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Perennial grassland agriculture restores critical ecosystem functions in the U.S. Upper Midwest

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Dominant forms of agricultural production in the U.S. Upper Midwest are undermining human health and well being. Restoring critical ecosystem functions to agriculture is key to stabilizing climate, reducing flooding, cleaning water, and enhancing biodiversity. We used simulation models to compare ecosystem functions (food-energy production, nutrient retention, and water infiltration) provided by vegetation associated with continuous corn, corn-soybean rotation, and perennial grassland producing feed for dairy livestock. Compared to continuous corn, most ecosystem functions dramatically improved in the perennial grassland system (nitrate leaching reduced ~90%, phosphorus loss reduced ~88%, drainage increased ~25%, evapotranspiration reduced ~29%), which will translate to improved ecosystem services. Our results emphasize the need to incentivize multiple ecosystem services when managing agricultural landscapes.

KEYWORDS

agroecology, ecosystem services, livestock, grazing, multifunctionality

Introduction

Agriculture is central to the fundamental challenges facing human society (Godfray et al., 2010; Foley et al., 2011; Wheeler and von Braun, 2013; Amundson et al., 2015; Kremen and Merenlender, 2018). We must develop and grow agricultural systems that provide for our well being while building the capacity of future generations to do the same. These agricultural systems must be resilient in the face of drought, flooding, and extreme weather, as well as socio-economic shocks such as pandemics and market failures (Lesk et al., 2016; Lioutas and Charatsari, 2021; Ortiz-Bobea, 2021).

Critical ecosystem functions of agricultural systems include plant and animal productivity, soil carbon storage (Rowntree et al., 2020; Guillaume et al., 2022; Rui et al., 2022), soil stabilization (Montgomery, 2007; Palm et al., 2014; Schulte et al., 2017), nutrient retention (Schulte et al., 2017; Hussain et al., 2019; Jackson, 2020), water infiltration and storage (Basche and DeLonge, 2019; Baker et al., 2022), and wildlife habitat (Kimoto et al., 2012; Tsiafouli et al., 2015; Schulte et al., 2017). While these factors range in their scale of influence (e.g., soil carbon storage influences greenhouse gas concentrations globally while habitat for soil arthropods is quite local), each of the functions have practical relevance for those living in the U.S. Upper Midwest where surface and groundwater pollution, flooding, soil erosion, and plummeting biodiversity undermine human welfare and well being (Werling et al., 2014; Hussain et al., 2019; Antolini et al., 2020; Bendorf et al., 2021; Borchardt et al., 2021; Burch et al., 2021; Raff and Meyer, 2022; Wisconsin Groundwater Coordinating Council Report to the Legislature, 2022).

Solutions to this multifaceted dilemma require holistic approaches that consider land management effects on ecosystem functions that underpin ecosystem services provided by farms and, more broadly, the landscapes or regions in which they are nested (Strauser et al., 2022). Holistic solutions are required because of the complexity and connectedness of these landscapes, where focusing on a single dimension typically exacerbates problems in others. We must understand and develop systems that solve for multiple variables simultaneously. While the currently dominant form of agriculture is immensely productive, it is also the world's leading driver of environmental change (Foley et al., 2005, 2011). Fortunately, agricultural approaches exist that have the potential to help stabilize global change as we move further into the Anthropocene (Campbell et al., 2017; Rockström et al., 2017).

The dominant agricultural system of the U.S. Upper Midwest is based on monocultures of corn and soybeans grown to feed mostly confined livestock. This system is incentivized by rewarding farmers almost exclusively for more production (Jordan et al., 2018), which comes at the expense of other functions critical to ecological and societal well being [e.g., purification of water, stabilization of soil, regulation of infectious disease, provisioning of wildlife habitat; Alexander et al. (2008), Wepking et al. (2017), Christianson et al. (2018)]. Currently, critical ecosystem functions and the services that they underpin are not properly valued, so their costs are externalized; borne by society as a whole (Suparak Gibson, 2022). An alternative agricultural system, based on perennial grassland, is possible (Jackson, 2022) but requires society to pivot away from the status quo toward a system that rewards a range of ecosystem services. Currently, farmers' individual decisions to participate in the corn and soybean dominated agricultural system are driven by constructed narratives around productivism and maximizing food production (Burton, 2004; McGuire et al., 2013), aesthetic preferences about the 'neatness'

and perceived care of the landscape (Nassauer, 1988), and definitions of *place* at regional scales (Strauser et al., 2022). To incentivize agricultural systems that simultaneously provide multiple ecosystem services to farmers and society, we must understand tradeoffs and synergies in ecosystem functions provided by alternative cropping systems.

