Environmental Science & Technology

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Fossil Energy Use, Climate Change Impacts, and Air Quality-Related Human Health Damages of Conventional and Diversified Cropping Systems in Iowa, USA

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Cite This: *Environ. Sci. Technol.* 2020, 54, 11002−11014

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ABSTRACT: Cropping system diversification can reduce the negative environmental impacts of agricultural production, including soil erosion and nutrient discharge. Less is known about how diversification affects energy use, climate change, and air quality, when considering farm operations and supply chain activities. We conducted a life cycle study using measurements from a nine-year Iowa field experiment to estimate fossil energy (FE) use, greenhouse gas (GHG) emissions, $PM_{2.5}$-related emissions, human health impacts, and other agronomic and economic metrics of contrasting crop rotation systems and herbicide regimes. Rotation systems consisted of 2-year corn-soybean, 3-year corn-soybean-oat/clover, and 4-year corn-soybean-oat/alfalfa-alfalfa systems. Each was managed with conventional and low-herbicide treatments. FE consumption was 56% and 64% lower in the 3-year and 4-year rotations than in the 2-year rotation, and GHG emissions were 54% and 64% lower. Diversification reduced combined monetized damages from GHG and $PM_{2.5}$-related emissions by 42% and 57%. Herbicide treatment had no significant impact on environmental outcomes, while corn and soybean yields and whole-rotation economic returns improved significantly under diversification. Results suggest that diversification via shifting from conventional corn-soybean rotations to longer rotations with small grain and forage crops substantially reduced FE use, GHG emissions, and air quality damages, without compromising economic or agronomic performance.

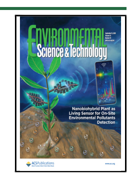
■ INTRODUCTION

The intensification of modern conventional agriculture has been effective at increasing crop yields, yet it has come at great cost to the environment and human health from fossil energy consumption and generation of emissions that contribute to climate change and reduced air quality. In 2014, United States agriculture comprised 1.7% of US primary energy consumption and in 2017, comprised 8.4% of total greenhouse gas (GHG) emissions,[1,2] driven by carbon dioxide (CO_2) emissions from soil carbon loss and fossil fuel use, nitrous oxide (N_2O) from nitrogenous fertilizer use, and methane (CH_4) from ruminant livestock production.[3] Increased concentrations of GHGs in the atmosphere cost society via harm to human health, property damage due to floods, and losses in agricultural productivity.[4]

Agriculture is also a major contributor to atmospheric fine particulate matter ($PM_{2.5}$) via the production and application of farming inputs and field operations.[5] $PM_{2.5}$, which adversely affects air quality and human health, is either emitted directly as a product of combustion or as dust (primary $PM_{2.5}$), or forms in the atmosphere (secondary $PM_{2.5}$) from reactions among ammonia (NH_3), nitrogen oxides (NO_x), sulfur oxides (SO_x), and volatile organic compounds (VOC).[6,7] Due to its small size, $PM_{2.5}$ can enter the lungs and bloodstream, leading to health effects that include chronic obstructive pulmonary disease, acute lower respiratory illness, ischemic heart disease, and lung cancer.[8] Chronic exposure to $PM_{2.5}$ generates societal costs via increased risk of premature death.[8,9] In the US, emissions of agricultural NH_3 are the dominant driver of $PM_{2.5}$-emissions related damages, which derive largely from fertilizer application and storage and application of manure. Emissions of $PM_{2.5}$ also result from diesel fuel production, herbicide production, dust from field operations, and fossil fuel combustion by farm machinery.[5,7,8,10,11] Recent research has shown, for example, that $PM_{2.5}$ from maize production in the US is responsible for 4300 premature deaths annually.[5]

Overall, increasing energy and resource efficiency while reducing environmental impacts is an important goal for improving the sustainability of agricultural systems. Because agricultural systems are vulnerable to energy price fluctuations, reducing reliance on fossil energy can reduce farm financial volatility and increase profitability, while decreasing fossil energy-related environmental damages. Additional strategies to mitigate GHG emissions from cropping systems include improving fertilizer and manure management, maintaining below- and above-ground soil carbon, and reducing reliance on synthetic inputs.[12] Methods for reducing $PM_{2.5}$-related emissions and resulting human health impacts include substitution of high NH_3-emitting fertilizers with lower ones,

Received: November 18, 2019
Revised: July 10, 2020
Accepted: August 10, 2020
Published: August 10, 2020



https://dx.doi.org/10.1021/acs.est.9b06929
Environ. Sci. Technol. 2020, 54, 11002−11014

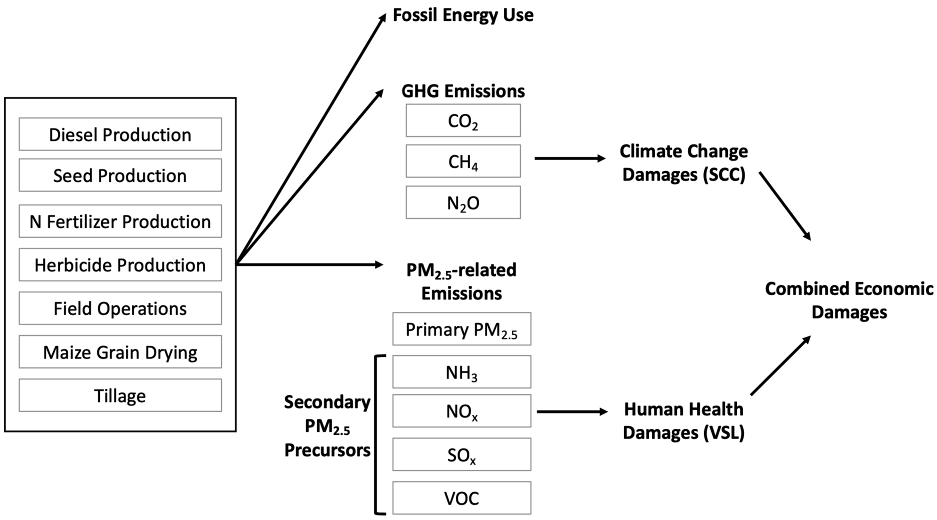


Figure 1. Flowchart of system boundaries, system outputs, and impacts.

using precision agricultural techniques, and selecting crops requiring less nitrogen fertilizer.[5,10,13]

Strategies for simultaneously reducing multiple environmental impacts are especially of interest. Among these is the diversification of conventional corn-soybean cropping systems, which has been shown to deliver several agronomic and environmental benefits, including increased per-hectare corn and soybean productivity, greater resilience to weed and pest infestations, and reduced dependence on synthetic herbicides.[14−17] Diversified cropping systems can also have reduced rates of soil erosion and nutrient discharge to the environment,[15] lower freshwater toxicity loads[14] and enhanced soil functioning.[18−21] The fossil energy use, climate change, and air quality implications of such strategies have not been widely explored.

This study examines the cradle to farm-gate fossil energy consumption, and climate change and air quality damages of three cropping systems differing in levels of crop diversity at the farm-scale. We also evaluated the effects of two contrasting herbicide regimes within each rotation system while focusing on the whole system inputs and whole system outputs. Our analyses were based on crop-specific yield, inputs, fuel consumption, and management data collected from 2008 to 2016 from a field experiment conducted in Boone County, Iowa, USA, in the central Corn Belt, where conventional corn-soybean rotations comprised 70% of planted acres in 2016.[22] We included an accounting of fossil energy consumption and emissions of GHGs, primary $PM_{2.5,}$ and secondary $PM_{2.5}$ precursors associated with fuel, fertilizer, and herbicide production with on-farm fuel combustion, fertilizer application, and field operations.

