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Agricultural Landscape Transformation Needed to Meet Water Quality Goals in the Yahara River Watershed of Southern Wisconsin

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Abstract

Balancing agricultural production with other ecosystem services is a vexing challenge. The Yahara River watershed in southern Wisconsin is a place where tensions among farmers, policymakers, and citizens at-large run high because nutrient loss from the agricultural practices of a few drive the impairment of surface waters for many. Reducing manure and fertilizer application, as well as increasing perennial grass cover have been proposed as potential solutions. Using the Agro-IBIS agroecosystem model, we examined 48 scenarios of future land management and climate for the Yahara River watershed to the year 2070. Scenarios included combinations of reduced livestock and increased perennial grassland under alternative climate trajectories. Results suggested that business as usual will lead to further environmental degradation with phosphorus-loading to waterways increasing 13, 7, and 23% under baseline, warmer and drier, and warmer and wetter climates, respectively. Watershed-wide phosphorous yield and nitrate leaching could be reduced by 50%, but only when nutrient application was reduced 50% and grassland cover was increased 50%. Furthermore, water quality improvements only materialized 50 years after modified land management practices were implemented under the most likely future climate. Our findings highlight that improving water quality under a changing climate will require long-term investment and transformative changes to current agricultural land use and land cover. Agricultural management solutions exist but are unlikely to be implemented without policies that incentivize transformative agricultural change.

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Highlights

- Transformative land management changes required for water quality improvement
- Inaction will lead to further water quality degradation under a changing climate
- Decades of land management change are needed before improvements occur

Introduction

We face growing challenges to balance food, feed, fuel, and fiber demands with needs for clean water, stable climate, flood suppression, and biodiversity (Hampe and Petit 2005; Ericksen and others 2009; Foley and others 2011). Past and current agricultural intensification degrade the environment by reducing biodiversity and soil carbon (C) while exacerbating water quality problems (Foley and others 2011; Zeng and others 2014) and flooding (Zipper and others; Tomer and Schilling 2009; Ahiablame and others 2019). Agronomic intensification in the form of cropland expansion, irrigation, and nitrogen (N) and phosphorus (P) application have produced higher crop yields (Foley and others 2011), but excess manure and fertilizer applications move from the soil into waterways causing algal blooms, fish kills, and human illness (Sharpley and others 1993; Lathrop and others 1998; Pimentel and others 2013; Panagopoulos and others 2014; Motew and others 2017). After applying nutrients, 70 to 80% of phosphorus remains in soil or sediment (Jarvie and others 2013,2015). Excess amounts of soil P (referred to as 'legacy P') can eventually pollute downstream aquatic ecosystems (Jarvie and others 2013; Chen and others 2015; Motew and others 2017). Recent research suggests N can behave similarly, compounding the legacy nutrient challenge (Van Meter and others 2016, 2018).

Despite the development of better management practices, expected water quality improvements are rarely observed (Graham and others 2017; Jarvie and others 2017; Liu and others 2017). Nutrients currently entering water bodies may have been applied to soils over decades of agricultural management (Dale and others 2010; Van Meter and Basu 2017) resulting in lagged nutrient loading that challenges land managers, policy makers, and community members evaluating mitigation efforts (Meals and others 2010; Jarvie and others 2013; Chen and others 2015; Motew and others 2017; Van Meter and others 2018). This calls into question mitigation approaches that do not fundamentally address the systemic problems of nutrient loss from agricultural lands where nutrient inputs exceed crop needs.

Perennial grasslands promote an array of ecosystem services while reducing further environmental degradation (Asbjornsen and others 2013) and have the potential to reduce legacy soil nutrient storage and improve water quality. The dense, fibrous root systems of perennial grasslands can reduce soil erosion and nutrient runoff relative to annual cropping systems (Smith and others 2014; Zhou and others 2014). Continuous plant cover and minimal soil disturbance may also promote soil C sequestration (Schreiner and others 2014; Qin and others 2016). Past research supports the strategic placement of perennial grasses within cropland dominated by row crops as a means of maximizing ecosystem services (Asbjornsen and others 2013; Jackson 2017). Furthermore, a transition from annual crops to perennial grassland increases biodiversity and bird and pollinator abundance (Castellano and Valone 2006; Meehan and others 2010, 2013; Werling and others 2014; Landis and others 2016).

Past studies using field- and plot-level experiments support the use of grasses as vegetative buffer strips for improving water quality (Storm and others 2010; Zhou and others 2014; Schulte and others 2017). A meta-analysis reviewed 73 studies finding reductions of 72% less P and 68% less N in runoff from fields with vegetated buffers (Zhang and others 2010). Past modeling studies of widespread deployment of perennial bioenergy crops also support the use of perennial vegetation for water quality improvement under hypoxic conditions (VanLoocke and others 2016).

Considering historical over application of nutrients, current nutrient management practices, and ongoing climate change, the objective of this study was to develop scenarios of future change with a goal of improving surface water quality. We used a full factorial design and the Agro-IBIS agroecosystem model to simulate 48 scenarios to the year 2070 for the Yahara River watershed of southern Wisconsin to study the impacts of changing land use, nutrient management, and climate on water quality. Agro-IBIS, a process based land surface module encompassing canopy physics, soil physics, and plant physiology, a crop management module including the role of planting date, crop type, crop rotation, and fertilizer application allowed for the inclusion of complex biophysical processes in scenario development. Specifically, we addressed how replacement of annual cropping systems with perennial grasslands and reducing livestock densities affected nutrient loading and other ecosystem processes under alternative climate change scenarios. To determine where tipping points may lie, nutrient application to cropland was reduced by 0%, 10%, 25%, and 50%. Similarly, cropland conversion to perennial grassland followed the same incremental changes. Across all scenarios, only cropland received any nutrient application. All land conversion and nutrient management scenarios included three future climate scenarios.

METHODS

Study Area

The Yahara River watershed covers approximately 1345 km^2 in south central Wisconsin (Dane County, USA) and features four lakes—Mendota, Monona, Waubesa, and Kegonsa. The Yahara River flows to the Rock River, which eventually connects to the Mississippi River and the Gulf of Mexico. The watershed contains the state capital Madison, Wisconsin (43°6′N, 89°24′W) and a human population of about 370,000 (U.S. Census Bureau 2017). Agricultural land accounts for about 45% of the watershed, with dairy, corn, and soybean the dominant products (Expo 2014; Carpenter and others 2015). Currently, grassland makes up only 0.4% of total land cover within the watershed (Carpenter and others 2015). The Yahara River watershed falls within one of the largest dairy cattle counties in the state, and the watershed contains seven registered concentrated animal feeding operations (CAFO) (Wisconsin DNR). Data based on the 2012 Census of Agriculture shows about 79,000 animal units within the Yahara River watershed, with 84% attributed to dairy cows (Larson and others 2016). Despite a decrease in the number of animal feeding operations, there has been no corresponding decrease in animal units on the landscape, as facility size has increased (Larson and others 2016). As the population of Dane County has increased by 11% over the last ten years (US Census Bureau), urban sprawl has led to a decrease in the amount of land available for manure application, despite the continued increase in animal units on the landscape.

