Grassland-to-cropland conversion increased soil, nutrient, and carbon losses in the US Midwest between 2008 and 2016

Xuesong Zhang[1,2], **Tyler J Lark**[3,4], **Christopher Clark**[5], **Yongping Yuan**[6], **Stephen D LeDuc**[7,*]

[1.]Joint Global Change Research Institute, Pacific Northwest National Laboratory and University of Maryland, College Park, MD 20740, USA

[2.]Earth System Science Interdisciplinary Center, University of Maryland, College Park, 5825 University Research Ct, College Park, MD, 20740, USA

[3.]Center for Sustainability and the Global Environment, University of Wisconsin-Madison, Madison, WI 53726, USA

[4.]Department of Energy Great Lakes Bioenergy Research Center, University of Wisconsin-Madison, Madison, WI 53726, USA

[5.]US Environmental Protection Agency, Office of Research and Development, Center for Public Health and Environmental Assessment, Washington, DC, USA

[6.]US Environmental Protection Agency, Office of Research and Development, Center for Environmental Measurement and Modeling, Research Triangle Park, NC, USA

[7.]US Environmental Protection Agency, Office of Research and Development, Center for Public Health and Environmental Assessment, Research Triangle Park, NC, USA

Abstract

After decades of declining cropland area, the United States (US) experienced a reversal in land use/land cover change in recent years, with substantial grassland conversion to cropland in the US Midwest. Although previous studies estimated soil carbon (C) loss due to cropland expansion, other important environmental indicators, such as soil erosion and nutrient loss, remain largely unquantified. Here, we simulated environmental impacts from the conversion of grassland to corn and soybeans for 12 US Midwestern states using the EPIC (Environmental Policy Integrated Climate) model. Between 2008 and 2016, over 2 Mha of grassland were converted to crop production in these states, with much less cropland concomitantly abandoned or retired from production. The net change in grassland-cropland conversion increased annual soil erosion by 7.9%, nitrogen (N) loss by 3.7%, and soil organic carbon loss by 5.6% relative to that of existing cropland, despite an associated increase in cropland area of only 2.5%. Notably, the above estimates represent the scenario of converting unmanaged grassland to tilled corn and soybeans, and impacts varied depending upon crop type and tillage regime. Corn and soybeans are dominant biofuel feedstocks, yet the grassland conversion and subsequent environmental impacts simulated in this study are likely not attributable solely to biofuel-driven land use change since other factors

*Corresponding author: telephone 919- 541-2183, leduc.stephen@epa.gov.

also contribute to corn and soybean prices and land use decisions. Nevertheless, our results suggest grassland conversion in the Upper Midwest has resulted in substantial degradation of soil quality, with implications for air and water quality as well. Additional conservation measures are likely necessary to counterbalance the impacts, particularly in areas with high rates of grassland conversion (e.g., the Dakotas, southern Iowa).

Keywords

Agriculture; corn; soybean; grassland; biofuel; land use; environmental impacts; erosion; carbon; nitrogen; soil; EPIC

1 Introduction

After decades of declining cropland area, the United States (US) has experienced a reversal of land use/land cover change in recent years. Total cropland decreased by approximately 24.9 million hectares in the US from 1982 to 2007 (170.1 to 145.2 million hectares, respectively) according to the US Department of Agriculture's (USDA) National Resources Inventory (NRI) (USDA, 2020). Starting in approximately 2007, however, cropland area started rising again, with an increase of approximately 3.5 million hectares from 2007 to 2017 (145.2 to 148.7 million hectares, respectively)—the latest data available in the NRI (USDA, 2020). Other major assessments of land use/land cover change in the US confirm this trend (see EPA, 2018a, Lark et al., 2015, 2020).

The recent expansion in active cropland is likely due in part to the production of corn ethanol and soy biodiesel, the two dominant biofuel types in the US. In the early-to-mid-2000s, corn ethanol volumes in the US increased as states and the federal government enacted renewable fuel mandates and discouraged the use of methyl tert-butyl ether (MTBE) as an oxygenate in fuel (Schnepf, 2013). In 2007, the US Congress enacted the Energy Independence and Security Act (EISA), mandating annual renewable fuel volumes of 36 billion gallons by 2022, with 15 billion gallons derived from corn grain (US 110th Congress, 2007). Area in corn cultivation increased sharply between 2006 and 2007 from 31.7 to 37.8 million hectares, and reached a high of almost 39.4 million hectares in 2012 (USDA-NASS, 2020). After declining in 2007, soybean area likewise increased from 30.6 to 33.8 million hectares between 2008 and 2016 (USDA-NASS, 2020).

While most increases in corn and soybeans came from the switching of crops on existing cropland, a small percentage derived from converting non-cropland to crop production, a shift with outsized environmental impacts. According to the USDA-NRI, non-cropland-to-cropland conversion caused a 3.3% increase in total U.S. cropland in 2017, relative to 2012 levels (USDA 2020). According to data from Lark et al. (2020), this conversion caused a 2.5% increase in cropland area between 2008 and 2016 across the 12 US Midwestern states focused on in this study (see Figure 1). Sources of this new cropland consisted predominantly of former grasslands, including pasture as well as grasslands leaving the Conservation Reserve Program (CRP) (Morefield et al., 2016, Lark et al., 2020, USDA, 2020). In the same 12 US Midwestern states, over 70% of the converted grasslands were

planted with corn or soybeans, while wheat, alfalfa and other crops combined accounted for the remainder (data from Lark et al., 2020).

In general, the conversion of grasslands to annual crops, like corn and soybeans, causes negative environmental impacts (National Research Coucil, 2009, LeDuc et al., 2016, EPA, 2018a,); yet with few exceptions, such as estimating carbon (C) changes (Lu et al., 2018, Spawn et al., 2019), the cumulative impact of almost a decade of grassland conversion in the US Midwest has not been estimated. Reduced plant cover and increased tillage leave soils less protected from wind and water erosion. Application of commercial fertilizer can result in excess nutrient (e.g., nitrogen (N) and phosphorus (P)) inputs into soils and eutrophication of waterways via runoff or leaching. Conversion from perennial cover to cropland also typically decreases soil organic carbon (SOC) stocks, increasing C loss to the atmosphere (Gelfand et al., 2011, Qin et al., 2016). Spawn et al. (2019) estimated that cropland expansion in the contiguous US released 55.0 Mg C per ha^{-1} between 2008 and 2012, with total emissions of 38.8 Tg C yr^{-1}, equivalent to the emissions from almost 26.8 million passenger cars per year (EPA, 2018b). Beyond several studies on SOC, however, the cumulative environmental effects of grassland-to-cropland conversion largely remain to be estimated, particularly for soil erosion, N and P. Doing so would help managers and decision makers understand the likely magnitude of impacts, aiding the design of mitigation strategies and informing future policies (Lark, 2020).

2 Methods

2.1 Study region

In this study, we assessed the cumulative environmental impacts of grassland conversion occurring in the US Midwest between 2008 and 2016. Specifically, we chose 12 states in the US Midwest (Figure 1) as our modeling area since they contained much of the grassland converted during this period (Lark et al., 2020) and >80% of the total corn and soybean acres planted in the US (USDA-NASS, 2020). Moreover, this highly productive agricultural area is a hotspot of cropland C sequestration in the US (West et al., 2010), while excess erosion and fertilizer loss from croplands in the region is a major cause of environmental problems, such as waterway siltation (Lal, 1998), and harmful algal blooms and hypoxia in the Great Lakes (NOAA, 2020) and the Gulf of Mexico (Rabalais et al., 2002).

2.2. Agroecosystem modeling

We used the Geospatial Agroecosystem Modeling System (GAMS) (Zhang et al., 2010, Zhang et al., 2015) to leverage high resolution geospatial datasets (e.g., soils, terrain, land use) to run the Environmental Policy Integrated Climate (EPIC) model (Williams et al., 1989, Izaurralde et al., 2006) at a 30 m resolution. EPIC is a process-based agroecosystem model capable of simulating key biophysical and biogeochemical processes, such as plant growth and development, water balance, carbon and nutrient cycling, soil erosion, and greenhouse-gas emissions. Detailed description of the GAMS, the input data for EPIC, and the evaluation of the model are provided in the Supplementary Information (SI; SIFigures 1–4 and Methods 1–4).