We used a life cycle assessment approach to estimate the effects of increasing crop rotation diversity and reducing herbicide use on fossil fuel consumption, and damages from GHG and $PM_{2.5}$-related emissions. We hypothesized that the diversified crop rotation systems would have lower fossil energy use and GHG and $PM_{2.5}$ damages than the conventional corn-soybean rotation system, and that a lower herbicide input regime would have lower life cycle impacts than a conventional herbicide regime. We also hypothesized that diversification of cropping systems could allow lower levels of inputs without compromising crop productivity, weed suppression, and profitability.

■ MATERIALS AND METHODS

Experimental Design. Data were collected from experimental plots at Iowa State University's Marsden Farm in Boone County, IA (42°01′N, 93°47′W). The experiment has been conducted since 2002. Experimental treatments comprised three crop rotations suitable for the Midwestern U.S., specifically a 2-year corn-soybean system, a 3-year corn-soybean-oat/red clover system, and a 4-year corn-soybean-oat/alfalfa−alfalfa system. Herbicide treatments included a conventional treatment (CONV) in which herbicides were broadcast-applied to corn and soybean crops, and no interrow cultivation was used, and an alternative low herbicide treatment (LOW), in which 38 cm-wide bands of herbicides were applied to corn and soybean, followed by cultivation between crop rows. Detailed descriptions of all experimental systems, economic data, and management practices have been provided by Davis et al.,[16] Tomer and Liebman,[23] Hunt et al.,[14,15] and the Supporting Information.

The 2-year rotation system received synthetic fertilizer applications in the form of urea and urea + ammonium nitrate (UAN) solution during the corn phase at conventional rates.[15] Composted cattle manure and biologically fixed nitrogen released from clover and alfalfa residues largely substituted for synthetic N fertilizer in the 3- and 4-year rotations. In the 3- and 4-year rotations, composted manure was applied in the fall prior to the corn phase, and synthetic nitrogen fertilizer was used as a supplement according to soil testing results. Following application, composted manure was tilled into the soil using a moldboard plow. Potassium and phosphorus fertilizers were not considered in this analysis as prior work demonstrated they are minor contributors to total GHG and $PM_{2.5}$-related emissions[9] and were intermittently applied in this experiment. Specific fertilizer application rates in the contrasting rotation systems are reported by Hunt et al.[15] and are included the Supporting Information.

All machinery used in the experiment was fueled by low-sulfur diesel, as is typical in Midwestern U.S. farming operations. On-farm operations for the 2-year rotation included fertilizer application, seed bed preparation (leveling and incorporating fertilizer), seed planting, interrow cultivation for weed control in the LOW herbicide regime, herbicide application, grain harvest using a combine, and postharvest chisel plowing following corn production. Field operations in the 3-year rotation system included those of the 2-year system plus seeding the oat and red clover mixture, combine harvest of oat grain, baling oat straw, manure application, and incorporation of manure and red clover using a moldboard plow. The 4-year rotation system included the same activities as the 2-year rotation plus the seeding and harvest of the oat/alfalfa mixture, followed by periodic mowing, raking, and baling of alfalfa throughout the fourth year. The 4-year rotation system concluded with application of composted manure using a manure spreader and incorporation of alfalfa using a moldboard plow.

Appropriate storage of corn grain requires moisture content to be below 15.5%, which was achieved by both field drying and high temperature air circulating drying bins powered equally by natural gas and electricity.[24] Bins powered by propane and electricity had a grain drying energy cost of 67.2 MJ Mg^{-1} for each percent of moisture content reduction.[25]

Life Cycle Assessment. We evaluated fossil energy consumption and air emissions of GHGs and $PM_{2.5}$-related species from "cradle to farm gate," with system boundaries shown in Figure 1. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model was used to evaluate fossil energy use and air emissions of a 3 × 2 factorial of three cropping systems and two weed management regimes.[26] All rotation and herbicide scenarios were constructed in GREET 2017 v1.3.0.13239 and represent management practices at the experiment site between 2008−2016. Our analysis estimated upstream and on-site fossil fuel consumption and emissions of greenhouse gases (e.g., CO_2, CH_4, and N_2O) and primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors (i.e., NH_3, NO_x, SO_x, and VOCs).

All field operations, inputs, yields, and economic returns were recorded in operations logs to represent the rotation systems and herbicide regime scenarios.[27] Emissions were inventoried for all field operations, the production and application of nutrient and herbicide inputs, and associated equipment used to harvest crops and dry corn grain from 2008−2016. These were categorized into diesel production, seed production, N fertilizer production and use, herbicide production, field operations, and corn grain drying system components (Figure 1). We excluded energy use and emissions associated with the manufacture and distribution of farm machinery and grain drying equipment and of the production and use of P and K fertilizers. This study took place on an established field where rotations were implemented in 2002, so no change in soil carbon stocks from land-use change was assumed.[16,21] Manure inputs were assumed to be a waste product from an offsite livestock operation, while composting took place onsite. Thus, emissions generated from the animal production system that produced the manure lay outside our system boundaries; however, fossil fuel use and emissions associated with manure composting and application were included in this analysis.

GREET inputs and outputs. The GREET model estimates upstream and on-farm emissions from management practices, including emissions from fuel combustion and from the manufacture, packaging, and distribution of fertilizers and herbicides. Specifically, GREET estimates the GHG species of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and the $PM_{2.5}$-related species of primary fine particulate matter with diameter ≤2.5 μm ($PM_{2.5}$) and secondary $PM_{2.5}$ precursors of nitrogen oxides (NO_x), sulfur oxides (SO_x), and volatile organic compounds (VOC).[26] Ammonia (NH_3) emissions are not tracked in GREET, and were estimated by other methods (see Ammonia Emissions Inventory). Modeling scenarios were built around the major system components of diesel, N fertilizer, and herbicide production, field operations, N fertilizer application, and corn grain drying postharvest. GREET does not estimate emissions associated with seed production, so this process was omitted from the analysis.

Fossil energy consumption for production of synthetic inputs was calculated using GREET and included fuel oil, electricity, and steam; the fossil energy feedstocks included naphtha, natural gas, and coke.[26] On-farm and upstream fossil energy consumption and emissions from low-sulfur diesel combustion were estimated using GREET emissions factors. Upstream emissions and energy consumption affiliated with diesel fuel production were also calculated using GREET emissions factors, expressed in units of g $MMBtu^{-1}$. Processes involved included low-sulfur diesel refining, transportation, distribution, and storage. The electricity grid was attributed to the Midwest Reliability Organization (MRO) region as defined in GREET. Energy consumption and emissions associated with the manufacturing of agricultural machinery were outside of the system boundary and thus not included in our analyses.

Herbicide inputs were calculated using the sum of mass of active ingredients applied each year within an herbicide treatment. These application rates were then averaged over each rotation system over all years. Energy consumed and emissions generated during herbicide production were taken from GREET databases, and default herbicide values were used.

