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Measuring Societal Benefits of Perennials

Integrated Analysis and Literature Review

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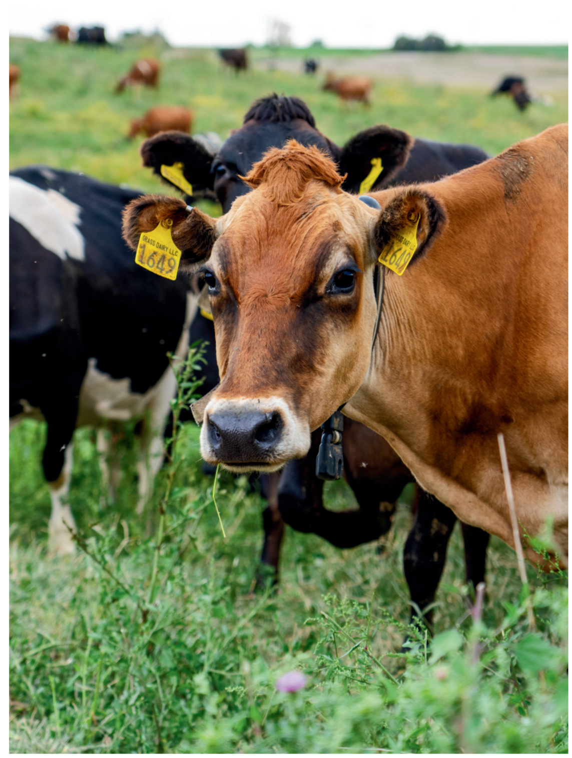
Introduction

A major question in agriculture is how to balance production of agricultural goods like food, feed, fiber, and fuel, with the conservation of the ecosystem services that are essential to our health and long-term well-being: for example, good soil, clean water, healthy air, and a stable climate. Our current agricultural system, dominated by row crops like corn and soybeans, is exceptionally good at maximizing yields of agricultural products, but this is done at the cost of losing valuable ecosystem services. This imbalance may be a result of a blind spot in our economic system, which causes many people to make decisions as though ecosystem services are worthless.

Usually, we decide how much something is worth using markets. For example, if most people in a town would buy or sell a 3-bedroom, 2-bathroom house for $200k, we can estimate that houses of that size in that town are worth $200k. However, a house and who owns it is usually very obvious: we have markets for the buying and selling of houses, and deeds and other legal documents to help us know who rightfully owns them. **It is much less clear how much ecosystem services are worth, because we all own them together and no one pays for the use or destruction of them.**

In contexts such as policy-making, where decisions require a defensible cost-benefit analysis, this blind spot for ecosystem services can lead to the type of imbalances we see in agriculture, where goods with markets (e.g., corn) are overproduced at the expense of goods without markets (e.g., clean water). With a better understanding of the value of these overlooked services, we may have a clearer idea of how to balance our agricultural system to maximize societal well-being, producing good amounts of both agricultural products and ecosystem services.

In this literature review and analysis, we attempt to estimate the value of a number of ecosystem services. We then use these values to compare two contrasting agricultural land uses to demonstrate how consideration of the value of ecosystem services can change what an optimal landscape might look like. For our first land use, we chose row crop agriculture typical of the upper Midwest, specifically corn and soybeans, because this represents business-as-usual in our current system that prioritizes commodity production. For our second land use, to serve as a contrast, we chose perennial grasslands because these are known to provide high levels of ecosystem services and are well-suited for the agricultural landscape of the Upper Midwest.



General methodological approach

To estimate the ecosystem services provided by row crops versus perennial grasses in the Upper Midwest United States, we conducted a literature review and synthesis. The first phase involved selecting ecosystem services to investigate further. To date, we have completed reviews for:

1. Nitrate loss[1]
    a. leaching to private wells
    b. loss to surface water
2. Nitrous oxide emission to the atmosphere[2]
3. Air pollution
4. Soil erosion
5. Phosphorus loading to surface water

For each of these ecosystem services, we conducted a two-step literature review. First, for each ecosystem service, we identified studies that estimated the quantity produced by grasslands and row crops simultaneously in an Upper Midwest context. We define grasslands as areas established in well-managed perennial grasses: hayfields, biofuel grasses like switchgrass and miscanthus, rotationally grazed pastures, and restored prairies. We excluded alfalfa fields. We define row crops as continuous corn or corn-soy rotations, usually with conservation tillage and typical fertilizer rates for the Upper Midwest.

As an example of a study we use in our literature reviews, Shrestha and others (2023) reported how much nitrate leached to groundwater in corn and soybean fields versus fields in perennial grass (Shrestha et al., 2023). We used Google Scholar and the University of Wisconsin digital library system to identify relevant studies. If we could not find relevant Midwest studies, we used studies from similar climates in other parts of the world. Studies conducted in very different climates (e.g., tropical) were excluded. The quantity of ecosystem service (for example, kg nitrate leached per acre) was averaged from these studies to arrive at an estimate for row crops and for grasslands.

Second, we conducted a literature review of the monetized value of those ecosystem services and disservices. The value of each ecosystem service/disservice may include mortality risk, consumer behavior change, property value change, or direct clean-up costs. All monetary values have been converted to USD 2024 (i.e., values from previous years were adjusted to account for inflation) to standardize comparisons.

[1] In technical terms, these are actually ecosystem disservices. It is possible to reframe them as services: for example, nitrate loss reduction rather than nitrate loss. However, that would require choosing a baseline business-as-usual nitrate loss, which would be arbitrary and make comparisons between ecosystem services more complicated. Quantifying instead the damages, (that is, the disservices), allows a more straightforward comparison, because all services share the same "baseline": zero damage done.

[2] We also intended to include methane and carbon dioxide emissions, as well as soil carbon storage, but disruptions to federal funding interrupted our work.

Report limitations

Our comparison of monetized ecosystem services between row crops and perennial grasslands is limited in several ways. First, our analysis only includes a handful of ecosystem services, not a complete inventory. For reasons noted in a later section, we did not generate estimates for health impacts to farmers and others from pesticide application, biodiversity and its benefits, methane emissions, carbon dioxide emissions, nitrate costs to public wells and water works, or flooding, among others. Thus, our results should be interpreted as a lower estimate of the societal benefits of perennials compared to row crops. Future work to incorporate other services could change the magnitude of these results.

Second, our literature reviews generalize results from the upper Midwest to find an average per-acre value, which glosses over spatial variation (e.g., soil type) that controls many of these ecosystem services. Therefore, any conclusions drawn from this report necessarily reflect a typical acre in the Upper Midwest, not any acre specifically.

