Agricultural Nutrient Balance in Minnesota Watersheds:

A Spatial Framework for Estimating the Contribution of Nitrogen and Phosphorus from Livestock Manure and Commercial Fertilizer

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06/26/2025

Funding for this project was provided by the Minnesota Pollution Control Agency (MPCA)

wq-s1-87l

Acknowledgements

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Introduction

This project aims to map the state of Minnesota's agricultural nutrient balance. This approach is distinct from a traditional nutrient budget analysis in two primary ways. First, nutrient balances reported here are estimated for cultivated cropland only. Nutrients added to or removed from the landscape from other land uses, such as forest or urban environments, are excluded from this analysis. Second, this analysis is centered on the two primary anthropogenic nutrient sources that are added to cropland on an annual basis, which are animal manure and commercial fertilizer. This contrasts with the goal of traditional comprehensive nutrient budgets which include additional sources such as atmospheric deposition and transformation mechanisms such as nitrogen (N) fixation or mineralization of soil nutrient pools; these additional sources and mechanisms are more variable and complex and not the focus of this work. Nutrient outputs are defined as either state fertilizer recommendations (N) or the estimated amount of nutrients removed with crop harvest (phosphorus, or P205). The resulting surplus or deficit is defined as the nutrient balance between these inputs and outputs, which is estimated for every agricultural watershed in the state.

Previous efforts to map nutrient balances have primarily relied upon county-level datasets, including the United States Department of Agriculture (USDA) Census of Agriculture (COA), surveys provided by the USDA National Agricultural Statistics Service (NASS), or other modeling outputs such as provided by the Nutrient Use Geographic Information System, or NuGIS (International Plant Nutrition Institute, 2016). County-level data can pose significant challenges for water quality management approaches focused on a watershed scale. Studies such as Booth and Kucharik (2022) highlight the lack of nutrient uniformity within a county, particularly when it comes to manure nutrient production and use.

This project improves upon prior efforts by incorporating high-resolution Minnesota-specific datasets to refine nutrient balance estimates. While certain datasets are only available at the county level, such as commercial fertilizer sales and crop yield estimates, other required datasets, such as the location of animal feedlots, are precisely known. Additionally, the Agricultural Conservation Planning Framework (ACPF) provides detailed field boundary and land use information for every agricultural field in the state (Tomer et al., 2017). This data set provides the analytical foundation for the entire nutrient balance approach, as all input and outputs are ultimately estimated at a field-scale. Results are then summarized at the Hydrologic Unit Code (HUC) 08 and 10 watershed scales.

Results are intended to inform the state regarding potential nutrient imbalances, highlighting watersheds that are more likely to be a source of surplus nutrients. Importantly, nutrient imbalance is distinct from nutrient loading, as landscape characteristics play a key role in the pathways for nutrient loss to waterways. The 2025 Minnesota Nutrient Reduction Strategy update provides detailed information on basin and watershed nutrient loads to watershed outlets and to the state line.

Timeframe: The timeframe for this analysis represents an average year between 2018 and 2023.

Nutrient Inputs

Manure

The following section describes the methods used for the estimation of crop-available manure nutrients (nitrogen as N, phosphorus as P205) in Minnesota. ***Crop-available manure nutrients are defined as those nutrients that are available for crop uptake in an average year.***

A significant portion of manure nutrients are lost between the point of manure production and crop uptake, with most of this nutrient loss associated with N volatilization. While not explicitly modeled in this analysis, the endpoint of these nutrients should be acknowledged for their potential contribution to local air and water quality issues. Loss pathways accounted for in this report include the proportion of manure that is unrecoverable (generally dispersed over the landscape as with grazing animals), storage and handling losses (dependent on manure storage method), application losses (dependent on method of application), as well as manure nutrients that are applied but unavailable for crop uptake.

A variety of reference values were relied upon to estimate crop-available manure nutrients, as described in detail below and Appendix A1. Despite best efforts, small differences between the actual nutrient content of manure and the average "reference value" can cause significant over- or under-estimation of crop-available manure nutrients (Wilson, 2021). Additional uncertainty around animal counts and manure management add to the expected variability in our estimates. To address this uncertainty, manure nutrients were estimated at a low, medium, and high end, with the intent of understanding the upper and lower bounds of the contribution of manure to watershed nutrient balances.

Multiple discussions between academic, state and federal agencies have resulted in two primary approaches for estimating manure nutrients in Minnesota, which differ primarily in how stored manure nutrients are calculated. Manure nutrients were estimated using both method 1 and method 2, then averaged between the two methods to produce results at a low, intermediate, and high end.

Method 1: Estimate the nutrient content of a volume or mass of stored manure, then subsequently reduce by application losses.
Method 2: Estimate excreted nutrients and subsequently reduce by storage and application losses.

Animal feeding operations. The Minnesota (MN) Feedlot Database was downloaded in shapefile format from the Minnesota Geospatial Commons on 01/03/2024. All operations in the state are included in the database, including those that are no longer active or that are below the size required for registration (more than 50 animal units (AU) or more than 10 AU within shoreland areas). The following steps were taken to filter the dataset, which reduced the number of operations from 37,924 to 17,353 active operations statewide.

- Feedlots were removed if their status was set to "Inactive".
- Feedlots were removed if their category was set to "Not Required to Register".

- Feedlots were removed if there were no listed animal counts for the primary animal categories of dairy, beef, poultry, or swine.

Adjustment of animal counts. Animal counts listed in the feedlot database represent the maximum number of animals that can potentially be housed at each site, while oftentimes facilities are not operating at this capacity. Reduction coefficients were developed by University of Minnesota (UMN) researchers (Lazarus et al., 2014) to reduce animal counts to align with recent NASS surveys (Appendix A1: "Animal Count Reduction Factor").

Manure nutrients were estimated for three scenarios:

1. High: assumes no reduction from animal counts listed in registration data
2. Low: animal counts are adjusted using reduction coefficients applied to all operations
3. Intermediate: average of high and low values.

Manure Excretion. A unique animal weight and liquid:solid ratio was assigned to each animal category (Appendix A1: "Weight", "% Liquid", "% Solid") based on the same assumptions used in the MN Watershed Nitrogen and Phosphorus Reduction Planning tool (Lazarus et al., 2014).

Assigned weights were used to convert from animal counts to animal units (AU), with one AU equal to 1,000 pounds of animal weight. Excretion values were taken from Minnesota Department of Agriculture (MDA) and UMN Extension Nutrient and Manure Management Table 1 (MDA & UMN Extension, 2012) to estimate manure excretion per AU per year. Method 1 estimates the tons and/or gallons of manure excreted while method 2 estimates the nutrients (N and P2O5) excreted per AU per year.

Recoverability Factor. Recoverable manure is defined as the portion of manure that is routinely collected and removed from buildings and lots where livestock are held, and which would thus be available for land application or other use. Unrecoverable manure therefore includes manure deposited by pastured animals or that is unrecoverable due to losses during manure collection.

Recoverability coefficients were taken from Kellogg et al. (2014) and vary over time, geographic region, and farm size. Coefficients were selected to represent the geographic region containing Minnesota (Appendix A1: "Recoverability Factor") and were applied to all operations in the state. Excreted manure (tons/gallons for method 1) or excreted manure nutrients (N and P2O5 for method 2) were subsequently reduced by the amount of manure that is considered unrecoverable.

Stored Manure Nutrients. The approach for method 1 is to estimate the nutrient content of a recovered volume or mass of manure. These values were provided by MDA and UMN Extension Nutrient and Nutrient and Manure Management Table 3 (MDA & UMN Extension, 2012) and were applied to the tons and gallons of recovered manure. These values inherently include nutrient storage losses.

Method 2 estimates nutrient (N only) storage loss explicitly, and MDA and UMN Extension Nutrient and Manure Management Table 2 (MDA & UMN Extension, 2012) provided N loss estimates by storage method. The following assumptions were made regarding manure storage methods for each primary animal type:

- Liquid dairy and cattle manure was assumed to be held in earthen storage (30% N loss)
- Solid dairy and cattle manure was assumed to be an average of daily scrape and haul, manure pack, and open lot (35% N loss).
- Swine manure is assumed to be stored in below ground covered pits (20% N loss)
- Poultry manure stored as litter (35% N loss).

Nutrient Availability. Not all manure nutrients applied to crops are available for crop uptake. Estimating crop-available manure nutrients is complex and depends both on manure composition (organic versus inorganic N) as well as manure application method.

The inorganic N portion of manure, while immediately plant-available, is highly subject to losses from ammonia volatilization. Application methods such as incorporation or injection have been shown to reduce N volatilization losses (UMN Extension, 2021). In contrast, the organic N portion of manure, while not subject to volatilization, is not immediately available for crop uptake. This organic N must be broken down before becoming plant-available, a process that can take years and is highly dependent on the initial manure composition.