Ammonia Emissions Inventory. Prior to planting corn, urea or UAN was applied using an air spreader or sprayer and incorporated into the soil using a field cultivator. UAN was also applied to corn after planting using either an air sprayer or injector. NH_3 emissions from urea and UAN were calculated from the mass of fertilizer applied, using application emissions factors from the Carnegie-Mellon University Ammonia Emissions Model and offsite production emission factors from the National Emissions Inventory.[28−30]

Ammonia released during the composting process is largely driven by the frequency of turning the manure compost. Here, the manure was turned at least once a week, so all ammonia emissions were allocated to the composting process. All ammoniacal nitrogen in the manure was assumed to have been volatilized off at the time of compost application. Composting of manure took place on-site, so associated NH_3 emissions were allocated entirely to the composting process by multiplying the emissions factor by the amount of manure used. Composting emission factors came from the University of Nebraska Ammonia Emissions Estimator.[31,32]

Seed Energy Accounting. Information on fossil energy consumption associated with seed production is limited, so the energy consumption estimate of 10.03 MJ kg^{-1} of corn seed was applied.[33] All other seeds used in the study (i.e., soybean, oat, red clover, and alfalfa) were assumed to consume 4.71 MJ fossil energy kg $seed^{-1}$.[34]

Fugitive Dust. Fugitive dust emissions of primary $PM_{2.5}$ from agricultural practices were estimated from the number of passes of machinery over the plots, which varied depending on the rotation and herbicide regime. We used PM_{10} (fine particulate matter with diameter ≤10 μm) emissions factors for activities related to soil preparation, tillage, and harvesting

https://dx.doi.org/10.1021/acs.est.9b06929
Environ. Sci. Technol. 2020, 54, 11002−11014

specific to the crop type; we followed established methods for estimating the emissions attributable to the $PM_{2.5}$ size fraction and determining the percentage of fugitive dust that would not be deposited near to the source (Table S1 in Supporting Information).[7,35−39]

System Energy Efficiencies. The energy output of each rotation system was calculated using the higher heating values of harvested crop materials using bomb calorimetry, while economic returns data were derived from previous studies conducted at the experiment site.[14,15,40,41] Efficiency ratios in the format of economic return to energy consumed ($ net return per GJ fossil energy consumed) and energy gain (GJ crop energy produced per GJ fossil energy consumed) were calculated for the three rotations and two herbicide regimes to assess the energy efficiency of each rotation system and herbicide treatment.

Modeling $PM_{2.5}$ Concentrations and Health Impacts. Damages from exposure to primary and secondary $PM_{2.5}$ were estimated using InMAP (Intervention Model for Air Pollution): a spatially explicit, annual-average, steady-state model designed to estimate changes in atmospheric $PM_{2.5}$ concentrations arising from marginal changes in primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursor emissions. InMAP estimates the expected excess mortality arising from the change in $PM_{2.5}$ concentrations, using a concentration−response relationship derived from epidemiological studies.[42] We assume that all $PM_{2.5}$ has equivalent toxicity, regardless of its source or composition. Details of model mechanism, assumptions, and performance are described in Tessum et al.[43] Human health damages were estimated as premature deaths per gram of air pollutant emitted.[9,43]

Human health damages associated with agrichemical production were estimated using shapefiles of ammonia, ammonium nitrate, nitric acid, and herbicide production facility locations in InMAP. Only those facilities within or intersecting with the MRO North American Electric Reliability Corporation (NERC) were used in this analysis.[44] Using the latitude and longitude of each facility located within the NERC region, we traced the associated human health damages associated with primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursor emissions using the InMAP-derived Source-Receptor Matrix.[9,43] Health damages from offsite nitrogen production emissions were allocated to a single nitrogen facility in northwest Iowa, where ammonia, urea, and UAN are produced. This facility was selected for our analysis because of its proximity to the experiment site and its synthetic nitrogen production portfolio. It was assumed that this facility produces all materials used in the production and mixing of urea and ammonium nitrate.[45]

Human health damages from offsite herbicide production were allocated across a weighted average distance of pesticide production plants within the same MRO as the experiment site. Human health damages associated with field operations were allocated to Boone County, Iowa.

Calculation of Economic Damages. Damages from emissions of GHG were monetized using the social cost of carbon (SCC), which considers damages to human health, property due to flood risk changes, and impacts to agricultural productivity as a result of climate change.[4] In this study, we applied a SCC of $43 Mg^{-1} of CO_2e emissions (2017 dollars, with 3% discount rate).[4] Human health damages as a result of chronic exposure to primary and secondary $PM_{2.5}$ were monetized using the United States Environmental Protection Agency (EPA) mortality risk valuation or value of statistical life (VSL). VSL assigns monetary value to an individual's avoided risk of mortality due to exposure to environmental pollution, so as to facilitate the comparison and aggregation of overall social costs.[9,46−48] Here, we used a VSL estimate of $9.1 M per life (2017 dollars, with 3% discount rate) and multiplied it by the number of premature deaths per gram of air pollutant emitted.[49] In this study, mortality risk valuation was used to facilitate comparison and aggregation of social and private costs of farming practices, although it is not the only measure of air pollution-related health impacts.[50] Though there are limitations to the VSL, it is overwhelmingly the convention in the United States both in science and policy.[51] Combined damages were the sum of climate change and air quality damages.

Data Analysis. Fossil fuel consumption and all emissions inventories were compiled using means and standard errors of annual consumption and emissions as affected by contrasting rotation systems and herbicide regimes across system components of diesel production, seed production, N fertilizer production, herbicide production, field operations, and grain drying. Means and standard errors were calculated across plots and over the duration of the experiment. Uncertainty as shown concerns the differences between plot treatments, and we acknowledge that other uncertainties exist. We assumed no temporal variability in emissions factors, dose−response metrics, or damage metrics across the duration of this study.

Response ratios were applied to measure the magnitude and significance of effect of changing rotation systems and herbicide regimes on environmental, agronomic, and economic performance. Ratios were calculated using the annual means of the 4-year rotation system to the 2-year system, the 3-year to 2-year system, the 4-year to the 3-year system, and the LOW to the CONV herbicide regime, and the percentage relative differences in emissions were estimated across the rotation systems between 2008 and 2016.[52] Natural log response ratios were calculated for each performance metric to describe the differences across rotation shifts and herbicide treatments.[52] Confidence intervals (95%) were calculated on the annual log response ratios, and the differences across rotation system shifts and herbicide treatments were considered significant ($\alpha < 0.05$) if there was no overlap of the confidence intervals with 0.0.[53,54] Paired t tests were run on the mean effect on environmental, agronomic, and economic outputs between rotation systems and herbicide treatments to determine the significance of those differences ($\alpha < 0.05$).

Agronomic and economic performance were calculated at the plot level within each rotation system and herbicide treatment and evaluated in terms of harvested crop, amount of energy produced, amount of energy consumed, and net returns to land and management. Energy produced was calculated using higher heating value of the harvested crop materials in kJ g^{-1}.[41] Economic data used to calculate net returns to land and management are included in Supporting Information.

