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Research Report

Boosting ecosystem services and farm economics with crop diversity and livestock integration using a validated modeling approach

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Abstract

Agriculture provides essential ecosystem services. Management influences the degree of their trade-offs and synergies. Here, we investigate the potential for ecological intensification of the US Midwest agricultural landscape by comparing at high spatial resolution (4-km-sided grids) over three decades, the impact of 18 diverse management scenarios on multiple services, using a validated crop simulation model. The assessment of numerous system performance criteria that includes productivity stability and resistance to extreme weather events, profitability, soil carbon accumulation, nitrate leaching, and greenhouse gas emissions, helps identify trade-offs and leverage synergies among these services. Increasing crop number and diversity—from a corn monoculture to a corn–soybean–wheat rotation with cover crops—increases productivity stability up to 65%, and a lower nitrogen rate decreases greenhouse gas emissions by 28%, converting scenarios from net sources of carbon to net zero or sinks. Pasture-cattle integration increases resistance to extreme droughts (5% compared to a maize monoculture) and provides greater productivity stability (159%). Increasing crop diversity and reducing nitrogen fertilization are key synergistic management strategies. Our innovative approach across twelve states and covering 46 million hectares, connects geographic scales from local to regional, without data loss and mismatch due to aggregation, quantifying the relative changes in these landscape services that are coincident in time and place to determine potential management additionality and inform decision-making.

Keywords: crop diversification, integrated crop-livestock system, ecosystem services, resistance, grazing intensity

Significance Statement

The environmental and economic services that agriculture provides are strongly influenced by management. In this modeling study, conducted across the US Midwest over three decades at 40,000 locations, we compared 18 different scenarios, ranging in complexity from monoculture corn to multiple crops in rotation to integrating pastures with cattle. We compared the impact of these systems on productivity and profitability, yield stability and resistance to weather extremes, soil carbon levels, nitrogen loss, and greenhouse gas emissions. We found that more crops in rotation increased productivity stability, lower nitrogen fertilizer inputs reduced greenhouse gas emissions, and integrating cattle-pastures increased system resistance to droughts. Comparing impacts across systems reveals trade-offs and synergies, helping farmers manage for better environmental and economic outcomes.

Introduction

Management of agricultural systems influences the delivery of ecosystem services (ES), generating trade-offs and synergies. Optimizing multiple services at the same time and location is challenging (1). Win–win scenarios for productivity and the environment are obtainable (2), but complex to implement at scale (3). ES assessments can be geographically broad, often leveraging limited data from a single land-use, and extrapolating to large scale without catering for local conditions, or narrow, focusing on a single service in a small area that is not readily scaled. Approaches that integrate small-scale rigor on multiple services with large scope and scale, and long-term data across multiple decades, are most informative (4) and beneficial for policy.

Competing Interest: The authors declare no competing interests.
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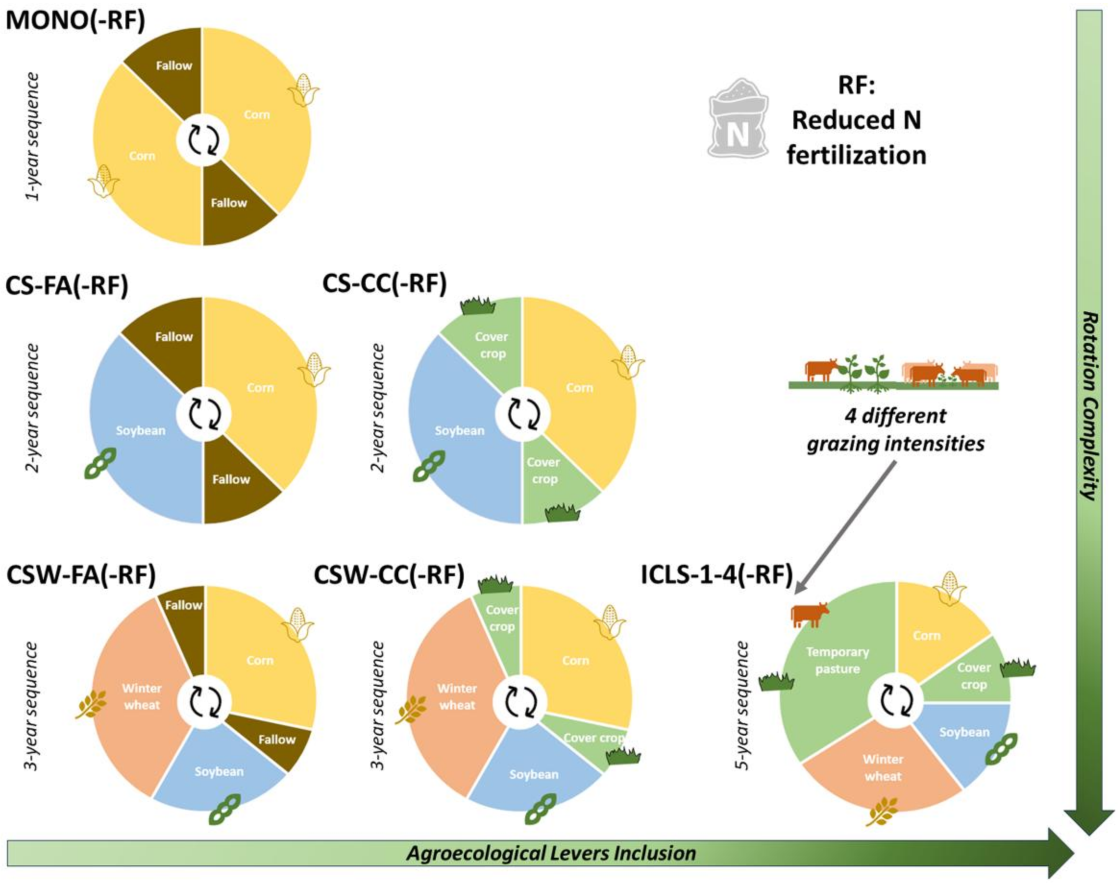

Fig. 1. Agronomic management scenarios, showing crop rotation complexity, and agroecological levers [cover crop, reduced synthetic nitrogen (N) fertilization, pasture, and livestock inclusion]. MONO, corn monocropping; CS-FA, corn–soybean with fallows; CS-CC, corn–soybean with cover crops; CSW-FA, corn–soybean–wheat with fallows; CSW-CC, corn–soybean–wheat with cover crops; ICLS-1–4, integrated crop-livestock systems with corn, soybean, wheat, and cover crops, and temporary pasture with beef cattle grazing intensity decreasing from 1 to 4 (e.g. ICLS1 = heavy grazing, ICLS4 = light grazing). The five crop and four crop-livestock scenarios are simulated with full fertilization and reduced fertilization (RF), where *N* rate was reduced by 25% solely for corn, for a total of 18 scenarios.