A 2014 survey (MDA, 2017) was used to inform how manure is commonly applied in the state. The survey reports the statewide distribution of manure application methods to corn for both liquid and solid manure (Table 1) and was used to weight manure availability values provided by MDA and UMN Extension Nutrient and Manure Management Table 4 (MDA & UMN Extension, 2012).

The liquid:solid ratio assigned to each animal category (Appendix A1) was used to weight nutrient availability by the proportion of the manure that is applied in liquid versus solid form. For example, 95% of the manure from a large dairy cow greater than 1,000 lbs. was assigned the N availability associated with liquid manure application, while 5% was assigned the N availability associated with solid manure application. The following assumptions were made regarding manure nutrient availability:

- Disc and knife injection were assumed to have the same nutrient availability.
- Broadcast with no incorporation and broadcast with incorporation after 96 hours were assumed to have the same nutrient availability.
- No 3rd year manure N credit was included.
- Manure P205 was assumed to be 80% available in year one (no year two availability) for all animal categories.

Final nutrient availability values assumed for each animal type are listed in Appendix A1: “N Year One”, “N Year Two”, and “P Year One”.

Table 1. Statewide Distribution of Method of Application of Liquid and Solid Manure to Corn Acres (MDA, 2017)	
Liquid Manure (From MDA Survey Table 58)	
Sweep Injection	17
Knife Injection	30
Disc Injection	30
Broadcast Incorporation within one day	10
Broadcast Incorporation within two to four days	6
Broadcast Incorporation over 4 days	5
Broadcast no Incorporation	2
Solid Manure (From MDA Survey Table 59)	
Broadcast Incorporation within one day	20
Broadcast Incorporation within 2 to 4 days	26
Broadcast Incorporation over 4 days	37
Broadcast no Incorporation	17

Manure Nutrient Results

Statewide Manure Nutrients. Table 2 reports estimated statewide manure nutrients for the low, intermediate, and high scenario, with all scenarios representing the average of method 1 and method 2. Unless explicitly stated, results presented in the remainder of this report reflect the intermediate scenario of manure nutrients.

Table 2. Statewide Manure Nutrients (US tons)			
	Low	**Intermediate**	**High**
N in Storage	187,850	230,680	273,509
N Year One	107,603	129,387	151,171
N Year Two	38,124	47,926	57,729
P205 in Storage	124,274	154,526	184,776
P205 Year One	99,421	123,621	147,821

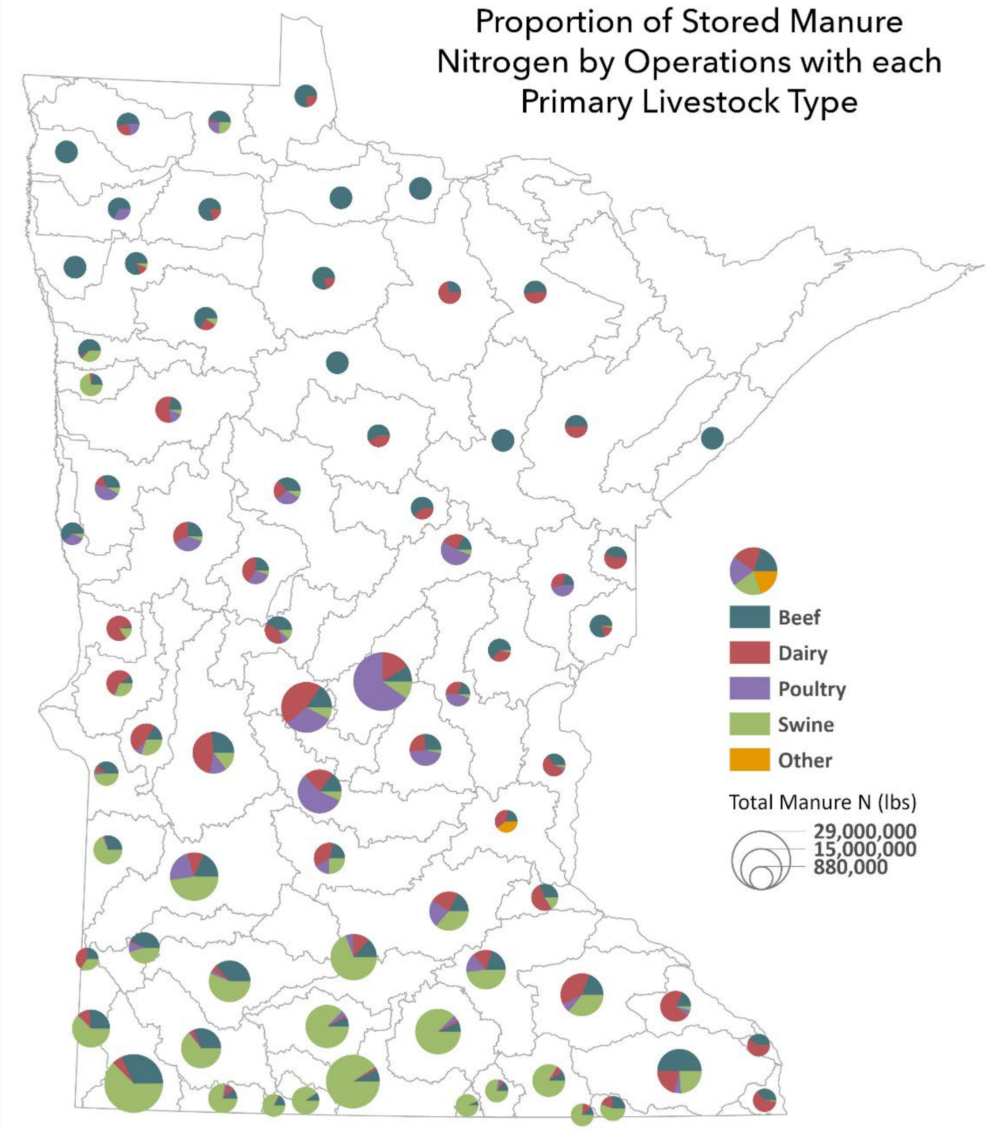


Figure 1. The dominant livestock type of feedlots contributing nitrogen to watersheds vary across the state (left). The size of the pie charts in the left map highlights the watersheds with the most manure nitrogen overall. The statewide manure nitrogen by primary livestock type (lower right), highlights how this variation balances out at the state level.