To further this understanding we used Agro-IBIS [Integrated Biosphere Simulator; Kucharik et al. (2000), Kucharik (2003), Kucharik and Brye (2003)] to represent a variety of biophysical and biogeochemical processes. These processes included nitrate leaching and phosphorus loss as indicators of nutrient retention and drainage and evapotranspiration as indicators of water retention. These indicators were then simulated across vegetation types associated with three dairy cropping systems (see Methods). In addition to controlling the type of vegetation grown in the model, different simulated land-use decisions can be made regarding fertilizer and manure applications and crop rotations.

Recent work with Agro-IBIS has focused on meeting targeted policy goals with increasing grassland cover. In particular, Campbell et al. (2022) estimated the amount of perennial grassland cover needed to meet water quality goals within the Yahara River Watershed in southern Wisconsin to the year 2070. Similarly, water quality outcomes were assessed with simulations designed to achieve the goals of the Renewable Fuel Standard providing insight into the beneficial water quality effects of improved miscanthus and switchgrass cover (Ferin et al., 2021). Other models, such as DairyMod, APSIM, and DayCent have been used to simulate soil N mineralization and pasture growth (Bilotto et al., 2021), and DairyMod in particular has been instrumental in simulating ammonia volatilization in pastures (Smith et al., 2020), but with a specific focus on Australia and New Zealand where DairyMod was calibrated (Johnson et al., 2008).

Within this stream of the literature, there is no work addressing regional variation in a broad suite of ecosystem services across the U.S. Upper Midwest. In particular, we contribute to the literature by including water quantity in addition to water quality, and matching regional variation within these environmental outcomes to food-energy production outcomes. By simulating these ecosystem functions across three common land cover-land use scenarios (described below), we are better able to anticipate how a wider range of ecosystem services might vary with management.

We examined ecosystem functions under three types of land cover associated with cropping systems typical of the U.S. Upper Midwest. We gathered site-specific data (previous cropping practices, soil type, slope, aspect) from five Wisconsin farms—two in the “Ridge & Valley” region of southwest Wisconsin (Vernon County) and three in the “Cloverbelt” region of central Wisconsin (Marathon County). While both of these regions have a strong agricultural focus, they vary in their topography as well as their edaphic and environmental characteristics.

TABLE 1 General descriptions of the five farms used in this analysis.

Farm	Location	Size (acres)	Primary soil type	Soil P	Soil pH	Slope	Slope length	Primary land use
1	Vernon County, WI, USA	145	Pepin	20	6.70	17.6	110	Grazing
2*	Vernon County, WI, USA	40	Arenzville	na	na	2	250	Grazing
3	Marathon County, WI, USA	483	Loyal	28.0	6.59	3.97	284	Corn-soy with some no till
4	Marathon County, WI, USA	407	Loyal	20.4	6.60	3.84	294	Grazing with some corn-soy
5	Marathon County, WI, USA	280	Loyal	30.9	7.05	3.67	292	Dairy rotation

Characteristics represent the acres that the operator of each farm uses for agricultural production. *Despite the listed slope, Farm 2 and its productive acreage are located at the base of a steep (>50°) ridge and is located in a highly flood-prone area. All soil types listed are silt loam.

We used simulation models and literature estimates to predict outcomes of ecosystem functions under three land cover-land use scenarios—continuous corn, corn-soy rotation, and grassland. Ecosystem functions included estimates of food-energy production as well as water and nutrient dynamics. We expected that increasing perennial cover would improve a range of ecosystem services with potential tradeoffs in food-energy (meat and dairy) production.

Methods

Study region

The Cloverbelt and Ridge & Valley regions of Wisconsin are both known for dairy, beef, and crop production and each region has a strong identity and ethos associated with agriculture and the environment (Supplementary Figure S1, Supplementary Tables S2–S4). In each region annual grain crops (mainly corn and soybeans) are grown on most agricultural land to feed confined livestock whose genetic improvements and concentration in space continue to increase production and efficiency when the latter is assessed as calories produced per input.