2.3. Modeling scenarios

We conducted model simulations for two purposes: (1) estimating the environmental impacts of cropland expansion and abandonment during 2008–2016, and (2) understanding the effects of varying crop types and tillage intensity. In the cropland expansion assessment, we considered the conversion of grassland (i.e., two Crop Data Layer (CDL) land use types: 37 Other Hay/Non-Alfalfa and 176 Grass/Pasture) into cropland. The pixels allowed to be converted to corn or corn/soy were those identified as converted to cropland in Lark et al. (2020). We selected two representative crop rotations, continuous corn and corn-soybean, as converted cropping systems to simplify the total number of simulations required. These rotations were selected for multiple reasons, including: (i) their prevalence, as corn and soybeans were the most dominant crops planted on newly converted land, as indicated above; and (ii) because corn-grain ethanol and soy biodiesel account for most of the biofuel volumes produced to date (EPA, 2018a). For each rotation, we also simulated two types of tillage, either conventional tillage or no-till.

For cropland abandonment, we employed land use change from different crops to the Other Hay/Non-Alfalfa and Grass/Pasture land use types. Due to the complexity and lack of historical CDL data to derive pre-abandonment crop rotations, we used a dominant crop rotation (i.e., corn-soybean) with conventional tillage to represent typical crop management in the cropland abandonment assessment. The pixels allowed to be abandoned were those identified in Lark et al. (2020) as moving from cropland to non-cropland.

To investigate cropland expansion effects, we executed the EPIC model for a 30-year period (1979–2008) under the grassland scenario to initialize the model for state variables, such as soil organic matter. Then, we again ran EPIC using the initialized values to simulate each of the grassland and cropland scenarios. For each scenario, we ran EPIC for a 30-year period to derive the annual, long-term average environmental impacts of the land converted between 2008 and 2016. We used historical climate data (from 1979–2008), so our scenarios did not incorporate future climate change effects. The environmental impacts of cropland expansion were then calculated by subtracting the baseline scenario outputs from those of each cropland-tillage scenario. To assess cropland abandonment impacts, we initialized EPIC for the 30-year period under a single cropland scenario (i.e., tilled corn-soybean), before running EPIC using these initialized values to simulate the grassland and cropland scenarios. The environmental impact from cropland abandonment was estimated as the difference between the grassland and cropping scenarios.

Using EPIC, we simulated soil erosion, N and P loss (lost from fields through erosion, runoff, and leaching) and SOC loss (lost from fields through emissions to the atmosphere and through runoff, erosion, and leaching.) For each environmental variable, we calculated total values for the region and values per unit area.

3   Results

3.1   Land use changes in the US Midwest

Across the 12 US Midwestern states in this study, approximately 2.05 and 0.34 million ha of cropland expansion and abandonment occurred, respectively, between 2008 and 2016

according to the data from Lark et al. (2020). Grasslands were the most common land cover converted to cropland, with the area of grassland-to-crop conversion in the US Midwest roughly equal to the size of New Jersey, or 3.3% of the total grassland area in the modeled region. Grasslands represented approximately 94% and 90% of total cropland expansion and abandonment area, respectively, in the US Midwest. The remaining 6% of cropland expansion and 10% of cropland abandonment were mainly from- or to- forests, wetlands, and shrublands (Lark et al., 2020). Given the complexity and large uncertainty in applying process-based models to simulate other land use transitions, here we focused on the conversion between grassland and cropland, and not the other land use transitions.

The spatial patterns of grassland-to-cropland conversion generally followed the distribution of grasslands in the region (Figures 2a,b). Most of the grassland is located in the central and western areas of the US Midwest, including the Dakotas, Nebraska, Kansas, Minnesota, southern Iowa and western Missouri (Figure 2a), and most of the conversion to cropland occurred in places like southern Iowa and the Dakotas (Figure 2b). The percent grassland converted in each county ranged from 0% to as high as 31%. Cropland abandonment often co-located with cropland expansion in the western Midwest, but also occurred in more easterly states including Wisconsin, Michigan, and Ohio (Figure 2c).

Land capability classes (LCC) is a system by which lands are grouped by ability to produce crop yields (Klingebiel and Montgomery, 1961). Values range between 1 and 8, with larger values indicating less productive soils for crop production. For the 12-state area simulated, the average LCC was 3.2 for the grassland areas converted to cropland, higher than the average for existing cultivated cropland, ca. 2.8 (Zhang et al., 2015). Abandoned cropland had an LCC of 3.0. Thus, the most productive soils are continuously being used for crops, while land converted to- and from- cropland mainly occurred on more marginal soils.

3.2 Environmental impacts of cropland expansion

Our modeling results found clear negative environmental impacts of cropland expansion on a per area basis (Figure 3) and in total across the region (Table 1), with the magnitude of the impacts varying greatly depending on crop type and tillage. These results represent the annual, long-term average environmental impacts of the land converted between 2008 and 2016, and barring additional changes in land use or management, would be expected to continue to accrue each year into the foreseeable future.

Tilled corn and corn-soybeans exhibited the highest amount of soil erosion, and N, P, and SOC loss; the grassland baseline was the lowest for all metrics; and no-till corn and corn-soybeans were intermediate (Figure 3). For soil erosion, tilled corn and corn-soybeans caused 4–6 times more loss than the baseline (Figure 3). Conversion to no-till corn-soybean and no-till corn rotations increased erosion above the grassland baseline, but this was substantially lower than the tilled crops. These differences reflect in part that perennial grasslands provide year-round protection from soil erosion relative to corn and soybeans. Similarly, tillage mixes surface residue with upper soil layers, reducing the amount of residue protecting the soil and thus increasing susceptibility to erosion.

In general, the spatial patterns of soil erosion reflected the spatial distribution of grasslands converted (Figure 2), with hotspots in the eastern Dakotas, southern Iowa, and Missouri (SI Figure 5). Despite a larger area of cropland expansion in the Dakotas, however, the amount of soil erosion was higher in Iowa and Missouri. Newly converted cropland in Iowa and Missouri had a higher slope than the grasslands converted in the eastern Dakotas, likely explaining this finding (SI Figure 6a).

Not surprisingly, grasslands experienced much lower nutrient (N and P) loss compared with the cropping systems (Table 1), mainly caused by the application of synthetic fertilizer to cropland. Notably, nutrient loss from grasslands is not zero, since grassland soils still contain N and P, some of which can be lost via leaching, runoff, or erosion. Tillage generally increases nutrient loss through higher soil erosion and soil organic matter decomposition. Converting grassland to no-till corn and no-till corn-soybean increased N loss by a factor of ca. 3–6 times, while grassland conversion to tilled corn and tilled corn-soybean led to an increase by 6–10 times. Similarly, grassland to cropland conversion increased P loss, but with less magnitude, mainly because the P application rates were lower than N application rates. The spatial patterns of N and P losses largely coincided with the spatial distribution of grassland conversions to cropland (SI Figures 7 and 8).

We also found that converting grassland into crop production decreased SOC stocks (Table 1). Without tillage, land use conversion led to moderate SOC loss in the soil profile with an average depth of 1.6 m. With tillage, the amount of SOC loss exceeded 800 Gg C yr^{-1} for both rotations (Table 1). The hotspots of SOC loss coincided with the spatial pattern of soil erosion and nutrient loss. Despite the overall loss of SOC from newly expanded cropland, the conversion resulted in slightly higher amounts of SOC in certain areas, particularly for no-till corn and no-till corn-soybean (SI Figure 9). This indicates that the SOC impacts vary from location to location, and with site specific conditions (such as climate, terrain, soil properties, and management).

All environmental impacts varied substantially across counties on per unit area basis. Figure 4 shows the spatial variability of soil erosion on expanded cropland. In general, the grassland-cropland conversion in the northern Midwest (including Dakotas, Wisconsin, Minnesota, and Michigan) resulted in less soil erosion per ha than in the southern portion (including Nebraska, Kansas, Iowa, Missouri, Illinois, Indiana, and Ohio). In addition, the spatial patterns of N, P, and SOC losses per ha (SI Figures 10–12) were very similar to that of soil erosion. Soil erosion per ha was modestly correlated with slope (R^2 of 0.35 under the grassland scenario), suggesting this is a partial driver of the soil erosion pattern.