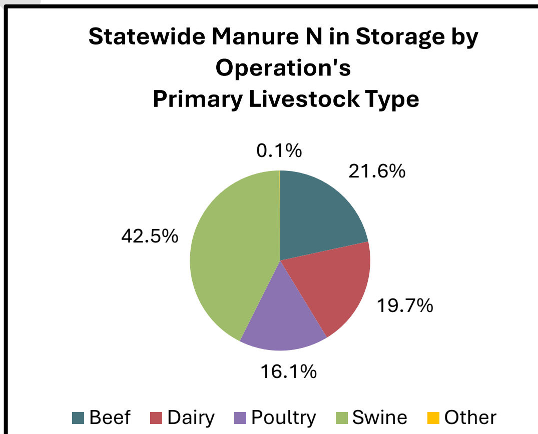
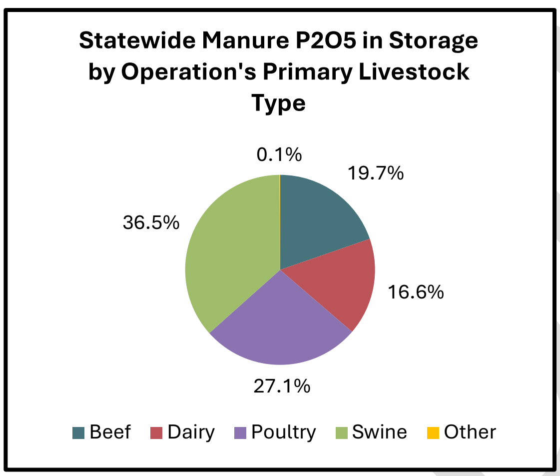
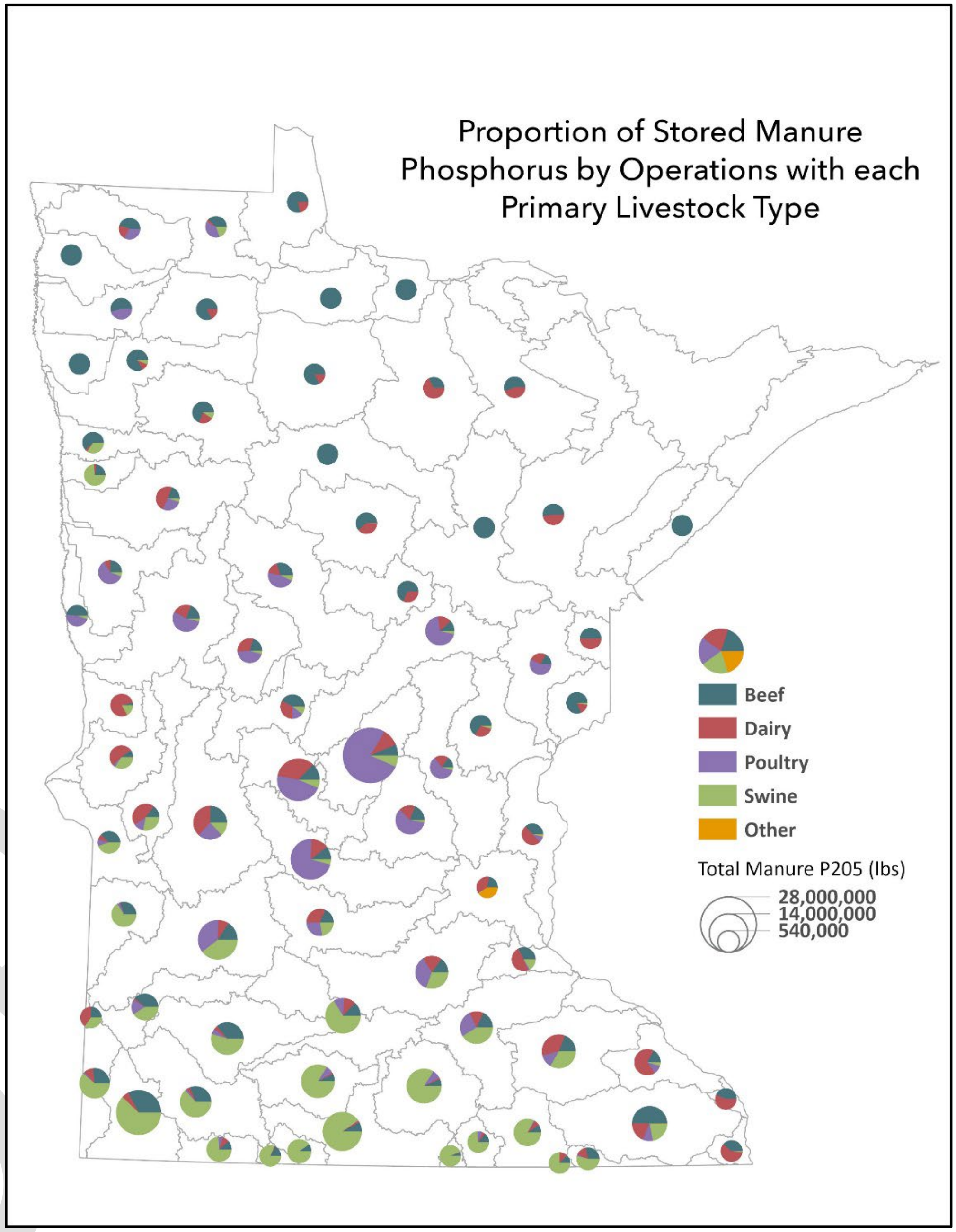


Figure 2. The dominant livestock type at feedlots contributing phosphorus to watersheds vary across the state (right). The size of the pie charts in the right map highlights the watersheds with the most manure phosphorus overall. The statewide manure phosphorus by primary livestock type (lower left), highlights how this variation balances out at the state level.





Manure nutrients by animal type. Figures 1 and 2 depict the regional patterns and variation of livestock distribution across the state. Manure nitrogen is produced primarily by swine operations in the south/southwest, while poultry and dairy facilities are dominant in the center of the state and beef is dominant in the northwest (there is low overall manure production in the northwest region of the state). Statewide, most nitrogen comes from swine operations, followed by beef, dairy, and poultry (Figure 1). For phosphorus, swine operations are the dominant producers in the south/southwest, poultry operations are dominant in the center of the state and beef operations are the most dominant in the northwest. Due to higher P205 concentrations in poultry manure as compared to other livestock types, poultry is the second most dominant livestock type (following swine) for statewide manure P2O5 in storage. Regional differences in livestock production have implications for nutrient management recommendations across the state.

Commercial Fertilizer

County level commercial fertilizer sales are provided by the Minnesota Department of Agriculture (MDA) for each year between 2010 and 2022. An average of the most recent six years of sales data (2016 to 2022) was used to represent the contribution of commercial fertilizers statewide (Table 5). Sales were summed for all counties in the state. A small percentage of sales data were classified as "unknown" and not attributed to a specific county; these were excluded from this analysis.

Table 3. Statewide Commercial Fertilizer Sales (MDA, 2025)		
Year	**N sold statewide (tons)**	**P205 sold statewide (tons)**
2017	743,856	334,738
2018	805,903	359,773
2019	755,627	320,317
2020	823,818	335,012
2021	838,216	384,898
2022	755,508	314,240
Six-Year Average	787,155	341,496

Nutrient Outputs

Field Based Approach

This section describes the methods used to estimate nutrient output for cultivated land in Minnesota (MN). Outputs from this analysis are based on estimated crop needs; nitrogen (N) output is represented by leading crop N fertilizer guidelines, while phosphorus (P2O5) output is represented by nutrient removal at crop harvest.

Field boundaries obtained from the Agricultural Conservation Planning Framework (ACPF) database provide the core structure for this analysis. Nutrient output at the field-scale is highly dependent on several factors that influence crop nutrient needs. These include whether the field is irrigated, the type of crop grown and expected yield or yield goal of that crop, and the organic matter content of the soil. The following sections provide a general background of the ACPF field boundary land use assignment as well as the process for assigning soil and management characteristics to each field.

Field Boundary Land Use Assignment. ACPF field boundaries were last updated in 2015, a process that involves manual editing of boundaries to align with recent land cover. All fields greater than 5 acres in size were included in this project. Using a process developed for use with the ACPF, field boundaries were overlaid with the National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) for each year between 2017 and 2023, and the majority land cover within each field was used to assign the crop grown to each field for each year in rotation. The process assigns the dominant land cover within each field to the entire acreage of the field; therefore, acreage estimates will differ from estimates derived from raw NASS CDL pixels. In general, acreages associated with less prevalent land use classes will decrease as pixels are aggregated within each field. While the timeframe for this project is 2018 to 2023, land use for the year 2017 was included to understand the previous crop grown for all years in the analysis.

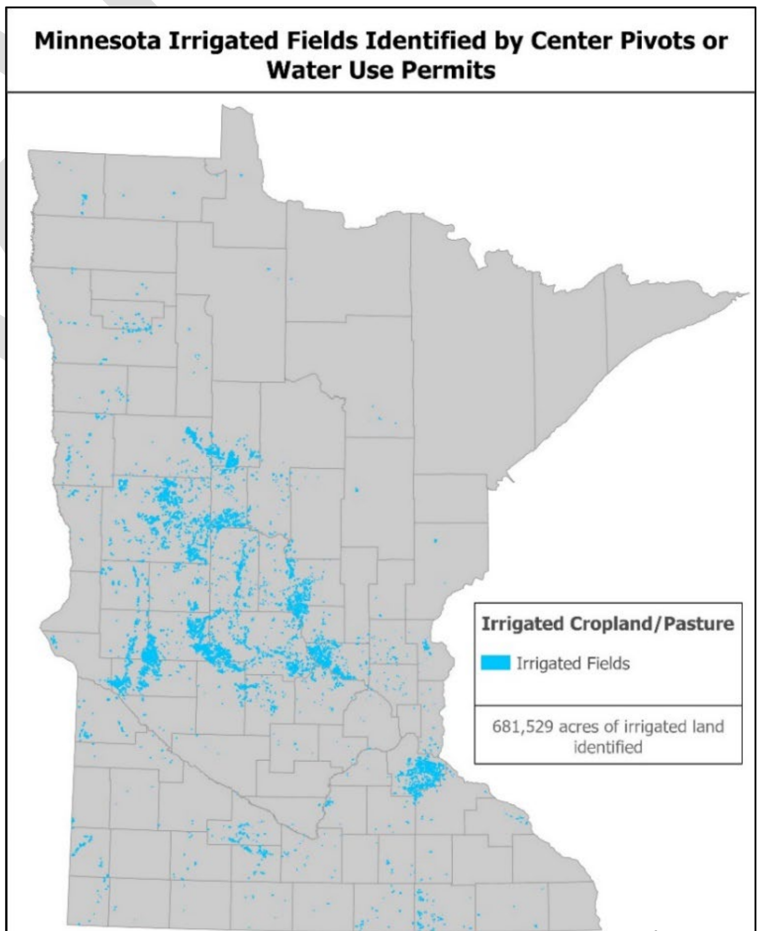


Figure 3.

Harvestable Crops. Only ***harvestable*** crops were included in the estimate of nutrient output, defined as: alfalfa, barley, canola, corn, dry beans, oats, other hay / non-alfalfa, peas, potatoes, rye, soybeans, spring wheat, sugar beet, sunflower, and turfgrass. Field planted to sweet corn represent 1% of MN corn acreage (NASS Minnesota Agriculture Overview, 2024) and were treated the same as corn for grain for this study.