Widespread agricultural specialization favors productivity over other ES (5), leading to well documented negative environmental consequences (6, 7). Climate change also impacts agriculture through an increasing frequency and intensity of extreme climatic events such as droughts and precipitation (8), leading to crop damage and yield loss (9, 10). Shifting towards more complex and diversified agroecosystems is seen as essential to increase resiliency to these events (11) and help balance production and environmental goals (12). Ecological intensification (EI)—ES enhancement that complements or substitutes for the role of anthropogenic inputs while maintaining productivity (13)—is a means to accomplish this (e.g. 14). Management that increases spatiotemporal variation through crop diversification, and reduces synthetic inputs, can enhance nutrient and water use efficiency, and increase soil structure and health (15). Leveraging natural synergies between crops and animals has numerous ecological and socioeconomic benefits (16). Despite this, integrated crop-livestock systems (ICLS) have decreased in number and land area in the United States (17), and the environmental factors that predispose ICLS to success or failure in a given location are not well studied (18).

Maximizing productivity is still regarded as the domain of conventional management, and the perceived or actual economic cost of reduced yields remains a major deterrent for farmers considering changes in land management (19). However, management that decouples high yield from high input is deployable through EI practices, such as reduced fertilization, no tillage, crop rotation, and manure recycling (13). Fulfilling the potential of EI at scale requires understanding how yields respond to different management practices and how dependent these responses are on context (20). ES are spatial phenomena, needing integrated quantification across multiple land uses, and on different spatiotemporal scales using environmental and socioeconomic metrics (21).

Studies on EI management that investigate the long-term productivity and environmental performance of crop rotations with varying complexity, including livestock integration, at high spatial resolution across large scale are rare. We conduct this work across the US Midwest, one of the most globally productive and photosynthetically active agricultural regions in the world (22).

We evaluate and compare 18 agroecosystem scenarios across management gradients that differ in crop type and rotation, and agroecological levers that include integrating cover crops, pasture, and cattle at varying grazing intensity, and reduced nitrogen fertilization rate (Fig. 1). We show the impacts of management over three decades on a wide range of ecosystem services, i.e. system stability and crop yield resistance to extreme climatic events, crop and animal productivity, economic profitability, carbon sequestration, greenhouse gas mitigation, and nitrate leaching. We also assess the variability, and the trade-offs and synergies

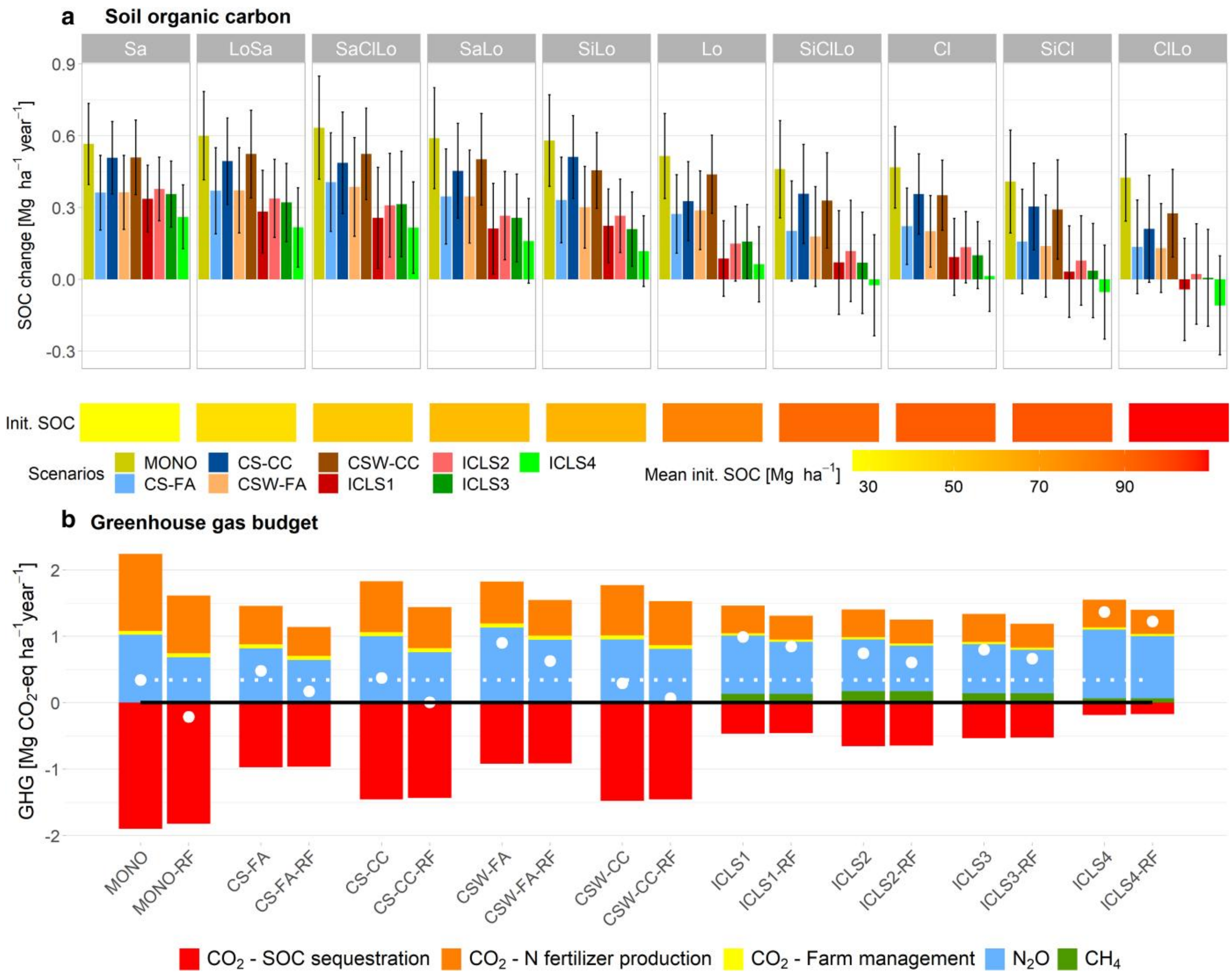

Fig. 2. a) Change in soil organic carbon (SOC) stock (mg ha^{-1} year^{-1}) at 0–30 cm depth for management scenarios with full nitrogen (N) fertilization and varying soil texture across the US midwest, with initial SOC stock (mg ha^{-1} year^{-1}) shown below; b) global warming potential (GWP*; (23); Table S1) of the greenhouse gas (GHG) emissions (CO_2, N_2O, and CH_4; Mg CO_2eq ha^{-1} year^{-1}) associated with management scenarios, showing positive emissions (above 0) and negative emissions (below 0; i.e. SOC sequestration representing atmospheric CO_2 removal) presented as paired fertilizer (full and reduced; RF) scenarios. White circles show the net GHG emissions of each scenario (sum of positive and negative emissions contributions), and the horizontal white dotted line represents net GHG emissions for MONO scenario for comparison. Cl, clay; ClLo, clay loam; Lo, loam; LoSa, loamy sand; Sa, sand; SaClLo, sandy clay loam; SaLo, sandy loam; SiCl, silt clay; SiClLo, silt clay loam; SiLo, silt loam.

of these services across the Midwest region that encompasses a wide range of pedoclimatic conditions.