RESULTS

Fossil Energy Consumption. The greatest consumer of fossil fuels was the corn-soybean rotation, for both absolute and normalized values, at 9,441 MJ ha^{-1} y^{-1} and 761 MJ Mg^{1-} y^{-1}, respectively. Means for fossil energy consumption by the 3- and 4-year rotations decreased by more than half to 4110 and 3366 MJ ha^{-1} y^{-1}, respectively. Energy consumption was dominated by N fertilizer production for the 2-year system

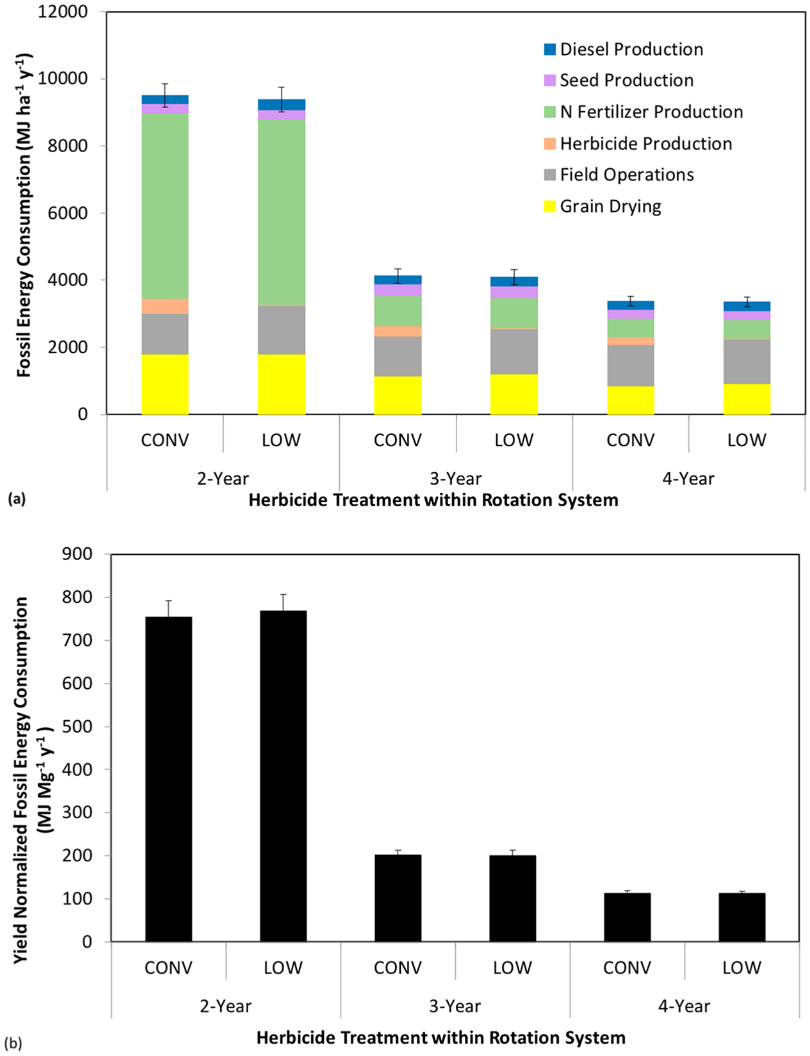


Figure 2. Mean annual fossil energy consumption (a) as affected by contrasting rotation systems and herbicide regimes across system components of diesel, seed, N fertilizer, and herbicide production, field operations, and grain drying and (b) as normalized by annual harvested dry commercial crop yields, including corn, soybean, oat grain and straw, and alfalfa. Error bars indicate one standard error of the annual mean annual total energy consumption.

(58%), while the 3- and 4-year systems' energy consumption was largely from fuel consumed during field operations (31%, 38%, respectively). Fossil energy consumption decreased by 56%, when adding a third crop phase to the corn-soybean rotation, and decreased by 64% when adding a third and fourth crop phase. When normalized for annual crop yields, consumption decreased by 70% and 84% when adding a third and fourth crop phase, respectively (Figure 2).

Greenhouse Gas Emissions. The corn-soybean rotation system generated the most GHG emissions at 776 kg CO_2e ha^{-1} y^{-1}across crop phases. Across rotation system and herbicide treatment, average annual GHG emissions were primarily from N fertilizer application (38%), followed by N fertilizer production (27%), and then fuel for field operations (24%). Rotation system diversification was a significant driver for reductions in overall greenhouse gas emissions, resulting in 54% and 64% lower emissions when adding a third and fourth crop phase to the rotation, respectively (Figure 3). This was due to the substitution of synthetic N fertilizers with composted manure and N derived from biological N fixation by clover and alfalfa in the 3- and 4-year rotation systems. While biological N fixation data were not collected during the present study, Tomer and Liebman (2014) calculated nutrient balances for the same diversification experiment during 2004–2011 and estimated that the combination of N fixation and net soil N mineralization provided 218–222 kg N ha^{-1} y^{-1} for soybean crop phases in the 2-year rotation, and 188–192 kg N ha^{-1} y^{-1} for alfalfa and soybean crop phases during the 4-year rotation system.[23] Nitrogen fixation plus net soil N mineralization within the 3-year rotation system provided 123–205 kg N ha^{-1} y^{-1} to red clover and soybean.[23] Published values for mean rates of N fixation in the Midwestern U.S. are 84–111 kg N ha^{-1} y^{-1} for soybean,[55,56] 92 kg N ha^{-1} y^{-1} for red clover,[57] and 152–165 kg N ha^{-1} y^{-1} for alfalfa.[55,58]

$PM_{2.5}$-Related Emissions (Primary $PM_{2.5}$, NH_3, NO_x, SO_x, and VOC). Across rotation system and herbicide treatments, mean primary $PM_{2.5}$ emissions were dominated by fugitive dust (92%), followed by N fertilizer production (4%) and field operations (4%). The remaining system components generated less than 1% of overall $PM_{2.5}$ emissions (Figure 4). Herbicide regime was a strong driver of total primary $PM_{2.5}$ emissions, where the CONV emissions were 31% lower than the LOW emissions (Table S6, Supporting Information).

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Environ. Sci. Technol. 2020, 54, 11002−11014

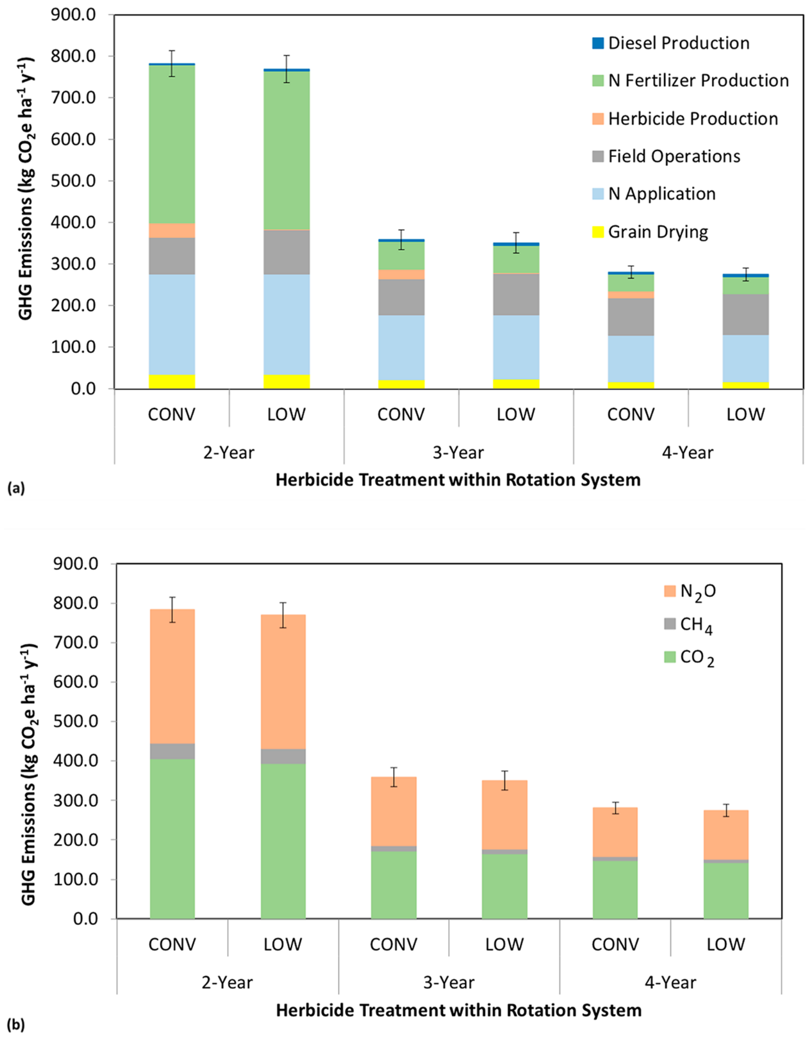

Figure 3. Mean annual GHG emissions (a) as affected by contrasting rotation systems and herbicide regimes across system components of diesel, N fertilizer, and herbicide production, field operations, N application, and grain drying and (b) as expressed in GHG emission species. Error bars indicate one standard error of the annual mean total emissions.