Irrigation Status. Irrigated soils often have higher nutrient needs as compared to non-irrigated soils, and therefore an accurate spatial representation of irrigated fields is a critical component of this work. Irrigation is on the rise in Minnesota. The 2022 Census of Agricultural (COA) reports 648,313 acres of irrigated land (harvestable cropland plus pasture) in the state, which represents a 24% increase from the 2012 COA estimate of 524,016 acres. (Census of Agriculture, 2012, 2017).

Two datasets were combined to identify irrigated fields:

First, a shapefile provided by MDA (circa 2014) identified the exact location of center pivot irrigation equipment in Minnesota. To merge this dataset with ACPF field boundaries, the single ACPF agricultural field (cropland or pasture) with the largest overlap with each center pivot polygon was labeled as irrigated. This accounted for approximately 334,000 acres, or slightly more than half the irrigated land in the state.

Second, MN water use permits (Minnesota Department of Natural Resources, 2024) provided the point location of water use data. The dataset was filtered to only active permits for agricultural irrigation use (excluding wild rice, golf course, orchard, and vineyard uses). For each point that did not intersect a field already labeled as irrigated, the nearest ACPF agricultural field was found and classified as irrigated.

This two-step process identified 681,529 acres of irrigated cropland or pasture in the state. This value is within roughly 1% of the expected 2024 value (673,172 acres) assuming year-over-year increases like those observed from 2012 to 2022 COA values (Figure 3).

Crop Yields. Higher crop yields generally demand higher fertilizer N input and result in higher levels of P2O5 removal. Significant variability in crop yields across the state of MN can have a large impact on nutrient balance at a local level. The best publicly available datasets for yield information, when considering data quality and resolution, are NASS surveys. For some crops that are grown broadly, like corn and soybeans, there is annual yield data for most MN counties through 2023. Less prevalent crops, however, have had dwindling county yield data over time, and some crops have only ever had state yield data published by NASS. To address this progressive loss of county yield information, an approach was implemented to approximate county yields using historic trends in state yields, while maintaining the spatial variability between counties. Annual yield data reported by USDA NASS was used as the basis for these methods. The general steps of this approach are outlined below:

1. A six-year rolling average of county-level yield information is generated for each harvestable crop. For each crop-county combination, a six-year running average is generated for each year between 2000 to 2023, with a minimum of three years of yield information required for each six-year window. For all county-crop combinations that have a value for the year 2023 (representing a six-year average between 2018 and 2023), that value is used to represent county yields in this analysis.
2. State-level yield information for each crop is compiled across the same time frame (2000 to 2023). A linear regression is then performed to determine if there has been a significant percent change in state-yields over time ($p < 0.05$).

3. Any county-crop combination that is missing county yield information for the year 2023 (from step one) is filled in by applying the same proportional change seen in state yields to the most recent average yield data that exists in that county. For example, If the average change in state soybean yields represents a 1% annual increase (year over year) and the most recent year that a county has a six-year average yield value is 2008, then 2009 would be filled in with [2008 average yield] * 1.01. Similarly, 2010 would be filled in with [2008 average yield] * 1.02, and so on.
4. After gap filling based on state yield trends (step 3), any remaining county-crop combinations that are still missing yield information are assigned the average yield found in its corresponding Best Management Practice (BMP) Region, with a minimum of one county required to generate a BMP region average.
5. Any remaining county-crop combinations that are still missing yield information for 2023 are assigned the statewide 6-year running average (2018 to 2023) for that crop.

The result of this process is that nearly all crop-county combinations are assigned a unique yield estimate (Figure 4). Turfgrass was omitted from this approach as no NASS yield information existed at any scale. Instead, a constant yield of 1,000 lbs/acre was assigned to all turfgrass in the state (pers. comm. Jake Jungers UMN, January 2025).

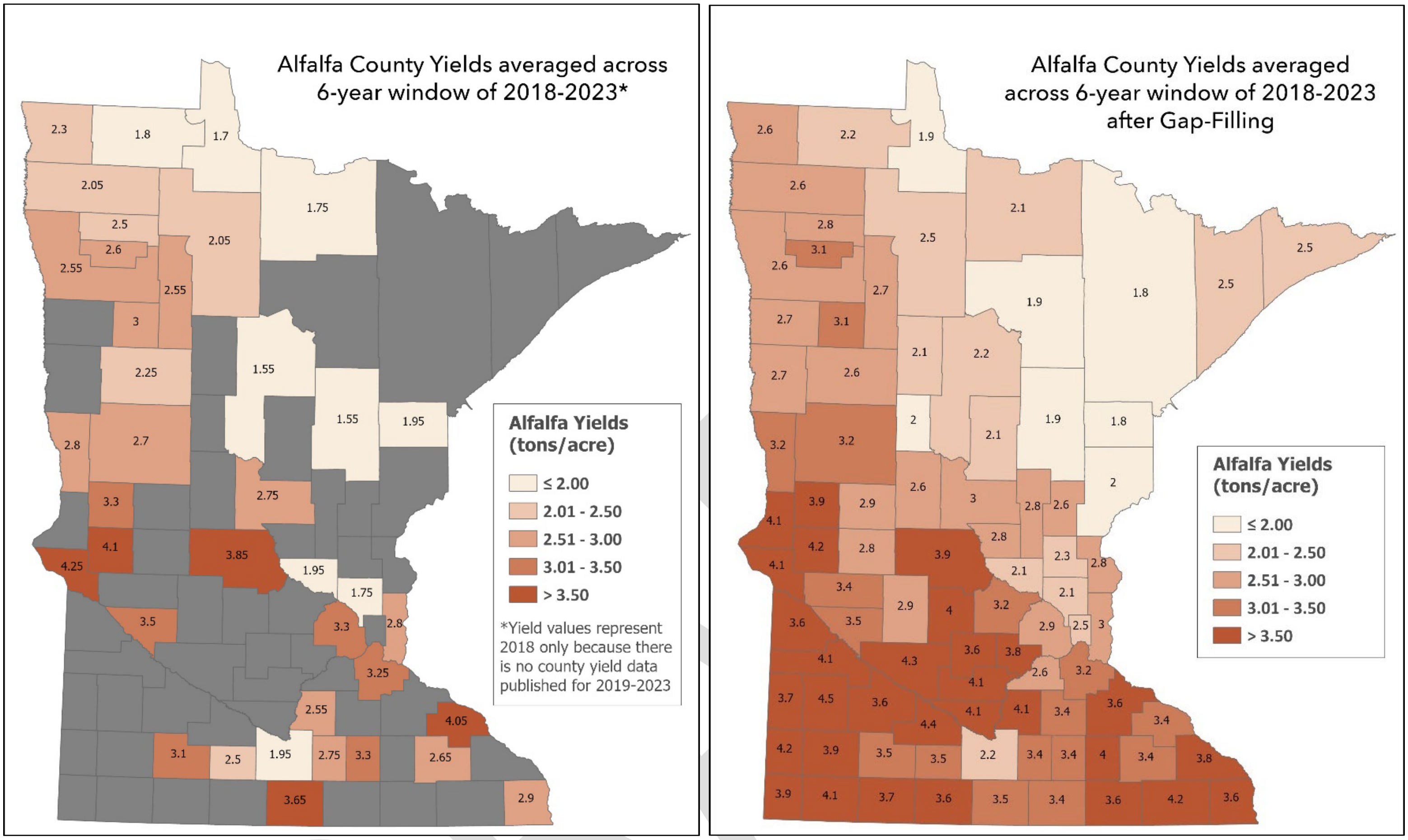
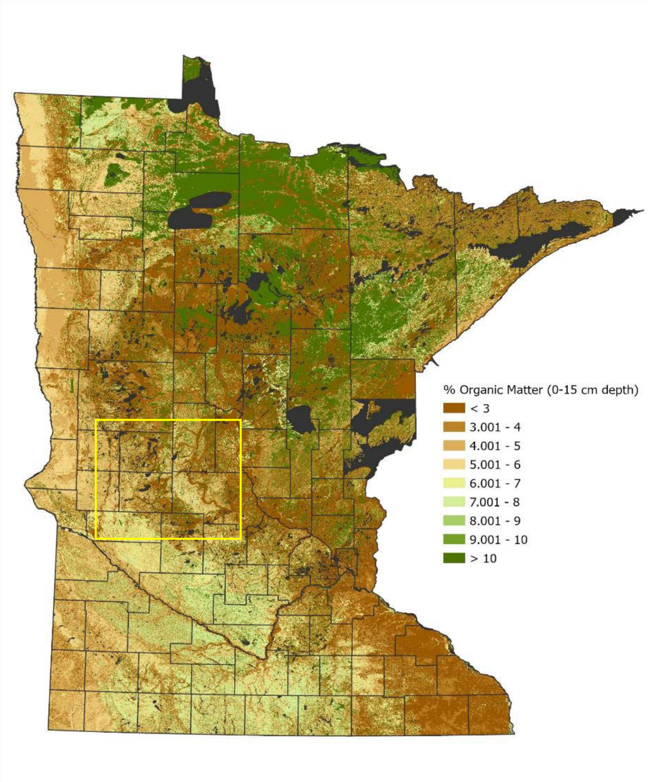


Figure 4. Example results of the methods used to gap-fill NASS county yield data. The most recent year that NASS reported any county yield information for alfalfa was 2018, with many counties having no published values between 2018 and 2023 (left map). The methods used to fill in county yields resulted in complete county data for all Minnesota counties (right map).