3.3 Environmental impacts of cropland abandonment

In contrast to cropland expansion, cropland abandonment produced positive environmental outcomes (Table 1). Compared with a tilled corn-soybean rotation, cropland abandonment to grassland reduced soil erosion and nutrient loss by a factor of 4–5, while increasing SOC stocks by 460 kg C ha^{-1} yr^{-1} on average (calculated as the difference between grassland and tilled corn-soybeans; see Table 1). Like that of grassland conversion, the spatial pattern of environmental benefits corresponded with the distribution of areas abandoned (Figure 2c and SI Figure 13). In addition, slope (SI Figure 6b) and other site-specific factors can

alter the pattern of the four environmental variables. Environmental benefits of cropland abandonment varied greatly between sites, as indicated by the large standard deviations in outcomes (Figure 5) and spatial variability of environmental impacts on a per unit area basis (SI Figure 14).

3.4 Net impact of cropland expansion and abandonment—Given the opposite effects of cropland expansion and abandonment, we estimated the net effects from both expansion and abandonment across the 12 states in the US Midwest. We calculated the net impacts of the tilled corn-soybean scenario, where we simulated grassland conversion to corn-soybeans and abandonment from corn-soybeans to grassland. In aggregate across the region, the negative effects of grassland conversion outweighed the benefits of cropland abandonment, such that the net outcome was greater erosion, and N, P, and SOC loss (Table 2; Figure 6). The net results are driven mainly by the cropland expansion, as it accounts for over 80% of the total converted land considered in this study.

3.5 Comparisons to cropland and CRP, and estimation of economic impacts

To put our findings into context, we compared our results to impacts from current cropland and the benefits of US CRP land (Table 2). Compared to the reported soil erosion, and N and SOC loss from cultivated cropland in previous literature (West et al., 2008, Zhang et al., 2015), the net impacts of cropland expansion and abandonment resulted in 7.9%, 3.7%, and 5.6% increases in soil erosion, N loss, and SOC loss, respectively, from US Midwestern cropland. Comparing directly for context, our findings also suggest the net land use change in these 12 states could counter many CRP benefits, with the magnitude, for instance, to offset up to 18.6% of the N retention benefits for the entire US (Table 2).

For further context, we also estimated the economic effects of net erosion and N loss. Based on 11.8 Tg yr^{-1} of soil erosion (Table 2) and assuming a value of $8 USD per metric ton of soil in 1992 (or $14.3 in 2018 after considering inflation) (Pimentel et al., 1995), the economic cost (including both on-site crop productivity and off-site siltation and water quality damage) of increased soil erosion in the Midwest amounts to $169 million USD per year. Thus, an estimated cost of $5.1 billion USD (not factoring inflation) would be expected over 30 years, if net soil erosion costs from grassland conversion (i.e., expansion and abandonment) were internalized. Similarly, Compton et al. (2011) estimated the cost of N pollution ranged between $2.20–$56.00 USD per kg N due to its impact on factors, such as biodiversity, recreation, and clean water. Based on that estimate, net cropland expansion and abandonment would cost ca. $10–246 million USD per year (or $30 million-7.4 billion USD over 30 years, not factoring inflation). Thus, even though there are large uncertainties associated with the estimates using the above approaches, increased erosion and N loss exert notable economic cost.

4 Discussion

Overall, this study finds that trends in grassland conversion to cropland led to increased soil erosion, and N, P, and SOC loss from soils in the US Midwest between 2008 and 2016. That grassland conversion to cropland causes environmental harm is not a new finding on a per area basis; yet despite these known effects, the cumulative, soil quality impacts

of almost a decade of grassland conversion in the US have been little quantified to date, outside of C loss. The total net, annual impacts (conversion minus abandonment) of recent land use change ranged from ca. 12 Tg yr^{-1} of eroded soil; 44 and 5 Gg yr^{-1} N and P lost, respectively; and 670 Gg C yr^{-1} lost across the 12-state region (Table 2). Our results suggest cropland expansion causes disproportionately large negative environmental impacts compared to those of existing cropland. In the US Midwest, cropland area increased by ca. 2.5% by 2016 relative to the total cropland area of ca. 73 million ha in 2008 (Lark et al., 2020); yet, the increase in environmental impacts relative to cropland ranged higher, from 3.7% to 7.9% (Table 2).

4.1 Comparison with previous estimates

To our knowledge, this is the first study to estimate the cumulative environmental quality impacts of observed grassland conversion to row crops across the US Midwest during this time period, apart from estimates of SOC loss. Despite this, our results can be compared in both directionality and on a per area basis to previous estimates in the literature. Our erosion simulations are consistent with previous findings that soil erosion is low for land in perennial cover (Nearing et al, 2017), and conversion to corn or soy will generally increase soil erosion (Yasere et al., 2016). In addition, our results are consistent with the scientific literature showing tillage intensity is a key factor influencing soil erosion (Chung et al., 1999, Hao et al., 2001, Wang et al., 2008). Typically, less tillage, such as conservation tillage and no-till management, and greater soil cover by crop residues will help minimize soil erosion (Seitz et al., 2019).

On a per unit area basis, the simulated N and P losses here (Table 1; Figure 3) also generally fall within the range of values reported in previous studies. For example, USDA's Natural Resources Conservation Service estimated an average total N loss between 20–60 kg N ha^{-1} yr^{-1}, while P losses were between 1–6 kg P ha^{-1} yr^{-1} from cropland across the US (USDA-NRCS, 2017a, USDA-NRCS, 2017b). Combining both field observation and modeling results, Syswerda et al. (2012) showed nitrate losses of 62.3±9.5 and 41.3±3.0 kg N ha^{-1} yr^{-1} respectively, for conventional and no-till row crops in Michigan. Our estimates of 17 to almost 50 kg N ha^{-1} yr^{-1} and 2.5 to 5.2 kg P ha^{-1} yr^{-1} fall within a reasonable range of these results.

In line with previous studies (Yu et al., 2019, Kämpf et al., 2016, Schierhorn et al., 2013), our simulations show that cropland abandonment increases SOC, while grassland conversion to cropland decreases it. In general, our estimate of ca. 0.5 Mg C ha^{-1} yr^{-1} (calculated as the difference between SOC under the grassland and tilled corn-soybean scenarios; see Table 1) is close to the previously reported SOC sequestration benefits from cropland abandonment of ca. 0.7 Mg C ha^{-1} yr^{-1} (Schierhorn et al., 2013, Kämpf et al., 2016). For grassland conversion to cropland, estimates of SOC loss can vary greatly, often depending upon tillage practices and the method of estimation. Our estimates of SOC loss of ca. 3.6 to 12 Mg C ha^{-1} for grassland to no-till corn or tilled corn-soybean, respectively (see Table 1 for per area values, multiplied by 30 years), are generally lower than in empirical studies (Gelfand et al., 2011; Spawn et al. 2019). For instance, Spawn et al. (2019) empirically estimated a release of 55.0 Mg C ha^{-1} (±39.9 Mg C ha^{-1}) for the entire contiguous US, and 47.2

Mg C ha^{-1} for the SOC component of converted grasslands within our 12-state region. Yet, for comparison purposes, they also calculated a much lower grassland-to-cropland SOC loss of 7.9 Mg C ha^{-1} from the National Greenhouse Gas Inventory (NGGI), which uses a process-based model (Spawn et al. 2019). Differences between empirical and process-based methods—the latter of which was employed in this study—has been widely acknowledged (Zhang et al., 2015), as they use different input data and mechanistic processes to represent the ecosystem responses. Overall, the SOC estimates for grassland conversion to cropland we provide here likely falls on the low end of the possible impacts, while others may estimate the high end.

4.2 Limitations

Several points should be considered when assessing the results of this study. Foremost, our results suggest a directionality and magnitude of effects, but these are modeling estimates of reality, not actual measurements. Our model verification, for example, indicates that EPIC may overestimate soil erosion by approximately 14% (SI Figure 4). Moreover, we did not model the exact crop and management-type for each converted parcel of land since this would have been computationally too demanding. Instead, we modeled the effects of conversion only to corn or corn-soybean. Corn (29.3%) and soybeans (26.7%) were the dominant crops planted on converted grasslands nationwide between 2008 and 2016, with wheat (22.6%) a close third (Lark et al., 2020). Alfalfa was the next closest with 3.6%. Corn and soybeans were even more prevalent across the 12 states we modeled—each planted on 36% of the land converted to crop production. We did not simulate the effects of wheat because this crop is not as common in the eastern portion of the US Midwest. The planting of wheat on grasslands may have comparatively lowered N and P loss, while also increasing SOC losses relative to corn or corn-soybean rotations. Corn requires more N and P fertilizer than wheat on average (USDA-ERS 2019), and replacing wheat with corn typically increases SOC (Qin et al. 2016).