Past research has established agriculture's impact on nutrient loading to the lakes of this watershed, which drives algal blooms, decreased water clarity, and reduced fish populations (Lathrop and others 1996; Lathrop and Carpenter 2014; Motew and others 2017). Water quality degradation is also linked to economic costs, loss of recreational activities, and human health concerns (Smith and others 2006; Huisman and others 2018). Over the past 40 years, significant investments in improved farm management practices and other initiatives have failed to reduce P loading to Lake Mendota (Lathrop and others 1998; Lathrop and Carpenter 2014; Gillon and others 2015). Lack of water quality improvement, or delayed improvement, can be attributed to the role of legacy phosphorus, which continues to supply phosphorus to the watershed (Motew and others 2017).

The region has also experienced an increase in mean annual precipitation and the frequency of heavy rainfall events during the last 50 years (Gillon and others 2015). The 30-year mean annual precipitation has increased 164.3 mm from 1950 to 2019 (NOAA). The lakes of the Yahara River watershed are on US EPA's impaired waters list because of excessive P concentrations and are thus subject to an ongoing total maximum daily load (TMDL) process to improve water quality. The Madison Metropolitan Sewerage District is the coordinating institution responsible for documenting reductions of 43,500 kg P per year by 2036 as specified by the TMDL. The agency is employing an adaptive watershed management strategy focused on altering land management and land cover on agricultural lands (Yahara WINS 2017; Wardropper and others 2018). Concurrent with the TMDL process, a 50% P-reduction goal has been established for the Yahara River watershed by local organizations (Clean Lakes Alliance 2012), which is predicted to double the number of days local beaches are open, increase water clarity, and reduce the frequency and extent of algal blooms (Clean Lakes Alliance 2012).

Agroecosystem Modeling

We used Agro-IBIS to simulate the daily phenology and growth of vegetation and the C, water, N, P, and energy exchange of the soil–plant-atmosphere system (Kucharik and others 2000; Kucharik and Brye 2003; Motew and others 2017). The model was run on a regularly spaced terrestrial grid of 220 × 220 m over the Yahara River watershed using a 60-min time-step. The model requires inputs of gridded soil textural data, annual land cover and land use, annual nutrient management (manure and inorganic fertilizer), and daily weather (temperature, precipitation, specific humidity, solar radiation, and wind speed), which is interpolated to an hourly time-step using statistical and stochastic modeling (Kucharik and others 2000). The process based approach of the biophysical model allows Agro-IBIS to simulate many of the challenges a grower in the region would face, such as challenging field conditions during typical planting time, temperature stress, soil moisture stress, nutrient stress, and the buildup of legacy nutrients in the soil.

Most recently, the HYDRUS-1D soil physics model was incorporated into Agro-IBIS (Soylu and others 2014), as well as the SurPhos model (Motew and others 2017, 2018) to account for manure as well as the biogeochemical cycling of P and loss of dissolved and particulate P to runoff (see Motew and others 2017 for a more detailed description of Agro-IBIS). By incorporating the SurPhos model, Agro-IBIS is able to simulate soil phosphorus through time and the legacy effects of long-term agricultural management and manure additions to the soil. Agro-IBIS also simulates the complete nitrogen cycle (Kucharik and Brye 2003) and carbon and nitrogen linkages through fully coupled biogeochemical cycling in the soil–plant-atmosphere system (Kucharik and others 2000). Therefore, Agro-IBIS is able to account for the accumulation of nutrients over time, and in response to land use, changes in the timing and amount of phosphorus loading to surface waterways or potential of leaching of nitrate to groundwater. This mechanistic approach paired with the spin-up procedure for all of our scenarios allows our simulations to capture the impact of legacy nutrients in all simulations.

Agro-IBIS has been extensively calibrated and validated for the Yahara River watershed using a variety of biophysical and biogeochemical data (Motew and others 2017, 2018). Specifically, Agro-IBIS has undergone validation at various spatiotemporal scales, across a range of ecosystems (El Maayar and others 2001; Kucharik and Brye 2003; Kucharik and others 2006; Kucharik and Twine 2007; Soylu and others 2014; Zipper and others 2015). Recently, Agro-IBIS was integrated with HYDRUS-1D to simulate variably saturated soil water flow (Soylu and others 2014). Additionally, once HYDRUS-1D was integrated into Agro-IBIS, it was validated for crop net primary production, leaf area index, and soil moisture and temperature performance across the Yahara River watershed (Soylu and others 2014; Zipper and others 2015). Additional work validated the soil moisture and temperature, LAI, and corn yields within the Yahara River watershed (Zipper and others 2015). Furthermore, SurPhos was integrated into Agro-IBIS to simulate the role of legacy phosphorus through the simulation of inorganic P cycling in manure and soils, as well as accounting for the loss of dissolved P through runoff. SurPhos has separately been validated across a range of manure types and rainfall patterns (Vadas and others 2004, 2007; Sen and others 2012; Collick and others 2016). As SurPhos is designed to be incorporated into more complex models, its incorporation into Agro-IBIS is consistent with other tools such as APLE (Vadas and others 2012) and SnapPlus (Good and others 2012).

Land Cover, Nutrient Management, and Climate Scenarios

Integrated scenarios focused on three key drivers of change from 2014 through 2070: 1) converting cropland (corn, soybean, small grains, and alfalfa) to perennial grassland (mix of C_3 and C_4 grasses), 2) decreasing the amount of nutrients applied to cropland in the watershed, and 3) climate change (warmer-wetter and warmer-drier).

At the landscape scale different percentages (0, 10, 25, and 50%) of the cropland area were converted to perennial grassland. We used a continuum of suitability ratings for agricultural land to develop an algorithm that decided when to replace current cropland with grassland (see Appendix A). The suitability ratings and identification of marginal land were based on the land capability classification (LCC) created by the Natural Resources Conservation Service (NRCS) of the USDA (Helms 1991) and extracted from the USDA-SSURGO soils database (NRCS 2013). Annual rotation of row crops was simulated using a semi-random algorithm. Each grid cell containing a row crop was randomly reassigned a different row crop each year of simulation, while maintaining a relative proportion of corn, soybean, alfalfa, and small grains on the landscape consistent with recent (2004 through 2013) historical data (Booth and others 2016). To simulate the potential use of perennial grass as a future crop for cellulosic biofuel in the future, 90% of aboveground biomass was harvested (Motew and others 2017) and corresponding adjustments to both C and P budgets were modeled.