Our objectives are to (i) assess the impacts of increasingly complex agroecological levers, including efficiency measures (reducing nitrogen fertilization), practice substitution (replacing winter fallows with cover crops), and system redesign (through crop diversification and the integration of pastures and livestock); and (ii) evaluate the variability, trade-offs, and complementarities of ecosystem services across a broad agricultural landscape under diverse pedoclimatic conditions.

We hypothesize that (i) crop diversification and the use of ICLS will increase farm profitability compared to less diversified management; (ii) moderate reductions in nitrogen fertilization will reduce environmental impacts while causing minimal reductions in profitability; (iii) the use of cover crops will enhance or stabilize profitability through benefits such as improved soil health and yield stability; and that (iv) certain combinations of these practices can generate synergies among ecosystem services, reducing trade-offs and help identify management scenarios that optimize both economic and environmental outcomes.

Results

Environmental outcomes

Soil organic carbon (SOC) is compared at 0–30 cm depth across the management gradients over a 30-year period (Fig. S1). All crop-only and ICLS scenarios (except ICLS4) result in an average annual increase in SOC stock, with the magnitude varying by soil texture; typically, larger gains in sandy loams where the initial SOC stock is lower, and lower gains in soils with higher clay content, particularly for ICLS (Fig. 2a). Corn monocropping (MONO) leads to the greatest SOC stock gains (e.g. 22% more when compared to CSW-CC and 72% more when compared to ICLS3; Fig. 2a). Growing cover crops increases SOC compared to the presence of fallow in otherwise corresponding rotations (e.g. an increase of 60% in CSW-CC compared to CSW-FA). For

ICLS scenarios, moderate grazing intensity (i.e. ICLS2 and ICLS3) leads to the largest SOC stock increases, i.e. 39 and 254% more for the ICLS2 scenario when compared to the intensive grazing scenario (ICLS1) and the light grazing scenario (ICLS4), respectively.

Across all scenarios, the largest contributions to greenhouse gas (GHG) emissions are from direct nitrous oxide (N_2O) emissions from the soil (average of 56% of total) and CO_2 emitted during N fertilizer production (37%). In scenarios with full N fertilization (Fig. 2b), MONO has substantially higher GHG emissions than other scenarios (e.g. 27% more when compared to CSW-CC, 54% more when compared to CS-FA, and 68% more when compared to ICLS3). This is primarily due to higher CO_2 emissions from N fertilizer production (e.g. 53% more when compared to CSW-CC and 177% more when compared to ICLS3), and to a lesser extent direct soil N_2O emissions (e.g. 11% more when compared to CSW-CC and 32% more when compared to ICLS3; Fig. S4). However, due to high SOC sequestration rates (Fig. 2b), MONO also has the second lowest net GHG emissions (340 kg CO_2-eq ha^{-1} year^{-1}) of scenarios with full N, only marginally higher than those from the most rotationally complex, crop-only based (CSW-CC) scenario (291 kg CO_2-eq ha^{-1} year^{-1}). ICLS systems show GHG emissions comparable to the more complex crop-only rotations, in part due to livestock methane (CH_4) emissions (particularly when GWP values are used; Fig. S3) compensating for the reduction in CO_2 emissions from lower N fertilizer consumption (production), in addition to direct N_2O emissions from the crop-based portion of the rotation. The SOC sequestration while modest in ICLS scenarios helps mitigate this; most notably in the moderate grazing intensity regimes (ICLS 2 and 3).

Overall, reduced N fertilization (RF) scenarios decrease GHG emissions when compared to their full N fertilization equivalents (Figs. 2b and S3). Emissions from the MONO-RF scenario were 28% lower than MONO. Given their almost similar SOC sequestration values, this reduction effectively converted the system from a net source (340 kg CO_2-eq ha^{-1} year^{-1}) into a net sink (−213 kg CO_2-eq ha^{-1} year^{-1}; Fig. 2b) for carbon; mostly due to lower direct N_2O emissions (i.e. 57% less for MONO-RF; Fig. S4) but also the associated lower CO_2 emissions from N fertilizer production (i.e. 25% less for MONO-RF; Fig. 2b). Other more complex, crop-only rotations also benefited from reduced N fertilization, such that the CS-CC-RF and CSW-CC-RF scenarios were near to net zero emitters (5 kg CO_2-eq ha^{-1} year^{-1} and 70 kg CO_2-eq ha^{-1} year^{-1}, respectively).

The nitrates available for leaching were much higher in the MONO (38 kg NO_3–N in average) than in any other scenario (Fig. S5b). Available nitrates were consistently lower in RF scenarios, when compared to their full N fertilizer equivalent (e.g. 52% lower in MONO-RF compared to MONO, 32% lower in CS-CC-RF compared to CS-CC, and 15% lower in ICLS4-RF than ICLS4). Moderate grazing ICLS scenarios decrease nitrate leaching compared to other ICLS systems (e.g. ICLS3 is 21 and 38% lower than ICLS1 and ICLS4, respectively), and compared to all crop-only scenarios (e.g. ICLS2 and ICLS3 are 28 and 30% lower than full N fertilizer crop-only scenarios in average). Introducing cover crops, which are fertilized (30 kg N ha^{-1} at sowing; Methods), into crop-only systems both reduces (CSW-CC 20% lower than CSW-FA) and increases (CS-CC 11% higher than CS-FA) nitrate leaching (Fig. S5).

Productivity and its stability and resistance

The productivity of each management scenario is compared using cumulative production over the 30-year simulation period as expressed by grain yield and pastures biomass (metric tons; Mg ha^{-1}), energetic value (cereal units; CU ha^{-1}) and economic value (US Dollars; USD ha^{-1}). The high biomass and energetic value of corn result in the highest productivity for the MONO scenario (Fig. S6a and b). When economic value is compared, the ICLS scenarios are shown to be nearly as profitable (e.g. 5% less for ICLS2 when compared to MONO), due primarily to the high added value of beef production (Fig. S6c), and particularly so in areas with sandy soil (Figs. S7–S9). Adopting a heavy-moderate grazing intensity maximizes grass production (Fig. S10), and animal live weight gain (Figs. S6–S8), with more intensive grazing management associated with greater pasture biomass production in the warmer Southern areas (Fig. S11). While the large N fertilizer reduction in corn (i.e. 75% of full N) results in lower average cumulative yield across the scenarios (1.9% less) and corresponding energetic value (2% less), the yield reductions are relatively small (e.g. 4.5% less yield in MONO-RF compared to MONO), a result reflected in the increased average income from all RF scenarios (3.2%) due to N fertilizer cost reductions (e.g. a 3% increase in USD ha^{-1} for MONO-RF compared to MONO). Other scenarios are almost as cost-efficient as MONO, including ICLS2-RF and CS-CC-RF (5 and 10% less, respectively; Fig. S6).