While similar in many ways, these regions are quite different. The Cloverbelt is relatively flat with moderate- to poorly-drained soils where local climate and edaphic conditions are favorable to clover production in pastures, giving the agriculture of the region a distinctive *Dairyland* signature. The Ridge & Valley region is characterized by silty, erodible soils on highly dissected topography that make the region flood prone. Annual average precipitation and temperature for the last 10 years (2010 through 2020) were 107.2 cm and 7.1°C for Vernon County (Ridge & Valley) and 93.7 cm and 6.4°C for Marathon County [Cloverbelt; PRISM Climate Group, Oregon State University (2022)]. This variation between farms and regions provides a representation of a significant part of farming in the U.S. Upper Midwest (see Tables S2–S4 for additional details).

Data collection

We gathered crop histories and soil tests from reports submitted by the operators of each of the five farms (Table 1). To protect the privacy of these farm operators, we retain the confidentiality of each farm and report only overall summaries of each. Data included farm size, individual field delineation, soil types, soil phosphorus, slope, slope length, and previous land use.

The physical characteristics of these farms are highly variable (Table 1) and they currently use a mix of row-crop rotations, tillage and no till, and managed grazing. Importantly, especially for water quality, soil P levels varied considerably among farms. Also, the slope and slope length of each farm likely affect water quality in different ways. Consistent with regional descriptions above, Cloverbelt farms were larger, flatter, and participated primarily in more row-crop agriculture for dairy production while Ridge & Valley farms were smaller, on steeper slopes, and used more pasture. We reported land in agricultural production only, not including some forested land, which for one farm was steep. Therefore, while the slope was relatively shallow for Farm 2 the adjacent forested land was steep and listed as highly flood prone.

Simulation models

Agro-IBIS is a spatially explicit agroecosystem and land surface model that simulates the movement of water, energy, momentum, carbon, nitrogen, and phosphorus, in both natural and managed ecosystems. The structure of Agro-IBIS has been described in detail (Kucharik et al., 2000; Kucharik, 2003; Kucharik and Brye, 2003; Motew et al., 2017) and many components and output variables of the model (e.g., crop yield, net primary productivity (NPP), net ecosystem exchange (NEE), evapotranspiration and drainage, nitrate leaching, soil temperature and moisture) have been validated across a range of ecosystems at various spatial and temporal scales (Kucharik et al., 2000, 2006; Kucharik, 2003; Kucharik and Brye, 2003; Kucharik and Twine, 2007; Motew and Kucharik, 2013;

Soylu et al., 2014; Zipper et al., 2015; Motew et al., 2017). Agro-IBIS was integrated with the variably saturated soil water flow model HYDRUS-1D to enable simulation of groundwater-vegetation interactions (Soylu et al., 2014), and P cycling and dynamics were recently added based on SurPhos, a state-of-the-art dissolved P loss model for agricultural systems receiving manure (Vadas et al., 2004, 2005, 2007; Motew et al., 2017). The P module features P application, transformation, and loss of dissolved P to runoff; in-soil cycling of organic and inorganic forms of P; and loss of particulate-bound P with erosion (Motew et al., 2017).

Before running the scenarios of land cover-land use, a long-term model spin-up run was executed from 1650 to 1961 to achieve a steady-state equilibrium in soil biogeochemical cycling that reflects changes in land use and build-up of soil organic C and N pools (Donner and Kucharik, 2003). Agro-IBIS model simulations were executed using a 60-min time-step on a 1 x 1-km regularly spaced grid; the model uses SSURGO soil textural data to delineate dominant soil texture and soil physical properties for each grid cell and soil layer, and daily weather data (air temperature, precipitation, relative humidity, solar radiation, and wind speed) from the gridMET (gridMET, 2013) that was interpolated from 4- to 1-km spatial resolution. Agro-IBIS uses statistical models to interpolate daily weather variables to the hourly time-step (Kucharik et al., 2000). During the model simulation period from 1650 through 1978, a random draw of weather years was taken from the actual data time-series of 1979 through 2016; simulation years from 1979 through 2016 represent the actual weather time-series from gridMET. Nutrient inputs (inorganic fertilizer and manure) originate from a spatiotemporal database of linked agricultural, environmental, and economic data (Lark et al., 2022).