Likewise, we could not apply an exact tillage type to each patch of converted land since this information at this level is not available. In this study, we bracketed the spectrum of tillage by applying both no-till and conventional tillage scenarios, representing the two extremes in tillage practices, with actual effects likely in between these endpoints. In addition, the converted grasslands were not necessarily undisturbed or unmanaged, but instead represented a spectrum of grassland and management types, including pasture, lands managed for hay, and CRP grasslands. This likely most affected the SOC findings. We used a 30-year spin-up time for the grasslands before converting to crops, yet some of these grasslands may have only been out of production for 6–10 years. Hence, this may have resulted in an overestimation of SOC stocks and subsequent losses in some locations when converted. However, as noted above, our estimates of effects appear to be in line, or even on the low-end, compared to other estimates of C loss.

We also could not follow the temporal dynamics of impacts through time due to computer-storage limitations and simulating so many parcels. Instead, we present annual, long-term average effects in this study, simulated over a 30-year period and consistent with the central aim of the study. It is likely that effects were not uniform across this entire period. For

instance, grassland conversion to tilled cropland typically causes a rapid loss of soil C in the first few years of cultivation due, in part, to the mixing of soil and decomposition (Davidson and Ackerman, 1993). By contrast, the accumulation of C after abandonment can take much longer as biomass inputs increase (Schierhorn et al., 2013). In a similar fashion, annual rates of erosion and nutrient loss were likely not uniform across the time period simulated.

Beyond the estimated effects on soil erosion, N, P, and SOC, there are additional environmental impacts of grassland-to-cropland conversion that we did not model here, including those on air and water quality. For example, recent cropland expansion is associated with an increase in airborne dust-generation in the Midwest, with implications for human health, downwind ecosystems, and visibility (Lambert et al., 2020). In addition, our estimates represent edge-of-field soil and nutrient losses, providing only the potential for water quality degredation. Hydrologic modeling is a logical next step, needed to translate these results to sediment and nutrient loading to waterways.

5   Conclusions

Between 2008 and 2016 over 2 million ha of grassland were converted to crop production in the US Midwest, with much less active cropland concomitantly abandoned or retired from production. In our simulations, the net change in cropland extent increased annual soil erosion by 7.9%, N loss by 3.7%, and SOC loss by 5.6% relative to that of existing cropland, despite an associated increase in area of only 2.5%. Thus, the impacts can counter many benefits derived from conservation programs, including the CRP. Economically, the soil erosion results alone could cause $169 million USD per year in damages to the environment, or $5.1 billion USD over the 30-year period simulated.

While the majority of the land use changes and our modeled environmental impacts stem from the conversion of grasslands to corn and soybeans—two common biofuel feedstocks— the results are not specifically attributable to biofuel driven land use change, since other factors contribute to corn and soybean prices and subsequent land use decisions. Therefore, actual biofuel-driven impacts would represent a subset of the total impacts. The benefits of perennial cover, such as for cellulosic feedstocks (LeDuc et al., 2016, Robertson et al., 2017), and reduced tillage practices (Deines et al., 2019, Busari et al., 2015) suggest that environmental degradation from cropland expansion could be reduced if actively managed using either of these practices. Moreover, additional conservation measures in places with high grassland conversion rates and soil quality effects, such as southern Iowa, are likely needed to lessen environmental impacts.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

References

BUSARI MA, KUKAL SS, KAUR A, BHATT R. & DULAZI AA 2015. Conservation tillage impacts on soil, crop and the environment. International Soil and Water Conservation Research, 3, 119–129.

CHUNG S, GASSMAN PW, KRAMER L, WILLIAMS JR & GU R. 1999. Validation of EPIC for two watersheds in southwest Iowa. Journal of Environmental Quality, 28, 971–979.

COMPTON JE, HARRISON JA, DENNIS RL, GREAVER TL, HILL BH, JORDAN SJ, WALKER H. & CAMPBELL HV 2011. Ecosystem services altered by human changes in the nitrogen cycle: a new perspective for US decision making. Ecology letters, 14, 804–815. [PubMed: 21624028]

DAVIDSON EA & ACKERMAN IL 1993. Changes in soil carbon inventories following cultivation of previously untilled soils Biogeochemistry, 20, 161–193.

DEINES JM, WANG S. & LOBELL DB 2019. Satellites reveal a small positive yield effect from conservation tillage across the US Corn Belt. Environmental Research Letters, 14, 124038.

EPA 2018a. Biofuels and the Environment: The Second Triennial Report to Congress. https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=IO&dirEntryId=341491.

EPA. 2018b. Greenhouse Gas Emissions from a Typical Passenger Vehicle [Online]. Available: https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle#:~:text=A%20typical%20passenger%20vehicle%20emits%20about%204.6%20metric%20tons%20of,8%2C887%20grams%20of%20CO2. [Accessed June 2 2020].

GELFAND I, ZENONE T, JASROTIA P, CHEN J, HAMILTON SK & ROBERTSON GPJPOTNAOS 2011. Carbon debt of Conservation Reserve Program (CRP) grasslands converted to bioenergy production. 108, 13864–13869.

HAO Y, LAL R, IZAURRALDE RC, RITCHIE JC, OWENS LB & HOTHEM DL 2001. Historic assessment of agricultural impacts on soil and soil organic carbon erosion in an Ohio watershed. Soil Science, 166, 116–126.

IZAURRALDE R, WILLIAMS JR, MCGILL WB, ROSENBERG NJ & JAKAS MQ 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecological Modelling, 192, 362–384.

KÄMPF I, HOELZEL N, STOERRLE M, BROLL G. & KIEHL K. 2016. Potential of temperate agricultural soils for carbon sequestration: A meta-analysis of land-use effects. Science of the Total Environment, 566, 428–435. [PubMed: 27232969]

KLINGEBIEL AA & MONTGOMERY PH 1961. Land-capability classification, Soil Conservation Service, US Department of Agriculture.

LAL R. 1998. Soil erosion impact on agronomic productivity and environment quality. Critical reviews in plant sciences, 17, 319–464.

LAMBERT A, HALLAR AG, GARCIA M, STRONG C, ANDREWS E. & HAND JL Dust Impacts of Rapid Agricultural Expansion on the Great Plains Geophysical Research Letters 47 e2020GL090347

LARK T, SPAWN S, BOUGIE M. & GIBBS H. 2020. Cropland expansion in the United States produces marginal yields with disproportionate costs to wildlife. Nature Communications 11, 4295

LARK TJ 2020. Protecting our prairies: Research and policy actions for conserving America's grasslands. Land Use Policy, 97, 104727.

LARK TJ, SALMON JM & GIBBS HK 2015. Cropland expansion outpaces agricultural and biofuel policies in the United States. Environmental Research Letters, 10, 044003.

LEDUC SD, ZHANG X, CLARK CM & IZAURRALDE RC 2016. Cellulosic feedstock production on Conservation Reserve Program land: potential yields and environmental effects. Global Change Biology Bioenergy, 9, 460–468.

LU C, YU Z, TIAN H, HENNESSY DA, FENG H, AL-KAISI M, ZHOU Y, SAUER T. & ARRITT R. 2018. Increasing carbon footprint of grain crop production in the US Western Corn Belt. Environmental Research Letters, 13, 124007.

MOREFIELD PE, LEDUC SD, CLARK CM & IOVANNA R. 2016. Grasslands, wetlands, and agriculture: the fate of land expiring from the Conservation Reserve Program in the Midwestern United States. Environmental Research Letters, 11.

NATIONAL RESEARCH COUCIL 2009. Liquid transportation fuels from coal and biomass: technological status, costs, and environmental impacts. National Academies Press.

NOAA. 2020. Harmful Algal Blooms (HABs) in the Great Lakes [Online]. Available at: https://www.glerl.noaa.gov/pubs/brochures/NOAA_HABs_in_Great_Lakes.pdf [Accessed May 2 2020].