Altering nutrient management involved incremental decreases (0, 10, 25, and 50%) in the amount of manure (via changes in total animal units) and fertilizer applied to corn, soybean, alfalfa, and small grain crops. Baseline manure applications in the model were determined using a recent (2013) spatially explicit livestock inventory that included estimated number of animal units and manure hauling distance for each livestock operation (Booth and others 2016). Baseline fertilizer application rates on non-manured cropland were based on University of Wisconsin–Extension guidelines, assuming high-yield potential soil, high-yield goals, and optimum soil nutrient status. Corn, soybeans, alfalfa, and small grains received 202, 0, 0, and 78 kg ha^{-1} of N, respectively (Laboski and others 2012). Phosphorus application rates for corn, soybeans, alfalfa, and small grains 39, 24, 33, and 17 kg ha^{-1} of P, respectively. Fertilizer applications of 101 kg ha^{-1} of N and 11 kg ha^{-1} of P were also applied to corn receiving manure. Reductions in manure application rates were modeled assuming a corresponding percent decrease in total animal units at the watershed scale that was then uniformly applied across each livestock operation. No manure or fertilizer was applied to perennial grassland. In scenarios incorporating increasing perennial grassland paired with no reduction in nutrient inputs, remaining cropland received the same amount of total manure as current cropland, but less fertilizer (due to less cropland). This choice was made to reflect realistic farmer decision-making, in which it is unlikely that 10 or 25% of manure would be exported out of the watershed. As a result, scenarios incorporating increasing perennial cover and no change in nutrient inputs receive the same amount of manure to current cropland as current conditions, but on a smaller amount of land area. See Appendix A for total amounts of phosphorus and nitrogen applied across scenarios.

Two scenarios of future climate to the year 2070 were taken from the core Yahara 2070 scenarios outlined in Booth and others (2016). These scenarios both depicted increased air temperature (per projected trends and climate models for this region) and atmospheric CO_2 concentration (Kucharik and others 2010; Wisconsin Initiative on Climate Change Impacts 2011; Gillon and others 2015), but differed in changes to annual average precipitation (Table 1). We used a baseline climate (BC) scenario that used cyclical, repeating timeseries of historical daily weather data from 2004 through 2013 over the course of BC simulations from 2014 through 2070. Therefore, the impacts of this repeating daily weather timeseries may be evident in some model output variables. For BC, atmospheric CO_2 concentrations remained constant at 373 ppm for the entire period of simulation. In comparison with BC, a warmer and drier climate (WDC) scenario included increased annual average temperature (4 °C) and decreased annual precipitation (50 mm) by 2070. In addition, under WDC atmospheric CO_2 concentrations reached 625 ppm by 2070. The warmer and wetter climate (WWC) scenario had an average annual temperature increase of 3.5 °C and about a 100 mm increase in annual average precipitation by 2070 relative to BC. Under WWC, atmospheric CO_2 concentrations reached 605 ppm by 2070 (see Booth and others (2016) for detailed scenario descriptions).

A full factorial approach was used for the incremental land management and nutrient changes and climate scenarios including four possible land cover/land use scenarios (baseline, 10, 25, and 50% increase in perennial grassland), four potential nutrient reduction scenarios (0, 10, 25, and 50%), and three climate scenarios (BC, WDC, and WWC). Collectively, a total of 48 scenarios were simulated through the year 2070. The land cover and nutrient management scenarios were simulated independently for each of the three climate scenarios. For each year of the simulations (2014 through 2070), annual land cover and nutrient management databases were used as inputs to Agro-IBIS along with daily weather from the climate scenarios.

Assessment of Ecosystem Service Indicators

We evaluated projected changes and tradeoffs for several ecosystem service indicators modeled by Agro-IBIS that underpin key ecosystem services. We focused on quantifying projected changes in surface water quality, groundwater quality, crop yield, and soil C content. For more detailed analysis, including projected changes in biomass yield, freshwater supply, and soil retention, we refer the reader to supplemental information provided. A range of ecosystem service indicators were selected to evaluate both provisioning and regulating services that have ecological and economic value. To address surface water quality, P yield, the amount of P leaving the landscape through runoff in both particulate and dissolved form, served as our indicator. Groundwater quality was measured as potential nitrate leaching, or the NO_3-N loss below the plant rooting zone. Crop yield was measured as the annual average yield of traditional row crops simulated (corn, soy beans, small grains, and alfalfa). Soil C represented the amount of C contained in the surface meter of soil. Soil C was selected as an ecosystem service in our study due to

Table 1. Annual Weather Data for Three Climate Scenarios: Baseline Climate (BC), Warmer Drier Climate (WDC), and Warmer Wetter Climate (WWC) Averaged Across Each Decade from 2004 through 2070

Years	Baseline				Warmer Wetter				Warmer Drier			
	T max (°C)	T min (°C)	Precip (mm)	CO2 (ppm)	T max (°C)	T min (°C)	Precip (mm)	CO2 (ppm)	T max (°C)	T min (°C)	Precip (mm)	CO2 (ppm)
2014–2020	13.8	3.2	964	372	16.1	5.0	900	412	16.4	5.5	1,030	414
2021–2030	14.1	3.3	935	373	15.9	4.8	1,075	439	16.7	5.7	1,056	443
2031–2040	14.1	3.3	935	373	16.9	5.8	985	477	16.8	6.2	1,005	484
2041–2050	14.1	3.3	935	373	17.1	5.9	933	517	17.7	6.7	1,012	528
2051–2060	14.1	3.3	935	373	17.5	6.6	1,089	562	18.2	7.1	795	577
2061–2070	14.1	3.3	935	373	17.6	6.6	963	605	18.2	7.0	846	625

Weather data includes average maximum temperature, average minimum temperature, average annual precipitation, and average atmospheric CO2 concentration.

its essential role in biogeochemical cycling and connection to sequestration. As the C, N, and P cycles are coupled, including soil C contributes to changes in both surface and groundwater quality, in addition to crop yield. The assessment was performed using changes in watershed-level averages. Temporal changes were examined using 9-year moving averages.

Model Output Analysis

Projections of water quality metrics were analyzed and discussed as watershed-level averages with an emphasis on temporal trajectories. We defined the historical reference period to be 2004 through 2013 and focused on comparing that period to 2061 through 2070. Changes in ecosystem service indicators are reported as percent change—calculated as the difference between the average of the last projected decade and the average of the defined historical decade, divided by the average of the defined historical decade. Analysis and visualization were completed in MATLAB v.2017a (Mathworks 2017) and RStudio v.3.6.3 (R Core Team 2020).

Results

Transformative Land Use Change Needed for Water Quality Improvement

Across all climate scenarios, inaction resulted in long-term P-yield increases of 13, 7, and 24% by 2070 under the baseline climate (BC), warmer drier climate (WDC) and warmer wetter climate (WWC) scenarios, respectively (Figure 1a). When holding land cover and climate constant with current values, our results indicated that reducing nutrient inputs resulted in lower P yields from the landscape (Figure 1a). However, under BC, P yield decreased by 5% only when nutrients were reduced by at least 25% from current levels. When incorporating changes in land cover, converting 25% of cropland to perennial grassland was required for P yield to decrease relative to current levels under BC. Incorporating nutrient reduction and increasing perennial grassland together provided the greatest declines in P yield. Under current climate conditions, P yield was reduced 48% by the year 2070 with 50% nutrient-input reduction and 50% of cropland converted to perennial grassland (Figure 1a).