Soil Organic Matter. For most crops other than corn, UMN N fertilizer guidelines are based in part on the field soil organic matter (SOM) content. The 2024 SSURGO soils database was used to determine the organic matter content of soils from the surface to a depth of 15 cm (pers. comm. Dan Kaiser UMN, November 2024). The process implemented both horizon and component weighting to represent SOM at depth (Figure 5). The median SOM content within each ACPF field was used to classify fields as low (< 3%) or medium/high (>= 3%) organic matter content.



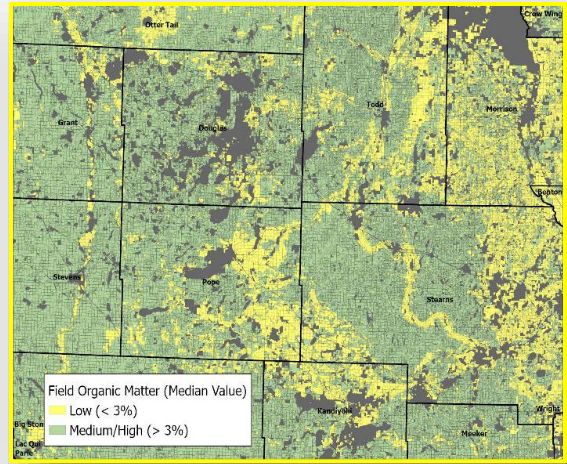


Figure 5. Left: horizon and component weighted representation of soil organic matter (SOM) content from the surface to a 15 cm depth. Right: ACPF field boundaries classified by a low (< 3%) or medium/high (>= 3%) median SOM content.

Nitrogen Fertilizer Recommendations

University of Minnesota (UMN) Extension fertilizer guidelines were used to define an annual N fertilizer recommendation for each ACPF field, using the six-year (2018 to 2023) crop rotation assigned to each field. Nitrogen fertilizer recommendations were determined for each field and year between 2017 and 2023, then summarized across the six-year timeframe of 2018 to 2023. The year 2017 was used as a warmup year to ensure that previous crop-dependent N rates were used for each year summarized. The total N recommendation across the six-year timeframe was then divided by six to obtain an annual average N recommendation for each field.

Corn. The upper end of the 0.10 Maximum Return to N (MRTN) rate (UMN Extension, 2024), which is the N rate where the economic net return to N application is maximized, was used for all fields and years planted to corn. Rates were adjusted for corn grown on irrigated soils or when following a legume crop (soybean, alfalfa, edible beans, or peas) (Table 6). A conservative approach for corn following alfalfa was used, and a one-year stand of alfalfa was assumed for all corn following alfalfa years. This resulted in the highest recommended N rate for corn following alfalfa for all scenarios.

Table 4. UMN Nitrogen Fertilizer Recommendations for Corn (UMN Extension, 2024)		
Crop	**Previous Crop**	**N Fertilizer Recommendation (lbs. per acre)**
Corn (Irrigated)	Corn / Other	225
	Soybean	195
	Alfalfa	170
	Edible Beans	205
	Peas	205
Corn (Non-Irrigated)	Corn / Other	190
	Soybean	150
	Alfalfa	80
	Edible Beans	170
	Peas	170
The upper end of the .10 MRTN ratio (2024) was used to assign recommended N fertilizer rates for corn.		

Slightly different corn fertilizer rate guidelines exist when using an organic (manure) versus inorganic fertilizer source, with a 5 lb. per acre increase for non-irrigated corn-following-corn and a 10 lb. per acre increase for irrigated corn (following either corn or soybean) when manure is the fertilizer source (Wilson et al., 2023).

To determine the impact of using the upper end of 0.10 MRTN versus manure application rate guidelines, statewide N fertilizer recommendations were estimated using both approaches. Corn fields modeled to receive manure each year (identified through the manure application approach described in subsequent sections of this report) were assigned manure application rate guidelines, while those not receiving manure were assigned the upper end of 0.10 MRTN rates.

The result was a less than one percent difference in statewide N fertilizer recommendations when using the upper end of 0.10 MRTN (792,111 tons) versus UMN guidelines for manure application to corn (794,714 tons). This informed the decision to use the upper end of 0.10 MRTN guidelines for all corn acres, regardless of fertilizer N source. UMN Extension also suggests applying a lower rate of manure and supplementing with commercial fertilizer to meet corn N fertilizer needs, particularly on soils with high leaching potential. Based on this recommendation, it's possible that manure application to corn occurs at rates similar to the 0.10 MRTN guidelines.

Other Crops. UMN Extension N fertilizer guidelines for crops other than corn are determined by several factors including: crop type, field organic matter level, previous crop grown, and either expected yield or yield goal. Table 5 provides the characteristics used to determine N fertilizer guidelines for each harvestable crop other than corn. When yield goal was used to determine N recommendations, 105% of the six-year average county yield (2018 to 2023) was assumed, based on the county in which the field is located. When expected yield was used to determine N recommendations, 100% of the six-year average yield was assumed.

An example is a field planted to "Other Hay / Non-alfalfa". UMN guidelines for fertilizing hay and pasture grass provide four N application rate recommendations that increase as the expected crop yield increases. If the six-year average expected yield for the county in which the field is located is 2.6 tons per acre, for example, the N rate assigned to this field would be weighted proportionally between 60 lbs/acre (expected yield of 2 tons dry matter/acre) and 90 lbs/acre (expected yield of 3 tons dry matter/acre) and would ultimately be assigned a N recommendation of 78 lbs/acre.

Rates were also adjusted when following a legume crop (soybean, alfalfa, edible beans, or peas). While specific adjustments varied by crop, UMN guidelines were followed closely. For example, most crops had per acre legume credit N rate reductions of 10 lbs. (edible beans, field peas), 20 lbs. (soybeans) and 25 lbs. (alfalfa at 1-2 plants per ft^2). Legume credits were slightly different for irrigated potato production at 20 lbs. per acre following edible beans, field peas, or soybeans, and 100 lbs. per acre following alfalfa. No legume rate credit was provided for "Other Hay / Non-alfalfa" or for "Sod / Turfgrass".

Sugarbeet, turfgrass, and sunflower guidelines did not follow the same structure as UMN guidelines for other crops. For example, sugarbeet guidelines are highly dependent on soil N testing. In lieu of this information, a standard rate of 65 lbs. per acre was used for all fields planted to sugarbeet, which assumes that half of the recommended N is provided by soil organic matter N pools. A standard rate of 150 lbs. per acre was used for all fields planted to sunflowers, for which recommendations are based on N cost and sunflower harvest price. No UMN recommendations were found for turfgrass, and a standard 140 lbs. per acre rate was assumed (pers. comm. Jake Jungers UMN, January 2025).

While research is ongoing to determine the benefits of supplemental N application to soybeans and alfalfa, the N recommendation for both crops was set at zero for this analysis, assuming that all crop N needs are obtained through N fixation.

Table 5. UMN Nitrogen Fertilizer Recommendations for Crops other than Corn

Crop	N Fertilizer Recommendation (lbs. per acre)
Soybean	0
Alfalfa	0
Spring Wheat	Yield goal, field OM, and previous crop
Winter Wheat	Yield goal, field OM, and previous crop
Other Hay / Non-alfalfa	Expected yield (grasses for hay/pasture)
Sugarbeet	Standard N rate of 65 lbs. per acre (adjusted by previous crop)
Barley	Yield goal, field SOM, and previous crop
Canola	Expected yield, field SOM, and previous crop
Oats	Expected yield, field SOM, and previous crop
Sod / Turfgrass	Standard N rate of 140 lbs. per acre
Dry Beans	Expected yield, field SOM, and previous crop
Potatoes	Yield goal, field SOM, and previous crop
Peas	Expected yield, field SOM, and previous crop
Rye	Expected yield, field SOM, and previous crop
Sunflower	Standard N rate of 150 lbs. per acre (adjusted by previous crop)

Phosphorus Removal

To estimate phosphorus (P205) removal at a field-scale, county yield estimates were used along with literature values for P205 removal rates (lbs. removed per unit yield).

For corn and soybeans, P205 removal rates were taken from UMN extension crop-specific nutrient need guidelines for maintenance-based P strategies. Three values were provided that represent the interquartile ranges (25^{th} percentile, median, and 75^{th} percentile) of pounds of P205 removed per unit yield. (Table 8). While the ranges may appear relatively small, small changes in P205 removal can have a large impact on statewide nutrient balance, particularly when extrapolated over the 15 million acres of corn and soybean grown in the state each year.