PIMENTEL D, HARVEY C, RESOSUDARMO P, SINCLAIR K, KURZ D, MCNAIR M, CRIST S, SHPRITZ L, FITTON L. & SAFFOURI R. 1995. Environmental and economic costs of soil erosion and conservation benefits. Science, 267, 1117–1123. [PubMed: 17789193]

QIN Z, DUNN JB, KWON H, MUELLER S. & WANDER MM 2016. Soil carbon sequestration and land use change associated with biofuel production: empirical evidence. GCB Bioenergy, 8, 66–80.

RABALAIS NN, TURNER RE & WISEMAN JR WJ 2002. Gulf of Mexico hypoxia, aka "The dead zone". Annual Review of ecology and Systematics, 33, 235–263.

RFA. 2017. Ethanol biorefinery locations [Online]. Available at: https://ethanolrfa.org/biorefinery-locations/ [Accessed June 1 2017].

ROBERTSON GP, HAMILTON SK, BARHAM BL, DALE BE, IZAURRALDE RC, JACKSON RD, LANDIS DA, SWINTON SM, THELEN KD & TIEDJE JM 2017. Cellulosic biofuel contributions to a sustainable energy future: Choices and outcomes. Science, 356.

SCHIERHORN F, MÜLLER D, BERINGER T, PRISHCHEPOV AV, KUEMMERLE T. & BALMANN A. 2013. Post-Soviet cropland abandonment and carbon sequestration in European Russia, Ukraine, and Belarus. Global Biogeochemical Cycles, 27, 1175–1185.

SCHNEPF R. 2013. Agriculture-based biofuels: Overview and emerging issues. Congressional Research Service [Online]. Available at: https://fas.org/sgp/crs/misc/R41282.pdf [Accessed May 19 2020].

SPAWN SA, LARK TJ & GIBBS HKJERL 2019. Carbon emissions from cropland expansion in the United States. 14, 045009.

SYSWERDA S, BASSO B, HAMILTON S, TAUSIG J, ROBERTSON GJA, ECOSYSTEMS & ENVIRONMENT 2012. Long-term nitrate loss along an agricultural intensity gradient in the Upper Midwest USA. 149, 10–19.

US 110TH CONGRESS 2007. Energy independence and security act of 2007. Public Law 110–140. Available at: https://www.govinfo.gov/content/pkg/PLAW-110publ140/pdf/PLAW-110publ140.pdf.

USDA. 2020. Summary Report: 2017 National Resources Inventory, Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available at: https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/USDA

USDA-NASS. 2020. Quick Stats [Online]. Available: https://www.nass.usda.gov/Quick_Stats/ [Accessed 6/3/2020 2020].

USDA-NRCS. 2017a. Effects of Conservation Practices on Nitrogen Loss from Farm Fields [Online]. Available at: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1365657.pdf [Accessed March 3 2019].

USDA-NRCS. 2017b. Effects of Conservation Practices on Phosphorus Loss from Farm Fields [Online]. Available at: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1365655.pdf [Accessed March 3 2020].

USDA-ERS. 2019. Fertlizer Use and Price [Online] Available at: https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx [Accessed January 11 2021]

WANG X, GASSMAN P, WILLIAMS J, POTTER S. & KEMANIAN A. 2008. Modeling the impacts of soil management practices on runoff, sediment yield, maize productivity, and soil organic carbon using APEX. Soil and Tillage Research, 101, 78–88.

WEST TO, BRANDT CC, BASKARAN LM, HELLWINCKEL CM, MUELLER R, BERNACCHI CJ, BANDARU V, YANG B, WILSON BS & MARLAND G. 2010. Cropland carbon fluxes in the United States: Increasing geospatial resolution of inventory-based carbon accounting. Ecological Applications, 20, 1074–1086. [PubMed: 20597291]

WEST TO, BRANDT CC, WILSON BS, HELLWINCKEL CM, TYLER DD, MARLAND G, DE LA TORRE UGARTE DG, LARSON JA & NELSON RGJSSSOAJ 2008. Estimating regional changes in soil carbon with high spatial resolution. 72, 285–294.

WILLIAMS J, JONES C, KINIRY J. & SPANEL DA 1989. The EPIC crop growth model. Transactions of the ASAE, 32, 497–0511.

YU Z, LU C, TIAN H. & CANADELL JG 2019. Largely underestimated carbon emission from land use and land cover change in the conterminous United States. Global change biology, 25, 3741–3752. [PubMed: 31310672]

ZHANG X, IZAURRALDE RC, MANOWITZ D, WEST T, POST W, THOMSON AM, BANDARU VP, NICHOLS J. & WILLIAMS J. 2010. An integrative modeling framework to evaluate the productivity and sustainability of biofuel crop production systems. Gcb Bioenergy, 2, 258–277.