Expansion to large temporal scales enables the investigation of productivity stability, i.e. the ratio of the mean economic productivity of each (1–5 year) rotation to its standard deviation over the 30-year period. ICLS scenarios 1, 2, and 3, and to a lesser extent 4, perform best, due to greater pasture stability when compared to annual crops (e.g. 159% increase in profitability stability for ICLS3 compared to MONO; Fig. S12). For crop-only based systems, increasing rotational complexity improves productivity stability, whether expressed as yield (+47%), energetic value (+48%), or economic value (+65%) for e.g. CSW-CC compared to MONO (Fig. S12). Reducing N fertilization does not significantly impact productivity stability, regardless of metric, even if it tends to slightly increase it (e.g. 5% higher for profitability stability for RF scenarios compared to full N fertilizer scenarios; Fig. S12).

We also investigate the ability of the rotations to withstand a sudden extreme climatic event, referred to here as its *resistance*. This is assessed by comparing corn yields within each scenario, when climatic conditions were *normal* to when they were *moderate* or *extreme* (see Methods). Results show that *extreme* and to a lesser extent *moderate* events have a strong negative impact on corn yields (e.g. MONO scenario; Fig. 3). Corn yields are significantly ($P < 0.05$) higher under *normal* climatic conditions, with *extreme* droughts resulting in the lowest yields (Fig. S13) with losses up to 7.5 Mg ha^{-1} (Fig. 3). When corn yields across the management gradient for each climatic scenario are compared (Fig. 3 boxplots), rotations comprised of less corn (i.e. more diversified) show an increased resistance to *extreme*, but not *moderate* droughts. The capacity for resistance to *extreme* droughts is highest ($P < 0.05$) for ICLS scenarios (Fig. 3) and for pairwise (corn planted simultaneously; Methods) comparisons with MONO (Fig. S14). For wet events, the MONO scenario has the highest resistance capacity ($P < 0.05$; Figs. 3 and S14), but the impacts of such events are lower than for droughts. RF scenarios also increase resistance to extremely dry events (e.g. 10% more for MONO-RF when compared to MONO), and to a lesser extent extremely wet events (Fig. 3). The impacts of the agroecological approaches (cover crops, rotational diversity, reduced N fertilization, pasture, and livestock inclusion) on the ecosystem services investigated for selected management scenario changes are summarized in Fig. 4.

Discussion

We evaluated over three decades, the impact of diverse EI practices on multiple ES at high spatial resolution. By using a dynamic

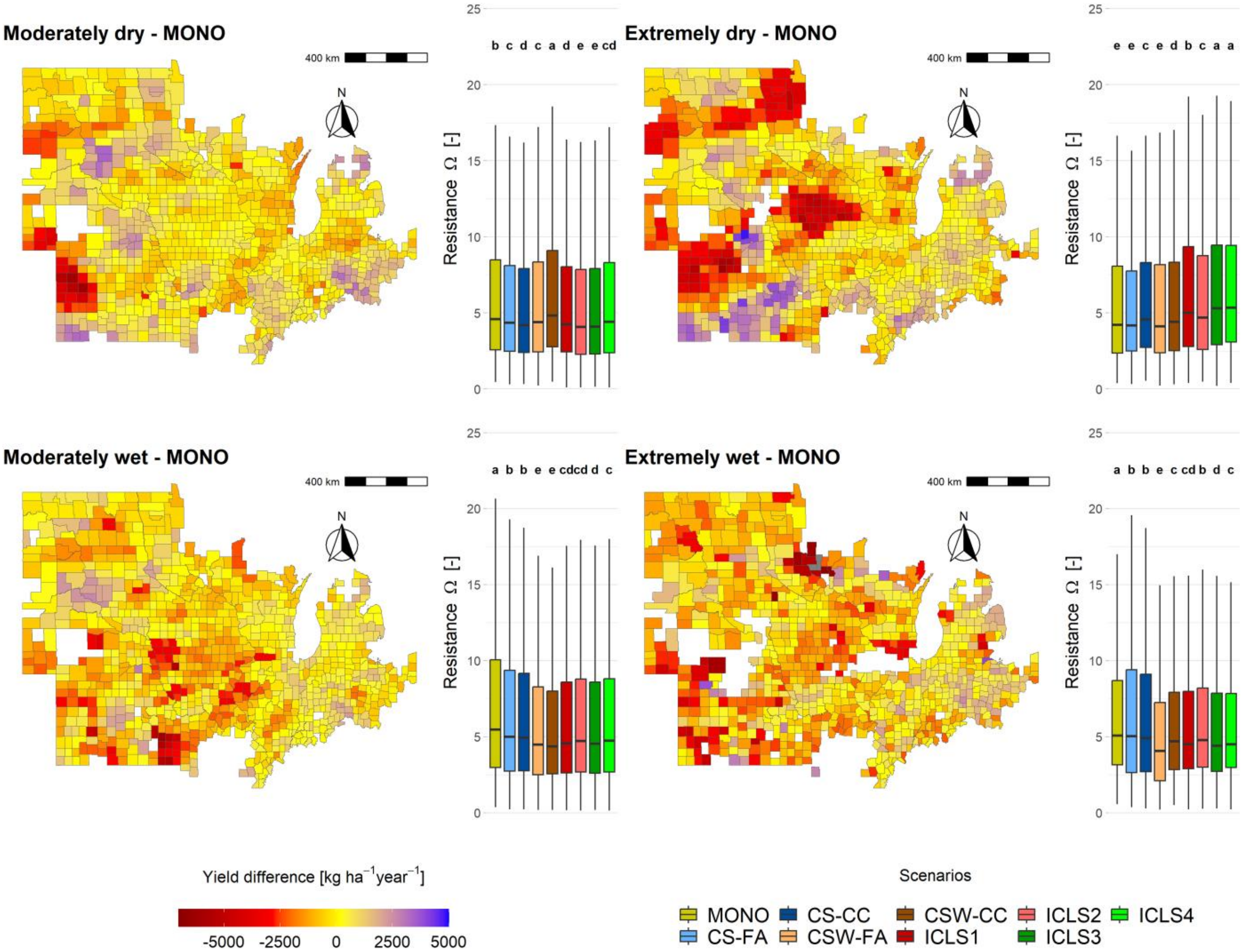

Fig. 3. Impact of extreme climatic events on corn yields at county scale across the US midwest. Each map represents the yield difference between a normal and moderate or extreme dry or wet climatic event for the corn monocropping (MONO) scenario. Boxplots for each category of extreme climatic event, show the resistance of all corn yields (see Methods) under each agronomic management scenario (full N), with the IQR (25–75th percentiles) shown, and minimal and maximal values displayed by vertical lines (outliers not shown). Different letters above the boxplots denote statistically significant differences between groups as determined by Dunn's test ($P < 0.05$).

baseline modeling approach, we can assess and compare their relative variability, trade-offs, and synergies. We discuss impacts using four major management approaches (ICLS, N fertilization, crop diversity, and cover crops) (Fig. 4).