An analysis was performed to determine the impact of using each of the three values of the interquartile range for corn and soybean on statewide P2O5 removal. Results showed significant impacts on statewide removal estimates, with the tons of P2O5 removed statewide increasing from 376,725 tons (25^{th} percentile), to 413,280 tons (median), to 461,877 tons (75^{th} percentile), an overall increase of 23%.

Per expert recommendations (conversation with MPCA, April 2025), the 75^{th} percentile was used to represent a conservative estimate of P2O5 removal for corn and soybeans.

For most other crops, P205 removal rates were taken from MDA and UMN Extension Nutrient and Manure Management Table 5 (MDA & UMN Extension, 2012) and are listed in Table 6. Nutrient removal rates were converted to the same units that yield information was reported by NASS surveys. Unit conversions were required for canola, dry beans, and sunflower, for which NASS yields were reported in lbs. per acre and P2O5 removal was reported per bushel (canola and dry beans) and CWT (sunflower). To perform these conversions, a bushel of canola was assumed to weigh 50 lbs (USDA, 2021) and a bushel of dry beans was assumed to weigh 60 lbs (Small Farm Canada, 2025).

The Nutrient and Manure Management tables do not provide P2O5 removal rates for peas or turfgrass. The USDA Crop Nutrient Tool (USDA, 2024) was used to estimate P2O5 removal for peas, and Oregon State Extension (Hart et al., 2012) was used to estimate P2O5 removal for annual ryegrass, which is the dominant species of turfgrass grown in MN.

Table 6. Phosphorus (P2O5) Removal Per Unit Yield (UMN extension and MDA)			
Crop	**Unit Yield**	**Crop Description**	**P205 Removal Per Unit Yield**
Alfalfa	Ton	Alfalfa	**12**
Barley	Bushel	Barley (grain)	**.4**
Canola	Lbs.	Canola	**.024**
Corn	Bushel	Corn (grain)	**0.33** (0.25-0.33, median 0.28)
Dry Beans	Lbs.	Beans, dry	**0.0132**
Oats	Bushel	Oats (grain)	**0.28**
Other Hay	Ton	Bromegrass	**10**
Peas	Lbs.	Pea-Field, for seed (dry)	**.01008**
Potatoes	CWT	Potatoes (tuber)	**0.12**
Rye	Bushel	Rye (grain)	**0.46**
Soybeans	Bushel	Soybeans	**0.74** (0.62-0.74, median 0.69)
Spring Wheat	Bushel	Wheat (grain)	**0.6**
Sugar beets	Ton	Sugar beets	**2.2**
Sunflower	Lbs.	Sunflowers	**0.0097**
Turfgrass	Lbs.	Annual ryegrass (seed)	**0.0009**

Nutrient Output Results

By-field N fertilizer recommendations were summed for each year between 2018 and 2023, then divided by six to obtain an annual average. Statewide, **792,111** tons of N fertilizer were recommended annually when following UMN guidelines.

By-field P removal was summed for each year between 2018 and 2023, then divided by six to obtain an annual average. Statewide, **461,877** tons of P205 are estimated to be removed by all harvestable crops.

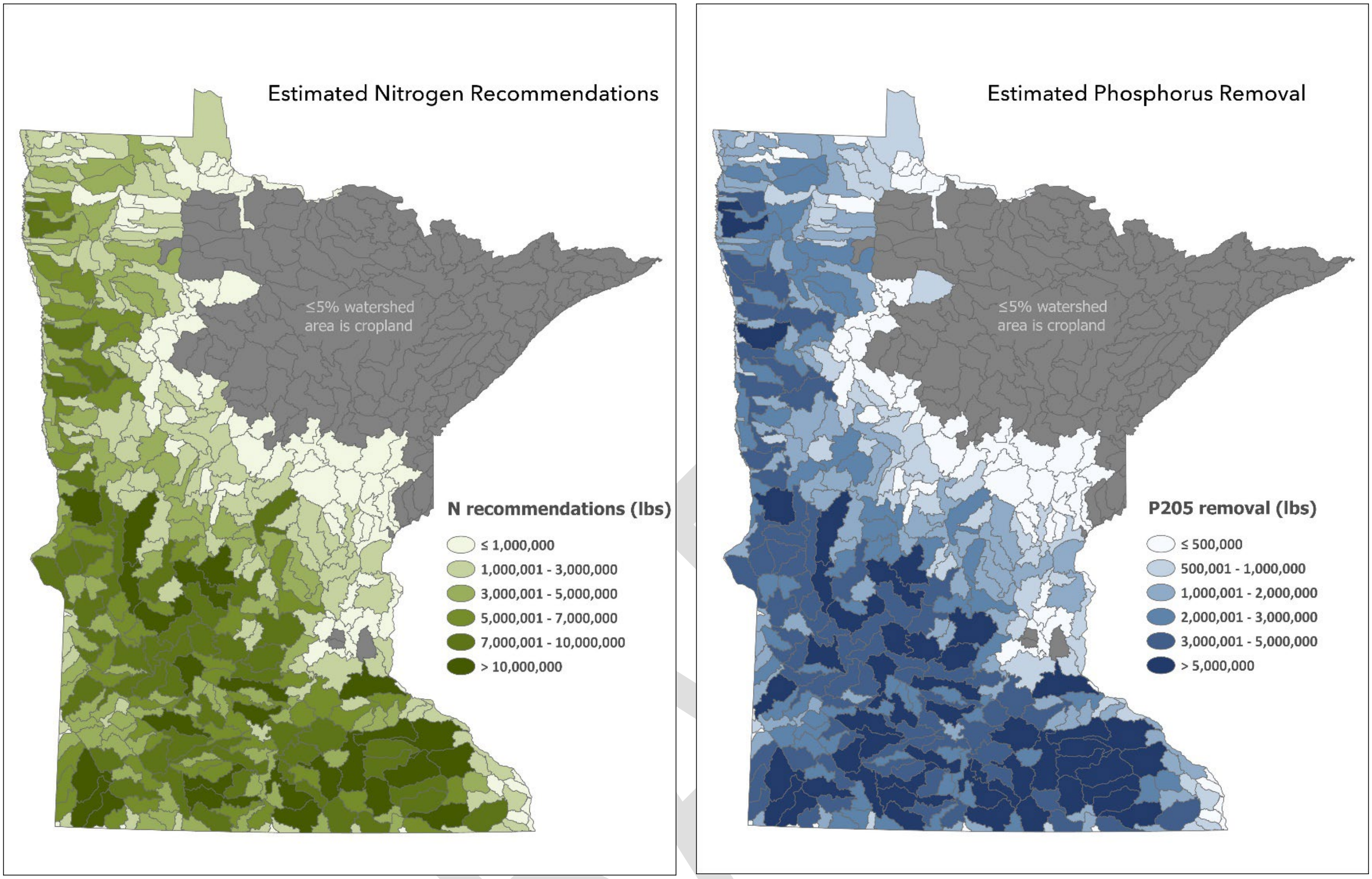


Figure 6. Nutrient output results represented as crop nitrogen fertilizer recommendations (left) and crop phosphorus removal (right) at HUC10 watersheds.

Spatial Allocation of Nutrients

The "Nutrient Input" section of this report described the methods used to estimate nutrient inputs from manure and commercial fertilizer. There is a significant mismatch in the spatial scale at which this information is provided, however, with manure nutrients provided at the point scale (associated with each animal feeding operation) and commercial fertilizer provided statewide (summation of MDA county sales data). Nutrient outputs (N fertilizer recommendations and P2O5 removal) are estimated at a field-scale. The modeling approach described below attempts to merge this disparate information to ultimately create a watershed-scale product of nutrient balance.

Many factors influence the rates at which farmers apply manure and commercial fertilizer, all of which we expect to have notable spatial trends across the state. These factors include but by no means are limited to: fertilizer and fuel costs, commodity prices, soil type and productivity, farm size, manure storage capacity, manure composition and livestock species, farmer demographics, and others. Incorporating all these factors is beyond the scope of this project and well beyond the availability of data at the watershed scale.

The approach taken here generally relies upon crop nutrient needs (N fertilizer recommendations and P205 removal) to drive the spatial distribution of manure and commercial fertilizer nutrients. Nutrient needs do not entirely explain the spatial variability in nutrient application across the state, however, and supplemental information was used to guide the spatial distribution approach. This supplemental information included the NASS Census of Agriculture (COA) county fertilizer expenditures and MDA county-level commercial sales data.

Supplemental information primarily informed the spatial distribution of commercial fertilizer nutrients, as manure nutrients can be modeled at a much higher resolution. In addition, due to the logistical constraints involved with the transport of manure nutrients, there are upper limits on how far these nutrients will travel from their source of production.