Third, we sought to compare “row crops” and “perennial grasslands.” There is large variation in management within these categories, which controls how beneficial or damaging they are to the environment. For example, row crops can range from full-tillage with long periods of bare soil to zero tillage and cover crops, the latter of which can decrease harms like nitrate leaching and air pollution. Perennial grasslands, too, vary widely: a restored prairie, a rotationally-grazed pasture, and a poorly managed, continuously grazed pasture will provide different levels of protection from phosphorus loading and soil erosion. Any recommendations or actions based on this report should involve more nuanced discussion of specific types of row crop and perennial grassland systems.

Next, the value of ecosystem services changes depending on their supply, or how common or rare they are, and their demand, or how much of them people want. In theory, polluting the only swimmable lake in Wisconsin would do far more monetary harm than polluting a clean lake in a state with thousands of clean lakes. So too with agricultural goods: corn overflowing from silos is cheap, but corn that meets our needs without exceeding them is worth far more per bushel. Some of the values in the study would change if we were to bring the production of commodities and other ecosystem services into balance. Therefore, the price assigned to each ecosystem service should be viewed not as an eternally fixed value, but as a reflection of our current agricultural system.

Additionally, this literature review and analysis differs from a quantitative meta-analysis. We did not exhaustively comb the available literature using a strict, methodical approach or weigh the studies according to the strength of their data and findings. However, we have attempted to create an accurate reflection of the current best understanding of these topics, as reported in the peer-reviewed literature.

Finally, the ecosystem services framework does not completely reflect how we as a society value land use and its effects. In some instances, no dollar value can adequately describe our relationship to something.

For example, the value of clean air comes mostly from the number of human lives saved when asthma attacks and other illnesses are prevented. To estimate this value requires estimating the dollar value of a human life. Most of us would intuit that a human life is invaluable. Practically speaking, however, we routinely risk our own lives in pursuit of less than infinite rewards (e.g., working a more dangerous job for more pay), suggesting that we put a value on human life that is substantially less than infinite. Regardless, some unit other than dollars, such as "human life-years protected", may be more appropriate in an analysis such as this one, but the research to support that type of analysis has not yet been done.

As another example, for many people, the natural world is a source of spirituality or emotional connection, the value of which cannot be fully captured by a transactional “services” framework. For communities where nature is considered to be sacred, God’s gift to humankind, or our species’ secularly shared inheritance, attempting to put a dollar value on the natural world may seem sacrilege, degrading, and inadequate.

We likely cannot estimate the value of everything that nature does for us; however, we argue that an incomplete analysis, when understood to be incomplete, is better than no analysis at all. In our present legal and economic system, which emphasizes cost-benefit analysis over rights-based or ethical frameworks (Berman, 2022), some attempt to understand the value of the natural world and its ecosystem services is necessary. Without such an attempt, their value will continue to be assumed to be zero and they will continue to be overlooked and destroyed (in economic terms, the harms will be “externalized”) by policies and markets that favor the production of goods that have explicit dollar values.

Detailed results

This section explains the context for each ecosystem service that we explored, as well as how we arrived at the cost per acre for the different land uses.

Nitrate loss: leaching to private wells

Nitrate, a highly mobile and plant-available form of nitrogen found in all soils, is susceptible to leaching and subsequent groundwater contamination. Nitrogen fertilizer application rates, soil type, precipitation, and other factors affect nitrate contamination of groundwater. Plants need nitrogen to photosynthesize and grow, and the plants we use in agriculture tend to be especially nitrogen-demanding. Thus, nitrogen-rich fertilizers (e.g., urea) are often applied in high amounts to agricultural land. Harvested grasslands, like hay fields, often receive some fertilizer, but usually at much lower rates than row crops like corn. Some grasslands, such as prairies, receive no fertilizer at all and leach very little nitrate. Because of this variation, we divided grasslands into two categories: fertilized and unfertilized.

Unfortunately, much of the nitrogen added by farmers does not stay where farmers put it. It can volatilize, becoming ammonia gas. It can also be converted in the soil to nitrous oxide. Much of it becomes nitrate, which is easily dissolved into rainwater and pulled down through the soil, a process called leaching.

When leached nitrate enters water bodies, it can cause problems, especially for people who drink well water and people who live downstream. Nitrate in well water is especially dangerous to babies, who can suffer or die from methemoglobinemia (aka, blue baby syndrome) if they drink contaminated water. Additionally, high levels of nitrate in drinking water have been linked to colon and rectal cancers, although the effects may be dependent on dietary factors (De Roos et al., 2003). Because of these and other hazards, the Environmental Protection Agency's standard for public drinking water is 10 mg/L nitrate-N or less (Environmental Protection Agency, 2025b) and many people avoid contaminated water even at lower concentrations (Keeler & Polasky, 2014).

Costs

It is difficult to quantify the health costs of nitrate leaching, as nitrate is only one of many factors that can combine to cause cancers and other diseases. Instead, we used the costs to people as they attempt to avoid drinking nitrate-contaminated water as a conservative proxy.

To estimate the cost of nitrate leaching to private well water due to a single acre being in row crops versus perennial grasses, we use the entire state of Wisconsin as a case study.

According to a report released in March, 2024, by the Wisconsin Department of Agriculture, Trade and Consumer Protection, 32.7% of private wells in Wisconsin have nitrate levels between 2 and 10 mg/L, with an additional 7.3% of wells having over that amount. (Romano et al., 2024). Since there are roughly 800,000 private wells in Wisconsin, these percentages translate to 58,400 wells that have >10-mg/L contamination and 261,600 wells with 2 to 10-mg/L contamination, for a total of 320,000 contaminated wells.

In a 2014 Minnesota study, researchers surveyed rural households to determine likely responses to well water contamination and their costs (Keeler & Polasky, 2014). On average, people spent about $460 per year for each well that was contaminated with nitrates beyond 4 mg/L. Unfortunately, our estimate of how many wells are contaminated in Wisconsin uses a measurement of 2 mg/L or more, not 4 mg/L or more. To align the two studies, we assume an even distribution of contamination levels, where three-fourths of the wells reported to have 2 to 10-mg/L contamination are assumed to exceed 4 mg/L, resulting in a total of contaminated wells of 254,600. Combining the cost per well with the number of contaminated wells, we estimate that nitrate contamination of private wells costs people in Wisconsin about $117,505,000 per year.

Not all nitrate contamination comes from agriculture. The fraction of nitrate contamination that does come from agriculture has not recently been studied; however, (Hensler, 1994) estimated in 1994 that 90% of nitrate comes from agriculture. Without a more recent estimate, this is the number that we will use. By assuming 90% of the nitrate cost to well water users comes from agriculture, we find $105,754,000 per year in Wisconsin.