ICLS enhance productivity stability and resistance while lowering GHG emissions

Incorporating short-term pastures with grazing cattle, into a diversified crop rotation enhances productivity stability and resistance to drought, essential system attributes for climate change adaptation (24), and corroborating ICLS research at experimental field-scale (25, 26). Despite cattle methane emissions, ICLS have lower GHG emissions (excluding SOC contribution) than fully N fertilized, crop-only systems, and when pastures are moderately grazed, have similar economic productivity to MONO. While overall crop yield is lower in ICLS scenarios compared to MONO—unsurprising given the lower frequency of corn in the rotation—crop and pasture yields are similar to other crop-only scenarios, particularly CSW, agreeing with Peterson et al. (18) and de Albuquerque Nunes et al. (27), who found crops in ICLS had the same yields as those crops in unintegrated systems.

Moderate cattle grazing intensity (ICLS2, 45 days between cuts), best for dry matter intake, leads to greater cattle live weight gain, optimizing the overgrazing and defoliation stimulation tradeoff (28). Overall, economically, ICLS2 was second only to MONO, outperforming it in some colder, lower-yielding locations. Under this grazing, more feces and urine return to the soil, with greater SOC accrual, as also found by Abdalla et al. (29) and Chang et al. (30).

Lower nitrogen fertilization reduces nitrous oxide and nitrate losses while raising profits

Our results show many well-known advantages of reduced N fertilization; lower N_2O emissions (31) and nitrate leaching (32). Also evident, but less studied is the increase in overall productivity stability (Fig. S12), and resistance to extreme climatic events. Corn N fertilizer rate reductions of 25%, large, but not unrealistic based on farmer willingness to adopt (33) bring about broad economic and environmental benefits. An associated small (2%) yield decrease is accompanied by an increase (3%) in economic return across all scenarios. Less reliance on N fertilizers will also help farmers buffer against the many factors that contribute to their price volatility (34, 35).

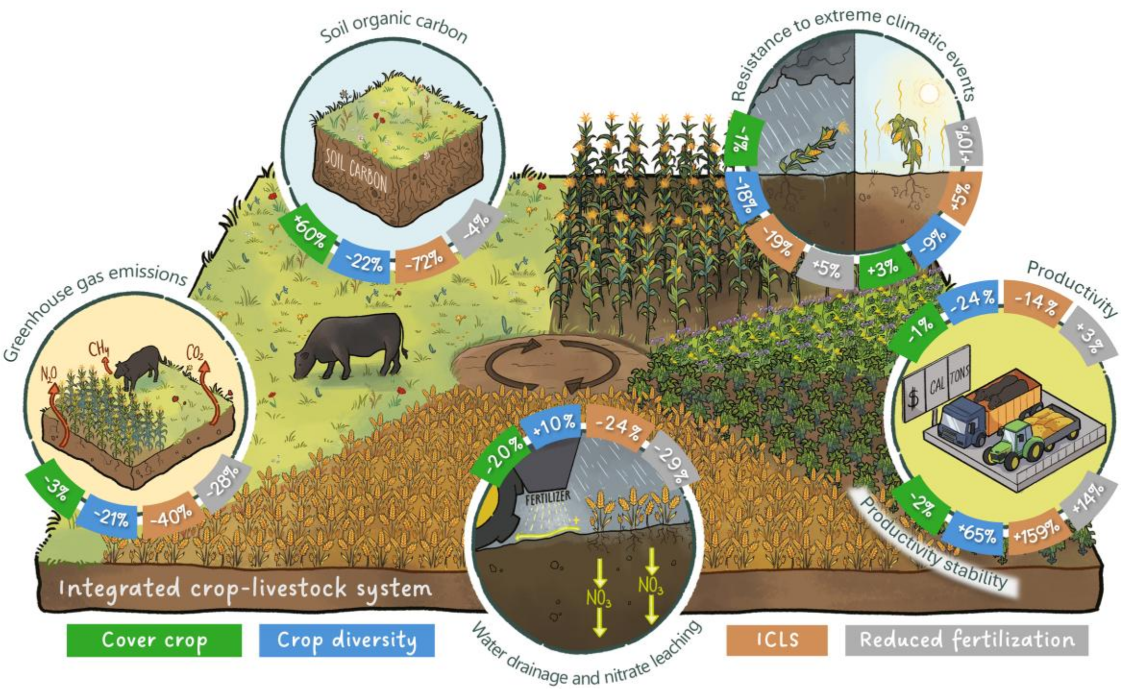

Fig. 4. Summary of the impacts on ecosystem services of (i) cover crop incorporation, as the difference between CSW-FA and CSW-CC scenarios; (ii) crop diversity, as the difference between MONO and CSW-CC scenarios; (iii) integrated crop-livestock systems (ICLS) with moderate grazing intensity, as the difference between MONO and ICLS3 scenarios, and (iv) reduced nitrogen fertilization, as the difference between MONO and MONO-RF scenarios. Resistance (top right circle) is assessed to extremely wet events (left part of the circle) and extremely dry events (right part of the circle). Background landscape shows ICLS rotation as the succession of corn, cover crop, soybean, wheat, and grazed pastures.

Crop diversification boosts stability through lower N inputs

Increasing rotational complexity improves productivity stability across all metrics (Fig. S12) as diversification strategies increase the likelihood of exploiting favorable growing conditions and decrease the risk of crop failure (11). Increased diversity can increase crop yields (12), but in our crop-only rotations, overall yields are lower in CS (37%) and CSW (47%) than in MONO, again based on the prevalence of corn. However, average corn yields were not impacted, and economic comparisons show a much smaller relative decrease in overall revenue (−15% and −25% for CS and CSW, respectively; Fig. S6), consistent with increases in economic profitability due to greater rotational complexity found by Volsi et al. (36). Our results show that complexity (i.e. less corn and more diverse rotations) reduces GHG emissions (e.g. 18% less in CSW than in MONO; Fig. 2), primarily due to reduced N fertilizer rate and its associated production, in agreement with Yang et al. (37). While diversified crop rotations are typically assumed to increase SOC (e.g. 38), lower productivity in CS and CSW results in less crop residue return to the soil, correlating with their lower rates of SOC sequestration (Fig. 2). Increased complexity can stimulate SOC decomposition, and alongside increased net N mineralization and N supply for the crop favors decreased N fertilizer use, more than increased SOC accrual as a climate benefit of these systems (39).

Cover crops enhance SOC sequestration

Adding winter cover crops to annual crops has long been seen as beneficial to the soil and environment (e.g. 40). Their inclusion in CS and CSW rotations has no impact on productivity or its stability, reflecting overall small yield decreases (41) and increases (42) typically found. Similarly, cover crop use has shown contrasting effects on N_2O emissions (e.g. 43), compatible with an N_2O emissions increase (22%) in CS and decrease (18%) in CSW, suggesting that if adopted, it is better to do so in a more diversified system. On average, net GHG emissions are decreased by 45% across both complex crop rotations, due to larger increases (55%) in SOC sequestration than often found (e.g. 44, 45), though their magnitude varies with latitude and pedoclimatic conditions (46).