Spatial Allocation of Manure

Manure application was modeled for each year separately between 2017 and 2023, then summarized across the six-year timeframe between 2018 and 2023. The year 2017 was used as a warmup year to ensure that residual manure N was appropriately credited for each year summarized. For each year, manure application was modeled from each feedlot to the nearest fields to meet the N recommendation of each field in that year. Beginning in 2018, residual manure N (from a previous year's manure application) was tracked and appropriately credited by deducting any residual N remaining on a field from the N recommendation of the field in the current year.

Manure application occurs based on spatial proximity with no limit on haul distance. Therefore, manure application is modeled outward from each feedlot until no manure nutrients remain. The model applies manure to meet the N fertilizer recommendation of fields and, depending on the N:P205 ratio of manure produced at a given feedlot (primarily influenced by the types of animals at the feedlot), a corresponding amount of applied manure P205 is calculated.

Adjustment for Poultry Manure. For animal types other than poultry, manure is applied to the nearest agricultural fields at a rate that meets 100% of the N fertilizer recommendation. While this may be appropriate for modeling the movement of manure that is heavy and therefore costly to haul long distances (i.e. liquid swine and cattle manure), it may not adequately represent the distances that poultry manure travels due to being lighter and easier to transport. A survey performed by Ali et al. (2012) suggests that 57% of Midwest farmers transfer their poultry manure to another farm, and that 81% transfer their turkey manure to another farm, with 14 miles as the average maximum distance traveled. This compares to an average maximum travel distance of roughly 3 miles for other livestock types, if the manure is transferred at all.

Though the impact of longer poultry haul distances to the statewide nutrient balance may be minimal, this can cause bias when estimating nutrient balance in watersheds that house large poultry operations. To address this concern, an adjustment was made so that poultry manure was applied to meet only 40% of a field's N fertilizer recommendation, based on the assumption that poultry manure applied to corn using a P-based strategy will supply approximately 40% of crop N fertilizer needs. This assumes a poultry manure N:P205 ratio of 1:1 and a corn N:P205 maintenance fertilizer need of 2.7:1 (Lory, 2018). A reduction in the amount of manure N applied to each field resulted in an increased haul distance for poultry manure.

Manure Application Results

The amount of manure N used annually by crops statewide was determined by summing all of year one manure N applied plus any residual manure N (year two manure N from a previous application) used by fields with a N fertilizer recommendation. Residual manure N remaining on fields without a N need (primarily soybeans and alfalfa) was assumed to be taken up by these crops and not included in this calculation, as no N fertilizer is recommended for these crops and any residual N therefore does not need to be credited. This value represents the crop-available manure N available in Minnesota each year.

Using the manure application modeling approach described above, the amount of manure N used annually by crops with a N recommendation ranges from 123,564 (low scenario) to 149,136 (intermediate scenario) to 174,494 tons (high scenario). This equates to 15.6% (low), 18.8% (intermediate scenario), and 22.0% (high scenario) of statewide crop N recommendations (792,111 tons) that can be supplied by manure. The results suggest that 100% of year one manure N and roughly 41% of year two manure N are used by crops with a N recommendation in an average year.

Eighty percent of manure P205 is assumed to be crop available in the same year it is applied. Average crop-available manure P205 ranges from 99,421 (low scenario) to 123,621 (intermediate scenario) to 147,821 (high scenario) tons statewide, which represents 21.5% (low scenario), 26.8% (intermediate scenario) and 32.0% (high scenario) of the total P205 removed by all harvestable crops (461,877 tons).

For non-poultry feedlot facilities, the average maximum haul distance for application was 0.47 miles, as compared to 6.25 miles for poultry facilities. This distance was calculated using a Manhattan distance measure to approximate transportation distance along roadways. While this is notably less than the roughly 3 miles (non-poultry facilities) and 14 miles (poultry facilities) found by Ali et al (2012), there are several potential explanations for this discrepancy. In contrast to this analysis, Ali et al (2012) focused solely on manure that is transferred, which tends to coincide with larger operations. Manure that is not transferred will be applied primarily on-farm and have a much shorter travel distance. Ali et al (2012) additionally recognized a skewed mean haul distance for poultry facilities, with a small amount of turkey manure travelling up to 100 miles. Even still, we recognize that the idealized nature of the manure application approach used in this analysis (i.e. manure applied to the nearest fields) may not reflect the true nature of local conditions impacting manure movement at the field and watershed scale.

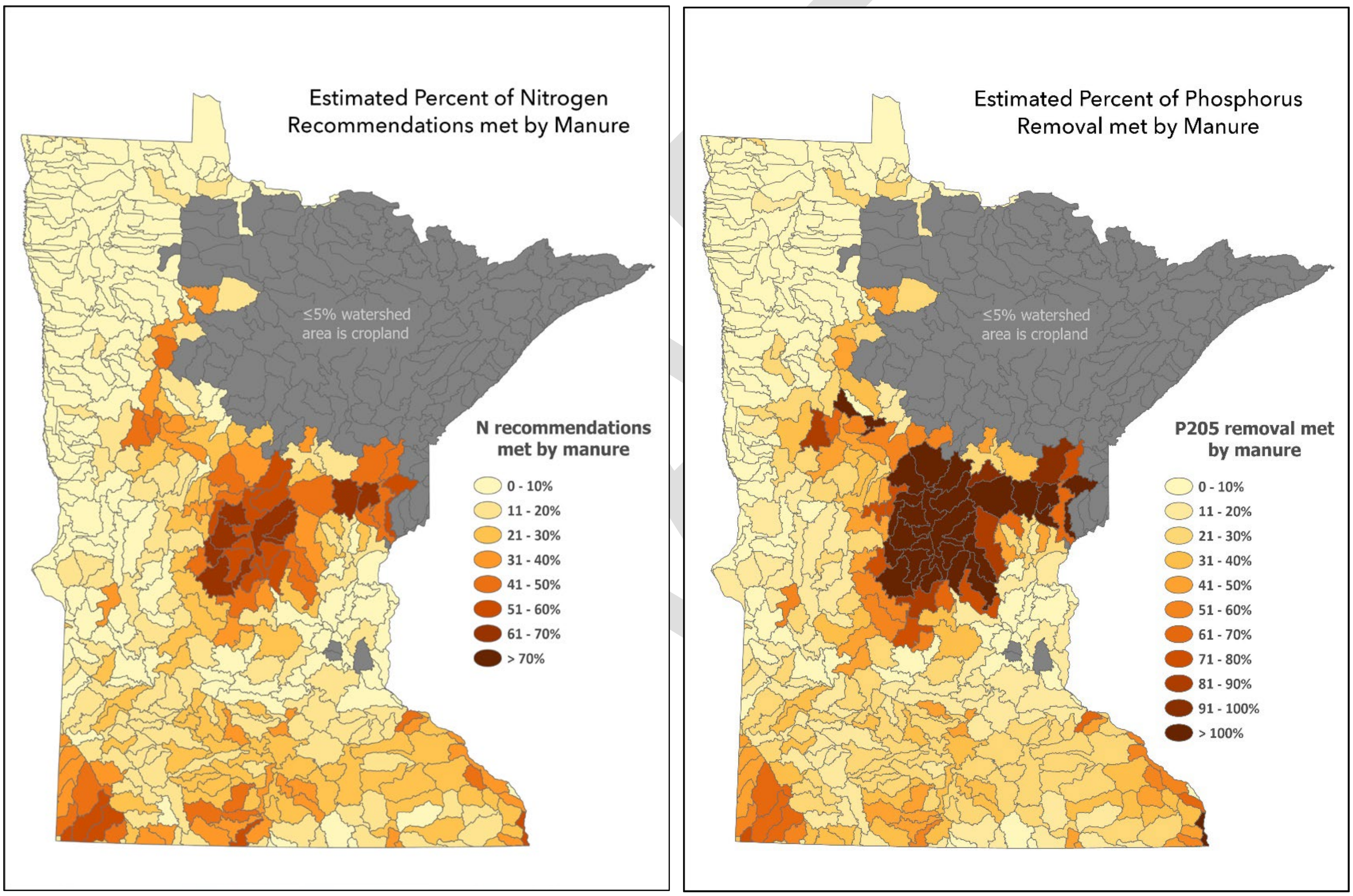


Figure 7. Results from manure application modeling (intermediate scenario) represented as the percentage of crop output (N fertilizer recommendation and P205 crop removal) met by manure, summarized at HUC10 watershed scale.

Contribution of Commercial Fertilizer

County level commercial fertilizer sales for 2017-2022 are provided by MDA, as previously outlined in the report on page 12 and table 3. The 6-year average commercial fertilizer N sold (787,155 tons) can supply

99.4% of statewide crop N fertilizer recommendations, while the 6-year average commercial fertilizer P205 sold (341,496 tons) can supply 73.9% of statewide crop P2O5 removal. The following section explains the methods for spatially redistributing commercial fertilizer nutrients first to the county, and then ultimately the field-scale.