We simulated three different agricultural scenarios or vegetation types: continuous corn, corn-soybean rotation, and generalized C4-dominant perennial grassland for five locations described in Table 1. Continuous corn and corn-years in the corn-soybean rotation received between 91.8 and 180 kg N ha⁻¹ yr⁻¹ and 9 and 22 kg P ha⁻¹ yr⁻¹ based on historical fertilization for that location, which varied by year; soybean and grass did not receive any N and P fertilizer because neither receive N and P fertilization as part of typical grass or soy production. Soil was tilled in continuous corn and corn-soybean rotation was tilled before planting while the grass was never tilled.

For the corn-soy rotation, we ran two scenarios starting with both corn and soybean and then aggregated the output. Annual estimates of nitrate leaching, phosphorus loss (including both sediment and dissolved phosphorus), evapotranspiration, and groundwater recharge (drainage) were gathered after running those different vegetation scenarios from 1961 through 2016. We then filtered out the first 18 years of data (keeping the 38 years from 1979 through 2016), as the model output took approximately 10 years after a restart simulation (the restart year

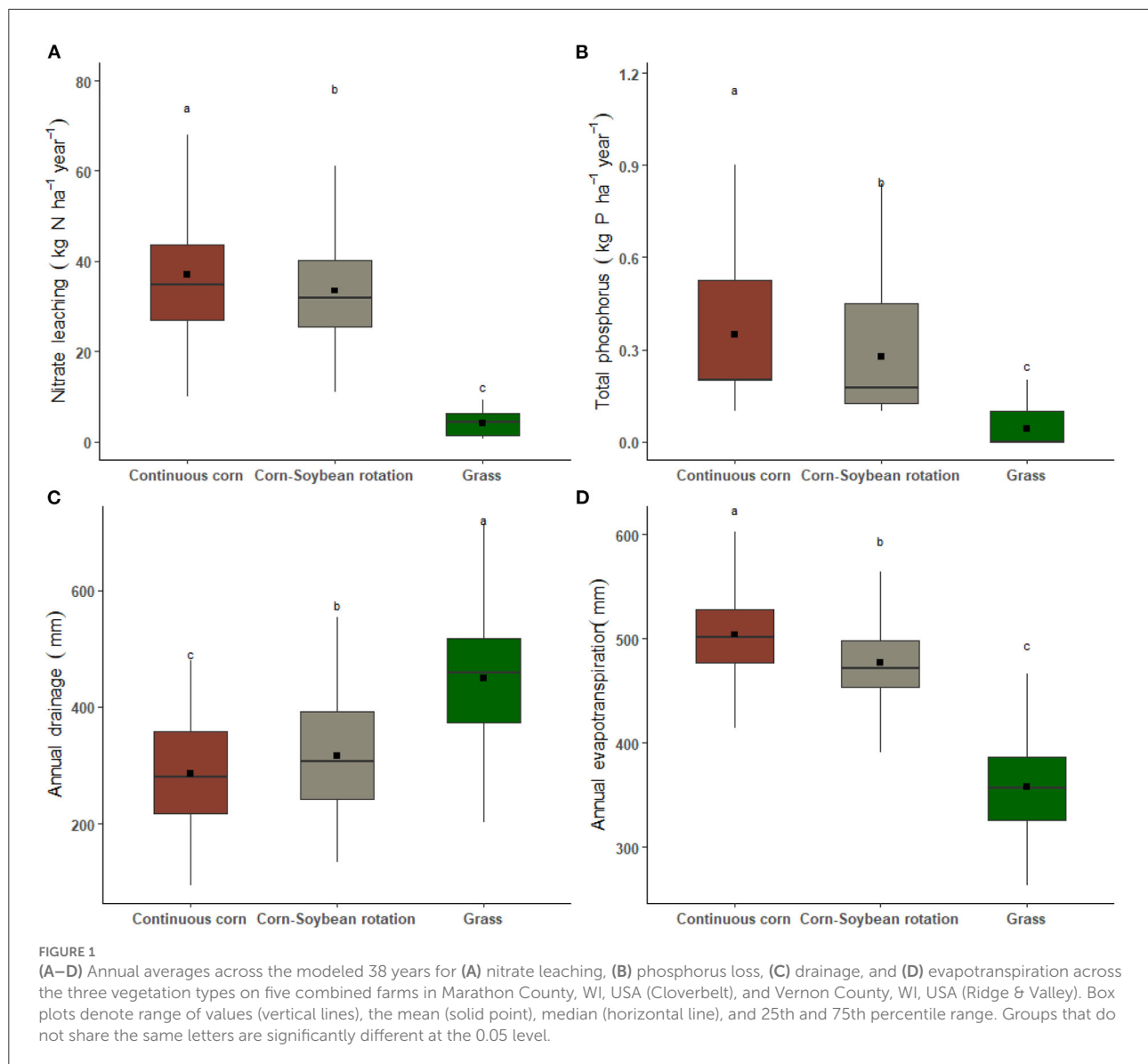
was 1961 for each scenario) to reach equilibrium, and because the time-series of actual weather begins in 1979.