Total VOC emissions decreased by at least 72% when diversifying the corn-soybean rotation, regardless of whether a third or fourth crop was added. Estimated SO_x emissions decreased by 71%, 80%, and 30% when shifting from the 2-year to 3-year system, 2-year to 4-year system, and 3-year to 4-year system, respectively (Figure 4).

Estimated NH_3 emissions decreased by 63%, 74%, and 30% when shifting from the 2-year to 3-year system, 2-year to 4-year system, and 3-year to 4-year system, respectively. All increases in crop rotation diversity yielded significant reductions in NO_x emissions when deviating from a corn-soybean rotation, with a 33% reduction when adding an oat/red clover phase and a 42% reduction when adding oat/alfalfa and alfalfa crop phases (Figure 4).

For each of the secondary $PM_{2.5}$ precursors, the 2-year corn-soybean rotation was the largest emitter, with decreasing emissions as rotation diversity increased (Figure 4). N fertilizer production dominated VOC (57%) and SO_x (56%) emissions, while N fertilizer application dominated NH_3 emissions (99%). NO_x emissions were primarily driven by field operations (48%) and N fertilizer application (28%) (Figure 4).

Economic Damages from GHG Emissions. Damages from GHG emissions were highest in the corn-soybean rotation, at \$34 $ha^{-1}y^{-1}$, and decreased as rotation diversity increased to \$15 ha^{-1} y^{-1} for the corn-soybean-oat-alfalfa rotation. On average, the largest contributor to climate change damages was from N fertilizer application (38%), followed by N fertilizer production (27%) and fuel combustion during field operations (25%). On average, climate damages were driven largely by CO_2 (50%) and N_2O (46%) emissions (Figure 5).

Economic Damages from $PM_{2.5}$-Related Emissions. The largest economic damages from $PM_{2.5}$-related emissions came from the corn-soybean rotation system at an average of \$702 $ha^{-1}y^{-1}$. Damages decreased as a third and fourth crop phase were added, by 42% and 57%, respectively, with avoided costs of \$291 and \$396 $ha^{-1}y^{-1}$, respectively. Damages were largely generated from NH_3 emissions, comprising between 42% and 69% of the total damages from reduced air quality (Figure 6).

Combined Economic Damages from GHG and $PM_{2.5}$-related Emissions. The corn-soybean rotation system yielded the highest combined economic damages at an average cost of \$735 ha^{-1} y^{-1}. This value decreased by \$309 ha^{-1} y^{-1} and by \$418 ha^{-1} y^{-1}, respectively, as oat-red clover and oat-alfalfa and alfalfa crop phases were added (Figure 7). Damages were due primarily to emissions associated with N fertilizer application

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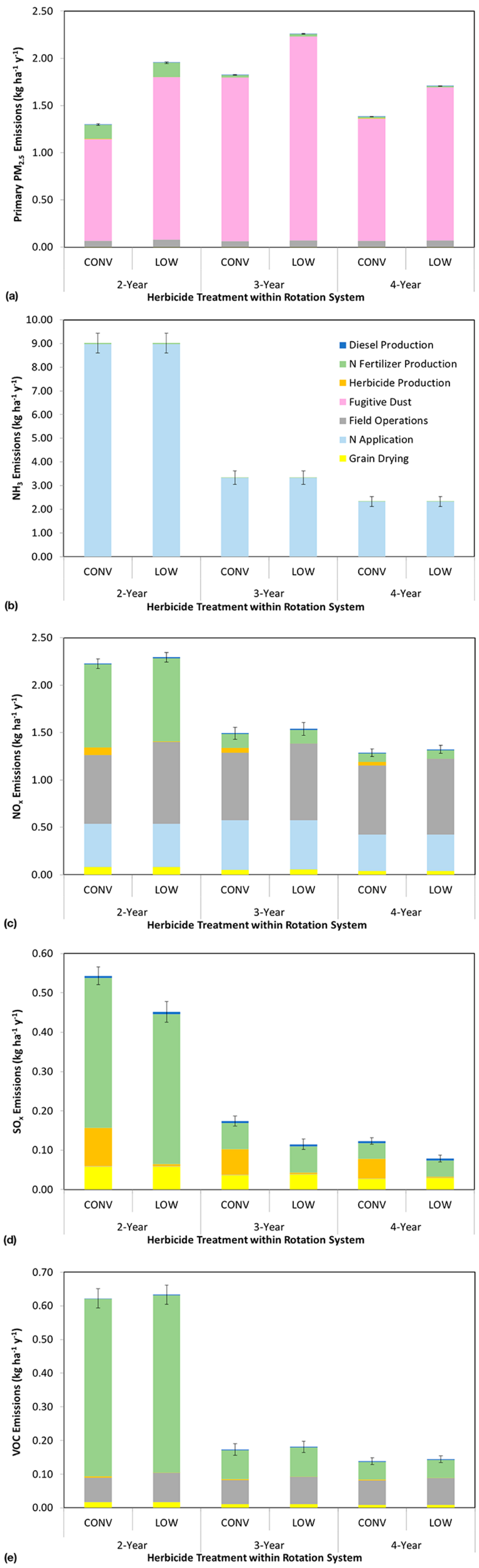

Figure 4. Mean annual emissions of (a) primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors of (b) NH_3, (c) NO_x, (d) SO_x, and (e) VOC by rotation system and herbicide regime across system components of diesel, N fertilizer production, herbicide production, fugitive dust, field operations, N application, and grain drying. Error bars indicate one standard error of the annual mean total emissions. The legend provided in panel b describes all panels.

across rotation systems and herbicide regimes, at 52% of overall combined damages (Figure 7). The smallest drivers of combined damages were from emissions from grain drying, upstream diesel, and herbicide production, comprising approximately 1%, 2%, and 3% respectively. Addition of oat-red clover to the corn-soybean rotation resulted in 42% reduction, while the addition of oat-alfalfa and alfalfa to the corn-soybean system resulted in 57% reduction (Figure 7). Combined damages were driven primarily by $PM_{2.5}$-related emissions, comprising 96% of total damages on average (Figure 7). Mean damages from combined GHG and $PM_{2.5}$-related emissions were \$735, \$426, and \$317 ha^{-1} y^{-1} for the 2-year, 3-year, and 4-year rotation systems, respectively (Figure 7). If these damages were to be accounted for in the rotation system budgets, they would comprise 90%, 49%, and 36% of the calculated net returns to land and management for the 2-, 3-, and 4-year rotation systems, respectively.