ZHANG X, IZAURRALDE RC, MANOWITZ DH, SAHAJPAL R, WEST TO, THOMSON AM, XU M, ZHAO K, LEDUC SD & WILLIAMS JR 2015a. Regional scale cropland carbon budgets: Evaluating a geospatial agricultural modeling system using inventory data. Environmental Modelling & Software, 63, 199–216.
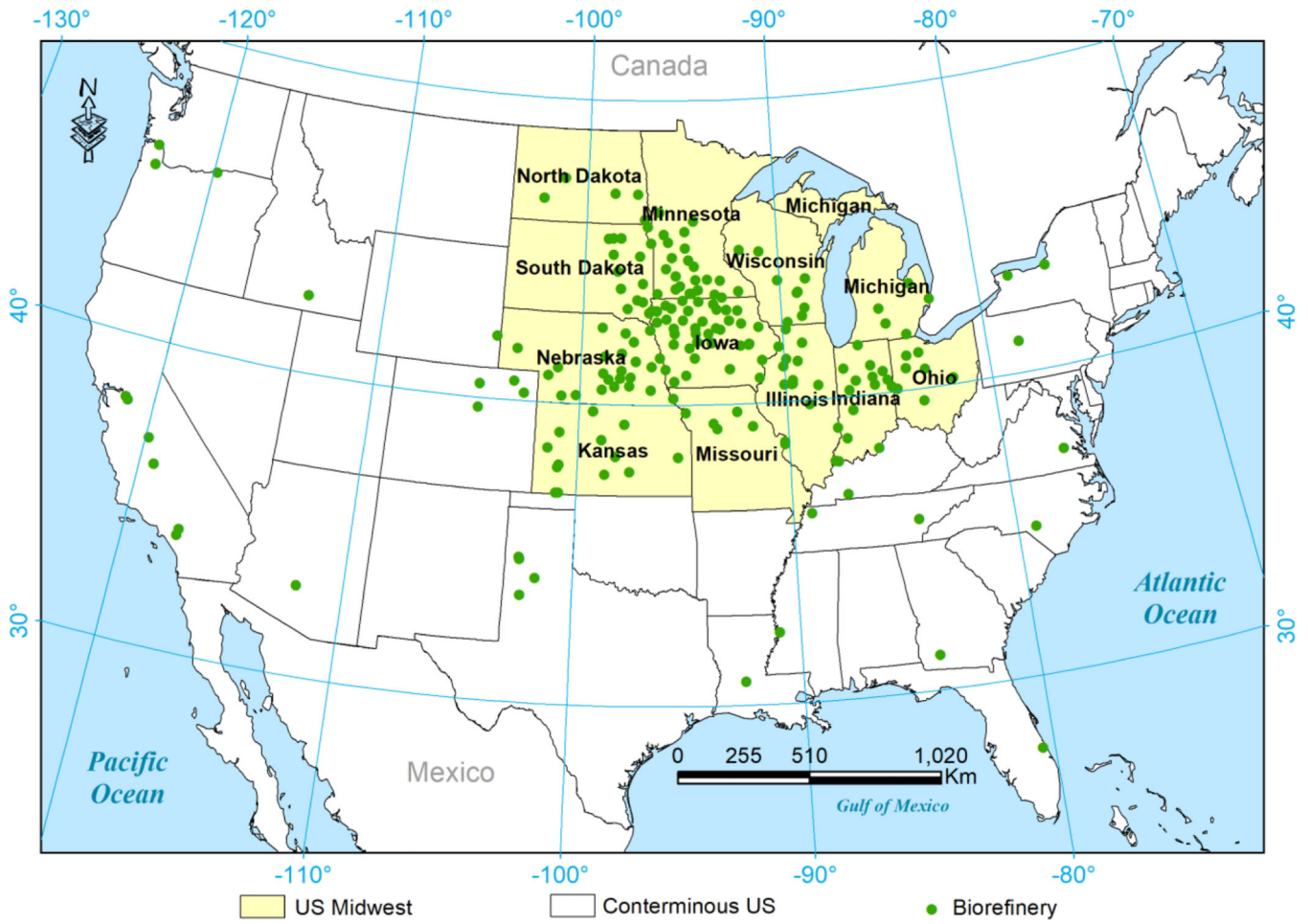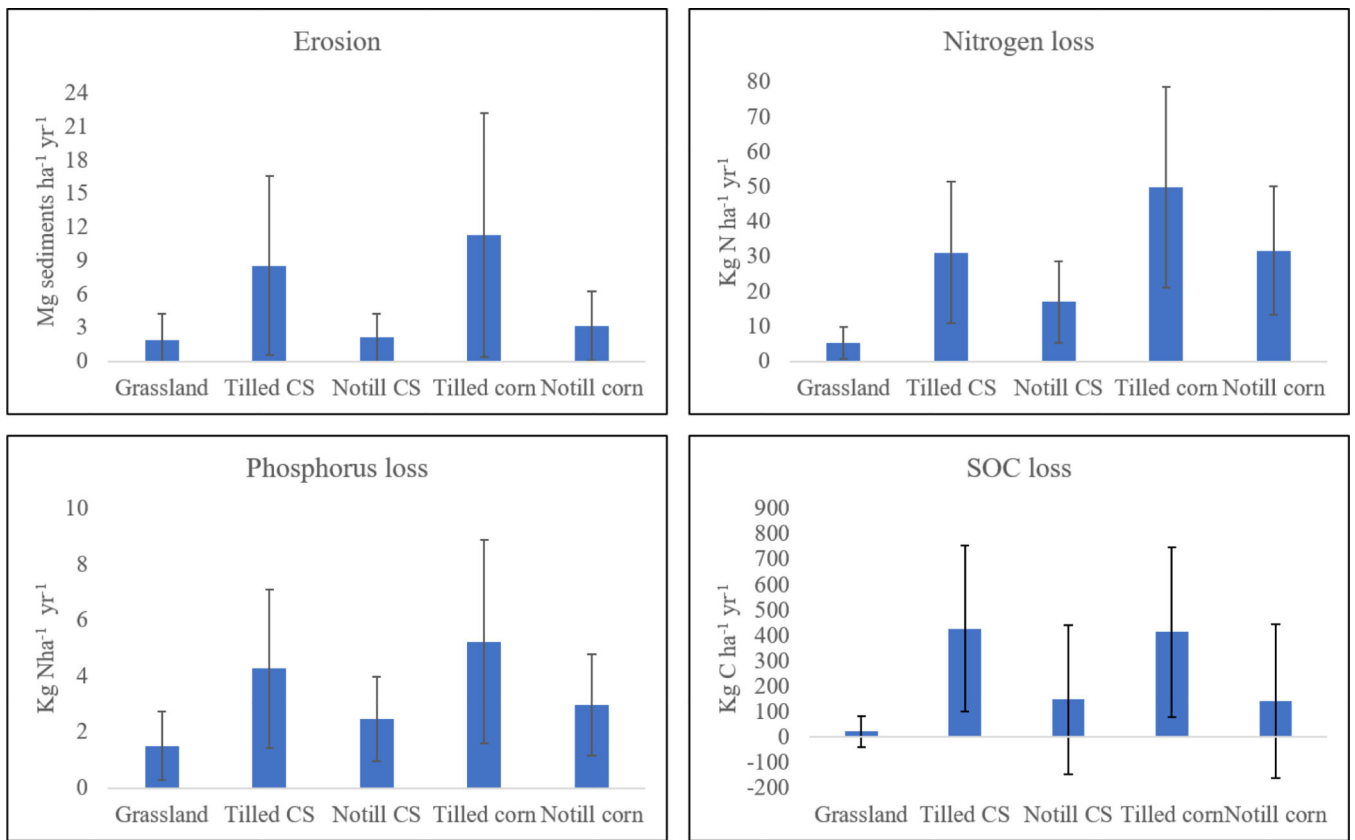
Figure 1.
States in modeling area in the Midwestern US, and location of US biorefineries (RFA, 2017).
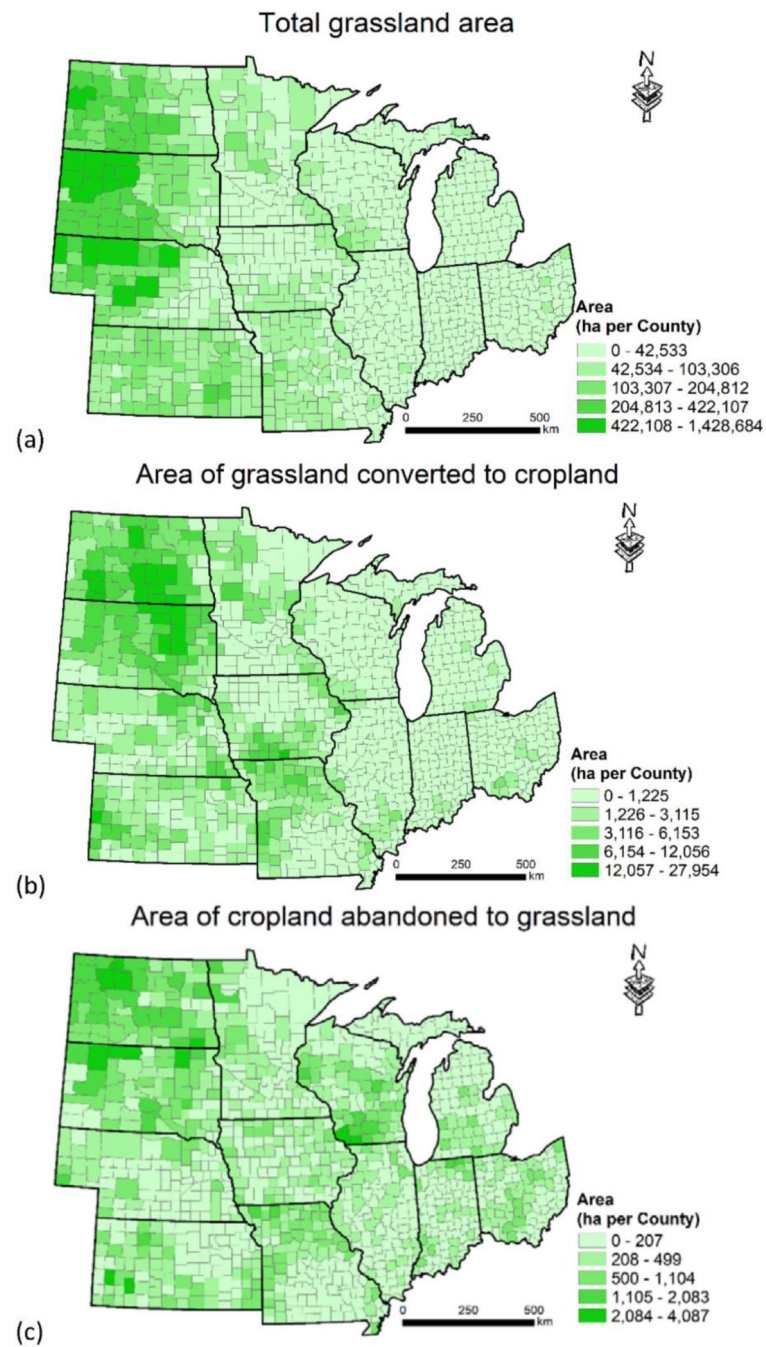
Figure 2a-c.