After gathering the output data, we used linear mixed effects models (one for each of the above dependent variables) using the *nlme* package in R (Pinheiro et al., 2022) to limit the effects of vegetation type and year (fixed effects) and farm nested within region (random effects) to account for site/geographical variation.

Food-energy calculations

We examined another important ecosystem function, agricultural production, for each of the three scenarios by calculating their food-energy output from harvested biomass. We used the historical cropping data for each farm to generate average farm-level output (bushels ha⁻¹). We then used this past output and created a “target” output to use in the counterfactual simulations. As a specific example, the average farm-level production at Farm 3 during the pre-simulation period was 354.1 bushels ha⁻¹ yr⁻¹ (9.6 Mg ha⁻¹ yr⁻¹) of corn grain and 49.8 bushels ha⁻¹ yr⁻¹ (3.3 Mg ha⁻¹ yr⁻¹) of soybeans. We therefore simulated food-energy production for Farm 3 using these values as output, while averaging the output over two years for the corn-soy rotation. We did not have farm-specific yield data for farms that did not practice a cropping system during the years for which we obtained observational data, so for these farms we used USDA Census of Agriculture average yield maps for that county and set the target yield at the value given in the map (USDA—National Agricultural Statistics Service, 2022). For pastures without yield data, we assumed an average height of the grass of 63.5 cm and multiplied that by an estimated harvest of 326 kg DM ha⁻¹ (Barnhart, 1998), which is equivalent to 8.4 Mg ha⁻¹ yr⁻¹ of harvested dry matter. We then converted these target yields for each farm to food-energy using the process described in Sanford et al. (2021). Like Sanford et al. (2021), our representative farms and cropping systems represent agricultural production in the U.S. Upper Midwest (WI), which is a major producer of dairy products. We therefore examined food-energy in the form of milk and dairy beef (Gcal ha⁻¹ yr⁻¹). Briefly, Sanford et al. (2021) make their conversion from harvested yield to food-energy using the following steps:

1. Convert volume yield (bushels ac⁻¹) to mass yield (Mg ha⁻¹), while assuming that 79.2% of soybean grain results in soybean meal and 18.7% results in soybean oil. We used national data from 1980 to 2016 to estimate these percentages (USDA-ERS, 2018).
2. Convert dry matter yield to total digestible nutrients (TDN) using mean nutrient content values from Dairy One Cooperative (Feed Composition Library | Dairy One, 2022): 88% for corn, 80% for soybeans, and 60% for grass.



- Convert TDN yield to milk and dairy beef food-energy using conversions from Peters et al. (2014) and USDA (USDA—FoodData Central, 2022). We used the same process as Sanford et al. (2021) to calculate a conversion factor of 1.04 Gcal Mg⁻¹ for milk (1,042 kcal kg⁻¹ TDN) and 0.37 Gcal Mg⁻¹ for dairy beef (366 kcal kg⁻¹ TDN).

Finally, we compared observable farm factors and ecosystem functions by assessing correlations among these variates.