Similar relationships between increased perennial grassland cover and decreased P yield were evident across WDC and WWC (Figure 1a). How-

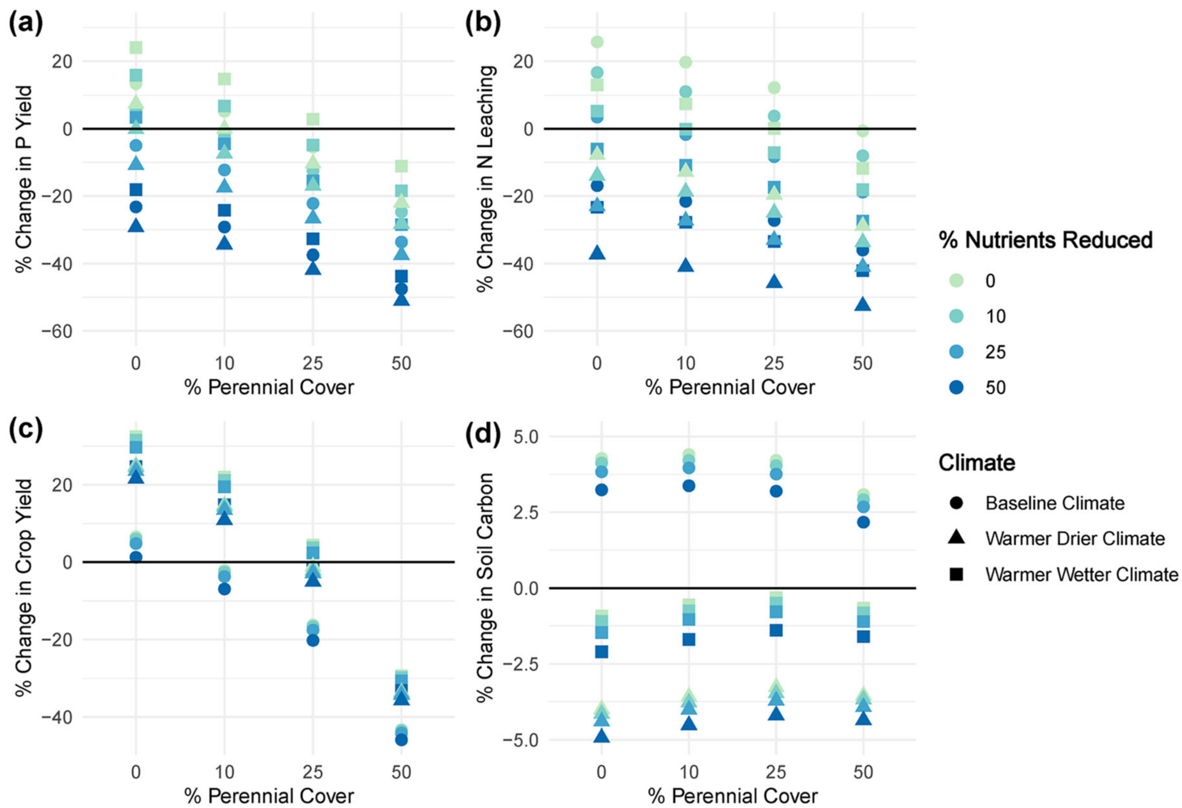

Figure 1. Projected change in **a** phosphorus yield, **b** nitrate leaching, **c** crop yield, and **d** soil C averaged across the Yahara River watershed (that is, percent change from 2004–2013 average to 2061–2070 average) in response to reduction in nutrient inputs, increased perennial grassland cover, and climate change. Point shape indicates the climate, with circle representative of baseline climate, triangle representative of warmer drier climate, and square representative of warmer wetter climate. Point color darkens with larger nutrient reductions (0, 10, 25, and 50%).

ever, across all scenarios, WDC resulted in the largest decline in P yield, whereas WWC often exacerbated current water quality problems. Under WDC, reducing nutrient inputs by 10% resulted in no change in P yield, but a 25% reduction in nutrients led to a 10% decrease in P yield. Similar trends emerged when increasing perennial cover alone. Considering only nutrient reduction under WWC scenarios, a 50% reduction in nutrients was required for a decrease in P yield. When only increasing perennial cover, a 50% increase in perennial grassland was needed for a decrease in P yield under WWC scenarios. Under all scenarios, a combined approach (increasing perennial grassland and reducing nutrients) was most effective, with a 44 and 51% reduction in P yield under WWC and WDC, respectively (Figure 1a).

When no changes to land management occurred, nitrate leaching increased across scenarios under BC and WWC with increases of 26 and 13%, respectively, but declined by 8% under WDC (Figure 1b). When holding land cover and climate constant, model output indicated that nutrient inputs and nitrate losses were positively correlated. Under the BC scenario, reducing nutrient applications by 10, 25 and 50% led to nitrate leaching changes of + 17, + 3, and -17%, respectively (Figure 1b). More than a 25% reduction in nutrient application was required for a reduction in nitrate leaching (compared to current values) to occur by the 2060s under BC. Increasing perennial cover was associated with decreases in nitrate leaching. However, reductions in nitrate leaching relative to today's values often did not occur in the absence of decreases to nutrient application. A 50% conversion of cropland to perennial grassland reduced leaching by only 1% (Figure 1b). Increasing perennial grassland and decreasing nutrient inputs simultaneously provided the greatest potential for minimizing nitrate leaching losses. Scenarios incorporating both a nutrient reduction of 50% and perennial cover increase of 50% under BC led to a 36% decrease in nitrate leaching by 2070.

Across all land management possibilities, WDC supported the largest reduction in nitrate losses followed by WWC, whereas BC exacerbated cur-

