Environmental Science & Technology

Article

Cite This: Environ. Sci. Technol. 2019, 53, 1344−1352

pubs.acs.org/est

Cropping System Diversity Effects on Nutrient Discharge, Soil Erosion, and Agronomic Performance

Natalie D. Hunt,[*,†] Jason D. Hill,[†] and Matt Liebman[‡]

[†]Department of Bioproducts and Biosystems Engineering, University of Minnesota, St. Paul, Minnesota 55108, United States

[‡]Department of Agronomy, Iowa State University, Ames, Iowa 50011, United States

Supporting Information

ABSTRACT: Nutrient, herbicide, and sediment loading from agricultural fields cause environmental and economic damage. Nutrient leaching and runoff pollution can lead to eutrophication and impaired drinking water resources, while soil erosion reduces water quality and agronomic productivity. Increased cropping system diversification has been proposed to address these problems. We used the ArcSWAT model and long-term Iowa field experimental measurements to estimate eutrophication and erosion impacts of three crop rotation systems under two weed management regimes. Rotations were comprised of 2-year corn−soybean, 3-year corn−soybean−oat/clover, and 4-year corn−soybean−oat/alfalfa−alfalfa systems. All were managed with conventional or low herbicide applications. Total N and P runoff losses were up to 39% and 30% lower, respectively, in the more diverse systems than the 2-year corn−soybean system, but NO_3^--N leaching losses were unaffected by cropping system. Diversification reduced erosion losses up to 60%. The 3- and 4-year systems maintained or increased crop yields and net returns relative to the 2-year conventional system. Reductions in herbicide use intensity generally did not affect nutrient and sediment losses nor crop yields and profitability. These results indicate that diversifying the corn−soybean rotation that dominates the central United States could reduce water nutrient contamination and soil erosion while maintaining farm productivity and profitability.

■ INTRODUCTION

A significant agricultural challenge of the 21st century is providing sufficient food, feed, and fuel for an increasing global population without degrading the planet's natural resources and productive capacity.[1−3] Consequently, balancing crop productivity, profitability, and maintenance or improvement of soil and water quality and biodiversity will be critical to meeting these goals.[4,5]

Current levels of agricultural productivity are closely linked to agrichemical use. Following World War II, lower commercial fertilizer and herbicide costs from improved manufacturing technologies and infrastructure allowed farmers to replace traditional methods of soil and weed management, including crop rotation, cultivation, and manuring strategies, with simplified cropping systems and synthetic fertilizers and herbicides. Between 1960 and 1990, global synthetic nitrogen use increased 700% and phosphorus use increased more than 300%.[6] From 1952 to 2008, application of herbicides to hectares planted with corn in the United States rose from 10% to >90%.[7]

While these changes have led to large increases in crop productivity, including a doubling of global cereal production and a 3-fold increase in production of vegetable-based proteins since the early 1960s, they have also been characterized by increased expenditures on purchased inputs and increased nonpoint pollution of surface and groundwater systems.[2,8−10] Surface water eutrophication drives increased algae growth and leads to reductions in dissolved oxygen content in the water column due to algal decomposition, which can result in reductions of populations of other aquatic organisms.[11] Nitrate leaching into groundwater systems can also increase costs of drinking water treatment and can pose threats to human health, particularly for infants.[12] Phosphorus, another driver of eutrophication, can lead to algal blooms of cyanobacteria, resulting in harm to human and animal health.[6]

Excess nutrients entering water bodies by agricultural runoff and leaching are often the result of an overabundance or asynchrony of applied nutrients between application and crop uptake. When more nutrients are applied than are taken up by crops, soil nutrient enrichment occurs, rendering a field susceptible to runoff or leaching losses under certain precipitation conditions.[9]

One approach for reducing the environmental impacts of conventional cropping systems in the U.S. Midwest is cropping system diversification. Increasing the length of corn- and soybean-based rotation systems with forage crops and small grains and applying organic matter amendments can boost crop yields[13−15] while reducing soil erosion[16] and risks of eutrophication due to runoff and leaching.[17−20] Increased crop

Received: April 24, 2018
Revised: December 18, 2018
Accepted: January 4, 2019
Published: January 4, 2019

DOI: 10.1021/acs.est.8b02193
Environ. Sci. Technol. 2019, 53, 1344−1352

rotation diversity with concomitant increases in the diversity of associated management practices can also disrupt weed life cycles, thereby reducing weed survival, reproductive output, and biomass production and enhancing weed suppression with lower reliance on herbicides.[21−24] As populations of a rising number of weed species evolve resistance to a wide range of herbicides, cropping system diversification has been identified as a key resistance management strategy.[25] Incorporating a reduced herbicide application regime into an increasingly diverse cropping system may not only suppress weeds effectively but also significantly reduce toxicity impacts to freshwater bodies in agricultural landscapes.[23,24]

Cropping system diversification is often linked to integration with livestock production. In integrated systems, grain concentrates and forages are fed to livestock and manure is used as a nutrient source for crops.[26] In addition to reducing requirements for purchased fertilizers, the soil-related benefits of this practice include improvements in soil carbon storage and microbial biomass, soil physical structure, plant-available nitrogen, and infiltration and retention of water.[27,28] Manure transfer between on-farm enterprises or neighboring farms provides an opportunity to integrate crop and livestock operations within a watershed and can alleviate costs associated with manure storage, handling, and disposal.[26]

The objective of this study is to extend previous findings by Davis et al.[23] and Hunt et al.[24] by estimating the potential eutrophication loading and erosion loss from a watershed under three crop rotation systems and two herbicide regimes. We used empirical data collected from 2008 to 2016 as well as modeling analyses to make the estimates. We predicted that soil erosion and nutrient losses would decrease as cropping system diversification increased. We also expected that a reduction in herbicide use intensity would have little or no impact on erosion and nutrient losses for the different rotation systems. On the basis of our previous work, we expected that the primary agronomic functions of crop productivity, weed suppression, and net returns to land and management would be sustained or enhanced under system diversification and largely unaffected by the herbicide regimes we assessed.

■ MATERIALS AND METHODS

Experimental Design. Empirical measurements were made at Iowa State University's Marsden Farm, which is situated in Boone County, IA (42°01′N, 93°47′W). All soil types at the experimental site are Mollisols. The site does not have a subsurface tile drainage system.

Experimental treatments were established in 2002. Preceding setup of the experiment, the site was used for corn and soybean production for at least 20 years using conventional management practices. Experiment plots were organized in a randomized complete block design, with four replicates of each crop phase of each rotation system present every year. Main plots, each 18 m × 85 m, comprised three different crop rotation systems. Starting in 2008, each main plot was split into two herbicide regimes, each applied over 9 m × 85 m subplots, generating a 3 × 2 factorial set of treatments.[24] Plots were managed with conventional farm machinery.