Results

Across the five farms and two regions, vegetation type significantly affected nitrate leaching (Figure 1A, Supplementary Table S1, Supplementary Figure S2). This

effect was driven by the low average level of nitrate leaching over the 38 years analyzed in the grass system ($4.1 \pm 0.2 \text{ kg ha}^{-1}$) compared to continuous corn ($39.9 \pm 1.0 \text{ kg ha}^{-1}$) and the corn-soy rotation ($33.5 \pm 0.8 \text{ kg ha}^{-1}$). Both continuous corn and the corn-soy rotation leached significantly more than the grass system in a pairwise comparison ($P < 0.001$ and $P < 0.001$, respectively), but continuous corn also leached significantly more than corn-soy ($P < 0.001$). Across the three vegetation types nitrate leaching generally increased over time, on average increasing $0.4 \text{ kg ha}^{-1} \text{ yr}^{-1}$ [$P < 0.001$ (Supplementary Figure S2)]. Annual variation in nitrate leaching was driven by precipitation and management differences (Supplementary Figure S3). When considered across the five farms and two regions separately within the grass vegetation, nitrate leaching appeared to vary by region with Marathon County ($6.0 \pm 0.1 \text{ kg ha}^{-1}$) exhibiting

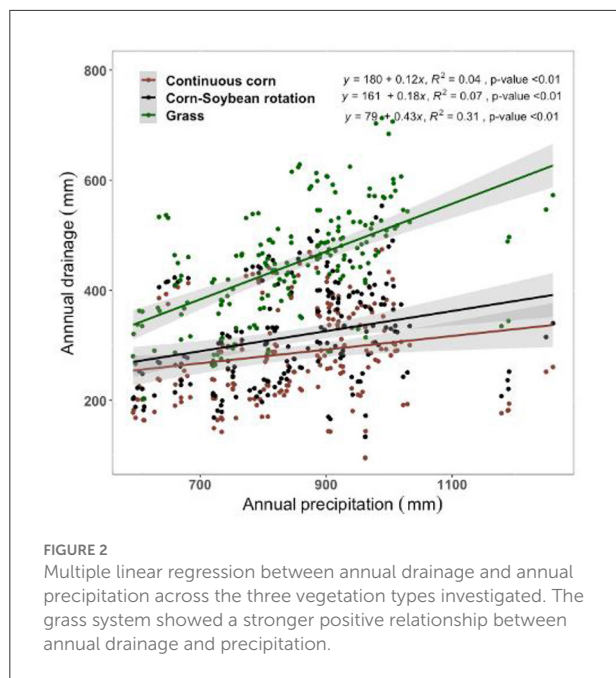


FIGURE 2
Multiple linear regression between annual drainage and annual precipitation across the three vegetation types investigated. The grass system showed a stronger positive relationship between annual drainage and precipitation.

greater leaching than Vernon County [$1.3 \pm 0.04 \text{ kg ha}^{-1}$ (Supplementary Figure S4)].

Continuous corn was found to have the highest level of phosphorus loss ($0.35 \pm 0.02 \text{ kg ha}^{-1}$) followed by the corn-soy rotation ($0.28 \pm 0.02 \text{ kg ha}^{-1}$); grass had the lowest level of phosphorus loss ($0.042 \pm 0.004 \text{ kg ha}^{-1}$) across the five farms and two counties investigated (Figure 1B, Supplementary Table S1). Phosphorus runoff with continuous corn vegetation was found to be significantly greater than both the corn-soy rotation ($P < 0.001$) and the grass vegetation types ($P < 0.001$). The grass vegetation type was found to exhibit significantly lower phosphorus than the corn-soy rotation vegetation type ($P < 0.001$). Phosphorus tended to decrease over time as well [$P < 0.001$ (Supplementary Figure S2)]. However, this decline over time appears to be driven by the row-crop vegetation types; the grass vegetation type held relatively steady over the course of the 38 years analyzed (Supplementary Figure S2).

The amount of annual drainage, or recharge to groundwater, was shown to vary by vegetation type (Figure 1C, Supplementary Table S1). The grass system showed the highest annual drainage ($449 \pm 7.4 \text{ mm yr}^{-1}$), significantly greater than both the continuous corn ($286 \pm 6.3 \text{ mm yr}^{-1}$; $P < 0.001$), and corn-soy rotation ($317 \pm 6.4 \text{ mm yr}^{-1}$; $P < 0.001$). The corn-soy rotation was shown to have significantly greater drainage than the continuous corn vegetation ($P < 0.001$). Over the course of the 38 years analyzed, annual drainage shows a general decrease over time, on average 2.23-mm lower annually ($P < 0.001$). In addition, grass vegetation was shown to have a stronger positive relationship than the other two vegetation types between annual drainage and annual precipitation (Figure 2).