To understand what fraction of this comes from row crops versus grassland agriculture, we need to understand how much nitrate is leached from these different land uses. Our literature review estimated that row crops, fertilized grasslands, and unfertilized grasslands leached 12.98, 2.94, and 0.72 kg of nitrate per acre per year, respectively. Using numbers from the National Agricultural Statistics Service's CropScape, we found that there were 6,767,000 acres in row crops, 1,388,000 acres in fertilized grass, and 3,960,000 acres in unfertilized grass in 2024 in Wisconsin (C. Boryan et al., 2011; C. G. Boryan et al., 2014; Han et al., 2012; Han, Yang, Di, & Yue, 2014; Han, Yang, Di, Yagci, et al., 2014). Combining these numbers, we estimate that row crops leach 87,870,000 kg, fertilized grasslands leach 4,081,000 kg, and unfertilized grasslands leach 2,869,000 kg nitrate per year, for a total of 94,819,000 kg nitrate per year in Wisconsin.

Combining the total cost to well users and the total amount of nitrate leached from agriculture, we estimate that nitrate causes $1.12 of well water damages per kg leached, leading to a cost of $14.48 for row crops, $3.28 for fertilized grasslands, and $0.81 for unfertilized grasslands, per acre per year. This is a difference in cost to Wisconsin well users of $11.20 or $13.67 per acre per year.

This estimate is likely conservative for the following reasons. There are likely more than 800,000 private wells in Wisconsin; people likely begin spending money to avoid drinking contaminated water at levels lower than 4mg/L; and most importantly, following the approach taken by Keeler and Polasky, we here assume no costs are incurred by taking no action to avoid contaminated water (Keeler & Polasky, 2014). This assumes zero health impact from drinking water with high levels of nitrates, which is unlikely.

COMPARISON

An acre of fertilized or unfertilized grasslands costs $11.20 or $13.67 less to Wisconsin well users per acre per year, compared to a typical row crop acre.

Nitrate loss: loss to lakes and rivers

Leached nitrates can travel far from their original sources, impairing downstream lakes and rivers. The resulting algal blooms and hypoxic, or low-oxygen, dead zones diminish recreational value and aquatic life and harm the industries that rely on them. These damages are difficult to value on a per-acre or per-kg nitrate basis. Instead, we use the direct nitrate clean-up costs as a proxy for nitrate reduction value.

Costs

In the Chesapeake Bay, the costs of cleaning up agricultural nitrate pollution was approximately $18/kg nitrate (Birch et al., 2011). A study from the EU found a similar cleanup cost of $24/kg N (Van Grinsven et al., 2013). Averaging these to $21 and using the nitrate leaching estimates above, the nitrate leached from row crops would cost $275, the nitrate from fertilized grasslands would cost $62, and from unfertilized grasslands cost $15 per acre per year.

COMPARISON

An acre of fertilized or unfertilized grasslands, compared to row crops, saves $212 or $259 respectively per acre per year by reducing potential downstream cleanup costs.

Table 1. Comparison of nitrate leaching in row crops versus perennial grasslands, including sources used in literature review.

Land use	Nitrate leached (kg / acre / year)	Sources
Row crops	12.98	(Chatterjee, 2020; Daigh et al., 2015; Hernandez-Ramirez et al., 2011; Hussain et al., 2020; Masarik et al., 2014; Qi et al., 2011; Randall et al., 1997; Shrestha et al., 2023; Smith et al., 2013; Zhou & Butterbach-Bahl, 2014)
Fertilized grasslands	2.94	(Daigh et al., 2015; Hussain et al., 2020; Qi et al., 2011; Shrestha et al., 2023; Smith et al., 2013)
Unfertilized grasslands	0.72	(Daigh et al., 2015; Hernandez-Ramirez et al., 2011; Hussain et al., 2020; Masarik et al., 2014; Randall et al., 1997; Shrestha et al., 2023; Smith et al., 2013)

Table 2. Cost of nitrate pollution, including sources used in literature review.

Cost	Cost per kg nitrate leached (USD 2024)	Sources
Avoidance of contaminated well water by well users	$1.12	(Hensler, 1994; Keeler & Polasky, 2014; Romano et al., 2024) CropScape: (C. Boryan et al., 2011; C. G. Boryan et al., 2014; Han et al., 2012; Han, Yang, Di, & Yue, 2014; Han, Yang, Di, Yagci, et al., 2014)
Downstream cleanup of contaminated water	$21.14	(Birch et al., 2011; Van Grinsven et al., 2013)

Table 3. Comparison of cost of nitrate leaching in row crops versus perennial grasslands.

Cost (USD 2024)	Row crops cost per acre per year	Fertilized grasslands cost per acre per year	Unfertilized grasslands cost per acre per year
Avoidance of contaminated well water by well users	$14.48	$3.28	$0.81
Downstream cleanup of contaminated water	$274.55	$62.14	$15.31

Nitrous oxide emissions

Temperatures across the Earth are controlled by energy coming in and energy going out. Energy enters in the form of shortwave radiation from the Sun. Some of this shortwave radiation bounces off clouds and the Earth's surface and returns to space. The rest strikes material (e.g., soil, parking lots), heating it. Heated material releases some of this heat as longwave radiation, some of which goes through the atmosphere and back into space.

Earth's atmosphere contains a number of gases that do not block shortwave radiation but do block longwave radiation. These gases act like a greenhouse around the Earth, trapping longwave radiation and allowing our planet to be much warmer than outer space, just like a greenhouse is warmer than the outdoors. Because of this, these gases are called greenhouse gases.

The trapping of some heat is essential for life on Earth. However, trapping excessive heat causes global average temperatures to rise, disrupting atmospheric patterns and causing "weird weather" which makes agriculture and other activities more difficult. Further, when heated, water expands slightly. Combined with melting ice caps and glaciers, this expansion causes sea level rise, which is devastatingly expensive and dangerous for people living on islands and coasts. For these and many other reasons, increasing levels of greenhouse gases poses a considerable threat to our current and future well-being.

The United States is a major contributor globally, responsible for about 11% of the world's greenhouse gas emissions in 2023 despite having only 4% of the global population (Population Division of the United Nations Department of Economic and Social Affairs, 2024; Ritchie et al., 2020). This means that we are well-positioned to be a major part of the solution. A majority of greenhouse gas emissions in the US comes from energy production and transportation, so the solutions will almost certainly require changes in those sectors. There is also potential for agriculture to contribute to solutions, as it produces approximately 10% of U.S. emissions (Environmental Protection Agency, 2025a).