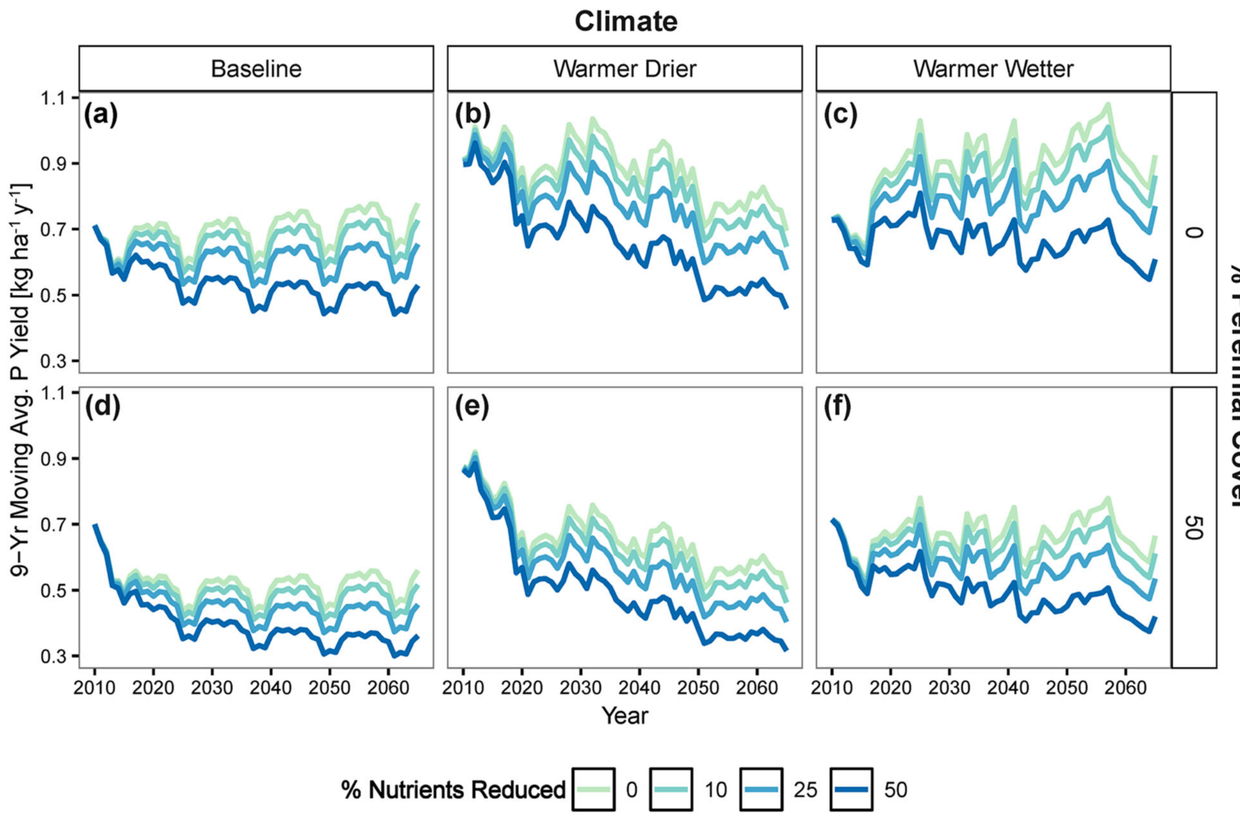

Figure 2. Nine-year moving average of projected P yield from 2004 to 2070 averaged across the Yahara River watershed in response to nutrient reductions, increased perennial grassland cover, and climate change scenarios. Only the baseline and most extreme land cover scenarios are depicted, with 0% conversion to perennial grassland **a**-**c**, and 50% conversion **d**-**f**. Column indicates climate scenario (baseline, warmer drier, and warmer wetter), row indicates conversion to perennial grass (0 and 50%), and line color indicates nutrients reduced. See supplemental information for full scenario responses.

rent challenges with nitrate leaching losses to groundwater (Figure 1b). In fact, under WDC all scenarios resulted in a decline in nitrate leaching. When evaluating either decreasing nutrient inputs or increasing perennial cover, decreasing nutrient inputs was slightly more effective at reducing nitrate leaching. A 50% reduction in nutrients led to a decrease in nitrate leaching of 37%, whereas a 50% increase in perennial cover resulted in a 29% decrease in nitrate leaching under WDC. Similar to P yield, a 25% reduction in nutrient inputs was required to decrease nitrate leaching relative to current levels across WWC scenarios (Figure 1b). When increasing perennial cover alone, a 50% increase in perennial grassland was needed to reduce nitrate leaching under WWC. Reducing nutrient inputs by 50% and increasing perennial grassland by 50% together provided the largest improvement, with a 53 and 42% decline in nitrate leaching under WDC and WWC, respectively.

Climate Influences Timeline Required to Meet Water Quality Goals

Decadal average changes in P yield indicate that reaching the previously established 50% reduction goal for P yield may be met sooner than the 2070 modeling horizon of this study (Figure 2). For the 2050s, when 50% of cropland was converted to grassland with a 50% decrease in nutrients applied to remaining cropland, the BC scenario resulted in a projected P yield of 0.35 kg ha^{-1} in comparison with the baseline average of 0.71 kg ha^{-1}, leading to a 51% reduction in P yield (Figure 2a, d). Under the same scenario conditions, the average projected P yield was 0.36 kg ha^{-1} from 2021 through 2040, representing a 48% reduction in P yield (Figure 2a, d). This suggests that substantial improvements in water quality could occur within ten years of transformative land management change to a highly perennialized system, while also highlighting the influence of weather variability on P yield. Although the greatest improvement in P yield came under WDC scenarios and earlier improvements