TABLE 2 Average \pm standard errors for food-energy production across three vegetation types.

Vegetation	Milk (Gcal $\text{ha}^{-1} \text{ yr}^{-1}$)	Dairy beef (Gcal $\text{ha}^{-1} \text{ yr}^{-1}$)
Continuous corn	8.45 ± 0.32	2.97 ± 0.11
Corn-Soybean rotation	5.36 ± 0.19	1.88 ± 0.07
Grass	5.27 ± 0.11	1.85 ± 0.04

Values are calculated using the methodology of Sanford et al. (2021) and represent means and standard errors for the two counterfactual years given past production on each farm.

Evapotranspiration trends were opposite of drainage (Figure 1D, Supplementary Table S1). Grass systems had the lowest evapotranspiration ($358 \pm 3.1 \text{ mm yr}^{-1}$; $P < 0.001$), corn-soy systems had the second-highest evapotranspiration ($477 \pm 2.5 \text{ mm yr}^{-1}$; $P < 0.001$), and continuous corn had the highest ($504 \pm 2.7 \text{ mm yr}^{-1}$; $P < 0.001$). Generally, evapotranspiration was higher in the Ridge & Valley than the Cloverbelt (Supplementary Figure S5). In addition, across all vegetation types, the annual average ET trend was 0.91 mm yr^{-1} ($P < 0.001$).

Finally, the vegetation types differed in their levels of food-energy production. Across all cropping systems, the same level of harvested dry matter produced higher amounts of food-energy in the form of milk compared to dairy beef (Table 2). Continuous corn had the highest food-energy output, producing over 3 Gcal $\text{ha}^{-1} \text{ yr}^{-1}$ more milk energy and over 1 Gcal $\text{ha}^{-1} \text{ yr}^{-1}$ more beef energy ($\sim 60\%$ for each) than the corn-soy rotation and grass ($P < 0.001$). However, no significant difference in food-energy production was observed between corn-soy rotation and grass for both milk ($P = 0.70$) and dairy beef ($P = 0.71$) output.

Discussion

Nitrate leaching was greatly reduced under grass vegetation compared to both continuous corn and corn-soy rotation because no manure or fertilizer was added to grass vegetation, which aligns with empirical field studies. Under most perennial grass bioenergy and grazed systems, nitrate leaching is much lower than corn-based cropping systems (Hussain et al., 2019; Jackson, 2020), differences that can lead to significant disparities in water quality for rural regions, where nitrate leaching contributes to impaired health and infant mortality (Knobeloch et al., 2013). Further, nitrate leaching from common corn-based systems contributes to eutrophication and consequently impaired rivers, lakes, and oceans (Orth et al., 2006; Liu et al., 2022). These waterways arguably are more impaired from phosphorus runoff, with nitrogen potentially working in concert with phosphorus to induce further eutrophication (Dodds and Smith, 2016; Schindler et al., 2016). As mentioned in the introduction, there is promise for reducing eutrophication and

meeting established water quality goals by reducing nutrients in watersheds and increasing perennial cover as shown by [Campbell et al. \(2022\)](#).

From a water quantity perspective, grassland promoted higher water drainage (i.e., more infiltration and less runoff) and lower evapotranspiration than the other systems. Increasing evapotranspiration reduces local temperatures through increasing latent heat flux, and has been shown to mitigate increased temperatures, e.g., the urban heat island effect ([Qiu et al., 2013](#)). In an agricultural context, however, higher evapotranspiration (e.g., continuous corn, corn-soy rotation) is linked to higher water demand and consequently higher irrigation rates or water demand for crops. Systems that promote higher evapotranspiration and lower recharge have a direct impact on the volume of surface water bodies. In the case of irrigation, this has been shown to deplete groundwater levels, especially as climate change increases evapotranspiration rates over time ([Condon et al., 2020](#)). While only 1.5 and 0.4% of agricultural land in Marathon County and Vernon County are irrigated, this is an important consideration in drier areas. While we found lower evapotranspiration rates in grasses than continuous corn or the corn-soy rotation, some grasslands can be comparable to corn-based systems ([Abraha et al., 2020](#)). Agricultural impacts on groundwater depend in large part on irrigation (which was zero in our modeled grassland) and drainage (which was highest in our modeled grassland) back into groundwater systems. While beyond the scope of our modeling study, many studies have also shown the potential of perennial grassland to reduce runoff and flood risk downstream because of its ability to enhance infiltration ([Jackson and Keeney, 2010](#); [Schilling et al., 2014](#)).