Hectares of total grassland in 2008 (a), grassland conversion to cropland between 2008 to 2016 (b), and cropland abandonment to grassland between 2008 to 2016 (c) across the 12 Midwestern states. Results expressed by county.
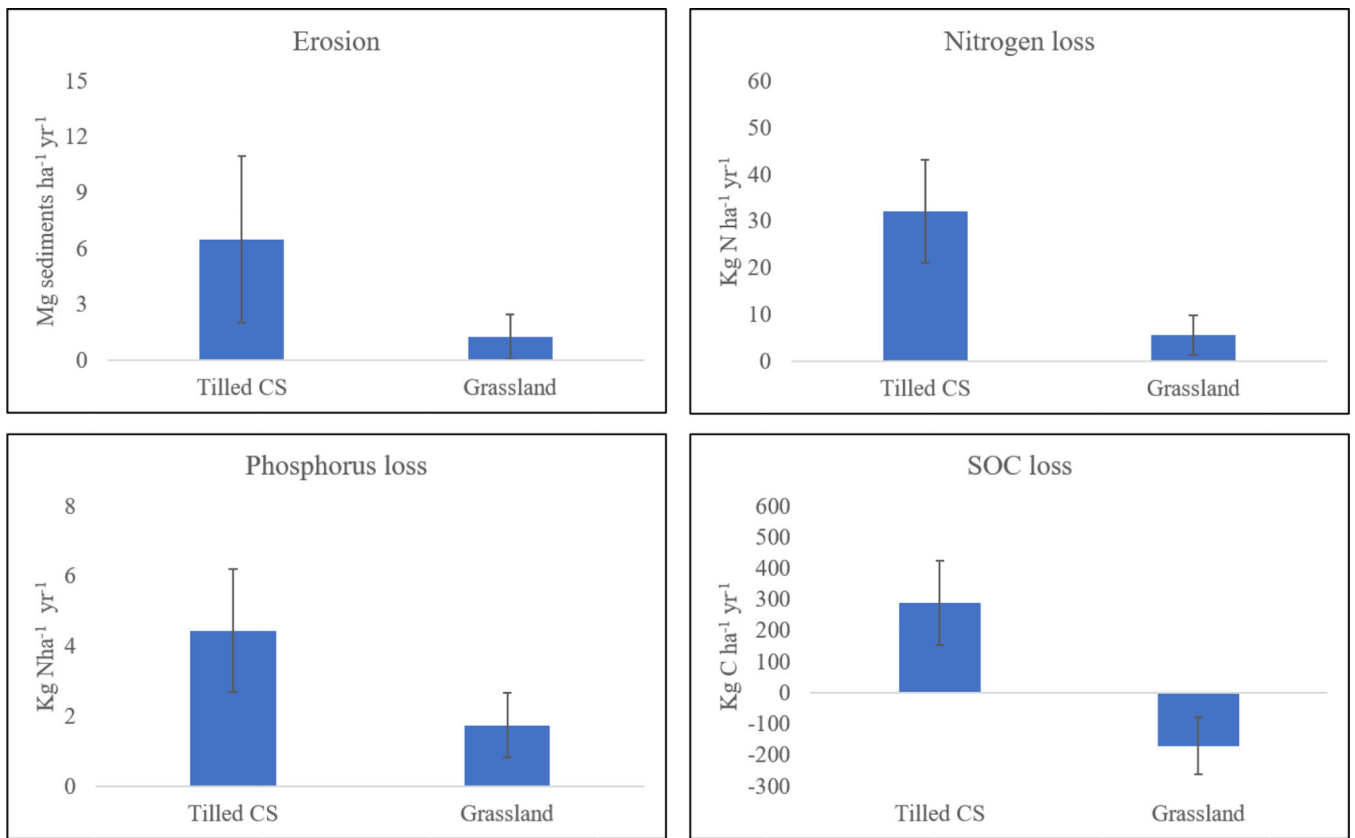
Figure 3.
Environmental impacts of cropland expansion scenarios across the converted parcels within the 12-state region, expressed on a per unit area basis. Whiskers represent ± 1standard deviation from the mean value. Corn-soybeans abbreviated CS. Grassland represents the baseline scenario (i.e., the effects if converted parcels had remained in grassland cover). Note: Negative SOC values reflect soil C accrual.
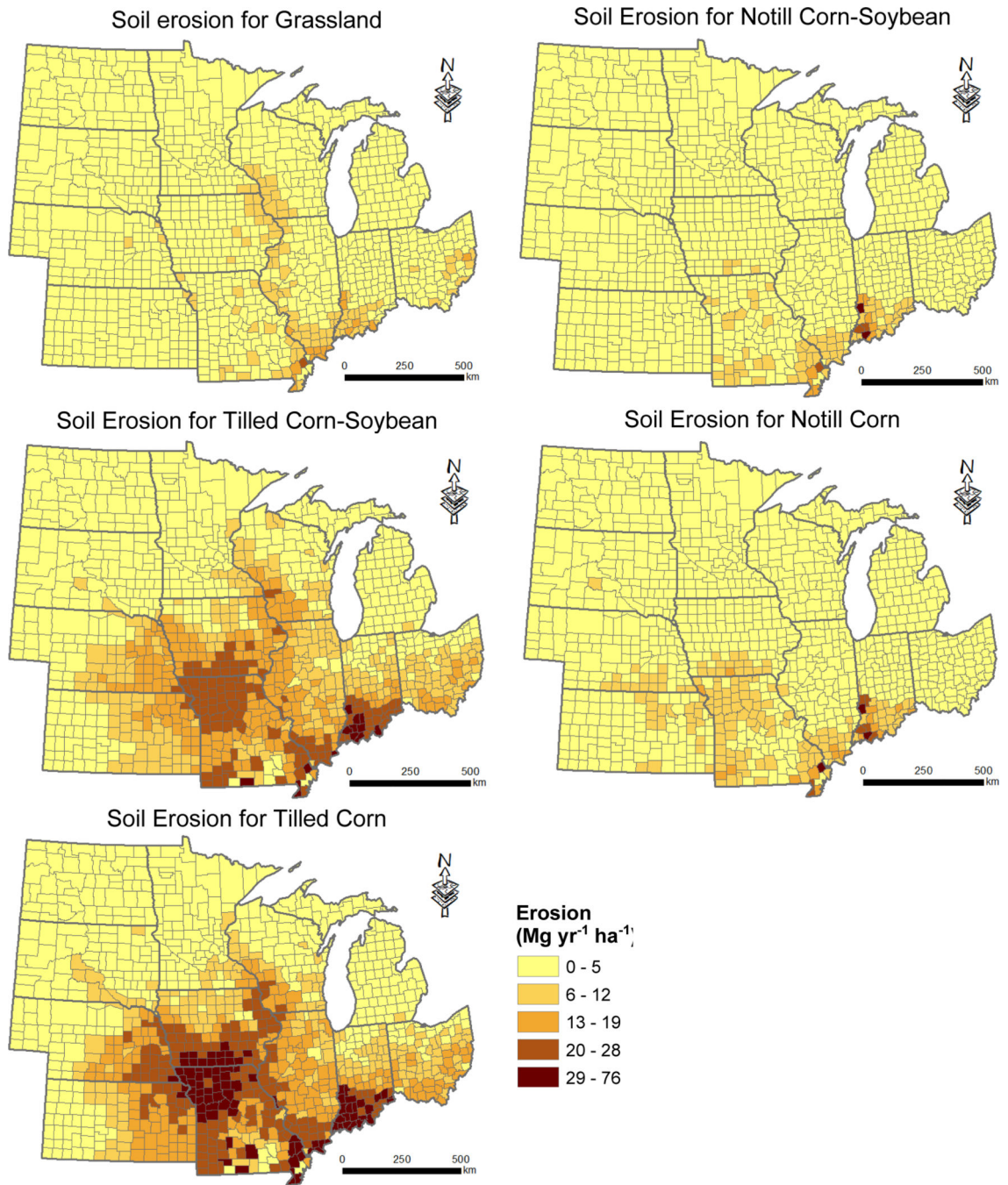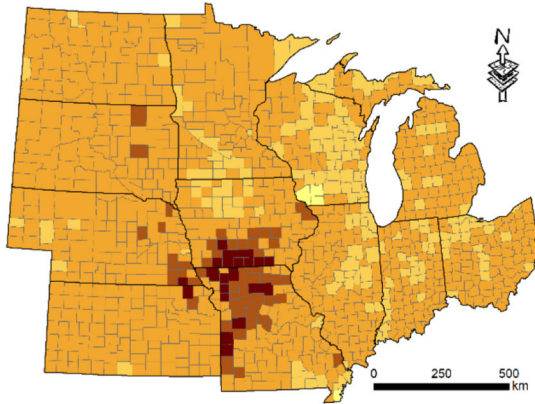
Figure 4.
Soil erosion per hectare for the baseline grassland scenario and the cropland expansion scenarios across the 12 Midwestern states. Results expressed by county average.
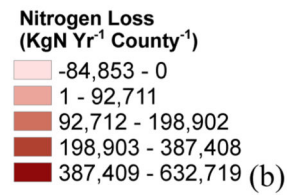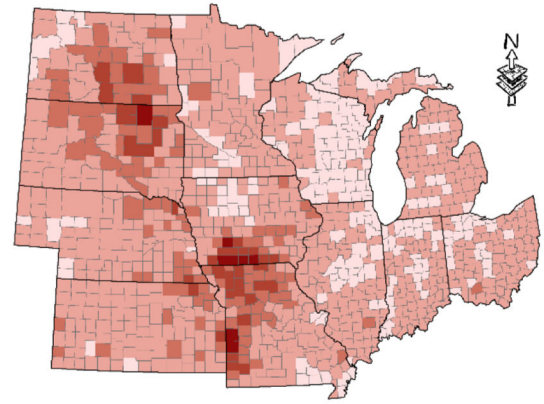
Figure 5.
Environmental impacts of cropland abandonment scenarios across the abandoned parcels within the 12-state region, expressed on a per unit area basis. Whiskers represent ± 1standard deviation from the mean value. Corn-soybeans abbreviated CS. Tilled CS represents the baseline scenario (i.e, the effects if the parcels had remained in crop production). Note: Negative SOC values reflect soil C accrual.
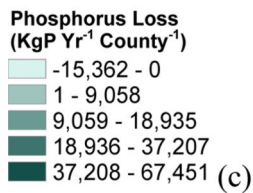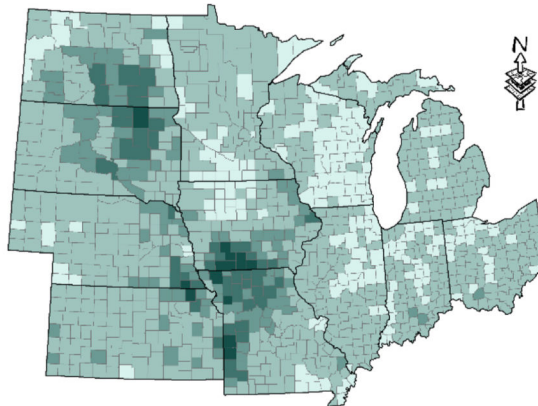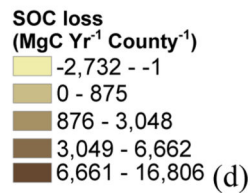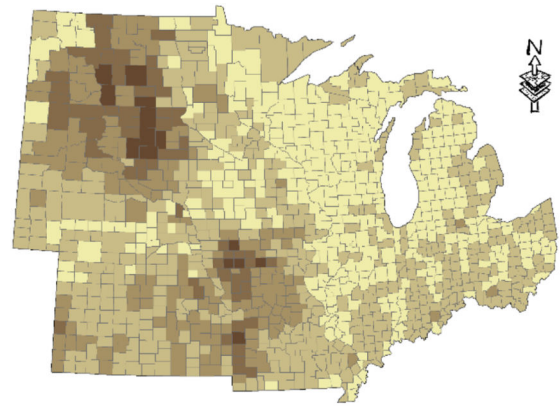
Erosion for Expansion - Abandonment