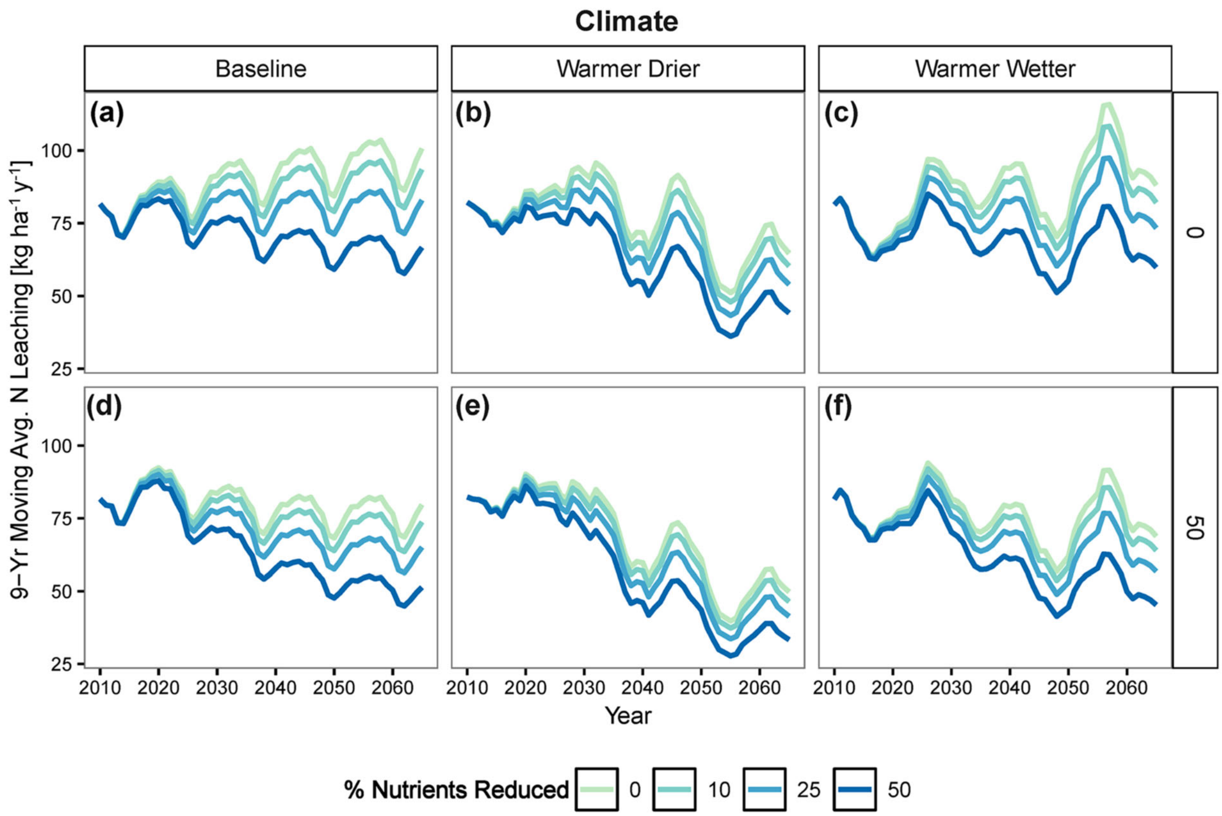

Figure 3. Nine-year moving average of projected nitrate leaching from 2004 to 2070 averaged across the Yahara River watershed in response to nutrient reductions, increased perennial grassland cover, and climate change scenarios. Only the baseline and most extreme land cover scenarios are depicted, with 0% conversion to perennial grassland **a**-**c**, and 50% conversion **d**-**f**. Column indicates climate scenario (baseline, warmer drier, and warmer wetter), row indicates conversion to perennial grass (0 and 50%), and line color indicates nutrients reduced (0, 10, 25, 50%). See supplemental information for full scenario responses.

were evident under BC scenarios, WWC scenarios consistently showed less water quality improvement in comparison with the drier climates (Figure 2).

Temporal analyses also indicate that N leaching varies considerably annually, allowing groundwater quality goals to be achieved in earlier decades (Figure 3). Under WDC with a 50% transition of cropland to perennial grassland paired with a 50% reduction in nutrient inputs, a 53% reduction in N leaching was possible by the last decade (2061 through 2070). Decadal analysis demonstrated watershed level annual average N leaching of 29.2 kg ha^{-1} for 2051 through 2060, in comparison with 79.3 kg ha^{-1} for 2004–2013, indicating a 63% reduction in N leaching (Figure 3b, e). Under a WDC with 0% perennial transition and a 50% reduction in nutrient application, N leaching goals were also achieved in an earlier decade. Under these conditions, model simulations projected average annual N lost to groundwater to be 38 kg ha^{-1} for the 2050's, or a 52% decrease relative to the recent past (2004 through 2013) (Figure 3b). However, under a BC and WWC, significantly longer time was required for improvements to occur.

Water Quality Improvements May Come at a Cost to Other Ecosystem Service Indicators

When no changes in land management occurred, average crop yield increased by 6, 25, and 35% under BC, WDC, and WWC scenarios, respectively. Holding watershed land cover and climate constant through 2070, a reduction in nutrient inputs was associated with lower crop yields in comparison with scenarios incorporating no reduction. However, in comparison with current yields, watershed average crop yield increased despite large reductions in nutrient inputs. Under BC, nutrient reductions of 10, 25, and 50% resulted in 6, 5, and 1% increases in average crop yield, respectively, by

2070 (Figure 1c). Average watershed crop yield declined with increasing perennial grassland, as expected as total cropland also declined. Under BC, converting 10, 25, and 50% of cropland to perennial grassland led to average watershed crop yield declines of 2, 16, and 43%, respectively, by 2070 (Figure 1c). A simultaneous decrease in nutrient application rates of 50% coupled with 50% replacement of row crops with grassland led to a 46% decline in average crop yield, which was comparable to the reduction attributed to solely increasing perennial grassland.

Climate change increased average watershed crop yield in the absence of any changes in nutrients or land cover. When changes to nutrient management were considered, scenarios incorporating a 50% reduction in nutrients, maintained crop yield increases of 22 and 25% under a WDC and WWC, respectively. When 50% of cropland was converted to perennial grassland, crop yield declined by 34 and 29% under WDC and WWC (Figure 1c). However, when 25% of cropland was converted to perennial grassland, crop yield increased by 4% under WWC, and minimal changes (-1%) occurred under WDC. Based on model output, a changing climate limited crop losses associated with reducing nutrients and transitioning to perennial grasslands.

With no changes to current practices, soil carbon changes ranged minimally from + 4 to -4% across climates (Figure 1d). Under current land cover and climate, a 10, 25, and 50% reduction in nutrients was associated with soil C increases of 4.1, 3.8, and 3.2% by the 2061 through 2070 time period (Figure 1d). Under BC scenario and no change to nutrient inputs, converting 10, 25, and 50% of cropland to perennial grassland led to soil C increases of 4.4, 4.2, and 3.1%, respectively, in comparison with values for the baseline period. When evaluating scenarios with increasing perennial grassland cover under BC with simultaneous decreases in nutrients, soil C increased 2.2 to 4.2%.

Soil carbon generally declined by 1 to 5% in the climate change scenarios, with the greatest reduction (5%) occurring under WDC (Figure 1d). Under WDC and WWC, the greatest loss in soil C was associated with a 50% decrease in nutrients, with losses ranging from 2.1 to 4.9%. Despite converting 50% of cropland to perennial grass, with no change in nutrient management, soil C was reduced by 0.6 and 3.5% under WWC and WDC, respectively. When considering a combined approach, converting to perennial grassland offset some of the soil C loss associated with a decrease in nutrient application. Converting 50% of cropland to perennial grassland and decreasing nutrients by 50%, soil C declined 1.6 to 4.3% (Figure 1d).

Discussion

To meet US EPA-mandated water quality goals for Wisconsin's Yahara River watershed, our model results suggest that animal units must be halved while simultaneously converting half the land in annual row crops to perennial grassland. Moreover, these goals will not be met until this alternative land use and land cover configuration has been in place for about 50 years under the most likely future climate scenario. These findings have profound and unsettling implications for current watershed adaptive management strategies that seek to incrementally employ conservation measures such as cover cropping, manure injection, and manure composting. These efforts, while well-intentioned, do not alter the fundamental problem of watershed-wide nutrient imbalance combined with inherently leaky annual grain crop production (Wang and others 2018; Motew and others 2019). Reducing animal units addresses this issue directly. Replacing inherently leaky annual cropping systems with perennial grasslands offers an opportunity to continue raising livestock while addressing water quality and other environmental concerns. More modest nutrient loss reductions were found in less transformative land use and land cover scenarios indicating some promise for improving soil and water quality over current conditions with more modest interventions. Reducing nutrient inputs alone consistently produced the largest reductions in P yield and N leaching across all climate scenarios, which can take the form of reduced fertilizer use, manure exports out of the watershed, or reduced animal units.

Previous surface- and ground-water quality research emphasized the role of legacy N and P (Jarvie and others 2013; Chen and others 2015; Van Meter and others 2016, 2017; Motew and others 2017; Christianson and others 2018), increased total precipitation, increased frequency of extreme rainfall events (Carpenter and others 2017), and continuing land nutrient inputs as significant barriers to quickly improving water quality. Increasing perennial grassland cover in agricultural watersheds has been shown to reduce nutrient losses and improve water quality (Vadas and others 2015; Dahal and others 2020), but slowly (Tomer and others 2019). Perennial grasslands nested within annual cropping systems increased retention of P, N, and sediment through soil building and conservation mechanisms that reduce erosion (Zhang and others 2010). Extensive root systems and continuous plant cover associated with perennial grasslands promote physical soil stabilization through soil aggregation, and increase soil nutrient and water-holding capacity through infiltration and absorption (Bharati and others 2002; Schulte and others 2006; Asbjornsen and others 2013; Brye and others 2013; Cates and others 2016; Diederich and others 2019).