Three crop rotation systems appropriate for the Midwest United States were incorporated in this study: a 2-year corn and soybean rotation and two more diverse systems: a 3-year corn−soybean−oat/red clover rotation and a 4-year corn−soybean−oat/alfalfa−alfalfa rotation. The 3-year rotation system consisted of planting oat with red clover following the soybean crop phase; oat grain and straw were harvested in midsummer, oat stubble was mowed for weed control, and red clover grew in the stubble until it was incorporated with a moldboard plow in the late fall. The 4-year rotation system consisted of planting oat with alfalfa following the soybean crop phase; oat grain and straw were harvested in midsummer, oat stubble was mowed once, and the alfalfa was left to grow into the fourth crop phase, when it was harvested three or four times, before being moldboard plowed in the late fall of the fourth year.[20,23,24] The more diverse cropping systems were representative of integrated farms that incorporate livestock through forage production and manure recycling. Synthetic fertilizers were applied to corn in the 2-year system at conventional rates based on soil tests. Composted cattle manure was applied in the fall prior to the corn phase, and reduced rates of synthetic fertilizers were applied to corn in the 3- and 4-year rotations (Table 1).

Table 1. Nutrient N and P Applications via Fertilizer and Composted Manure During 2008−2016 Averaged over All Crop Phases of Each Rotation System

	crop rotation system		
	2 year (kg ha^{-1} yr^{-1})	3 year (kg ha^{-1} yr^{-1})	4 year (kg ha^{-1} yr^{-1})
fertilizer N	89	13	8
fertilizer P	15	0	9
manure N	0	46	34
manure P	0	15	11

Alternative herbicide application regimes were applied to the corn and soybean crop phases within each rotation system. We implemented a conventional treatment (CONV) comprising broadcast applications of pre- and postemergence materials and a low-herbicide regime (LOW) involving postemergence banded herbicide application followed by one or two passes with an interrow cultivator. Oat stubble in the 3- and 4-year systems was mowed to suppress weeds 19−28 days after grain harvest. Repeated cutting of alfalfa hay suppressed weeds in the alfalfa crop grown in the 4-year system. Details of the management of the experimental plots are given in Davis et al.,[23] Tomer and Liebman,[20] and Hunt et al.[24]

During the 2008−2013 field seasons, as part of a related study examining contrasting "technology packages" of crop genotypes paired with particular herbicide regimes, a glyphosate-resistant variety of soybean was used in the CONV herbicide regime, while a nonglyphosate-resistant soybean variety was used in the LOW herbicide regime.[29] From 2014 to 2016, the same glyphosate-resistant soybean variety was used for both herbicide treatments, thus avoiding confounding of crop genotype and weed management strategies.[24] Glyphosate was used consistently in the CONV herbicide treatment but was not used in the LOW herbicide treatment during 2008−2016.

Tillage practices varied among rotation systems. The 2-year rotation was chisel plowed in the fall following corn harvest and surface cultivated in the spring following soybean harvest. Similar practices were used following corn and soybean phases of the 3- and 4-year systems, but additionally, soybean residue was disked before planting oat and red clover or oat and alfalfa, and red clover and alfalfa were moldboard plowed in the fall preceding corn production. The effects of these tillage practices were intertwined with those of the crop rotation

DOI: 10.1021/acs.est.8b02193
Environ. Sci. Technol. 2019, 53, 1344−1352

systems in which they were used and were part of system-level comparisons in which suites of farming practices varied across the different rotation systems and herbicide regimes.

Model Calibration and Parameterization. ArcSWAT is a hydrologic process model that estimates nutrient and sediment fluxes within a watershed. It was applied to the Marsden Farm watershed for 2008–2016, and generated annual estimates of total nitrogen runoff, total phosphorus runoff, sediment loading from erosion, and nitrate leaching loads at the scale of the watershed on a per-hectare basis (Figure 1).

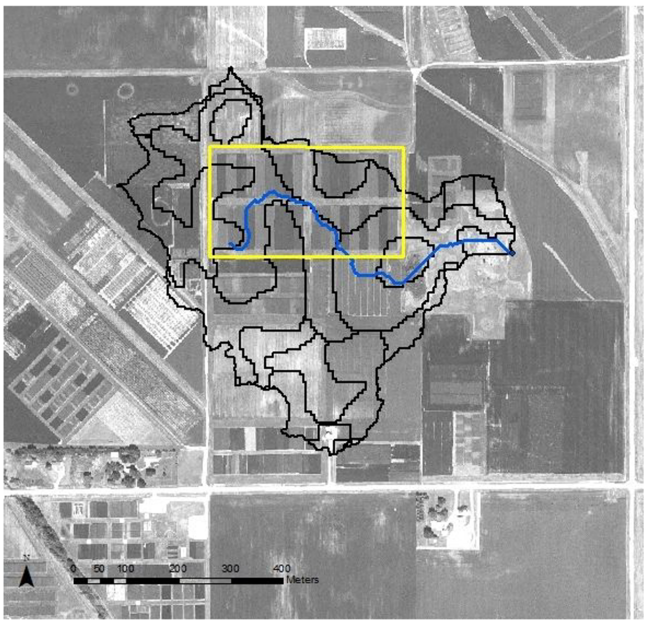

Figure 1. Aerial view of the Marsden Farm experiment boundary shown in yellow, ArcSWAT-created watershed with representative Hydrologic Response Units shown in black, and simulated water flow in blue.

Because no surface water bodies exist within the Marsden Farm watershed, ArcSWAT was calibrated for a 31 km^2 watershed using U.S. Geological Survey streamflow data (05451080) on the South Fork of the Iowa River near Blairsburg in Hamilton County, IA. This site is located at 42°32′37″N, 93°35′22″W and was selected due to the similarity of soil types to those in the Marsden Farm watershed, duration of available streamflow data for comparison, and similarity of land use. Monthly and daily USGS streamflow measurements were obtained for 2006–2016, and the highest rated quality data were used in the calibration. U.S. Department of Agriculture National Agricultural Statistics Service (NASS) annual corn and soybean yield measurements for Hamilton County were used for comparison against ArcSWAT dry yield estimates (https://quickstats.nass.usda.gov).