Balancing our current emphasis on agricultural production with other ecosystem services is critical. The continuous corn system produced more food-energy than the corn-soy and grass systems, which is consistent with previous work ([Peters et al., 2014](#)). However, while the grass and corn-soy systems produced similar output from a food-energy perspective, the grass system outperformed the corn-soy rotation on all other ecosystem metrics. While recent research has shown that the current amount of beef raised within the U.S. could be raised entirely on grass—and without adding acreage not already in some form of agricultural production ([Jackson, 2022](#))—more work is needed to better understand the ramifications of transformative changes to our agricultural landscape. Spatially explicit research that can show where various forms of agriculture can either do the least damage, or conversely, can promote the most beneficial ecosystem services, is a clear need in improving our understanding and decision making around agricultural production.

From a dairy perspective, milk yields dropped when cows were fed from grassland exclusively ([Jackson, 2022](#)). However, this drop in milk production with the grass-based system can be countered by a dramatic drop in production costs ([Dartt et al., 1999](#); [Kriegel, 2005](#); [Hanson et al., 2013](#)) making grass-based

dairies economically competitive with confinement dairies; work that shows that grass-based systems can outperform others from a multifunctionality perspective. Other work shows that from a *true-cost accounting* perspective, grass-based farms provide much more value to society than what are considered conventional farms, and are dramatically undervalued ([Suparak Gibson, 2022](#)). Instances such as this require a framework to reward farmers for the societal good produced, whether it be from a policy perspective or some other structure ([Rissman et al., in this volume](#)).

While we focused on agricultural production from an energetics perspective to broadly compare the vegetation types in question, there is more to food than energy. Nutritional profiles are an important consideration to include in future analysis of tradeoffs among ecosystem services. Research on this topic shows that grassfed livestock production improves both animal health and the nutritional profile of livestock products compared to conventionally raised livestock ([van Vliet et al., 2021b](#)). A key driver of this improvement in nutritional profile was the biodiversity of the plants consumed by grassfed livestock, suggesting that the promotion of biodiversity is strongly linked with human health ([Provenza et al., 2021](#); [van Vliet et al., 2021a](#)).

Our model did not include a grazing module that mimicked disturbance-plant growth dynamics, nutrient uptake and NPP, which would likely be stimulated to an even greater degree under well-managed grazing resulting in improvement in most ecosystem functions. Current work is adding grazing and cover crop modules to further explore continuous living cover in agroecosystems. These types of modeling advances, integrated with the other capabilities of Agro-IBIS, will allow scientists to develop advanced decision support tools (DSTs) that contain model output data from many scenarios representing the potential impacts of a changing climate and land management on ecosystem services. The goal is to have crop consultants, land managers, farmers and other end users use DSTs to guide future agroecosystem management decision-making to meet sustainable development goals for humanity.

Conclusions

With the exception of food-energy yield, all the ecosystem functions we explored were improved under the grassland-based system compared to annual grain crops. If agricultural policy continues to reward yield exclusively, it will be difficult to transition to more multifunctional agricultural systems. Continuous corn yielded more food-energy than corn-soy rotation and perennial grassland, but a significant tradeoff was observed: this system had the poorest performance across all other ecosystem functions – nitrate leaching, phosphorus loss, drainage, and evapotranspiration. While the corn-soy rotation provided slightly better outcomes than continuous corn (except for yield), it was inferior to perennial grassland

for most outcomes and not significantly different in food calorie yield. A more balanced delivery of ecosystem functions underpinning critical ecosystem services will require more reliance on perennial grassland for livestock production.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CW, DS, HM, AO, ZR, EB, CK, CG, and RJ designed the research. DS, HM, AO, and ZR performed the research and analyzed the data. CW wrote the manuscript. CW, DS, HM, AO, ZR, EB, CG, and RJ edited the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2022.1010280/full#supplementary-material>

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