All systems that included adding a third and fourth crop phase to a conventional corn-soybean rotation yielded significant reductions in total fossil energy consumption (16–65%), economic damages from GHG emissions (19–65%), and $PM_{2.5}$-related emissions (26–57%), while herbicide regime had no effect (Tables 1, S2, S11, S13). Total fossil energy consumption was reduced by more than half when substituting in composted manure and biological N fixation due to the avoided energy consumption from the production of synthetic fertilizer (Table 1, Figure 2). Economic damages from GHG emissions also were reduced by more than half when substituting in composted manure and biological N fixation due to the avoided emissions from the production of synthetic fertilizer (Table 1, Figure 2). While GHG damages from N application had a greater proportion of the overall damages in the more diverse systems, those increases were less than the reductions in avoided damages due to synthetic fertilizer production (Figure 2). Economic damages from $PM_{2.5}$-related emissions were also significantly reduced when substituting in composted manure and N-fixing legumes due to the avoided $PM_{2.5}$-related emissions associated with application of synthetic fertilizer (Table 1, Figure 2).

Greater rotation diversity significantly increased dry corn yields on a per hectare basis by 4 and 5% when adding a third and fourth crop phase, respectively, while herbicide regime had no effect (Table 1, Table S17). However, soybean yields were influenced by both rotation and herbicide regime and increased by 23–30% when adding oat/alfalfa and alfalfa crop phases to a corn-soybean rotation. Soybean yields under the LOW herbicide regime were 8% lower than CONV soybean yields as a result of a confounding effect of soybean genotype and herbicide regime prior to 2014 (Table 1).[15] We also detected a rotation system increase in net returns to land and management when deviating from a corn-soybean rotation, with an average 11% increase as one or more crop phases were added (Table 1). Weeds in corn and soybean were affected by both rotation system and herbicide regime with an increase when adding a third crop phase and when under the LOW herbicide regime (Table 1).

As crop rotation diversity increased so did the economic and energy efficiency of the system, with between 2- and 3-fold increases in economic and energy gain efficiencies when shifting away from a corn-soybean rotation. Herbicide regime had no effect on the economic and energy efficiency ratios (Table 2).

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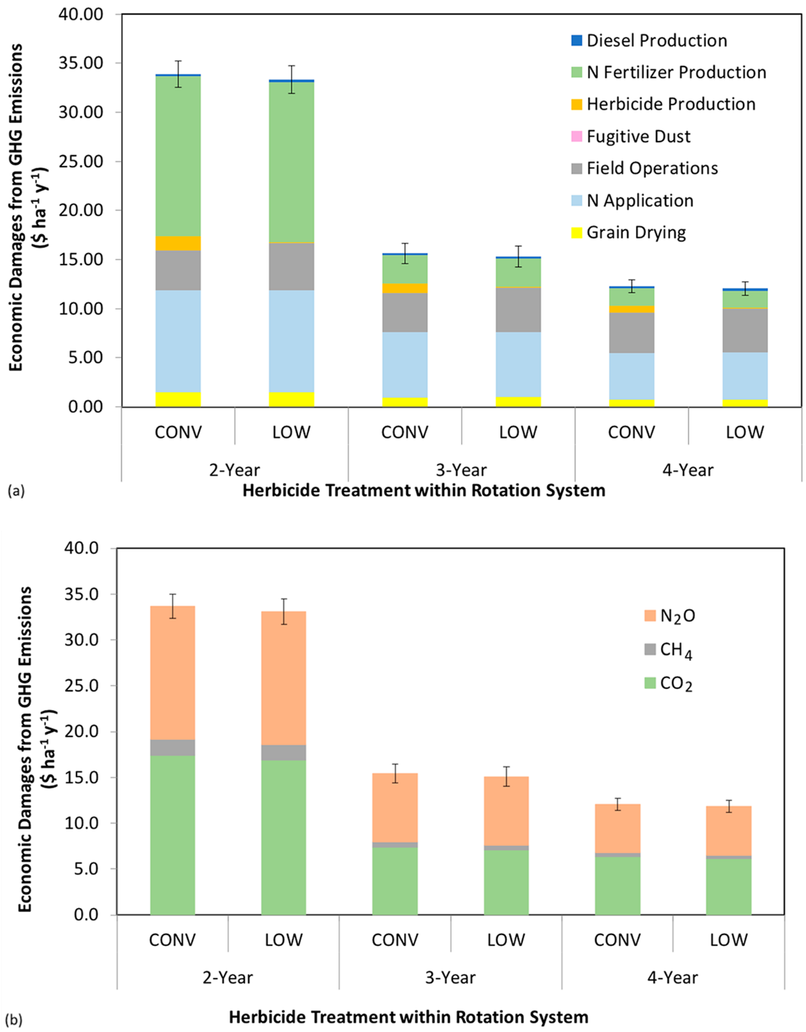

Figure 5. Mean annual damages from GHG emissions (a) as affected by contrasting rotation systems and herbicide regimes across system components of diesel, N fertilizer, and herbicide production, fugitive dust, field operations, N application, and grain drying and (b) as expressed in GHG species. Error bars indicate one standard error of the annual mean total economic damages.

DISCUSSION

Cropping system diversification significantly reduced fossil energy consumption and economic damages from GHG and $PM_{2.5}$-related emissions. We found that more diverse crop rotation systems had lower fossil energy consumption and life cycle total GHG and $PM_{2.5}$-related emissions than the conventional corn-soybean rotation system and as a result, lower combined economic damages. This was largely due to the reduced reliance on synthetic fertilizer and reduced fossil energy consumption from the substitution of synthetic N fertilizers with organic N sources. We also found that the diversified cropping systems enhanced crop productivity and profitability. Corn and soybean productivity and net returns to the whole rotation system were maintained or improved as crop diversity increased, which is consistent with prior findings at the experiment site.[14−16] Increases in soybean yields due to greater rotation diversity were likely due to reduced incidence and severity of soybean Sudden Death Syndrome (SDS) caused by the pathogen *Fusarium virguliforme*.[59] The confounding effect of soybean genotype and herbicide regime prior to 2013 was introduced by using a soybean genotype more vulnerable to SDS in the LOW herbicide treatments and a genotype less susceptible to SDS in the CONV regime. From 2014 to 2016, the same soybean cultivar was used in both herbicide regimes, and there were no significant differences in yield due to herbicide regime.[15] Weed populations in corn and soybean crop phases were at most 1.4% of harvested biomass across all rotation systems.[14−16]

As noted in previous research, increases in crop rotation diversity resulted in significant reductions in herbicide emissions to freshwater systems.[14,15] We saw reductions of 81−96% in estimated freshwater toxicity as a result of the use of a low-herbicide treatment, and the incorporation of more diverse crop rotations lowered freshwater toxicity by 25−51%.[14] For the same rotation and herbicide treatments evaluated in the present research, total nitrogen and phosphorus runoff decreased by 39% and 30%, respectively, as crop rotation diversity increased.[15] We also found reductions in erosion losses of 60%.[15] Similar to a previous study conducted at our research site, as rotation diversity increased, so did economic and energy efficiency.[41] Across all these experiments, corn and soybean productivity were maintained or increased, weed populations in corn and soybean were managed effectively, and whole rotation system economic returns to land and management were maintained.[14,15]