A 2-year corn–soybean rotation was used to drive hydrological and productivity dynamics for the calibration site. Daily climate data included precipitation, solar radiation, relative humidity, wind speed, and maximum/minimum air temperature, and were obtained from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) program in the format appropriate for ArcSWAT inputs.[30] Precipitation data for calibration were derived from a climate station near the Blairsburg site. The model was run for 4 years to equilibrate to steady state conditions, and from there the model ran for the time period parallel to available USGS streamflow and yield data and Daily Erosion Project (DEP) surface runoff estimates (https://dailyerosion.org). Criteria for evaluating model performance included visual assessment of hydrographs, Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and coefficient of determination (R^2).[31] Model parameters evaluated for performance included average daily streamflow over a monthly time step (m^3 s^{-1}), annual dry corn and soybean yields (Mg ha^{-1}), mean annual surface runoff estimates (mm), and annual evapotranspiration (mm). Calibration results are reported in the Supporting Information.

Following calibration within the Hamilton County watershed, ArcSWAT was applied to the Marsden Farm watershed. Only site-specific parameter values changed between the two watersheds, including climate, soils, elevation, topography, land cover, and absence of subsurface tile drainage, thus reflecting characteristics specific to the Marsden Farm site.

ArcSWAT Parameters. Simulated nutrient transport within the watershed was driven by the hydrologic cycle in ArcSWAT, which disaggregated the study site into multiple sub-basins to model all iterations of soil types and management practices within the watershed. The Marsden Farm watershed was comprised of seven sub-basins, each representing a distinct topography, soil type, and management operation (Figure 1).

The modeling unit was comprised of the land cover, soil type, and hillslope of the Marsden Farm, as represented by a 3-m LiDAR digital elevation model (https://datagateway.nrcs.usda.gov/), SSURGO soil classification (https://datagateway.nrcs.usda.gov/), and the 2012 NLCD cropland data set (https://nassgeodata.gmu.edu/CropScape/). Hydrologic Response Units (HRU) were generated to represent a modeling unit comprised of soil type, land cover, slope, and management (Figure 1). Dominant soil types represented in the Marsden Farm watershed included Canisteo silty clay loam (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls, 0–2% slope) (7.0% of watershed area), Webster silty clay loam (fine-loamy, mixed, superactive, mesic, Typic Endoaquolls, 0–2% slope) (21.5%), Harps clay loam (fine-loamy, mixed, superactive, mesic Typic Calciaquolls, 0–2% slope) (15.9%), Nicollet loam (fine-loamy, mixed, superactive, mesic, Typic Hapludolls, 2–5% slope) (26.5%), and Clarion loam (fine-loamy, mixed, superactive, mesic, Typic Hapludolls, 2–5% slope) (25.0%).[32] Average slope for the watershed was 1.7%, and all biophysical crop characteristics were represented by the agricultural land cover database type.

The model was run from 1991 to 2016 and included a 17-year spin-up period of generic agricultural row crop production to equilibrate the soil pools to steady state conditions. Following this, ArcSWAT simulated the rotation systems as described in the experimental design. Modeling scenarios included specific dates for planting, nutrient application, tillage, and harvest derived from experiment logs, and represented all rotation system and herbicide regime characteristics. The ArcSWAT Land Cover/Plant Growth Database contains crop-specific parameters that characterize specific crop traits. In the absence of Marsden Farm-specific physiological crop data, we used parameter values from published literature for calibration. Within the field experiment, each crop phase in each rotation system and herbicide regime was present every year. This was replicated in the ArcSWAT modeling environment by

DOI: 10.1021/acs.est.8b02193
Environ. Sci. Technol. 2019, 53, 1344–1352

Table 2. Agronomic Performance Metrics As Affected by Contrasting Rotation Systems and Herbicide Regimes[a]

rotation[b]	herbicide	annual corn yields (Mg ha^{-1})	annual soybean yields (Mg ha^{-1})	net returns (\$ ha^{-1})	weed biomass in corn and soybean (kg ha^{-1})
2 year	CONV	10.2 (0.3)	2.8 (0.2)	833 (71)	9.7 (2.6)
	LOW	10.1 (0.4)	2.5 (0.2)	809 (72)	26.4 (6.5)
3 year	CONV	10.5 (0.4)	3.2 (0.2)	863 (57)	14.4 (6.7)
	LOW	10.5 (0.4)	3.1 (0.1)	883 (59)	94.2 (29.0)
4 year	CONV	10.6 (0.3)	3.3 (0.2)	871 (60)	7.7 (2.4)
	LOW	10.6 (0.3)	3.3 (0.1)	893 (61)	18.9 (4.4)
		statistical results			
main effect: rotation[b]		annual corn yields (Mg ha^{-1})	annual soybean yields (Mg ha^{-1})	net returns (\$ ha^{-1})	weed biomass in corn and soybean (kg ha^{-1})
2 year		10.1 (0.2)b	2.6 (0.1)b	821 (100)	18.1 (6.5)b
3 year		10.5 (0.3)a	3.2 (0.1)a	873 (81)	69.4 (31.9)a
4 year		10.6 (0.2)a	3.3 (0.1)a	880 (86)	20.7 (6.4)b
		statistical results			
main effect: herbicide[b]		annual corn yields (Mg ha^{-1})	annual soybean yields (Mg ha^{-1})	net returns (\$ ha^{-1})	weed biomass in corn and soybean (kg ha^{-1})
CONV		10.4 (0.2)	3.1 (0.1)a	854 (72)	13.4 (3.9)b
LOW		10.4 (0.2)	2.9 (0.1)b	862 (73)	58.7 (21.6)a
		mixed effect modeling results			
source of variation[c]		annual corn yields (Mg ha^{-1})	annual soybean yields (Mg ha^{-1})	net returns (\$ ha^{-1})	weed biomass in corn and soybean (kg ha^{-1})
ROT		**	***	NS	**
HERB		NS	*	NS	*
ROT × HERB		NS	NS	NS	NS

[a]Means and their standard errors are shown for raw data. Parametric linear mixed effects analyses were performed on untransformed data for annual corn yields, soybean yields, and annual net returns to land and management and on ln-transformed data for weed biomass in corn and soybean. Within columns, means followed by the same letter are not significantly different, as determined by Tukey's HSD test (α = 0.05). [b]ANOVA results. [c]Significance is described as follows: NS p > 0.05, and * p < 0.05, ** p < 0.01, *** p < 0.001.

simulating multiple sets of each crop phase within each rotation system and herbicide regime over 1 year across each HRU within the entire watershed. Averages of the modeling outputs were calculated across the staggered simulations, years, and HRUs, and were expressed in per-hectare units.[30] To reconcile the empirical data with the modeling outputs, we assumed that the plot outputs were representative of the average HRUs across the Marsden Farm watershed. Watershed scale values were expressed in per-hectare units to align with the per-hectare plot scale outputs.

Performance Metric Calculations. Performance metrics for the contrasting crop rotation systems and herbicide regimes included annual N and P in runoff water, NO_3^--N in leached water, and eroded sediment yield per land area (ha^{-1}). Agronomic performance metrics included net returns to land and management (\$ ha^{-1}), dry corn and soybean yields (Mg ha^{-1}), and weed biomass (kg ha^{-1}) in corn and soybean crops.