Within agriculture, the main greenhouse gas is nitrous oxide, accounting for about half of U.S. agriculture's contributions to climate change (EPA, 2024). The emission of nitrous oxide comes largely from the application of nitrogen fertilizer. As such, the rates at which nitrous oxide is emitted are controlled by nitrogen fertilizer rates, as well as the presence of legume crops, which add nitrogen to the soil, and soil moisture, which influences the behavior of soil microbes who convert nitrogen to its various forms.

Costs

The main approach used by researchers to estimate the costs of emitting greenhouse gases is known as the social cost of carbon (SCC), which is the net cost of the harms and benefits to human society of the emission of an additional metric ton of carbon dioxide. The exact SCC is not known. Estimates depend on many things, such as how human life is valued, whether lives in other countries or only the United States are valued, and how the future is valued or devalued over time. A conservative estimate of the SCC previously used by the United States government is $53, although newer studies suggest around $224 may be more accurate (Prest, 2023; Rennert et al., 2022).

Other greenhouse gases are converted to a carbon dioxide-equivalent in order to use the SCC to estimate the costs of their emission. However, this is complicated. Different gases have different insulating properties. They also stick around in the atmosphere for different lengths of time. This makes it difficult to compare the climate-warming impacts of different gases. One gas might trap a lot of heat but only do it for a short time before it gets removed from the atmosphere by plants, microbes, or other processes. Another gas might trap less heat in a day, but because it sticks around for a very long time, the amount of heat it traps over its residence in the atmosphere may be much higher.

The U.S. commonly uses the 100-year Global Warming Potential as a way to compare different greenhouse gases. For the purpose of this study, I will assume that one unit of nitrous oxide has the impact of 298 units of carbon dioxide, as is commonly done for a 100-year time span. Combining this with the low (high) SCC estimate above, one ton of nitrous oxide causes an estimated $15,650 ($66,700) of damages per ton, or $15.65 ($66.71) per kg.

COMPARISON

Our literature review estimated a per acre per year cost of $21.40 ($91.19) for row crops, $14.16 ($60.34) for fertilized grasslands, and $2.62 ($11.16) for unfertilized grasslands from nitrous oxide emissions.

Table 4. Comparison of nitrous oxide emissions in row crops versus perennial grasslands, including sources used in literature review.

Land use	Nitrous oxide emitted (kg)	Sources
Row crops	1.36	(Abraha, Gelfand, et al., 2018; Ansari et al., 2023; Chatterjee, 2020; Gelfand et al., 2016; Smith et al., 2013)
Fertilized grasslands	0.90	(Abraha, Hamilton, et al., 2018; Ansari et al., 2023; Smith et al., 2013)
Unfertilized grasslands	0.17	(Ansari et al., 2023; Gelfand et al., 2016)

Table 5. Cost of nitrous oxide emission climate impacts, including sources used in literature review.

Cost	Cost per kg nitrous oxide (USD 2024)	Cost sources
Contribution to destabilized climate	$15.63 ($66.71)	(Prest, 2023; Rennert et al., 2022)

Table 6. Comparison of cost of nitrous oxide emissions climate impacts in row crops versus perennial grasslands.

Cost	Row crops cost per acre per year	Fertilized grasslands cost per acre per year	Unfertilized grasslands cost per acre per year
Contribution to destabilized climate	$21.40 ($91.19)	$14.16 ($60.34)	$2.62 ($11.16)

Air pollution

Air pollution is one of the leading environmental risk factors for disease in the United States. Exposure to fine particulate matter ($PM_{2.5}$, fine particles that measure less than 2.5 microns in diameter) creates the greatest health harms. $PM_{2.5}$ is associated with premature death from lung cancer, stroke, ischemic heart disease, chronic obstructive pulmonary disease, type II diabetes, and lower respiratory infections. $PM_{2.5}$ is a mix of chemicals that includes primary $PM_{2.5}$ (i.e. directly emitted) and secondary components that form from precursor pollutants such as ammonia (NH_3), nitrogen oxides ($NO_x = NO + NO_2$), sulfur dioxide (SO_2), and volatile organic compounds (VOCs).

Livestock waste and agricultural fertilizers are the two largest sources of NH_3 emissions in the United States, and biogenic sources (i.e. vegetation and soils) constitute the largest source of VOC emissions. Agriculture also contributes to $PM_{2.5}$ pollution via NO_x emissions from diesel farm equipment and primary $PM_{2.5}$ emissions from dust and agricultural field burning. Air pollution can travel hundreds of miles, potential causing premature death and other health harms far from where it was emitted.

The U.S. EPA monetizes the mortality risk of air pollution using the value of a statistical life (VSL). Importantly, the VSL is not the value of a human life: it represents society's total willingness to pay for small reductions in mortality risk for large groups. VSL estimates have previously been used by the EPA in analyses of proposed regulation to inform estimates of the societal costs and benefits of policy. In this report, we use the U.S. EPA's recommended central value of $7.4 million (2006 USD), which when adjusted for inflation is $11.5 million (2024 USD).

Costs

Two landmark studies on air pollution damages from conventionally produced crops and livestock have been published in the past decade (Domingo et al., 2021; Hill et al., 2019). Hill et al. (2019) provides county-level estimates of air pollution damages from corn production. Domingo et al. (2021) expands this to 95 commodities and 67 food products using 2014 USDA and EPA data. County-level air pollution damages reported in deaths per county attributable to 95 commodities in Domingo et al. (2021) were obtained from authors by J. Mehre via personal communication. We selected corn and soybean air pollution damages and summed these over the 72 counties in Wisconsin. Total air pollution death in the state of Wisconsin for 2014 was 134.9 and 45.6 deaths attributable to corn and soybean air pollution, respectively.

We then divided these damages by the total acres of corn (3,977,732) and soybeans (1,790,678) in Wisconsin in 2014 to calculate a per acre mortality increase, and averaged these values to calculate the annual air pollution damages of a corn-soybean rotation. These damages were decreased by 7% assuming a reduced tillage practice (Domingo et al., 2021). Air pollution deaths per acre of corn-soybean reduced tillage rotation were 0.0000276 deaths per year. Combining this mortality estimate with the VSL of $11.5 million results in health damages of $315.53/acre for a reduced tillage corn-soybean rotation.