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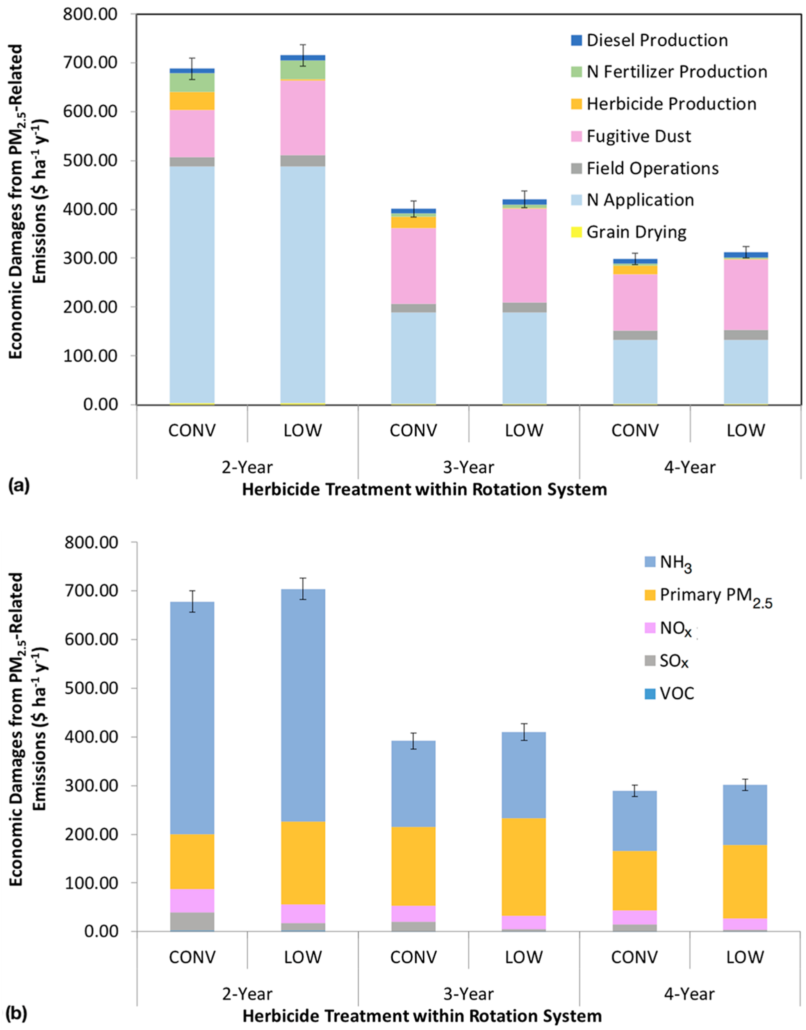

Figure 6. Mean annual economic damages from $PM_{2.5}$-related emissions (a) as affected by contrasting rotation systems and herbicide regimes across system components of diesel, N fertilizer, and herbicide production, field operations, N application, fugitive dust, and grain drying and (b) as expressed in emissions species. Error bars indicate one standard error of the annual mean total economic damages.

NH_3 emissions from fertilizer application comprised the largest component of $PM_{2.5}$-related emissions and were responsible for the greatest proportion of economic damages of $PM_{2.5}$-related species. This echoes the findings of many studies highlighting the linkages between NH_3 emissions and reduced air quality.[5,7] Estimated primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursor damages per kg emitted were in alignment with those reported in other air quality studies.[9] Fugitive dust was a large contributor to primary $PM_{2.5}$ and was largely driven by the increased number of tractor passes for tillage and oat and alfalfa harvest under the more diversified rotations. Because the largest component of NH_3 emissions comes from N fertilizer application, enacting strategies for reducing N fertilizer inputs, improving N crop uptake, and minimizing NH_3 emissions should be prioritized.[60] The improvement of the use of N on farms by improving practices such as fertilizer rates and forms, application method, placement, and timing could reduce pollution from excess reactive nitrogen by 30–50%.[5,61] The substitution of manure and legume residues for synthetic N fertilizer production can also contribute to reductions in emissions of reactive N while reducing a waste burden on a farming landscape scale.[17,62,63]

Economic damages from $PM_{2.5}$-related emissions were also significantly reduced by increased rotation diversity. Economic damages are a function of population density, concentration-exposure patterns, existing incidence rates, and marginal changes in $PM_{2.5}$ exposure.[43,64] If this experiment were to be implemented elsewhere, damages per-hectare would be a function of the proximity of the farming systems to nearby human population densities and of the proximity of herbicide and fertilizer production facilities to nearby population densities. This experiment considered both upstream and on-site processes generating both GHG and $PM_{2.5}$-related emissions. Upstream damages were allocated to Midwestern production facilities, while on-site emissions were allocated to Boone County, IA. The largest component of combined damages was from N fertilizer application comprising 52% across herbicide treatments and rotation systems. All other system components comprised approximately a third or less of overall combined human damages across all rotation systems and herbicide regimes. It should be noted, however, the relative magnitude of reductions across the rotation systems and herbicide regimes would not change, as all systems and regimes would take place at the same experimental site. The location of the experiment would not affect damages from

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Environ. Sci. Technol. 2020, 54, 11002−11014

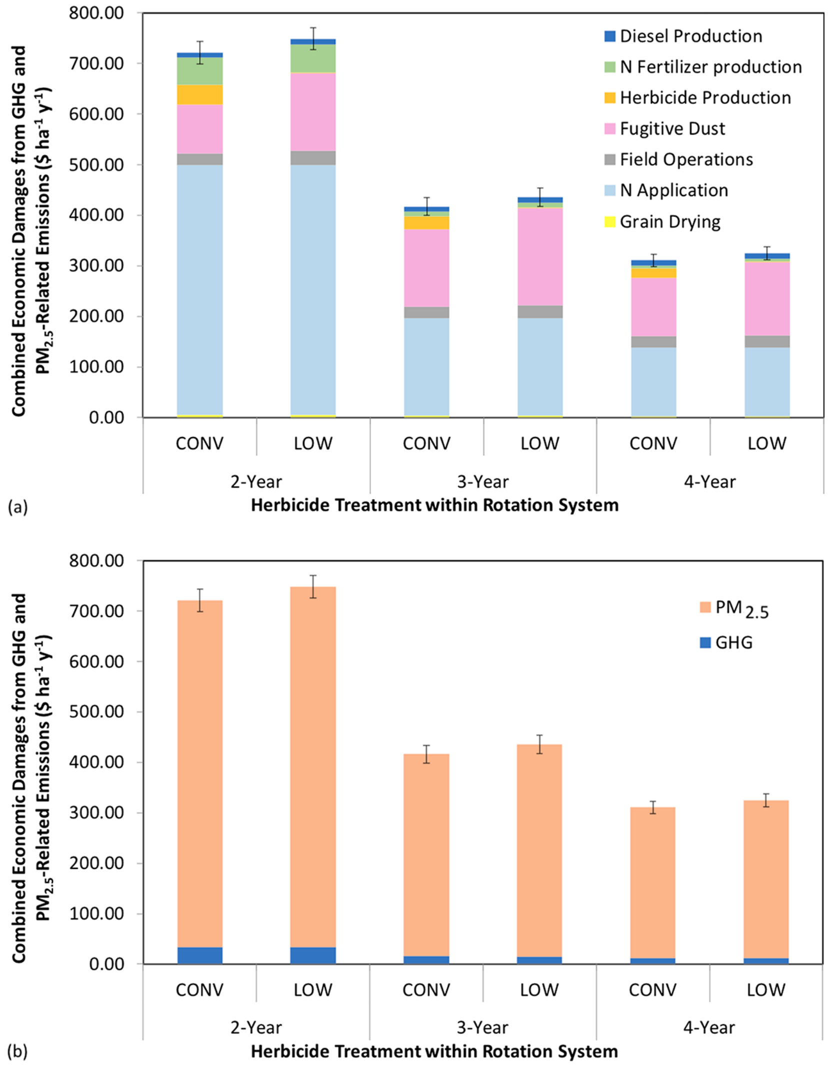

Figure 7. Mean annual combined economic damages from GHG and $PM_{2.5}$-related emissions (a) as affected by contrasting rotation systems and herbicide regimes across system components of diesel, N fertilizer, and herbicide production, field operations, N application, fugitive dust, and grain drying and (b) as expressed by type of economic damage. Error bars indicate one standard error of annual mean total economic damages.