Climate, Biophysical Processes and Biogeochemical Cycling Form Complex Interactions

When land management and land cover were consistent across climates, P yield and N leaching declined the most under the WDC projections. Reductions in rainfall and a lower frequency of extreme rainfall events potentially decreased the likelihood of soil particle disturbance or sediment yield (Carpenter 2008). In turn, this reduced the opportunity for stored P in the soil, or legacy P, to mobilize and enter waterways (Sharpley and others 2013; Lathrop and Carpenter 2014; Motew and others 2017). Additionally, decreased annual precipitation in WDC supports reductions in dissolved P runoff, which constitutes 60% of annual total P in the Yahara River watershed (Motew and others 2018), as well as the leaching of nitrate that occurs with current manure and fertilizer application practices. Across our scenarios, increases in annual temperature increased evapotranspiration, reducing soil moisture and drainage that carry nitrate more quickly past the root zone to groundwater (Long and Ort 2010; Hatfield and others 2011). Simulated ET values for both WDC and WWC indicated a 10% increase in ET by 2070, in comparison to baseline ET values. The increase in ET values suggests rising temperatures can support reduced nutrient losses with increased photosynthesis, despite confounding factors such as increased N mineralization and plant water stress. Increased frequency of extreme rainfall events have been demonstrated to increase N loss (Maharjan and others 2016) and generally support our findings.

Ecosystem Service Tradeoffs will Challenge Future Policy-Making

Land managers and policy makers are faced with the challenge of managing for competing goals in addition to evaluating tradeoffs that arise, even when working toward a common goal. As a result, it is critical we evaluate not only water quality changes across scenarios, but the corresponding tradeoffs expressed among other key ecosystem services. For instance, a decrease in crop production as a result of managing land specifically with a goal of water quality improvement is concerning. However, although reductions in nutrient application limited future increases in crop yield, the tradeoffs may be less severe than anticipated (Varvel and others 2008) allowing for an increase in yield relative to current conditions. Our findings provide evidence that farmers could reduce N fertilizer additions by a substantial amount, with little impact on crop yield over a long-term average.

Additionally, our scenarios found increases in temperature under the WWC and WDC scenarios positively impacted crops phenologically and physiologically by expanding the growing season and increasing photosynthesis (Hatfield and others 2011; Sacks and Kucharik 2011). Our results contrast with previous findings indicating declining crop yields with predicted climate change (Long 2006; Schlenker and Roberts 2009; Rosenzweig and others 2014; Schauberger and others 2017), which can be partially attributed to our use of algorithms that automatically adjust springtime planting dates based on weather and selecting crop hybrids that are best adapted for the current climate conditions (Kucharik 2003). This approach simulates the impacts of farmer adaptation to climate change, and suggests that some simple adaptive strategies can benefit yield increases in regions like Wisconsin that are challenged with shorter growing seasons (Sacks and Kucharik 2011).

Other studies have also projected crop yield increases for states in the central and northern Corn Belt. Specifically, past studies indicate a potential increase in soybean yields by 120% due to earlier planting and elongated growing season (Southworth and others 2002). Previous work by Kucharik (2006, 2008) and Sacks and Kucharik (2011) using USDA crop progress data also supported our modeling results. They reported a significant and widespread trend toward earlier corn and soybean planting dates in the Midwest US from 1979–2005 and the positive impacts this had on yield trends. Averaged across the Midwest US, corn planting dates advanced about 10 days from 1979 to 2005, and soybean planting dates by about 12 days (Sacks and Kucharik 2011). For both crops, this was accompanied by a lengthening of the growth period, with the specific period from corn planting to maturity about 12 days longer by 2005 than it was in 1979 (Sacks and Kucharik 2011). This change was supported by a 14% increase in the number of growing degree days needed for crops to progress through the reproductive period, which potentially reflected an adoption of longer season cultivars by farmers (Kucharik 2008; Sacks and Kucharik 2011). If these adaptive changes in cultivars had not occurred, yields around 2005 would have been approximately 26% lower (Sacks and Kucharik 2011). For Wisconsin specifically, Kucharik (2008) reported that from 1979–2005, the earlier planting date contribution to the maize yield trend was 22%. These results using observed data of historical trends suggest that earlier planting and lengthening growing seasons can have a significant impact on yield increases. This is especially true in more northern Corn Belt locations like Wisconsin that have a shorter growing season than places further south and cooler average growing season temperatures (Kucharik 2008). Additionally, field-grown soybeans under elevated CO_2 have been demonstrated to increase in yield when exposed to a low-intensity heat wave (Thomey and others 2019). We also point out that in future climate scenarios, atmospheric CO_2 is increased and Agro-IBIS captures the response of plant physiology to these changes using observational data for calibration and validation (Twine and others 2013).

Crop yield increases were also evident under BC scenarios, when climate change was not present to extend the growing season. This may be explained as biogeochemical processes also do not remain static across time, even under consistent climatic and land management conditions, and scenarios led to increases of soil NO_3 concentrations of 20%. Higher concentrations of soil NO_3 signify an increase in available N for mineralization, supporting observed increases in crop yield (Bundy 2005; Laboski and others 2012; Van Meter and others 2018). Some of this increase is supported by increases in soil C in the baseline climate scenario. The total annual N mineralization in this region is approximately 80–120 kg N/ha (Kucharik and Brye 2003). This supports approximately 50% of total corn uptake for contemporary yields, and thus increases in N mineralization resulting from increasing soil C could both support higher yields but could also cause increases in nitrate leaching depending on plant demand for nitrogen, and how much mineralization is occurring outside of the period of active nitrogen uptake by plants.

Although soil C changes were minimal, a reduction in nutrient applications was associated with a loss of soil C. Declines in soil C may be attributed to a decrease in available N for mineralization and reduced soil C inputs associated with reduced crop yield. Land cover and land management changes that could promote increased C uptake and soil C sequestration (e.g., longer growing seasons, CO_2 fertilization) appear to be overwhelmed by the effect of climate for our scenarios (Bellamy and others 2005), resulting in a small loss of soil C in all scenarios under climate change. Our results depict the greatest amount of soil C lost under a WDC indicating that increases in air and soil temperature likely increased microbial activity and soil respiration (Davidson and Janssens 2006), overpowering potential C sequestration associated with increased net primary productivity (NPP) and reduced decomposition rates associated with a decrease in precipitation and lower water filled pore space. However, these model results need to be reconciled with recent experimental results indicating greater Soil C storage under drier conditions, irrespective of temperature (Cates and others 2019).