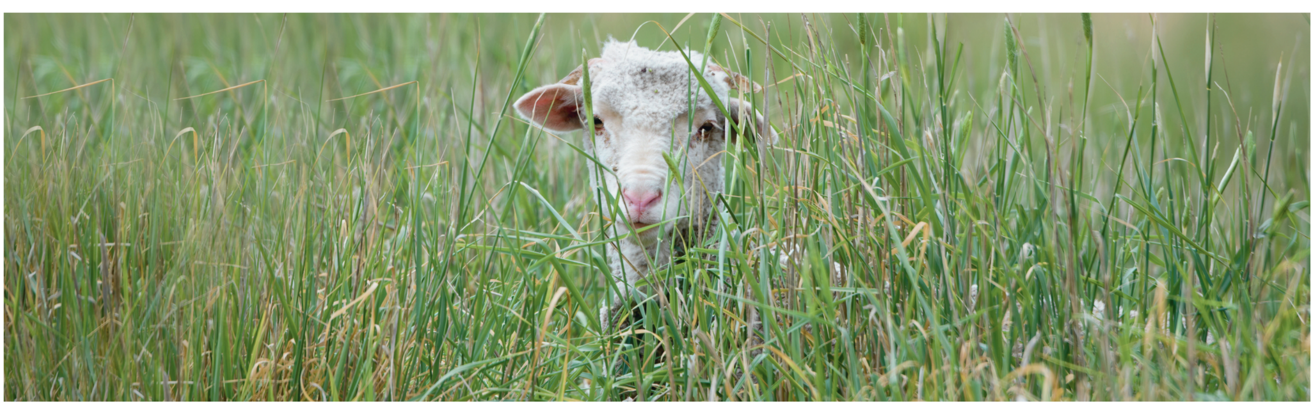
The air pollution harms of perennial grasslands hinges on their management. Grasslands can decrease air pollution, though these benefits are not well quantified. Prescribed burns, fertilization, and grazing on grasslands produces air pollutants. For this analysis, we calculated air pollution for a rotationally grazed pasture. Pasture-raised cattle production generates air pollution from tractor diesel usage and livestock ammonia emissions. Sommer and Hutchings (1995) estimated the ammonia emissions from beef cattle grazed for half the year and manure spread during the non-grazing season to be 4.2 kg ammonia-N per animal per year or 5.23 kg NH3 (Sommer & Hutchings, 1995). We assume a stocking rate of 0.56 animal units (AU) per acre (Tichenor et al., 2017) which equates to 2.93 kg ammonia emissions per acre. Tichenor et al. (2017) estimated tractor diesel use of 0.51 gallons of per acre with a 50-horsepower tractor. We estimate 1 gallon of diesel fuel to be 137,381 British thermal units (Btu) according to the U.S. Energy Information Administration (U.S. Energy Information Administration, 2025). Tractor emission factors for a 50-horsepower tractor are 10.3, 0.4, and 434 g/Btu for $PM_{2.5}$, SO_2, NO_x, respectively (Li et al., 2016). Total emission values were converted to monetized health farms using the Estimating Air pollution Social Impact Using Regression (EASIUR) model (Heo et al., 2016) with the location set to central Wisconsin, VSL at $11.5 million, and population and income year set to 2024 to price each emission at ground level, averaged across seasons. After multiplying these air pollution damage costs per metric ton by the total amount of air pollution per acre, we calculate the total air pollution damage of pasture at $80.63/acre.

Table 7. Comparison of cost of health damages due to air pollution in row crops versus perennial grasslands.

Cost	Row crops cost per acre per year	Grasslands cost per acre per year
Health damages of air pollution	$315.53	$80.63

COMPARISON

A corn-soybean rotation produced $315.53 per acre per year of air pollution damages. Pasture supporting grass-fed beef produced $80.63 per acre per year of damages, a difference of $234.90.



Soil erosion

Wind and water carry sand, silt, and clay particles, and their adsorbed nutrients, away from agricultural fields. In the Upper Midwest, water erosion deposits soil into drainage ditches, lakes, and rivers. In addition to farmers' loss of productive topsoil and the impact of the nutrients in these sediments, soil erosion can impede irrigation, make necessary ditch dredging by public works, and increase flooding potential.

Costs

Our literature review of soil erosion found that cropland (average of continuous corn, cash grain rotations, and dairy rotations) lost 3.02 tons soil/acre while grasslands (switchgrass, pastures) lost 0.68 tons soil/acre. In a USDA ERS report, Hansen & Ribaudo (2008) value soil erosion as the benefit gained by reducing soil erosion by 1 ton, which includes marine recreation, flood damage reduction, and soil productivity (Hansen & Ribaudo, 2008). These benefits are reported for each county in the U.S. The average social benefit of soil erosion reduction for all 72 counties in Wisconsin was $12.77/ton (adjusted to 2024USD). Multiplying our tons/acre estimate by this monetized value, we find that the benefit of reducing all soil erosion is $38.54/acre and $8.73/acre for row crop and grassland, respectively.

Table 8. Comparison of soil erosion in row crops versus perennial grasslands, including sources used in literature review.

Land use	Soil eroded (ton/acre)	Sources
Row crops	3.02	(Jokela & Casler, 2011; Merriman et al., 2019; Wang et al., 2020; Young et al., 2023; Zhang et al., 2021)
Grasslands	0.68	(Jokela & Casler, 2011; Merriman et al., 2019; Wang et al., 2020; Young et al., 2023; Zhang et al., 2021)

Table 9. Cost of soil erosion, including sources used in literature review.

Cost	Cost per ton (USD2024)	Cost sources
Soil erosion	12.77	(Hansen & Ribaudo, 2008)

Table 10. Comparison of cost of soil erosion in row crops versus perennial grasslands.

Cost	Row crops cost per acre per year (USD2024)	Grasslands cost per acre per year (USD2024)
Soil erosion	38.54	8.73

COMPARISON

The costs of soil erosion were $29.81 per acre per year less for grassland acres compared to row crop acres.

Phosphorus loading

In non-arid environments such as the Upper Midwest, algal blooms are primarily caused by increases in water phosphate concentrations. Algal blooms themselves produce harmful chemicals and limit recreational use of water bodies. Once these algae die and begin to decompose, oxygen concentrations plummet in surface waters, causing fish kills. Phosphorus that runs off fields can travel through watersheds and damage waterbodies far from their source, as is the case with the Gulf of Mexico Dead Zone.

Costs

Our literature review estimated annual phosphorus loading at 1.13 kg/acre for cropland (continuous corn, cash grain, and dairy rotation) and 0.59 kg/acre for grasslands (bioenergy crops, general grasslands, and pasture). A study of phosphorus trading in the Yahara watershed found that the benefit of phosphorus loading reduction was $93.13/kg P in 2024 USD, which includes property value loss, recreation loss, and local clean-up costs (Sampat et al., 2021). Eliminating P loading would result in a benefit of $104.90 and $54.61 for cropland and grassland, respectively.

Table 11. Comparison of phosphorous loss in row crops versus perennial grasslands, including sources used in literature review.

Land use	Phosphorus loss (kg P/ acre/yr)	Sources
Row crops	1.13	(Jokela & Casler, 2011; Meehan et al., 2013; Merriman et al., 2019; Young et al., 2023; Zhang et al., 2021)
Grasslands	0.59	(Jokela & Casler, 2011; Meehan et al., 2013; Merriman et al., 2019; Young et al., 2023; Zhang et al., 2021)

Table 12. Cost of phosphorous loss (e.g., loading), including sources used in literature review.