Surface runoff nutrient loads were represented by total nitrogen and total phosphorus loss, calculated with the following equations

$$\text{total nitrogen runoff (kg N ha}^{-1}) = \Sigma(\text{particulate N, dissolved N})$$

$$\text{total phosphorus runoff (kg P ha}^{-1}) = \Sigma(\text{particulate P, dissolved mineral P})$$

where particulate N was comprised of organic N, dissolved N was comprised of NO_3^--N, particulate P was comprised of organic P and sediment P, and dissolved mineral P was comprised of soluble P.[33] While ammonium (NH_4) is a significant contributor to dissolved N, ArcSWAT does not directly simulate NH_4 runoff from a watershed, and it was thus excluded from the dissolved N content.[33] Erosion losses (Mg sediment ha^{-1}) were calculated in ArcSWAT using the Modified Universal Soil Loss Equation, which is driven by the following factors: soil erodibility (K), cover and management (C), support practices (P), slope length and slope angle (LS), and coarse fragment content (CFRG).[34] Nitrate-N leaching was also simulated and was estimated in kg NO_3^--N ha^{-1}.[33] All simulations were run in ArcSWAT 2012.10.3.18 through ArcGIS 10.4.1.

Annual dry corn grain and soybean yields were measured at the plot scale and were present for each block within each rotation system from 2008 to 2016. Economic returns to land and management at Marsden Farm were calculated at the plot level for each rotation system and herbicide treatment using field operations logs for labor demands, seed and chemical inputs, crop yields, and year- and product-specific databases for materials costs, operations costs, and crop prices. Input costs included seeds, fertilizers, and herbicide products, and were obtained from local retailers and Iowa and Midwest-based reports. Labor, fuel, and machinery cost data were derived from Iowa State University Extension and Outreach publications. Costs associated with manure application in the 3- and 4-year rotation systems assumed that manure was produced by on-farm or neighboring-farm livestock with the costs of labor and machinery required for application; no cost was assigned to the manure itself, which was assumed to be a waste product from the livestock enterprise. This approach is appropriate with the caveat that if crop farmers purchased manure, net returns would be reduced.[26] Iowa market year crop prices were obtained from the USDA National Agricultural Statistics Service, and gross revenue was calculated as the product of crop price and yield. Costs and revenue from mortgage, lease, and government payments were excluded from the study. Net returns to land and management were

DOI: 10.1021/acs.est.8b02193
Environ. Sci. Technol. 2019, 53, 1344−1352

calculated as the difference between gross returns and nonland and nonmarketing costs. Calculations of net returns to land and management are described in detail in Davis et al.,[23] Hunt et al.,[24] and in the Supporting Information.

Data were analyzed with linear mixed effects models where crop rotation system, herbicide regime, and the interaction between them were treated as fixed effects and the significance of F values was assessed using $\alpha = 0.05$. For metrics that varied among replicate blocks (e.g., net returns, corn and soybean yields, and weed biomass), we included both year and block in the models as random effects. For response variables that did not vary among replicate blocks (e.g., total N runoff ha^{-1}, total P runoff ha^{-1}, and eroded sediment yield ha^{-1}), only year was included as a random factor in the models. To meet assumptions of homoscedasticity, phosphorus runoff loads per hectare and nitrogen loads per hectare were natural log transformed before analysis. Following the mixed effects modeling, Tukey's HSD multiple comparison tests (α = 0.05) were applied for pairwise comparisons of means. The eroded sediment yield response variable did not meet ANOVA assumptions of homoscedasticity, so a Welch's test for equal means was conducted, followed by pairwise means comparisons using the nonparametric Wilcoxon Method, where rotation × herbicide treatment was treated as a single fixed effect. All statistical analyses were executed using JMP Pro 13 software (JMP Software, SAS Institute, Inc.).

■ RESULTS

Agronomic Performance. Rotation system but not herbicide regime had a significant effect on dry corn yields, with the 3- and 4-year systems producing 4.5% higher yields than the 2-year system (Table 2). Corn yields at the Marsden Farm site were slightly greater than yields reported for Boone County for 2008−2016 (9.3 Mg ha^{-1}). Rotation system and herbicide regime each had a significant effect on soybean yields, with the more diverse systems having 23−27% greater yields than the corn−soybean rotation and CONV soybeans having 6% greater yields than LOW soybeans (Table 2). Observed Marsden soybean yields were similar to reported Boone County averages at 2.9 Mg ha^{-1} for the same time period (https://quickstats.nass.usda.gov).

Because differences in soybean yields between herbicide regimes may have been related to differences in soybean cultivar identity (cultivars were confounded with herbicide regime in 2008−2013, though not in 2014−2016), we compared soybean yield among three categories: the conventional herbicide regime with a soybean cultivar genetically engineered for glyphosate tolerance (ConvGE); the low herbicide regime with the glyphosate-tolerant cultivar (LowGE); and the low herbicide regime used with a nongenetically engineered cultivar not tolerant of glyphosate (LowNonGE). ConvGE yields did not differ from LowGE yields, whereas ConvGE yields were 12% higher than those from LowNonGE (Table 3).

Net returns to land and management were unaffected by rotation system or herbicide regime, with a mean value of \$859 ha^{-1} (Table 2).

Rotation and herbicide regime each had a significant effect on weed biomass in corn and soybean crops (Table 2), where greater weed biomass was observed in the LOW herbicide regime and in the 3-year rotation system. The 2- and 4-year systems were comparable in terms of weed biomass in corn and soybean crops, with a mean weed biomass of 19 kg ha^{-1}.

Table 3. Annual Dry Soybean Yields in Contrasting Genotype-Herbicide Regimes Averaged over Rotation Systems[a]

genoytype-herbicide regime	soybean yields (Mg ha^{-1})
ConvGE	3.18 (0.07)a
LowGE	3.10 (0.05)ab
LowNonGE	2.78 (0.08)b

[a]ConvGE: conventional herbicide regime with glyphosate tolerant soybean cultivar. LowGE: low herbicide regime with glyphosate tolerant cultivar. LowNonGE: low herbicide regime with nongenetically engineered cultivar not tolerant of glyphosate.

Across all rotation systems, average corn and soybean weed biomass was 36 kg ha^{-1}(Table 2). As a proportion of mean dry yields for the different crops, weed biomass ranged from 0.3% in corn, 1.1% in established alfalfa, 1.4% in soybean, to 5.1% in oat, averaged across all rotation systems and herbicide regimes.