GHG emissions, as the GHG species evaluated here are long-lived and well-mixed in the atmosphere.[4]

Because of the high proportion of damages from combined GHG and $PM_{2.5}$-related emissions across the 2-, 3-, and 4-year rotation systems (90%, 49%, and 36%, respectively, of net returns to land and management), the accounting of these true costs in farm enterprise budgets could incentivize crop diversification and concomitantly reduce reliance on synthetic fertilizer applications.[65]

While research increasingly describes great economic and environmental promise of diversified cropping systems, such systems are in place in but a few Iowa farms. This is due to a complex array of economic, policy, cultural, and other factors. Barriers to adopting more diverse cropping systems include perceptions of uncertain long-term profitability, relatively few markets for small grains and alfalfa, a lack of infrastructure support from retailers of seeds and other inputs, and a lack of social support within the "culture of Iowa agriculture".[66] Shifts in policy and economic investments will be essential to expand diversification on US agricultural landscapes, specifically those that support farmers in applying farming practices that enhance soil, water, and air quality, and increase energy efficiency on farm.[22] From the grower's perspective, improvement of crop insurance programs for small grains, provision of informational resources and necessary equipment, and technical support from agribusiness institutions would reduce perceived barriers to adopting extended crop rotation systems.[66]

The potential for scaling up such diversified cropping systems could have significant impacts on existing markets, including potential shifts in supply and demand for corn and soybean amidst newly introduced small grain and forage crops. Large-scale shifts to more small grains and forages could constrain domestic corn production, resulting in increased corn prices whereby farmers become incentivized to revert to growing previous corn-soybean rotations. Concurrently, potential expanded production of small grains and forages could result in reduced prices, again, incentivizing farmers to revert back to growing corn and soybean. Nonetheless, economic analyses of such scenarios found that scaling up diversified systems to 20–40% of arable cropland in Iowa (2–4 million ha) could occur without generating price incentives favoring existing corn and soybean rotations.[22]

Here, we estimated changes in the damages associated with GHG and $PM_{2.5}$-related emissions as a result of implementing

https://dx.doi.org/10.1021/acs.est.9b06929
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Table 1. Mean Effects of Rotation or Herbicide Treatment Shifts Across Performance Metrics of Fossil Energy Consumption, Economic Damages from GHG Emissions, Economic Damages from $PM_{2.5}$-Related Emissions, Corn Yield, Soybean Yield, Rotation-System Net Returns to Land and Management, and Mass of Weeds in Corn and Soybean

Performance Metric	System Shift	Mean Effect (% relative difference)[a]	Lower 95%	Upper 95%
fossil energy consumption (MJ ha^{-1} y^{-1})	3 to 4	−16.3[a]	−18.5	−14.1
	2 to 3	−57.6[b]	−63.2	−52.1
	2 to 4	−64.5[c]	−68.9	−60.1
economic damages from GHG emissions ($ ha^{-1} y^{-1})	3 to 4	−19.3[a]	−21.5	−17.1
	2 to 3	−56.4[b]	−63.7	−49.1
	2 to 4	−64.8[c]	−71.1	−58.5
economic damages from $PM_{2.5}$-related emissions ($ ha^{-1} y^{-1})	3 to 4	−25.6[a]	−27.2	−24.0
	2 to 3	−42.0[b]	−48.9	−35.1
	2 to 4	−56.9[c]	−63.2	−50.5
corn yield (Mg ha^{-1} y^{-1})	3 to 4	1.2[b]	−0.8	3.1
	2 to 3	4.0[ab]	1.8	6.3
	2 to 4	5.3[a]	3.2	7.3
soybean yield (Mg ha^{-1} y^{-1}) Rotation	3 to 4	5.9[c]	2.6	9.2
	2 to 3	23.1[b]	16.6	29.7
	2 to 4	30.3[a]	23.9	36.9
soybean yield (Mg ha^{-1} y^{-1}) Herbicide	CONV to LOW	−7.5	−11.1	−3.9
net returns to land and management ($ ha^{-1} y^{-1}) (Rotation)	3 to 4	1.1[b]	−3.8	6.1
	2 to 3	10.5[a]	4.6	16.5
	2 to 4	10.5[a]	3.5	17.6
weed biomass in corn and soybean (kg ha^{-1} y^{-1})	3 to 4	−50.9[c]	−97.7	−4.0
	2 to 3	81.6[a]	34.9	128.4
	2 to 4	−5.0[b]	−48.3	38.2
weed biomass in corn and soybean (kg ha^{-1} y^{-1})	CONV to LOW	307.6	269.0	346.2

[a]Mean effect values with different letters indicate significant differences ($p < 0.05$) across treatment shifts as determined by paired t tests.

Table 2. Energy Use and Economic Efficiency Ratios Including Net Returns to Land and Management, and Energy Gain to Fossil Energy Consumed by Rotation System and Herbicide Regime[a]

rotation	herbicide regime	Economic return to energy ratio ($ net return GJ fossil energy consumed^{-1})	Energy gain ratio (GJ crop energy produced GJ fossil energy consumed^{-1})
2-year	CONV	101.2 (13.2)	12.6 (0.7)
	LOW	99.4 (13.6)	12.3 (0.7)
3-year	CONV	248.4 (24.9)	27.3 (1.9)
	LOW	261.6 (27.6)	27.2 (2.1)
4-year	CONV	287.0 (27.1)	35.4 (2.1)
	LOW	296.9 (27.3)	35.6 (2.2)

[a]Standard errors are shown in parentheses.

diversified cropping systems and an alternative herbicide regime. More diverse cropping systems that include recycled manure and biological nitrogen fixation by forage legumes, such as the 3- and 4-year rotation systems studied here, may not only require less fossil energy but also generate less GHG and $PM_{2.5}$-related emissions, while maintaining primary agronomic functions. This will be a priority in agriculture in the face of a changing climate and a growing and increasingly affluent global population. Incorporation of a diverse suite of practices and inputs will aid in maintaining systems that are weed-suppressive, productive, profitable, and protective of environmental quality and human health. As shown in the present study, increased reliance on ecological processes and thereby reduced reliance on synthetic inputs can maintain agronomic functions and decrease environmental damage.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.9b06929.

Detailed information on emissions, economic net returns, economic damages, agronomic, and experimental design (PDF)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We express our thanks to Matthew Woods, Ann Johanns, and Riddhiman Bhattacharya for assistance with data collection and analysis. This research was supported by 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). This publication was developed as part of the Center for Air, Climate and Energy Solutions (CACES), which was supported under Assistance Agreement No. R835873 awarded by the U.S. Environmental Protection Agency. It has not been formally reviewed by EPA. The views expressed in this document are solely those of authors and do not necessarily reflect those of the Agency. EPA does not endorse any products or commercial services mentioned in this publication.

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