Cost	Cost per kg P (USD2024)	Cost sources
Phosphorous loading	$93.13	(Sampat et al., 2021)

Table 13. Comparison of cost of phosphorous loss in row crops versus perennial grasslands.

Cost	Row crops cost per acre per year (USD2024)	Grasslands cost per acre per year (USD2024)
Phosphorous loading	104.90	54.61

COMPARISON

Due to lower Phosphorus loading, grasslands result in a net benefit of $50.29 per acre per year compared to row crops.

Production of agricultural goods

Valuing an ecosystem includes pricing its harvestable and marketable goods. After all, having food, feed, fiber, and fuel is beneficial to society. As mentioned in the introduction, it is easy to determine the value of agricultural commodities, because people buy and sell them. However, it is important to note that the price of corn and soybeans is partially artificial: the “value” of corn and soybeans, as reflected in the market price, is higher than it would be without the spending of taxpayer money on bolstering demand for these commodities.

The most obvious example of this bolstering is corn-based ethanol: demand for ethanol largely comes from government mandates, and about a third of all corn produced in the United States goes to ethanol production. Other examples include research into turning corn and soy into other products (e.g., bioplastics (Krapfl, 2013)), which would, if successful, induce demand for these agricultural commodities, therefore boosting their prices.

We will use the market prices as an estimate of the true value of these goods, understanding that this further biases our comparison in favor of row crops.

Costs

The average yield, price, and value for corn, soybeans, and hay are detailed in the below table. Yields and prices reflect average Wisconsin values in recent years.

Table 14. Comparison of production of agricultural goods.

Product	Yield per acre (USDA National Agricultural Statistics Service, 2025a)	Price (USDA National Agricultural Statistics Service, 2024, 2025b)	Value per acre
Corn	176.67 bu	$4.93 / bu	$743.48
Soybean	51 bu	$12.07 / bu	
Hay	2.64 ton	$117.69 / ton	$310.71

COMPARISON

A corn-soybean rotation produces $743 per acre per year in agricultural goods, compared to $311 per acre per year for hay, a difference of $433.

Additional services

As mentioned previously, some services were not included, though they may be possible to quantify and price. For some, we simply ran out of time. For others, we found knowledge gaps and other challenges that hindered our ability to include them in this report. The following is an incomplete list, but included for the sake of future efforts:

Methane and carbon dioxide emissions, which are greenhouse gases commonly emitted in agriculture, were not quantified and priced in this study due to disruptions to federal funding that interrupted our work. Following our methodology, it should be possible for future researchers to complete this portion of the analysis.

Nitrate pollution of public wells and water works were not considered in this analysis, only pollution of private wells.

The health impacts of consumption of nitrate-contaminated water were not considered in this analysis, due to a lack of scientific consensus on the relationship between nitrates and health outcomes such as cancer. One approach, which we did not pursue, may be to take the number of methemoglobinemia (aka, blue baby syndrome) deaths in a region, multiply them by the portion of nitrate leaching attributable to agriculture, then divide them by the acres of row crops in that region, to arrive at a nitrate deaths per acre estimate. This would be a conservative estimate, as it is likely that consuming water contaminated with nitrates causes other negative health outcomes besides methemoglobinemia.

The health impacts of exposure to phosphorous-contaminated water were not considered in this analysis. The studies on cost that we found only included property value loss, recreation loss, and local clean-up costs. The direct health harms of toxic algal blooms, driven primarily by phosphorous, were not included in (Sampat et al., 2021), which hindered our ability to include those costs.

Flood prevention, thought to be a result of improving water infiltration and overall "sponginess" of the soil, was not explored in itself, although some of the damages were included in our valuation of soil erosion stem from increased flooding. A previous paper entitled *Measuring Societal Benefits of Soil Health: Biophysical Dynamics and Hydrological Ecosystem Services* explores the connection between soil health and flood prevention, and can be found on the MFAI Policy Program website (www.michaelfields.org/federal-state-policy).

Pesticide exposure was not included due to the difficulty of estimating on average which chemicals are applied, at what rates and with what precautions. This makes it difficult to understand the hazards and harms of general pesticide application. One approach, which we did not pursue, may be to take the number of acute pesticide exposure deaths in a region, then divide them by the acres of row crops in that region, to arrive at a pesticide deaths per acre estimate. This would be a conservative estimate, as it is likely that people die and are harmed from chronic exposure (that is, low level exposure over long timeframes) to pesticides, without that information being made public.

Biodiversity improvements were not included. Biodiversity is the range of different species present in an area, and it remains difficult to quantify at the per-acre level we focused on for this report. Increases in specific songbird populations, for example, depend on the surrounding landscape, not just what is done in a particular field or on a particular acre. The specific services provided by diverse wildlife populations, such as pest control and recreation opportunities, are also determined by landscape-level composition. Furthermore, deriving a dollar value for biodiversity proved difficult. There are not sufficient studies to estimate how much the average person inherently values biodiversity, or how biodiversity is connected to pest control and recreation opportunities. To incorporate biodiversity into this study, we recommend future researchers focus on specific species and conduct their analysis on a larger scale.

Conclusions

In this report, we provide cost estimates of ecosystem services and disservices to more equally compare different agricultural systems. The table below summarizes our findings.

When considering the ecosystem services we reviewed, **perennial grasslands produce at least $144 more per acre per year in value for society compared to row crops**. With the exception of agricultural production, perennial grasslands produce more of every ecosystem service. Because the dollar value of increased ecosystem services exceeds the lost value in commodity production, these results suggest that society would see a net benefit from an increase in the number of agricultural acres in perennial grasses in the Upper Midwest.

Table 15. Summary of the differences in ecosystem services provided by perennial grasslands version row crops.

Ecosystem service or disservice	Perennial grasslands compared to row crops (benefit to society in $/acre/year)
Nitrate loss (contamination of well water)[a]	12.44
Nitrate loss (clean-up of downstream water)[a]	235.82
Nitrous oxide emission	13.02 (55.44)[b]
Air pollution	234.90
Soil erosion	29.81
Phosphorous loading	50.29
Agricultural production	-432.77[c]
Total	**143.51 (185.93)**

[a] Results for fertilized and unfertilized grasslands are averaged.

[b] The larger numbers in parentheses result from a higher estimate of the damages associated with climate change.

[c] The negative result for agricultural production indicates that row crops produce more than grasslands of this ecosystem service.