Marsden Farm Simulation Results. Dry yields of corn, soybean, oat, and alfalfa simulated by ArcSWAT were compared against measured Marsden Farm yields and NASS yield measurements for 2008−2016. All simulated crop yields were within 16% of reported Marsden Farm yields and within 22% of reported Boone County yields (Figure 2).

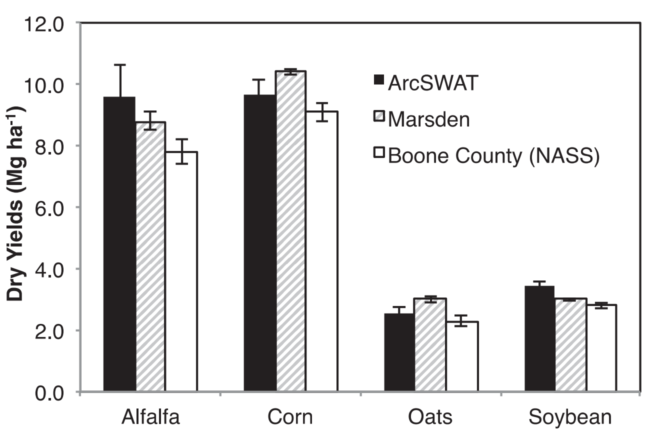

Figure 2. Mean annual dry yields as simulated by ArcSWAT and measured at the Marsden Farm experiment and commercial farms in Boone County, IA, for 2008−2016.

Eroded Sediment Yield. Because assumptions of homoscedasticity were not met for eroded sediment yield, possible differences among rotation systems and herbicide regimes were evaluated using the Welch's test, where rotation × herbicide treatment was treated as a fixed effect with six levels. This was followed by a nonparametric comparison of means via the Wilcoxon method. There was no significant effect of herbicide regime alone ($p > 0.05$), but rotation system had a significant effect on reducing sediment yields and increasing corn and soybean yields at the same time (Table 2). The addition of oat and alfalfa to the 2-year rotation resulted in a 60% reduction ($p < 0.05$) in sediment loading on a per-hectare basis (Table 4).

Nitrogen and Phosphorus Runoff Estimates. Rotation system alone had a significant ($p < 0.05$) effect on total nitrogen runoff on a per-hectare basis (Table 4). On a per-hectare basis, adding at least one additional crop phase to the corn and soybean system resulted in 36−39% reductions in nitrogen runoff ($p < 0.05$) (Table 4).

DOI: 10.1021/acs.est.8b02193
Environ. Sci. Technol. 2019, 53, 1344−1352

Table 4. Soil Sediment Yields, Total N Runoff, Total P Runoff, and Nitrate-N Leaching Losses As Affected by Contrasting Rotation Systems and Herbicide Regimes[a]

rotation	herbicide	soil sediment yields (Mg ha^{-1})a	total N runoff (kg N ha^{-1})	total P runoff (kg P ha^{-1})	NO_3^--N leached (kg NO_3^--N ha^{-1})
2 year	CONV	2.6 (0.5)a	10.0 (1.8)	2.3 (0.5)	20 (7)
	LOW	2.6 (0.5)a	10.0 (1.8)	2.2 (0.4)	20 (7)
3 year	CONV	1.7 (0.3)ab	6.5 (1.0)	1.6 (0.2)	22 (6)
	LOW	1.6 (0.3)ab	6.3 (1.0)	1.4 (0.2)	22 (6)
4 year	CONV	1.0 (0.2)b	6.2 (0.9)	1.6 (0.2)	15 (5)
	LOW	1.0 (0.2)b	6.1 (0.9)	1.5 (0.2)	15 (4)
		statistical results			
main effect: rotation[b]		soil sediment yields (Mg ha^{-1})	total N runoff (kg N ha^{-1})	total P runoff (kg P ha^{-1})	NO_3^--N leached (kg NO_3^--N ha^{-1})
2 year		2.6 (0.3)a	10.0 (1.2)a	2.3 (0.3)a	20 (5)
3 year		1.6 (0.2)ab	6.4 (0.7)b	1.5 (0.2)b	22 (4)
4 year		1.0 (0.1)b	6.1 (0.6)b	1.6 (0.2)b	15 (3)
		mixed effect modeling results			
source of variation[c]		soil sediment yields (Mg ha^{-1})	total N runoff (kg N ha^{-1})	total P runoff (kg P ha^{-1})	NO_3^--N leached (kg NO_3^--N ha^{-1})
ROT		***	**	**	NS
HERB		NS	NS	NS	NS
ROT × HERB		*	NS	NS	NS

[a]Means and their standard errors are shown for raw data. Parametric linear mixed effects analyses were performed on untransformed data for NO_3^--N and on ln-transformed data for total N and P losses in runoff. For sediment yields, data were analyzed using the nonparametric Welch's test. For soil sediment yields, means followed by the same letter are not significantly different, as determined by pairwise means comparisons using the Wilcoxon method. For all other metrics, within columns means followed by the same letter are not significantly different, as determined by Tukey's HSD test ($\alpha = 0.05$). [b]ANOVA results. [c]Significance is described as follows: NS $p > 0.05$, and * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Increasing rotation diversity from a 2-year to a 3-year system resulted in a 35% reduction in total phosphorus runoff per-hectare, while adding a fourth year to the 3-year system to make it a 4-year system reduced runoff by 30% compared to the 2-year system (Table 4).

Nitrate Leaching. We observed no significant effect of rotation system or herbicide regime on nitrate-N leaching (Table 4).

DISCUSSION

Rotation system and herbicide regime were significant drivers of the major agronomic functions of crop yield, weed suppression, and net returns to land and management. Rotation was a significant and positive driver of corn and soybean yields, with significant increases observed as at least one crop phase was added to the 2-year rotation. Increasing rotation diversity increased corn yields in the present experiment, perhaps due to enhanced nitrogen fertility from legumes (i.e., red clover and alfalfa)[35,36] and fertility-related and nonfertility-related stimulatory effects of manure.[37] Our results are consistent with those of other studies, which have shown that alternative cropping systems that include inter- or double-cropping or use of green manure can improve crop performance due to increases in soil fertility, enhanced soil structure, and disruption of crop diseases and pests compared to shorter rotations and monocultures.[14]

Higher soybean yields in the longer rotations can be attributed to lower incidence and decreased severity of soybean sudden death syndrome (SDS), a soil-borne disease caused by the fungus *Fusarium virguliforme*.[38] Decreases in soybean yields between the CONV and the LOW herbicide regime can be attributed in part to the confounding effect of herbicide regime and soybean genotype prior to 2014. During 2008−2013, a nongenetically engineered soybean genotype with greater susceptibility to SDS was used with the low herbicide regime, whereas a cultivar genetically engineered for glyphosate tolerance, which also had greater resistance to SDS, was used in the conventional herbicide regime. From 2014 to 2016, the same GE soybean genotype was used in both the conventional and the low herbicide treatments, and there were no significant differences in yield between them.