Unraveling trade-offs and synergies through large-scale and scope studies

Our overall findings highlight the limitations of investigating only a small number of “common” ecosystem services when evaluating synergies and trade-offs. For example, high yielding MONO results in greater SOC sequestration than more diverse crop rotations (Fig. 2), in agreement with Poffenbarger et al. (47). Yet, across all scenarios, the combination of adapted N fertilizers and no-till led to an overall increase in SOC in the Midwest (Fig. 2), consistent with multi-model simulations (46) and meta-analyses based on field measurements (48). An apparent win–win, narrow focus on SOC neglects the limited climate change mitigation impact its accumulation often has, a function of initial stock and proximity to equilibrium prior to management change (Fig.2,a; 49), as well as other environmental trade-offs associated with low crop diversity and high inputs. For example, GHG emissions are much higher in MONO than other scenarios, and while not investigated here, higher pesticide use with monocultures is also a large GHG source (50), making our study conservative in this regard. Similarly, available nitrate is considerably higher in MONO (Fig. S5b), leading to an increased likelihood of leaching and other reactive N loss (51), and re-emphasizing the overall environmental benefit of reducing N input in monocultures and more diverse rotations (39). Biodiversity impacts, investigated fully in other studies, consistently show that corn monocultures are also deficient in multiple beneficial above- and below-ground taxa

(52), especially pollinators, leading to increased susceptibility to pests and economic loss (53).

The use of process-based ecosystem models enables the investigation of numerous EI scenarios across large spatial scales and over extended (decadal) time periods but also allows the evaluation of environmental and economic benefits that are not context-dependent and accumulate over time. Other EI strategies that could be investigated include ICLS where cover crops and/or crop residues are grazed (54). Future work could also investigate scenarios that vary by location, tailored to pedoclimatic contexts—for example, crop-based rotations on more fertile soils, pasture-based rotations on less fertile ones, or replacing winter wheat with spring wheat in colder areas. For future economic comparisons of diverse agronomic scenarios across large geographic scales, it would be valuable although challenging to obtain precise cost and price estimates that reflect management practices and contexts, particularly for crop-livestock systems involving complex and specialized management of pasture and livestock. Finally, and although implementation would be complex at scale and over time, incorporating decision-making processes into models, such as shifting grazing dates according to pasture establishment and growth or replanting in the event of crop failure, will be valuable and better simulate actual management activities.

Trade-offs in ES driven by spatiotemporal variability are common in practice, but not inevitable. There is no well-established, systematic approach for a "win–win" scenario, however evaluating a broad range of ES across multiple management scenarios and taking account of why trade-offs occur can help unlock "hidden' synergies. Without proposing an aggregated ES metric (55), our approach helps connect various scales without data loss and mismatch due to aggregation (4, 56). Similar to SOC studies (57), quantifying relative changes in ES coincident in time and place allows for evaluation of management "additionality" when compared to baseline trends. Relatedly, our long-term, large scale approach can help evaluate environmental risk from aggregated practice reversal, useful when national initiatives or policy interventions are being considered. Such multicriteria approaches are crucial for identifying the key levers that can drive wider adoption of EI. Our analysis suggests that the main limitation lies in reduced profitability, which is linked to most of the agroecological practices under consideration. Profitability, however, remains a decisive factor in farmers' decision-making, as they operate within a socioeconomic system shaped by dependencies on credit institutions and input suppliers (58). Interestingly, our results indicate that lowering nitrogen fertilization can improve profitability. However, translating such recommendations into practical application in the field is challenging. Farmers in the US Corn Belt often underutilize available N management tools, and the prevailing belief that "higher yields require more fertilizer" remains deeply ingrained (59). They perceive the use of additional nitrogen as a form of risk management, ensuring stable yields, and safeguarding their economic security (19).

In conclusion, our work shows that crop models are an essential tool to evaluate the potential of EI over large agricultural landscapes. Investigating the impacts of diverse crop and animal management on a large suite of ES at high spatial resolution over the long-term, enables comprehensive identification and comparative analysis of their trade-offs and synergies, and can help inform decision-making that better avoids or leverages these outcomes. Studies of this type that investigate stability and resistance to more frequent and intense climate perturbations are particularly relevant and timely.

Materials and methods

Agronomic management scenarios

We compare five crop management scenarios that differ by rotation: corn monocropping, corn–soybean and corn–soybean–winter wheat both with and without cover crops (winter rye, incorporated before summer crops), and four crop-livestock systems that in addition to corn–soybean–wheat, include 2.5 years of pasture with varying beef cattle grazing intensity (Fig. 1 and Table 1). Each crop rotation and crop-livestock system have a full and reduced nitrogen (N) fertilization (RF) rate, leading to a total of 18 scenarios.

For corn and soybean, crop maturity regions were chosen to depict the distribution of their cultivars across the Midwest. These regions were based on six latitude bins, with each bin determined by crop growing degree days (GDD) accumulated at maturity. Maize GDD data for each site were sourced from Abendroth et al. (60), and soybean GDD was calculated using weather data based on the USDA National Agricultural Statistics Services (NASS) planting and harvest dates. The distinctions among

Table 1. Agroecological approaches for the eighteen agronomic management scenarios.

Scenario	Rotation duration (years)	Tillage	Cover crop	Animal integration	Grazing intensity	Nitrogen fertilization (%)
MONO	1	No-till	No	No	/	100
MONO-RF	1		No		/	75
CS-FA	2		No		/	100
CS-FA-RF	2		No		/	75
CS-CC	2		Yes		/	100
CS-CC-RF	2		Yes		/	75
CSW-FA	3		No		/	100
CSW-FA-RF	3		No		/	75 (corn), 100 (wheat)
CSW-CC	3		Yes		/	100
CSW-CC-RF	3		Yes		/	75 (corn), 100 (wheat)
ICLS1	5		Yes	Yes	Heavy	100
ICLS1-RF	5		Yes		Heavy	75 (corn), 100 (wheat)
ICLS2	5		Yes		Heavy-moderate	100
ICLS2-RF	5		Yes		Heavy-moderate	75 (corn), 100 (wheat)
ICLS3	5		Yes		Light-moderate	100
ICLS3-RF	5		Yes		Light-moderate	75 (corn), 100 (wheat)
ICLS4	5		Yes		Light	100
ICLS4-RF	5		Yes		Light	75 (corn), 100 (wheat)

maturity regions were determined by calculating quantile-based breaks to achieve the target of six bins. These breaks were then applied to categorize all sites into specific maturity region (MR) groups. Finally, the GDD values for each MR were calculated as the median within each group. Maps of MR groups and further details about GDD computation and values are in Basso et al. (46).