References

Abraha, M., Gelfand, I., Hamilton, S. K., Chen, J., & Robertson, G. P. (2018). *Legacy effects of land use on soil nitrous oxide emissions in annual crop and perennial grassland ecosystems. E*cological Applications, 28(5), 1362–1369. https://doi.org/10.1002/eap.1745

Abraha, M., Hamilton, S. K., Chen, J., & Robertson, G. P. (2018). *Ecosystem carbon exchange on conversion of Conservation Reserve Program grasslands to annual and perennial cropping systems.* Agricultural and Forest Meteorology, 253–254, 151–160. https://doi.org/10.1016/j.agrformet.2018.02.016

Ansari, J., Udawatta, R. P., & Anderson, S. H. (2023). *Soil nitrous oxide emission from agroforestry, rowcrop, grassland and forests in North America: a review.* In Agroforestry Systems (Vol. 97, Issue 8, pp. 1465–1479). Springer Science and Business Media B.V. https://doi.org/10.1007/s10457-023-00870-y

Berman, Elizabeth P. (2022). *Thinking like an Economist: How Efficiency Replaced Equality in U.S. Public Policy.* Princeton University Press

Birch, M. B. L., Gramig, B. M., Moomaw, W. R., Doering, O. C., & Reeling, C. J. (2011). *Why metrics matter: Evaluating policy choices for reactive nitrogen in the Chesapeake Bay watershed.* Environmental Science and Technology, 45(1), 168–174. https://doi.org/10.1021/es101472z

Boryan, C. G., Yang, Z., & Willis, P. (2014, September 25). *US geospatial crop frequency data layers.* The 3rd International Conference on Agro-Geoinformatics, Agro-Geoinformatics. https://doi.org/10.1109/Agro-Geoinformatics.2014.6910657

Boryan, C., Yang, Z., Mueller, R., & Craig, M. (2011). *Monitoring US agriculture: The US department of agriculture, national agricultural statistics service, cropland data layer program.* Geocarto International, 26(5), 341–358. https://doi.org/10.1080/10106049.2011.562309

Chatterjee, A. (2020). *Extent and Variation of Nitrogen Losses from Non-legume Field Crops of Conterminous United States*. In Nitrogen (Switzerland) (Vol. 1, Issue 1, pp. 5–51). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/nitrogen1010005

Daigh, A. L. M., Zhou, X., Helmers, M. J., Pederson, C. H., Horton, R., Jarchow, M., & Liebman, M. (2015). *Subsurface Drainage Nitrate and Total Reactive Phosphorus Losses in Bioenergy-Based Prairies and Corn Systems*. Journal of Environmental Quality, 44(5), 1638–1646. https://doi.org/10.2134/jeq2015.02.0080

De Roos, A. J., Ward, M. H., Lynch, C. F., & Cantor, K. P. (2003). *Nitrate in public water supplies and the risk of colon and rectum cancers*. Epidemiology, 14(6), 640–649. https://doi.org/10.1097/01.ede.0000091605.01334.d3

Domingo, N. G. G., Balasubramanian, S., Thakrar, S. K., Clark, M. A., Adams C ⍰, P. J., Marshall, J. D., Muller, N. Z., Pandis, S. N., Polasky, S., Robinson, A. L., Tessum, C. W., Tilman, D., Tschofen, P., Hill, J. D., & Behrens, P. (2021). *Air quality-related health damages of food*. Proceedings of the National Academy of Sciences, 118(20). https://doi.org/10.1073/pnas.2013637118/-/DCSupplemental

Environmental Protection Agency. (2025a). *Inventory of U.S. Greenhouse Gas Emissions and Sinks.*

Environmental Protection Agency. (2025b, September 22). *National Primary Drinking Water Regulations.* Https://Www.Epa.Gov/Ground-Water-and-Drinking-Water/National-Primary-Drinking-Water-Regulations#Inorganics.

EPA. (2024). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022*.

Gelfand, I., Shcherbak, I., Millar, N., Kravchenko, A. N., & Robertson, G. P. (2016). *Long-term nitrous oxide fluxes in annual and perennial agricultural and unmanaged ecosystems in the upper Midwest USA.* Global Change Biology, 22(11), 3594–3607. https://doi.org/10.1111/gcb.13426

Han, W., Yang, Z., Di, L., & Mueller, R. (2012). *CropScape: A Web service based application for exploring and disseminating US conterminous geospatial cropland data products for decision support*. Computers and Electronics in Agriculture, 84, 111–123. https://doi.org/10.1016/j.compag.2012.03.005

Han, W., Yang, Z., Di, L., Yagci, A. L., & Han, S. (2014). *Making Cropland Data Layer Data Accessible and Actionable in GIS Education.* Journal of Geography, 113(3), 129–138. https://doi.org/10.1080/00221341.2013.838286

Han, W., Yang, Z., Di, L., & Yue, P. (2014). *A geospatial web service approach for creating on-demand cropland data layer thematic maps.* Transactions of the ASABE, 57(1), 239–247. https://doi.org/10.13031/trans.56.10020

Hansen, L., & Ribaudo, M. (2008). *Regional Values for Policy Assessment Economic Measures of Soil Conservation Benefits.* https://ssrn.com/abstract=2014840Electroniccopyavailableat:https://ssrn.com/abstract=2014840