We found no significant effect of rotation system or herbicide regime on net returns to land and management, revealing potential for increased rotation diversity to reduce impacts to surface water quality in agricultural watersheds while maintaining profitability. These results are consistent with those obtained from a prior study at the Marsden Farm site in which economic returns were maintained among a 2-year corn−soybean rotation managed with conventional herbicide inputs and 3-year and 4-year rotations with small grains, red clover, and alfalfa added to corn and soybean and managed with low herbicide inputs.[23] While annual labor costs increased with rotation diversity (Supporting Information), the allocation of labor requirements varied throughout the growing season. The more diverse cropping systems require increased labor during the summer for small grain and hay harvests, and in the fall after corn and soybean harvests for manure application and tillage operations. The timing of the labor requirements for the 3- and 4-year systems is unlikely to conflict with corn and soybean production, whose labor requirements peak during planting (early spring) and harvesting (late fall). Exceptions would be for the first cut of alfalfa and for cultivations in the low herbicide regime.[26] Increasing crop diversity while maintaining total land area constant would mean lower labor requirements for a given crop. Moreover, if farmers were unable to provide all of the necessary labor themselves, additional off-farm labor might be hired or custom harvesting services might be contracted.

We observed significant effects of rotation system and herbicide regime on weed biomass in corn and soybean crops. The greatest amount of weed biomass was measured in the LOW treatments, largely driven by high weed biomass in the 3-

DOI: 10.1021/acs.est.8b02193
Environ. Sci. Technol. 2019, 53, 1344−1352

year LOW system in 2015. In contrast, weed biomass in the 4-year system was equivalent to that in the 2-year system. Over all rotation systems and herbicide regimes, the percentage of weed biomass relative to harvested crop mass was at most 5.1% in the oat phase and at the minimum less than 1% in corn phases. Incorporation of noncash cover crops can facilitate weed suppression by interrupting the life cycle of certain weed species, and the early spring planting of cash crops such as oat can facilitate competition against warm-season weeds commonly encountered in corn and soybean.[39] In addition to reducing herbicide requirements overall, crop diversification has also been effective in reducing threats from herbicide resistant weeds in the U.S. Northern Plains and Canadian Prairie regions.[25]

We found significant effects of increased cropping system diversity on nutrient and eroded sediment runoff. While we did not observe significant effects of rotation diversity or herbicide regime on NO_3^--N leaching, our simulated leaching patterns were reflective of those measured in empirical studies, in which the 3-year rotation had the highest concentrations of NO_3^--N in drainage water, followed by the 2- and then the 4-year systems.[20] Our nutrient leaching estimates were within the range of values found in the literature for Iowa agricultural systems (13.4−55.8 kg NO_3^--N ha^{-1}).[40−42] Similarly, our estimated nitrogen runoff values were within the range of reported values (3.0−39.6 kg N ha^{-1}), as were our simulated phosphorus runoff values (0.01−3 kg P ha^{-1}).[40−42]

Increasing crop rotation diversity increases system complexity, which can deliver a host of ecosystem services that support the agricultural system, including pest suppression, improved water quality, and increased sediment and nutrient retention.[4] The substitution of synthetic fertilizers with manure can also lead to enhanced environmental performance and lower operation and energy costs over the long term by reducing life cycle impacts associated with the Haber−Bosch process.[36,43,47] On a landscape scale, the use of manure alleviates the burden of a waste product on one farm and turns it into an asset on another, providing opportunities for profit for a diverse array of farming operations.[26]

Oat, red clover, and alfalfa residues can have beneficial effects on cropping system performance, including biological nitrogen fixation and storage for slower release to crops in coming years and enhanced microbial community activity,[32] which facilitates nutrient cycling and enhances the biological and physical soil characteristics.[44] A substantial amount of the nitrogen fixed from the atmosphere by leguminous forage crops such as red clover and alfalfa is returned to the soil pool.[45] Increasing crop residue and biomass cover can also enhance soil water storage and reduce soil water evaporative loss and soil erosion by wind and rain. The addition of crops with extensive and deep rooting systems, such as alfalfa, also delivers physical soil structure enhancements to keep arable soil on the field.[44]

By fine tuning soil nutrient management and use of alternative nutrient sources, we observed significant reductions in sediment and nutrient loads. Not only does this ensure that crop nutrient needs were met, but also impacts on surface water bodies were reduced. The addition of an oat−leguminous crop mixture delivers many benefits to a cropping system, including maintenance of soil structure through an extensive rooting system. The substitution of synthetic nitrogen inputs by biological nutrient sources such as manure and biomass from leguminous forage crops can also contribute to reduced soil carbon loss over the long term.[27,46]

The incorporation of additional crop phases to the corn and soybean rotation resulted in significant reductions in nutrient discharge and sediment erosion while increasing corn and soybean yields and sustaining net returns. At the same time we observed no significant effect of herbicide regime on any runoff impacts, indicating that an alternative herbicide regime can significantly reduce potential toxicity loading with low risk of exacerbating nutrient or sediment runoff problems on fields with low slope and soils with low erodibility potential.[24]

Overall, this study indicates that partial substitution of synthetic fertilizer inputs with composted manure and crop residues could be an important strategy to reduce nutrient and sediment losses to water bodies while maintaining major agronomic functions of productivity and profitability. Extended crop rotation systems and integrated crop−livestock systems should be considered as components for improved nutrient management and soil conservation strategies in the U.S. Midwest and other intensively farmed regions.

■ ASSOCIATED CONTENT

Supporting Information

This information is available free of charge via the Internet at The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b02193.

Detailed information on ArcSWAT calibration and economic data (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: hunt0416@umn.edu.

ORCID

Natalie D. Hunt: 0000-0002-0782-0488

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We express our sincere thanks to Matthew Woods, Ann Johanns, Philip Gassman, Brent Dalzell, James Almendinger, Peter Vadas, and Jaehak Jeong for assistance with data collection and analysis. This research was supported by research grants from the U.S. Department of Agriculture's Agriculture and Food Research Initiative (2014-67013-21712), the Leopold Center for Sustainable Agriculture (2014-XP01), and the U.S. Department of Agriculture Hatch Project (MIN-12-083).

■ REFERENCES

(1) Cassman, K. G. Ecological Intensification of Cereal Production Systems: Yield Potential, Soil Quality, and Precision Agriculture. *Proc. Natl. Acad. Sci. U. S. A.* **1999**, *96* (11), 5952−5959.

