water quality, and groundwater quality) also have ecological or socially accepted thresholds beyond which quality is considered unacceptable (see *SI Text* for details). Thus, we also mapped areas exceeding ecological thresholds for these services, then recalculated the coldspots map and compared it to the map derived from the lowest 20th percentile data. Spatial patterns of hotspots and coldspots were quantified by computing the proportion of watershed occupied, patch density, area-weighted mean patch size, and patch cohesion index in Fragstats 3.3 (52).

Spatial interactions among multiple ecosystem services were analyzed based on 1,000 randomly sampled points across the watershed. To identify tradeoffs and synergies among services, we used factor analysis, a powerful statistical procedure that determines a smaller number of distinct "factors" that account for the structure of a set of correlated variables (53, 54). The

Table 3. Stepwise backward logistic regression result for the occurrence of win–win exceptions: parameter estimates and significance test using the Wald statistic

Explanatory variables	Standardized β	SE	*z*-value	Probability > *z*
Intercept	−0.03	0.09	−0.35	0.72
% wetland (buffer radius, 560 m)	0.33	0.12	2.77	0.006
Slope, %	−0.37	0.10	−3.76	0.0002
Soil permeability, m/s	−0.27	0.11	−2.54	0.01
Depth to water table, mm	0.51	0.12	4.45	<0.0001
Silt content,%	0.42	0.11	3.74	0.0002
Soil erodibility, (Mg × h)/(MJ × mm)	−0.29	0.11	−2.64	0.008
Distance to stream, m	−0.60	0.12	−5.15	<0.0001

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number of factors was determined by a scree test and the interpretability of derived factors, and we extracted the first three orthogonal factors (with varimax rotation). Scores for all three factors were computed for each grid cell based on the loading matrix and mapped to represent the magnitude of tradeoffs and synergies across landscape. All correlation and factor analyses were performed using SAS 9.2 (SAS Institute, Cary, NC).

Multicriteria analysis was used to identify locations of win–win exceptions for crop and water quality tradeoffs (Fig. S6). Specifically, areas with crop production, ground water quality, and surface water quality in the upper 20th, 50th, and 50th percentile, respectively, were identified and defined as win–win exceptions. Cutoffs for each service were derived from their CFDs (Fig. S3). To determine the characteristics that distinguished these win–win areas from other croplands in the landscape, we used a backward logistic regression model fitted by maximum likelihood with Bayesian Information Criterion. Three hundred win–win and 300 non–win–win cropland cells were randomly selected and assigned binary values of 1 and 0, respectively. We considered potential explanatory variables at the local (cell) scale (slope, soil physical properties, population density, distance to stream, distance to nearest wetland and forest) and landscape scale (landscape context within a 560-m radius, including the percentage of forest, agricultural, and wetland, as well as percentage of areas restricted for nutrient and manure application). The radius for landscape-scale variables was determined as 10 times the size of the largest win–win patch. Please see Table S3 for a full list of candidate variables. All variables were standardized before analysis. Multicollinearity was not a problem among the selected variables, as variance inflation factors ranged from 1.18 to 2.94. We selected the final most parsimonious model and assessed its overall fit using a Hosmer and Lemeshow goodness-of-fit test (55). All logistic regression procedures were performed using R statistical software (56).

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