Sowing and harvest dates are adapted spatially as a function of maturity regions based on dates reported by the NASS. Similarly, N fertilization (as urea ammonium nitrate; UAN) amounts for corn are adapted for the same regions based on the USDA ARMS database (61), and are specific to each crop and similar across crop rotations, except for RF scenarios where they are reduced by 25% for corn only. This reduction, following the results of Ransom et al. (62), modifies the average overall N fertilization for corn across the US Midwest from 187 to 141 kg N ha^{-1}, with negligible yield impact. The N fertilization application for corn is split, with one-third of the total applied at planting and incorporated to 5 cm, and the remaining two-thirds applied at day 45 after planting and incorporated to 2 cm. For wheat, all N (120 kg N ha^{-1}) is applied at a single event in mid-April and incorporated to 5 cm. The winter rye cover crop (sown 7 days after harvesting the cash crop), is fertilized at planting with 30 kg N ha^{-1} (UAN) incorporated to 2 cm. Corn is sown at 5 cm depth with 76 cm row spacing and a plant density equal to eight seeds m^{-2}; soybean is sown at 2.5 cm depth with 50 cm row spacing and a plant density equal to 38 seeds m^{-2}; wheat is sown at 2.5 cm depth with 19 cm row spacing and a plant density equal to 420 seeds m^{-2}; and winter rye is sown at 3 cm depth with 15 cm row spacing and a plant density equal to 200 seeds m^{-2}. All crops are in no-till management (63), under rainfed conditions. For all scenarios, we did not incorporate decision-making processes—such as simulating replanting or canceling in-season nitrogen fertilization in the event of crop establishment failure—as this was beyond the scope of the study.

ICLS simulation

In this study, we investigate ICLS scenarios that consisted of the sequence: corn—cover crop (winter rye)—soybean—winter wheat—pasture (Fig. 1). To reproduce cattle herbivory, livestock pasture grazing was simulated through regular cuts of the sward biomass. Regardless of pasture height, the remaining sward biomass after a cut is assumed to be 50% of the precut biomass. This reflects the feeding behavior of steers, which typically remove about 50–55% of the canopy with each bite (see Appendix AS2). Following the approach of Delandmeter et al. (64), residue inputs are used to simulate cattle feces and urine input, and were computed from the biomass removed in the cut and which simulates the animals' dry matter intake (details about parameterization of carbon and nitrogen contents in residue inputs are in Appendix AS2).

The different grazing intensities were defined by the number of days between consecutive cuts; 30 (ICLS1—Heavy grazing), 45 (ICLS2—Heavy-moderate grazing), 60 (ICLS3—Light-moderate grazing), and 90 (ICLS4—Light grazing). Since the pasture is sown after the wheat harvest (around mid-July), grazing takes place only during the following two years, from early May to late October—allowing sufficient time for crop establishment.

Cattle live weight gain was determined from the biomass removed by grazing, simulating dry matter intake, using a fixed feed conversion ratio. From this, methane (CH_4) emissions were estimated using a fixed ratio of methane emitted to live weight gain. Further details on ICLS simulation methodology are in Appendix AS2.

Soil-crop model simulation

All scenarios are modeled using SALUS (65, 66), a highly validated, process-based model that simulates crop, soil, water and nutrient dynamics at a daily time scale under different management strategies and for multiple years. In our study, each scenario is simulated over a 30-year period from 1981 to 2010, and upscaled to cover a substantial portion of US cropland (~46.2 million hectares) in the Midwest region within the states of Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin. Simulations are conducted at 1/24th degree spatial resolution, with each grid that was upscaled ($n = 40{,}000$) covering an approximately 4-km-sided square and labeled with a unique identifier (UID). Further details on weather and soil input data are available in Appendix AS3.

The SALUS model, previously used in several studies in the US Midwest (e.g. (63, 67), was further calibrated and validated for our particular study area (46), using quantitative goodness-of-fit criteria (Appendix AS4).

Corn, soybean, and wheat phenology was calibrated and validated by fitting their yields observed in 17 experimental sites located throughout the US Midwest (Figs. S15 and S16). These experimental sites were selected following a literature review when five criteria were satisfied, ensuring high quality: (i) initial soil conditions (before the experimental treatments began), including SOC stock, (ii) several years of crop yield data, (iii) a time series for SOC (with either SOC stock values or data on bulk density and carbon percentage for calculating SOC stock), (iv) detailed management practices and ancillary information, and (v) the cultivation of corn, soybean or wheat, either grown continuously or within a rotation. In total, 17 experimental sites were identified across North America, with 16 located in the USA and 1 in Canada (Fig. S15). Details about the experimental sites are provided in Table S4.

Cultivar parameters used for upscaling simulations were retrieved from corresponding experimental sites located in each maturity region. The model's ability to simulate SOC dynamics was evaluated using the same experimental sites, but without site-specific soil calibration (Appendix AS4 and Fig. S17). This approach was used to validate the uncalibrated model's performance in reproducing SOC dynamics before scaling up across the Midwest, where calibrating soil-specific parameters is not feasible.

For cover crop biomass, default model parametrization was used without specific calibration. For pasture simulations, based on the validated methodology of Delandmeter et al. (64), we used the field experiment situated at the Lake City AgBioResearch Center (Northern Michigan) to validate pasture growth (Fig. S18). Our aim was to not only compute the total biomass productivity of grasslands throughout the season, but also to capture the regrowth dynamics between animal bites (Fig. S19). Pasture total productivity was then compared to literature values. For N_2O calibration, we fine-tuned the SALUS parameter associated with the potential for N_2O emissions due to denitrification (similar across all UIDs) using data from the annual row crop component (corn—soybean—winter wheat rotation) of the MCSE field experiment at the Kellogg Biological Station (KBS), located in Southwest Michigan (Figs. S20 and S21). Additionally, the average simulated annual N_2O emissions were consistent with emission factors reported in the literature. Further details and results of the model calibration and validation are in Appendix AS4.

Comparative indicators

Using the 30-year simulation period, scenarios are compared based on their provision of five services: soil organic carbon

(SOC) sequestration, greenhouse gas (GHG) emissions abatement, nitrate leaching reduction, productivity and the stability and resistance of productivity.

Soil organic carbon

Changes in SOC stock (Mg ha^{-1} $year^{-1}$) are determined at 0–30 cm depth as an annual average over the 30-year period.

Greenhouse gas emissions

The greenhouse gas budget of each scenario is calculated at the field scale: following the methodology of Autret et al. (68), which computed GHG balances from soil-crop model simulations, pesticides and PK fertilizers are not considered, as their CO_2 contribution is negligible (69) and they are not simulated by the model, neither are tertiary sources such as manufacturing and maintenance of equipment. In summary, each budget includes (i) soil CO_2, calculated as the total difference in SOC stock at 0–30 cm depth over the 30-year period; (ii) direct soil N_2O emissions simulated by the SALUS model through nitrification and denitrification processes, (iii) indirect soil N_2O emissions from N leaching and N fertilizers (68); (iv) CO_2 from fossil fuels emitted from vehicle use during management practices: since no-till is applied, only combine harvester was considered; (*v*) CO_2 emitted during the N fertilizer (UAN solution) synthesis; and (vi) cattle CH_4 emissions from ICLS scenarios, computed from live weight gain. Further details of the values for the GHG budget are included in Table S2.