**Erosion
(Mg Yr^{-1} County^{-1})**
- -31,881 - -7,410
- -7,409 - 0
- 1 - 41,010
- 41,011 - 90,684
- 90,685 - 241,405 (a)
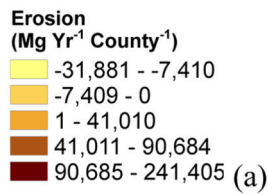
Nitrogen Loss for Expansion - Abandonment

**Nitrogen Loss
(KgN Yr^{-1} County^{-1})**
- -84,853 - 0
- 1 - 92,711
- 92,712 - 198,902
- 198,903 - 387,408
- 387,409 - 632,719 (b)

Phosphorus Loss for Expansion - Abandonment

**Phosphorus Loss
(KgP Yr^{-1} County^{-1})**
- -15,362 - 0
- 1 - 9,058
- 9,059 - 18,935
- 18,936 - 37,207
- 37,208 - 67,451 (c)

SOC loss for Expansion - Abandonment

**SOC loss
(MgC Yr^{-1} County^{-1})**
- -2,732 - -1
- 0 - 875
- 876 - 3,048
- 3,049 - 6,662
- 6,661 - 16,806 (d)

Figure 6a-d.
Net environmental effects annually of grassland conversion (grassland to corn/soy) and
cropland abandonment (corn/soy rotation to grassland) across the 12 Midwestern states.
Results expressed by county. Corn/soybean rotations simulated with conventional tillage.
Note: Negative SOC values reflect soil C accrual.

Table 1.

Environmental impacts of each expansion and abandonment scenario. Values reflect the simulated impacts summed across all converted or abandoned parcels within the 12-state region. Corn-soybeans abbreviated CS.

Scenario	Area	Erosion			Nitrogen loss			Phosphorus loss			SOC loss		
	Total	Total	Mean	SD	Total	Mean	SD	Total	Mean	SD	Total	Mean	SD
	(Mha)	(Tg yr⁻¹)	(Mg ha⁻¹ yr⁻¹)		(Gg N yr⁻¹)	(kg N ha⁻¹ yr⁻¹)		(Gg P yr⁻¹)	(kg P ha⁻¹ yr⁻¹)		(Gg C yr⁻¹)	(kg C ha⁻¹ yr⁻¹)	
Expansion													
Grassland (Baseline)	2.05	3.9	1.9	2.3	10.7	5.2	4.7	3.1	1.5	1.2	45.6	22.3	62.2
Tilled CS	2.05	17.5	8.6	8	63.8	31.2	20.2	8.8	4.3	2.8	875.8	428.0	325.7
Notill CS	2.05	4.4	2.1	2.1	34.7	17.0	11.6	5.1	2.5	1.5	301.7	147.5	294.3
Tilled Corn	2.05	23.1	11.3	10.9	102.1	49.9	28.7	10.7	5.2	3.7	848.6	414.7	334.4
Notill Corn	2.05	6.4	3.2	3.1	64.9	31.7	18.5	6.1	3.0	1.8	293.2	143.3	302.8
Abandonment													
Tilled CS (Baseline)	0.34	2.2	6.5	6.3	10.9	32.2	15.5	1.5	4.5	2.5	98.7	290.6	191.4
Grassland	0.34	0.43	1.3	1.7	1.9	5.7	6.0	0.59	1.8	1.3	−57.7	−169.7	129.3

Note: Negative SOC values reflect soil C accrual.

Table 2.

Net environmental impacts of cropland expansion (grassland to tilled corn-soybeans) and abandonment (tilled corn-soybeans to grassland) for US Midwestern states between 2008 and 2016. Values reflect the simulated impacts summed across all converted and abandoned parcels within the 12-state region.

	Erosion/Sedimentation	*Total N loss*	*Total P loss*	*Total SOC loss*
Total net impact over 12 state area	11.8 (Tg yr^{-1})	44.0 (Gg N yr^{-1})	*4.8* (Gg yr^{-1})	673.8 (Gg C yr^{-1})
Relative amount compared to US Midwest cropland[a]	7.9%	3.7%	N/A	5.6%
Relative amount compared to CRP benefits for entire US[b]	6.8%	18.6%	10.3%	7.3%

[a] Relative amount is calculated by comparing with the estimate soil erosion (150 Tg sediment yr^{-1}) (Zhang et al., 2015), N loss (1,200 Gg N yr^{-1}) (Zhang et al., 2015), and SOC loss (12,000 Gg C yr^{-1}) (West et al., 2008) from the cultivated cropland in the US Midwest.

[b] Relative to the environmental benefits of Conservation Reserve Program (CRP) for the US in 2017, estimated in https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/EPAS/natural-resouces-analysis/nra-landing-index/2017-files/Environmental_Benefits_of_the_US_CRP_2017_draft.pdf

Note: EPIC estimates of erosion, and N and P loss are compared to CRP estimates of sediment, N, and P not leaving field or intercepted by buffers. The EPIC estimate of SOC loss is compared to the CRP estimate of CO_2 equivalents sequestered. It was not compared to the C benefits of reduced fuel and fertilizer use, which was not included in our EPIC modeling.