Modeled soil C changes were generally consistent with the findings of (Bellamy et al. 2005), which indicated that across England and Wales, soil C was lost regardless of land management. Slight reductions and minimal responses of soil C, even under perennial grass systems, are also supported by ongoing long-term field research in the Yahara River watershed (Sanford and others 2012) and the upper Midwest generally (Fornara and others 2020). Additionally, the composition of perennial grass systems may influence C sequestration potential. Perennial grass systems containing a higher composition of C_4 to C_3 grasses may store more C (Spiesman and others 2017). Our scenarios did not alter the ratio of C_4 to C_3 perennial grass, which may have limited the potential for soil C sequestration.

From Scenarios to Reality

Although scenarios can be a useful way to visualize our future, the transitions from scenario development to on-the-ground implementation can prove complex and daunting. Transformative change requires a shift in values that encompasses changes in policy, government incentives, and consumer choices, as well as changes to management by farmers. Additionally, due to the legacy stores of phosphorus within the soil, improvements to water quality are delayed. As a result, managing the land for water quality improvements will require a substantial time investment. Some existing practices could be implemented in combination or at larger scales, offering examples of potential pathways to bridge scenario development with implementation. For instance, the creation of the Conservation Reserve Program (CRP) has provided land owners with an economic incentive to voluntarily keep land out of production. As a result, the CRP program is credited with reducing soil erosion by approximately 1 ton per acre during the 1980's (Goodwin and Smith 2003). Additionally, farmers have integrated livestock and crop systems through grazing for millennia (Russelle and others 2007). Although not completely comparable to our scenarios, the use of perennial forage showcases an option in which rotational grazing may reduce current stressors such as limited biodiversity (Skopec and others 2018), greenhouse gas emissions (Jackson and others 2015), profitability (Dartt and others 1999; Hanson and others 2013), feed production (Oates and others 2011), manure and fertilizer application, and number of cattle (Russelle and others 2007; Sulc and Tracy 2007; Wiesner and others 2020). Alternatively, the use of perennial grass as a cellulosic biofuel has potential to generate economic profitability if policy reflects second-generation renewable fuel as a priority (Sanderson and Adler 2008; Porter and others 2015; Mitchell and others 2016; Oates and others 2016; Robertson and others 2017; Gelfand and others 2020). Additionally, advancements in crop breeding that focus on improving perennial grain crops offer promise for incorporating perennial plants into the landscape (Culman and others 2013; Lubofsky 2016).

Policy and economic incentives have promoted agricultural intensification, using subsidies and crop insurance subsidies to prop up an unsustainable system of agriculture. By continuing to incentivize corn and soybean production, subsidies promote a business as usual approach within our agricultural system, despite the environmental ramifications. Previous research indicates that crop insurance subsidies encourage crop production on marginal land that is more susceptible to erosion and flooding (Goodwin and Smith 2003; Lubowski and others 2006). Additionally, over the last six years, without subsidies, corn was profitable a total of zero years in the USA (USDA 2019). If federal subsidies and government programs continue to conflate the economic value of traditional row cropping systems, growers and consumers alike will be disadvantaged.

Consumer demand and a shift in economic markets will also be necessary in transforming our agricultural system. Theoretically, a decrease in meat and dairy consumption would significantly reduce the amount of animals stocked on our agricultural landscapes, specifically reducing manure production as well as reducing the amount of crop production required for animal feed. However, recent declines in milk demand have not had this effect, indicating the need for supply management and incentives for alternative production approaches. Changes such as these must be offset by new revenue sources for farmers and growers. To more accurately represent the benefits of ecosystem services within our economic markets, societal demand for such services will have to be harnessed. Past research has highlighted citizens' willingness to pay for maintenance or improvements of certain regulating ecosystem services (Mitchell and Carson 1981; Jordan and Elnagheeb 1993; Loomis and others 2000; Kragt and others 2016). As a result, ecosystem service markets are arising as a means of paying farmers and ranchers for regulating services such as carbon sequestration and water quality improvement (Bohlen and others 2009; Grolleau and McCann 2012; Rodríguez-Ortega and others 2014). Continuing to implement ecosystem service markets will be a complex process and must consider ecosystem service capacity, ecological pressures, ecosystem service demand, and ecosystem service flow (Villamagna and others 2013; Andersson and others 2015).

Study Limitations

In our study, scenario development focused on the agricultural portion of the landscape but ignored urbanization. However, continued urbanization will influence many of the ecosystem service indicators studied. Similar to increasing perennial grassland scenarios, an increasing urban footprint will decrease cropland and result in more concentrated application of nutrients. Furthermore, the increase in impervious area will increase runoff into our waterways and increase the ''flashiness'' or hydrologic response of the region to extreme rainfall events (Usinowicz and others 2017). We point readers to the work of (Carpenter and others 2015; Booth and others 2016; Motew and others 2017) for future scenarios in the Yahara River watershed by 2070 that do incorporate urban and societal changes. Additionally, while we converted some marginal land from cropland to perennial grassland, we were not able to restrict conversions to marginal land alone. In an effort to depict more realistic management choices, we also chose not to reduce manure application quantity under scenarios focused on increasing perennial grassland cover alone. As a result, the total amount of manure in the watershed did not change for scenarios focused on increasing perennial grassland, but the area available for spreading decreased in some instances. Additionally, our scenarios modeled a reduction in nutrient application through a corresponding reduction in animal units on the landscape. By taking this approach, we excluded the role of manure digesters and other nutrient removal systems that may aid in reducing total nutrient application to the landscape without reducing animal units. Furthermore, our study design did not target areas of disproportionate nutrient loss, which may have improved water quality with lower costs to other ecosystem services.

Additionally, model limitations exclude the influence of pests and weeds on crop yield. Specifically, crop yield and biomass yield are modeled as direct functions of climate and weather, excluding the role of pests, disease, and weeds in altering yields. As the climate changes, it is likely insects will develop new life cycle spans and geographic ranges, possibly hindering crop production through range expansion, higher abundance, and increased crop vulnerability (Doll and Baranski 2011; Hatfield and others 2011; IPCC 2014). Additionally, weeds are likely to increase in biomass under conditions of increased atmospheric CO_2 and elongated growing seasons, promoting increased competition of resources between weeds and crops (Wisconsin Initiative on Climate Change Impacts 2011; Zhao and others 2017).

Conclusions

Our study demonstrated that the substantial reductions in N and P losses to the environment that are required to improve water quality are possible, but will require transformative change in agricultural land use and land cover. In addition, the sooner these changes are implemented, the more quickly they will combat the impact of legacy N and P in the linked land–water system, especially under changing climate. The only scenario that achieved a 50% reduction in P yield and nitrate leaching was transforming half the agriculture landscape from annual grain production to perennial grass with a concurrent 50% reduction in manure and fertilizer to remaining cropland. Furthermore, focusing on water quality improvements resulted in tradeoffs with crop production and soil C.

Although our results suggest monumental shifts in land use and land cover are required to improve water quality, we show that they are not out of reach or impossible, even under alternative climate change scenarios. Our current land management and land use trajectory will require more significant, disruptive, and costly changes the longer we wait to adapt our agricultural ecosystems.

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