(2) Tilman, D.; Cassman, K. G.; Matson, P. A.; Naylor, R.; Polasky, S. Agricultural Sustainability and Intensive Production Practices. *Nature* **2002**, *418* (6898), 671−677.

(3) Rockstrom, J.; Steffen, W.; Noone, K.; Persson, A.; Chapin, F. S.; Lambin, E. F.; Lenton, T. M.; Scheffer, M.; Folke, C.; Schellnhuber, H. J.; Nykvist, B.; deWit, C. A.; Hughes, T.; van der Leeuw, S.; Rodhe, H.; Sorlin, S.; Snyder, P. K.; Costanza, R.; Svedin, U.; Falkenmark, M.; Karlberg, L.; Corell, R. W.; Fabry, V. J.; Hansen, J.; Walker, B.; Liverman, D.; Richardson, K.; Crutzen, P.; Foley, J. A. A Safe Operating Space for Humanity. *Nature* **2009**, *461* (7263), 472−475.

DOI: 10.1021/acs.est.8b02193
Environ. Sci. Technol. 2019, 53, 1344−1352

(4) Robertson, G. P.; Gross, K. L.; Hamilton, S. K.; Landis, D. A.; Schmidt, T. M.; Snapp, S. S.; Swinton, S. M. Farming for Ecosystem Services: An Ecological Approach to Production Agriculture. *BioScience* **2014**, *64* (5), 404−415.
(5) Tian, H.; Lu, C.; Pan, S.; Yang, J.; Miao, R.; Ren, W.; Yu, Q.; Fu, B.; Jin, F.; Lu, Y.; Melillo, J.; Ouyang, Z.; Palm, C.; Reilly, J. Optimizing Resource Use Efficiencies in the Food−Energy−Water Nexus for Sustainable Agriculture: From Conceptual Model to Decision Support System. *Curr. Opin. Environ. Sustain.* **2018**, *33*, 104−113.
(6) Ansari, A. A.; Gill, S. S. *Eutrophication: Causes, Consequences and Control*; Springer, 2014; Vol. 2.
(7) Fernandez-Cornejo, J.; Nehring, R. *Pesticide Use in US Agriculture: 21 Selected Crops, 1960−2008*; Elsevier, 2014.
(8) Robertson, G. P.; Vitousek, P. M. Nitrogen in Agriculture: Balancing the Cost of an Essential Resource. *Annu. Rev. Environ. Resour.* **2009**, *34* (1), 97−125.
(9) Dubrovsky, N. M.; Burow, K. R.; Clark, G. M.; Gronberg, J. M.; Hamilton, P. A.; Hitt, K. J.; Mueller, D. K.; Munn, M. D.; Nolan, B. T.; Puckett, L. J.; Rupert, M. G.; Short, T. M.; Spahr, N. E.; Sprague, L. A.; Wilber, W. G. *Nutrients in the Nation's Streams and Groundwater, 199 2004*; USGS, 2010.
(10) Lassaletta, L.; Billen, G.; Grizzetti, B.; Anglade, J.; Garnier, J. 50 Year Trends in Nitrogen Use Efficiency of World Cropping Systems: The Relationship between Yield and Nitrogen Input to Cropland. *Environ. Res. Lett.* **2014**, *9* (10), 105011.
(11) Galloway, J. N.; Dentener, F. J.; Capone, D. G.; Boyer, E. W.; Howarth, R. W.; Seitzinger, S. P.; Asner, G. P.; Cleveland, C. C.; Green, P. A.; Holland, E. A.; Karl, D. M.; Michaels, A. F.; Porter, J. H.; Townsend, A. R.; Vorosmarty, C. J. Nitrogen Cycles: Past, Present, and Future. *Biogeochemistry* **2004**, *70*, 153−226.
(12) Cassman, K. G.; Dobermann, A.; Walters, D. T. Agroecosystems, Nitrogen-Use Efficiency, and Nitrogen Management. *Ambio* **2002**, *31* (2), 132−140.
(13) Ball, B. C.; Bingham, I.; Rees, R. M.; Watson, C. A.; Litterick, A. The Role of Crop Rotations in Determining Soil Structure and Crop Growth Conditions. *Can. J. Soil Sci.* **2005**, *85* (5), 557−577.
(14) Bennett, A. J.; Bending, G. D.; Chandler, D.; Hilton, S.; Mills, P. Meeting the Demand for Crop Production: The Challenge of Yield Decline in Crops Grown in Short Rotations. *Biol. Rev.* **2012**, *87* (1), 52−71.
(15) Magdoff, F.; Weil, R. R. *Soil Organic Matter in Sustainable Agriculture*; CRC Press: Boca Raton, 2004.
(16) Gantzer, C. J.; Anderson, S. H.; Thompson, A. L.; Brown, J. R. Evaluation of Soil Loss after 100 Years of Soil and Crop Management. *Agron. J.* **1991**, *83*, 74−77.
(17) Blesh, J.; Drinkwater, L. E. The Impact of Nitrogen Source and Crop Rotation on Nitrogen Mass Balances in the Mississippi River Basin. *Ecol. Appl.* **2013**, *23* (5), 1017−1035.
(18) Drinkwater, L. E.; Wagoner, P.; Sarrantonio, M. Legume-Based Cropping Systems Have Reduced Carbon and Nitrogen Losses. *Nature* **1998**, *396* (6708), 262−265.
(19) Gardner, J. B.; Drinkwater, L. E. The Fate of Nitrogen in Grain Cropping Systems: A Meta-Analysis of ^{15}N Field Experiments. *Ecol. Appl.* **2009**, *19* (8), 2167−2184.
(20) Tomer, M. D.; Liebman, M. Nutrients in Soil Water under Three Rotational Cropping Systems, Iowa, USA. *Agric., Ecosyst. Environ.* **2014**, *186* (3), 105−114.
(21) Frison, E. A. *From Uniformity to Diversity: A Paradigm Shift from Industrial Agriculture to Diversified Agroecological Systems*; International Panel of Experts on Sustainable Food Systems: Brussels, 2016; http://www.ipes-food.org/images/Reports/UniformityToDiversity_FullReport.pdf.
(22) Chikowo, R.; Faloya, V.; Petit, S.; Munier-Jolain, N. M. Integrated Weed Management Systems Allow Reduced Reliance on Herbicides and Long-Term Weed Control. *Agric., Ecosyst. Environ.* **2009**, *132*, 237−242.
(23) Davis, A. S.; Hill, J. D.; Chase, C. A.; Johanns, A. M.; Liebman, M. Increasing Cropping System Diversity Balances Productivity, Profitability and Environmental Health. *PLoS One* **2012**, *7* (10), No. e47149.
(24) Hunt, N. D.; Hill, J. D.; Liebman, M. Reducing Freshwater Toxicity While Maintaining Weed Control, Profits, And Productivity: Effects of Increased Crop Rotation Diversity and Reduced Herbicide Usage. *Environ. Sci. Technol.* **2017**, *51* (3), 1707−1717.
(25) Beckie, H. J.; Harker, K. N. Our Top 10 Herbicide-Resistant Weed Management Practices. *Pest Manage. Sci.* **2017**, *73* (6), 1045−1052.
(26) Poffenbarger, H.; Artz, G.; Dahlke, G.; Edwards, W.; Hanna, M.; Russell, J.; Sellers, H.; Liebman, M. An Economic Analysis of Integrated Crop-Livestock Systems in Iowa, U.S.A. *Agric. Syst.* **2017**, *157* (June), 51−69.
(27) Blackshaw, R. E.; Pearson, D. C.; Larney, F. J.; Regitnig, P. J.; Nitschelm, J. J.; Lupwayi, N. Z. Conservation Management and Crop Rotation Effects on Weed Populations in a 12-Year Irrigated Study. *Weed Technol.* **2015**, *29* (4), 835−843.
(28) Liebig, M.; Carpenter-Boggs, L.; Johnson, J. M. F.; Wright, S.; Barbour, N. Cropping System Effects on Soil Biological Characteristics in the Great Plains. *Renew. Agric. Food Syst.* **2006**, *21* (1), 36−48.
(29) Gómez, R.; Liebman, M.; Sundberg, D. N.; Chase, C. A. Comparison of Crop Management Strategies Involving Crop Genotype and Weed Management Practices in Conventional and More Diverse Cropping Systems. *Renew. Agric. Food Syst.* **2013**, *28* (3), 220−233.
(30) Winchell, M.; Srinivasan, R.; Di Luzio, M.; Arnold, J. G. *ArcSWAT User's Guide*; ArcSWAT, 2013; p 464.
(31) Moriasi, D. N.; Arnold, J. G.; Van Liew, M. W.; Bingner, R. L.; Harmel, R. D.; Veith, T. L. *Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations*; ASABE, 2007; Vol. *50*, 3, pp 885−900.
(32) King, A. E.; Hofmockel, K. S. Diversified Cropping Systems Support Greater Microbial Cycling and Retention of Carbon and Nitrogen. *Agric., Ecosyst. Environ.* **2017**, *240*, 66−76.
(33) Arnold, J. G.; Kiniry, J. R.; Srinivasan, R.; Williams, J. R.; Haney, E. B.; Neitsch, S. L. *Soil & Water Assessment Tool: Input/Output Documentation*, Version 2012; UNESCO-IHE, 2012.
(34) Neitsch, S. L.; Arnold, J. G.; Kiniry, J. R.; Williams, J. R. *Soil & Water Assessment Tool-Theoretical Documentation*, Version 2009; 2009.
(35) Fox, R. H.; Piekielek, W. P. Fertilizer N Equivalence of Alfalfa, Birdsfoot Trefoil, and Red Clover for Succeeding Corn Crops. *J. Prod. Agric.* **1988**, *1*, 313−317.
(36) Liebman, M.; Graef, R. L.; Nettleton, D.; Cambardella, C. A. Use of Legume Green Manures as Nitrogen Sources for Corn Production. *Renew. Agric. Food Syst.* **2012**, *27* (03), 180−191.
(37) Chen, Y. M.; Nobili, D.; Aviad, T. Stimulatory effects of humic substances on plant growth. In *Soil Organic Matter in Sustainable Agriculture*; Magdoff, F., Weil, R. R., Eds.; CRC Press: Boca Raton, 2004; pp 35.
(38) Leandro, L.; Eggenberger, S.; Chen, C.; Williams, J.; Beattie, G. A.; Liebman, M. Cropping System Diversification Reduces Severity and Incidence of Soybean Sudden Death Syndrome Caused by *Fusarium virguliforme. Plant Dis.* **2018**, *102*, 1748−1758.
(39) Liebman, M.; Baraibar, B.; Buckley, Y.; Childs, D.; Christensen, S.; Cousens, R.; Eizenberg, H.; Heijting, S.; Loddo, D.; Merotto, A., Jr. Ecologically Sustainable Weed Management: How Do We Get from Proof-of-Concept to Adoption? *Ecol. Appl.* **2016**, *26* (5), 1352−1369.
(40) Harmel, D. R.; Haney, R.; McBroom, M.; Qian, So.; Christianson, L. *Nutrient Loss Database for Agricultural Fields & Forests in the US*; USDA Agricultural Research Service: Temple, TX, 2016.
(41) Harmel, D.; Potter, S.; Casebolt, P.; Reckhow, K.; Green, C.; Haney, R. Compilation of Measured Nutrient Load Data for Agricultural Land Uses in the United States. *J. Am. Water Resour. Assoc.* **2006**, *42* (5), 1163−1178.
(42) *Model Simulation of Soil Loss, Nutrient Loss, and Change in Soil Organic Carbon Associated with Crop Production*; USDA NRCS