A standardized GWP (e.g. for a 100-year time horizon) may not adequately account for the large differences in atmospheric longevity of the three GHGs of interest (Table S1). Therefore, we also use GWP* (70,; TableS1) which equates an increase in the emission rate of a short-lived climate pollutant (SLCP), e.g. CH_4, with a one-off pulse emission of CO_2 while still capturing the long-term response to CH_4 emissions by considering prior SLCPs emissions. This metric is better suited for ruminant livestock production where herd size is constant (71). Assumption of a fixed herd size makes baseline emissions more reliable, avoiding the limitations when GHG emissions are compared between regions or countries with arbitrary baseline emissions (49).

Nitrate leaching

The annual average amount of nitrate (NO_3–N) leached at the base of the soil profile (specific to each UID and specified from gSSURGO data; Appendix AS3) was determined over the 30-year simulation. The amount potentially available for leaching is also computed, as the quantity of NO_3–N present after 30 years below the root zone (57 cm depth, which is a depth available in model outputs).

Productivity

Following Delandmeter et al. (64), the total productivity of each agronomic management scenario is computed for three metrics: (i) grain and pasture biomass yield (Mg ha^{-1}); (ii) energetic value (cereal units; CU ha^{-1}) based on metabolizable energy contained in agronomic products (72); and (iii) economic value (US Dollars ha^{-1}) based on fixed costs (accounting for reduced costs associated with RF scenarios) and average commodity prices (maize, wheat, and soybean grain, and beef) between 2019 and 2023 (73). The cost analysis does not account for labor expenses associated with either crop production or pasture and livestock management. Instead, we considered operating costs related to seed, fertilizer, chemicals, custom services, fuel, lubricants and electricity, and repairs. For pasture and livestock profitability, we used the net farm value from USDA statistics for beef (73). Using the methodology of de Albuquerque Nunes et al. (27) and Delandmeter et al. (64), we computed livestock income from live weight gained during the grazing period, assuming same price per unit mass of beef at purchase and sale. All energetic values, costs and prices are available in Table S3.

Stability and resistance

The stability of overall productivity, summing corn, soybean and wheat grain yield, and live weight gain, is computed for each UID as the ratio of the mean productivity of a single rotation (1 to 5 years depending on scenario) to its standard deviation across the 30-year period (74):

$$\text{Stability} = \frac{\mu}{\sigma}.$$

The stability is then averaged spatially over all 40,000 UIDs in the Midwest.

In addition to long-term stability, we also investigate the resistance of agroecosystems to extreme climatic events, i.e. the capacity of an agroecosystem in the short-term to recover and return to near-normal productivity levels following a sudden climatic period, such as excessive drying or wetting (64). In our study, this resistance is represented by corn yields, due to its sensitivity to environmental shocks (75) and presence in all scenarios. To determine resistance, we characterize cropping seasons, associated to each yield, as "normal" or "moderately" or "extremely" dry or wet based on the Standardized Precipitation-Evapotranspiration Index (SPEI) drought index (74). The SPEI, which defines the onset, duration, and severity of drought by measuring the difference between precipitation and potential evapotranspiration (76), is calculated for each month over the 30-year period and for each UID, such that it reflects the influence of temperature on water demand. Following Delandmeter et al. (64), we use a 3-month time scale, such that for each month, the SPEI-3 index is calculated based on the water balance of that month and the two prior months. Then, following Isbell et al. (74) and Delandmeter et al. (64), within each UID, climatic events are classified as "extreme" if they occurred less than once per decade (below the $q_{0.1}$ quantile for extreme dry events and above the $q_{0.9}$ quantile for extreme wet events) and "moderate" if they occurred between once per decade and once every 4 years (falling between quantiles $q_{0.1}$ and $q_{0.25}$ for moderately dry events and between quantiles $q_{0.75}$ and $q_{0.9}$ for moderately wet events). Events outside these categories are considered "normal." Then, for each month and UID, all corn yields are matched to their harvest month SPEI-3 index, allowing each growing season to be characterized based on the 3-month period leading up to harvest to indicate the degree of dryness or wetness during the crucial preharvest growth phase. Finally, following Isbell et al. (74), resistance is calculated as:

$$\Omega = \frac{\overline{Y_n}}{|\, Y_e - \overline{Y_n} \,|},$$

where within each UID, $\overline{Y_n}$ is the mean productivity during normal years, and Y_e the productivity during an extreme event (moderately or extremely wet or dry). As corn presence differs between scenarios (e.g. MONO scenario has only corn cropping seasons whereas ICLS scenarios have one out of five, Table 1), we compare resistance capacity using two methods: (i) by comparing global corn distribution (Fig. 3), accounting for all cropping seasons, an approach that considers the ratio of corn cropping seasons within each scenario to be an intrinsic feature of rotation design; and (ii) by performing a pairwise comparison for two scenarios at a time

(Fig. S13), where we compare the corn cropping seasons that occur in both scenarios in the same year.

Statistics

Statistical analyses were performed in R programming language (77). Because normality of data was not satisfied, statistical differences between groups were determined using Dunn's test following a Kruskal–Wallis analysis. Due to the large datasets, these two tests were conducted on subsamples, each randomly selected to comprise 1/50th of the data points, with comparable samples used across scenarios. Within each state, outliers were detected using the interquartile range (IQR) method, as data points which fall below the first quartile (25th percentile) minus 1.5 times the IQR, or above the third quartile (75th percentile) plus 1.5 times the IQR.

When generating maps, data were aggregated by county. A weighted mean was computed, considering the differences in cropland area sizes linked to each UID within the county, as follows:

$$\text{Weighted mean} = \frac{\sum_{i=1}^{n} w_i \times x_i}{\sum_{i=1}^{n} w_i}$$

with x_i the value of the ith UID value and w_i the weight associated with the ith observation.

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Supplementary Material

Supplementary material is available at *PNAS Nexus* online.

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Mathieu Delandmeter (Conceptualization, Software, Formal analysis, Investigation, Visualization, Methodology, Writing—original draft, Writing—review & editing), Bruno Basso (Conceptualization, Software, Supervision, Validation, Methodology, Writing—review & editing), Neville Millar (Writing—review & editing), Lydia Price (Data curation, Software, Writing—review & editing), Tommaso Tadiello (Data curation, Software, Writing—review & editing), Jason Rowntree (Data curation, Validation, Writing—review & editing), Joao Paulo Sacramento (Data curation, Writing—review & editing), Prateek Sharma (Data curation, Software), Jérôme Bindelle (Conceptualization, Supervision, Validation, Methodology, Writing—review & editing), and Benjamin Dumont (Conceptualization, Supervision, Validation, Methodology, Writing—review & editing)

Data Availability

SALUS model output data are publicly available in a persistent repository: 10.6084/m9.figshare.28750523, referenced as Delandmeter et al. (78). All model inputs (weather and soil data) are described in the Supplementary Information.

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