Hensler, R. F. (1994). *CONFERENCE PROCEEDINGS NITRATE IN WISCONSIN'S GROUNDWATER: STRATEGIES AND CHALLENGES.*

References Continued

eo, J., Adams, P. J., & Gao, H. O. (2016). *Public Health Costs of Primary PM2.5 and Inorganic PM2.5 Precursor Emissions in the United States*. Environmental Science and Technology, 50(11), 6061–6070. https://doi.org/10.1021/acs.est.5b06125
Hernandez-Ramirez, G., Brouder, S. M., Ruark, M. D., & Turco, R. F. (2011). *Nitrate, Phosphate, and Ammonium Loads at Subsurface Drains: Agroecosystems and Nitrogen Management*. Journal of Environmental Quality, 40(4), 1229–1240. https://doi.org/10.2134/jeq2010.0195
Hill, J., Goodkind, A., Tessum, C., Thakrar, S., Tilman, D., Polasky, S., Smith, T., Hunt, N., Mullins, K., Clark, M., & Marshall, J. (2019). *Air-quality-related health damages of maize*. Nature Sustainability, 2, 397–403.
Hussain, M. Z., Robertson, G. P., Basso, B., & Hamilton, S. K. (2020). *Leaching losses of dissolved organic carbon and nitrogen from agricultural soils in the upper US Midwest*. Science of the Total Environment, 734. https://doi.org/10.1016/j.scitotenv.2020.139379
Jokela, W. E., & Casler, M. D. (2011). *Transport of phosphorus and nitrogen in surface runoff in a corn silage system: Paired watershed methodology and calibration period results.* Canadian Journal of Soil Science, 91(3), 479–491. https://doi.org/10.4141/cjss09095
Keeler, B. L., & Polasky, S. (2014). *Land-use change and costs to rural households: A case study in groundwater nitrate contamination*. Environmental Research Letters, 9(7). https://doi.org/10.1088/1748-9326/9/7/074002
Krapfl, M. (2013, October 7). *Iowa State building research and development program for bioplastics*. Https://Www.News.Iastate.Edu/News/Iowa-State-Building-Research-and-Development-Program-Bioplastics.
Masarik, K. C., Norman, J. M., & Brye, K. R. (2014). *Long-Term Drainage and Nitrate Leaching below Well-Drained Continuous Corn Agroecosystems and a Prairie.* Journal of Environmental Protection, 05(04), 240–254. https://doi.org/10.4236/jep.2014.54028
Meehan, T. D., Gratton, C., Diehl, E., Hunt, N. D., Mooney, D. F., Ventura, S. J., Barham, B. L., & Jackson, R. D. (2013). *Ecosystem-service tradeoffs associated with switching from annual to perennial energy crops in Riparian zones of the US Midwest*. PLoS ONE, 8(11). https://doi.org/10.1371/journal.pone.0080093
Merriman, K. R., Daggupati, P., Srinivasan, R., & Hayhurst, B. (2019). *Assessment of site-specific agricultural Best Management Practices in the Upper East River watershed, Wisconsin, using a field-scale SWAT model.* Journal of Great Lakes Research, 45(3), 619–641. https://doi.org/10.1016/j.jglr.2019.02.004
Population Division of the United Nations Department of Economic and Social Affairs. (2024). *World Population Prospect 2024: Release note about major differences in total population estimates for mid-2023 between 2022 and 2024 revisions*.
Prest, B. (2023, December 19). In Focus: The US Environmental Protection Agency's New Social Cost of Carbon. Resources.
Qi, Z., Helmers, M. J., Christianson, R. D., & Pederson, C. H. (2011). *Nitrate-Nitrogen Losses through Subsurface Drainage under Various Agricultural Land Covers*. Journal of Environmental Quality, 40(5), 1578–1585. https://doi.org/10.2134/jeq2011.0151
Randall, G. W., Huggins, D. R., Russelle, M. P., Fuchs, D. J., Nelson, W. W., & Anderson, J. L. (1997). *Nitrate Losses through Subsurface Tile Drainage in Conservation Reserve Program, Alfalfa, and Row Crop Systems*. Journal of Environmental Quality, 26(5), 1240–1247. https://doi.org/10.2134/jeq1997.00472425002600050007x
Rennert, K., Errickson, F., Prest, B. C., Rennels, L., Newell, R. G., Pizer, W., Kingdon, C., Wingenroth, J., Cooke, R., Parthum, B., Smith, D., Cromar, K., Diaz, D., Moore, F. C., Müller, U. K., Plevin, R. J., Raftery, A. E., Ševčíková, H., Sheets, H., … Anthoff, D. (2022). *Comprehensive evidence implies a higher social cost of CO2*. Nature, 610(7933), 687–692. https://doi.org/10.1038/s41586-022-05224-9
Ritchie, H., Rosado, P., & Roser, M. (2020). *Our World in Data: Greenhouse Gas Emissions*. Https://Ourworldindata.Org/Greenhouse-Gas-Emissions.
Romano, C., Cook, C., Potrykus, K., McColloch, M., Berzinski, R., Personette, R., Blanchard, D., Engelhardt, A., Gramse, M., Kelley, G., Hubbell, A., Woodstock, H., & Bussler, G. (2024). *AGRICULTURAL CHEMICALS IN WISCONSIN GROUNDWATER.*
Sampat, A. M., Hicks, A., Ruiz-Mercado, G. J., & Zavala, V. M. (2021). *Valuing economic impact reductions of nutrient pollution from livestock waste*. Resources, Conservation and Recycling, 164. https://doi.org/10.1016/j.resconrec.2020.105199
Shrestha, D., Masarik, K., & Kucharik, C. J. (2023). *Nitrate losses from Midwest US agroecosystems: Impacts of varied management and precipitation*. Journal of Soil and Water Conservation, 78(3), 141–153. https://doi.org/10.2489/jswc.2023.00048

References Continued

Smith, C. M., David, M. B., Mitchell, C. A., Masters, M. D., Anderson-Teixeira, K. J., Bernacchi, C. J., & DeLucia, E. H. (2013). *Reduced Nitrogen Losses after Conversion of Row Crop Agriculture to Perennial Biofuel Crops.* Journal of Environmental Quality, 42(1), 219–228. https://doi.org/10.2134/jeq2012.0210

Sommer, S. G., & Hutchings, N. (1995). *TECHNIQUES AND STRATEGIES FOR THE REDUCTION OF AMMONIA EMISSION FROM AGRICULTURE*

Tichenor, N. E., Peters, C. J., Norris, G. A., Thoma, G., & Griffin, T. S. (2017). *Life cycle environmental consequences of grass-fed and dairy beef production systems in the Northeastern United States*. Journal of Cleaner Production, 142, 1619–1628. https://doi.org/10.1016/j.jclepro.2016.11.138

U.S. Energy Information Administration. (2025). *Energy conversion calculators*.

USDA National Agricultural Statistics Service. (2024). *Wisconsin 2024 Agricultural Statistics*.

USDA National Agricultural Statistics Service. (2025a). *Crop Production 2024 Summary*.

USDA National Agricultural Statistics Service. (2025b). *Quick Stats. In USDA-NASS*.

Van Grinsven, H. J. M., Holland, M., Jacobsen, B. H., Klimont, Z., Sutton, M. A., & Jaap Willems, W. (2013). *Costs and benefits of nitrogen for Europe and implications for mitigation*. Environmental Science and Technology, 47(8), 3571–3579. https://doi.org/10.1021/es303804g

Young, E. O., Sherman, J. F., Bembeneck, B. R., Jackson, R. D., Cavadini, J. S., & Akins, M. S. (2023). *Influence of Pasture Stocking Method on Surface Runoff and Nutrient Loss in the US Upper Midwest.* Nitrogen (Switzerland), 4(4), 350–368. https://doi.org/10.3390/nitrogen4040025

Zhou, M., & Butterbach-Bahl, K. (2014). *Assessment of nitrate leaching loss on a yield-scaled basis from maize and wheat cropping systems*. In Plant and Soil (Vol. 374, Issues 1–2, pp. 977–991). Kluwer Academic Publishers. https://doi.org/10.1007/s11104-013-1876-9

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