DOI: 10.1021/acs.est.8b02193
Environ. Sci. Technol. 2019, 53, 1344−1352

Conservation Effects Assessment Project: Washington DC, 2006; https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_012757.pdf.
(43) Deytieux, V.; Nemecek, T.; Freiermuth Knuchel, R.; Gaillard, G.; Munier-Jolain, N. M. Is Integrated Weed Management Efficient for Reducing Environmental Impacts of Cropping Systems? A Case Study Based on Life Cycle Assessment. *Eur. J. Agron.* **2012**, *36* (1), 55−65.
(44) Tanaka, D. L.; Anderson, R. L.; Rao, S. C. Crop Sequencing to Improve Use of Precipitation and Synergize Crop Growth. *Agron. J.* **2005**, *97* (2), 385−390.
(45) Hepperly, P.; Lotter, D.; Ulsh, C. Z.; Seidel, R.; Reider, C. Compost, Manure and Synthetic Fertilizer Influences Crop Yields, Soil Properties, Nitrate Leaching and Crop Nutrient Content. *Compost Sci. Util.* **2009**, *17* (2), 117−126.
(46) Khan, S. A.; Mulvaney, R. L.; Ellsworth, T. R.; Boast, C. W. The Myth of Nitrogen Fertilization for Soil Carbon Sequestration. *J. Environ. Qual.* **2007**, *36* (6), 1821.
(47) Gelfand, I.; Snapp, S. S.; Robertson, G. P. Energy Efficiency of Conventional, Organic, and Alternative Cropping Systems for Food and Fuel at a Site in the U.S. Midwest. *Environ. Sci. Technol.* **2010**, *44*, 4006−4011.

DOI: 10.1021/acs.est.8b02193
Environ. Sci. Technol. 2019, 53, 1344−1352