Redistribution of County Level Commercial Sales Data. The MDA sales data is the best resource in Minnesota for estimating the tons of commercial N and P205 sold statewide. Redistribution of county-level commercial sales data is required, however, as fertilizer may be purchased in one county and used in another. This is recognized by MDA and supported by Figure 8 which plots the six-year average MDA N sales against six-year average N fertilizer recommendations in each county.

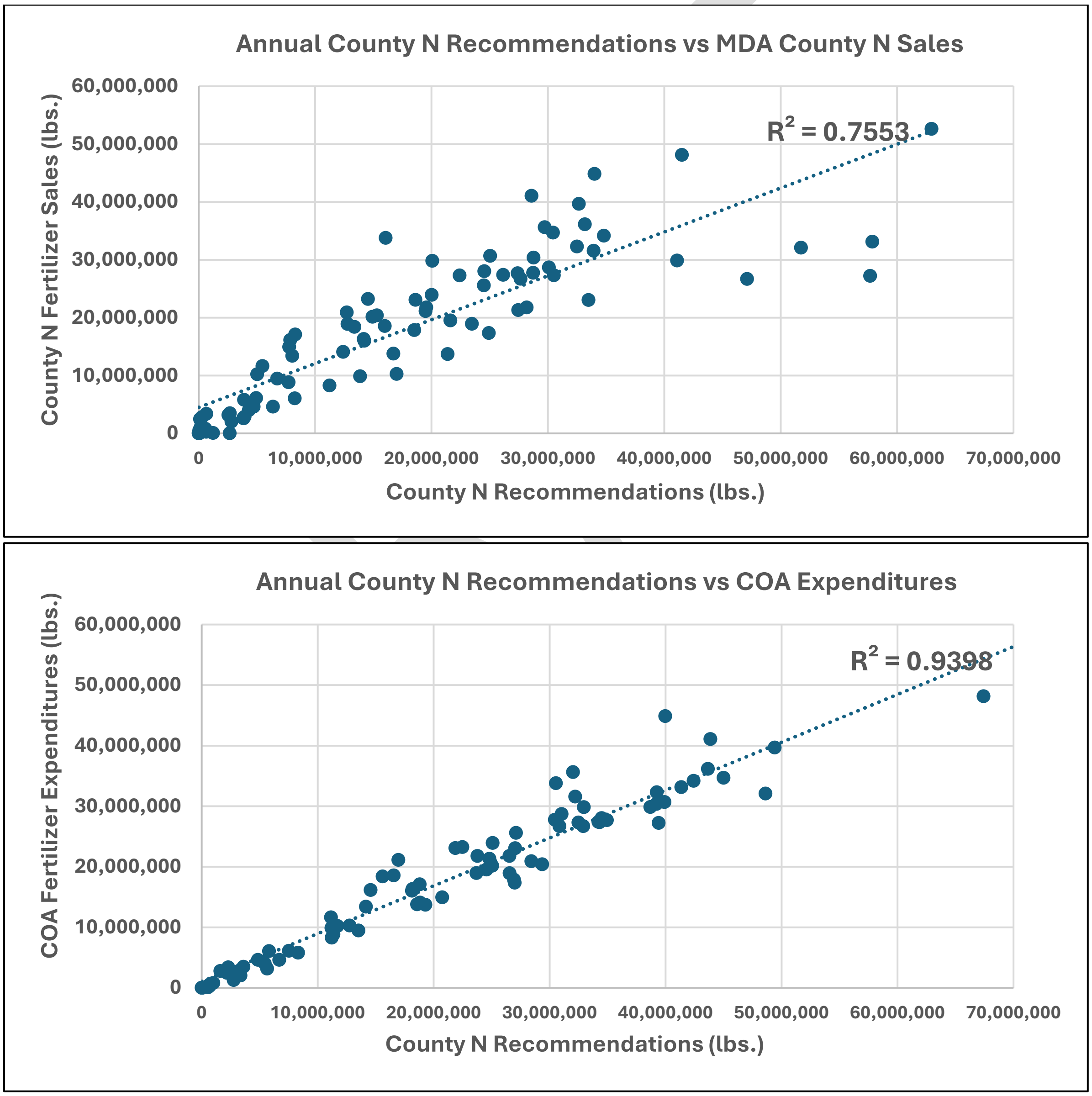


Figure 8. The correlation between county N fertilizer recommendations and MDA county fertilizer N sales (top) is much weaker than the correlation with Census of Agriculture (average of 2012, 2017, and 2022) county fertilizer expenditures (bottom).

While Figure 8 shows an overall correlation between county N fertilizer recommendations and the amount of N sold, there is significant noise. Other leading studies, such as the USGS "Estimate of County-Level Nitrogen and Phosphorus from Fertilizer and Manure" (Falcone, 2021), used random forest modeling on 11 predictor variables and found the Census of Agricultural (COA) fertilizer expenditures to be the dominant variable for predicting county-level commercial fertilizer use for both nitrogen and phosphorus.

Two major limitations with the COA fertilizer expenditure data include 1) the amounts are provided in dollars, and 2) the expenditure data covers all nutrients (N, P, K) as well as lime and soil conditioner. One benefit of the COA data, however, is that the survey is designed such that the values represent products that are used in each county rather than purchased there.

Despite the limitations of the COA expenditure data, it provides additional insight into how fertilizer use might be spatially distributed across the state. When county N recommendations and COA county fertilizer expenditures (average of 2012, 2017, and 2022 expenditure data in each county) are regressed against each other, the correlation is visibly stronger than that of the raw MDA sales data (Figure 8) and the R^2 value improves from 0.76 to 0.94. This supports the idea that the spatial location of fertilizer sales can differ significantly from the location of fertilizer use.

MDA statewide N sales were first redistributed to counties based on the proportion of statewide COA fertilizer expenditures that each county represents. The primary assumption in this approach is that N expenditures dominate the overall fertilizer expenditures in each county. The average fertilizer expenditures from the last three Census years (2012, 2017, and 2022) were used for this approach.

Once statewide N sales (in tons of N and P2O5) were redistributed to counties using the approach described above, redistributed county commercial N was then allocated to agricultural (ACPF) fields within each county, based on the proportion of each field's N recommendation relative to the county total N recommendation. This step enabled the aggregation of nutrient inputs (commercial fertilizer plus manure) to the watershed rather than the county scale, as all nutrient inputs are ultimately allocated to each agricultural field in the state.

When determining the proportion of county total N recommendation that each agricultural field represents, fields within each county may or may not have already met their N recommendation with manure N applied (see *spatial allocation of manure* section above). An assumption was therefore required to determine if fields already receiving manure would receive any additional commercial fertilizer. The consequence of this assumption impacts whether any modeled surplus nutrients are attributed to over-application of commercial fertilizer alone (would occur if no additional commercial fertilizer is allocated to fields that have already received manure), or if over-application is also occurring on fields receiving manure alone or commercial fertilizer plus manure.

The most recent MDA survey (2019) suggests that N over-application (N applied at rates above UMN guidelines) occurs on fields receiving commercial fertilizer alone as well as fields receiving manure alone or manure plus commercial fertilizer. This is not spatially uniform, however, and BMP (Best Management

Practice) region averages for N application to corn rates highlight spatial as well as rotational differences. Interestingly, average MDA survey rates for corn following corn fell below UMN recommendations in all BMP regions and for all crop rotations, regardless of manure or commercial source. In contrast, average corn following soybean rates exceeded UMN recommendations in all three southernmost BMP regions (Southwest, South-Central, and Southeast) for both manure and commercial fertilizer sources. Survey rates for corn following soybean fell below UMN recommendations in the Northwest BMP region (for both manure and commercial fertilizer), while corn following soybean rates exceeded UMN recommendations in the IRR (Irrigated and Sandy Soils) region, but only for manure. Corn following alfalfa rates provided by the survey significantly exceeded corn following alfalfa rate recommendations for all regions of the state, whether a manure or commercial source.

Survey results guided our decision to allocate some commercial N to fields that have already received manure in our analysis, but to assume a standard percentage of manure N that is credited. Mulla et al. (2013) assumed a 50-70% credit on first year manure N in 2013, which guided our assumption that 70% of manure N is credited on fields already receiving manure in our analysis. We applied this assumption uniformly throughout the state and chose the high end of the range (70%) as a conservative estimate to reflect that manure crediting has likely improved in the last decade.

To illustrate the impact of this approach, take an example field that has already met 100% of its N recommendations through manure applied. We assume that only 70% of the applied manure is credited, and that 30% of the field N recommendation remains when determining the proportion of total county N recommendations that the field represents.

The impact of this assumption is minimized in that it only affects how commercial fertilizer N is allocated from the county to the field-scale, as COA fertilizer expenditures are used to allocate county-level commercial fertilizer N. However, it does create a bias in that over-application of N is more strongly weighted to those fields receiving manure within any given county.

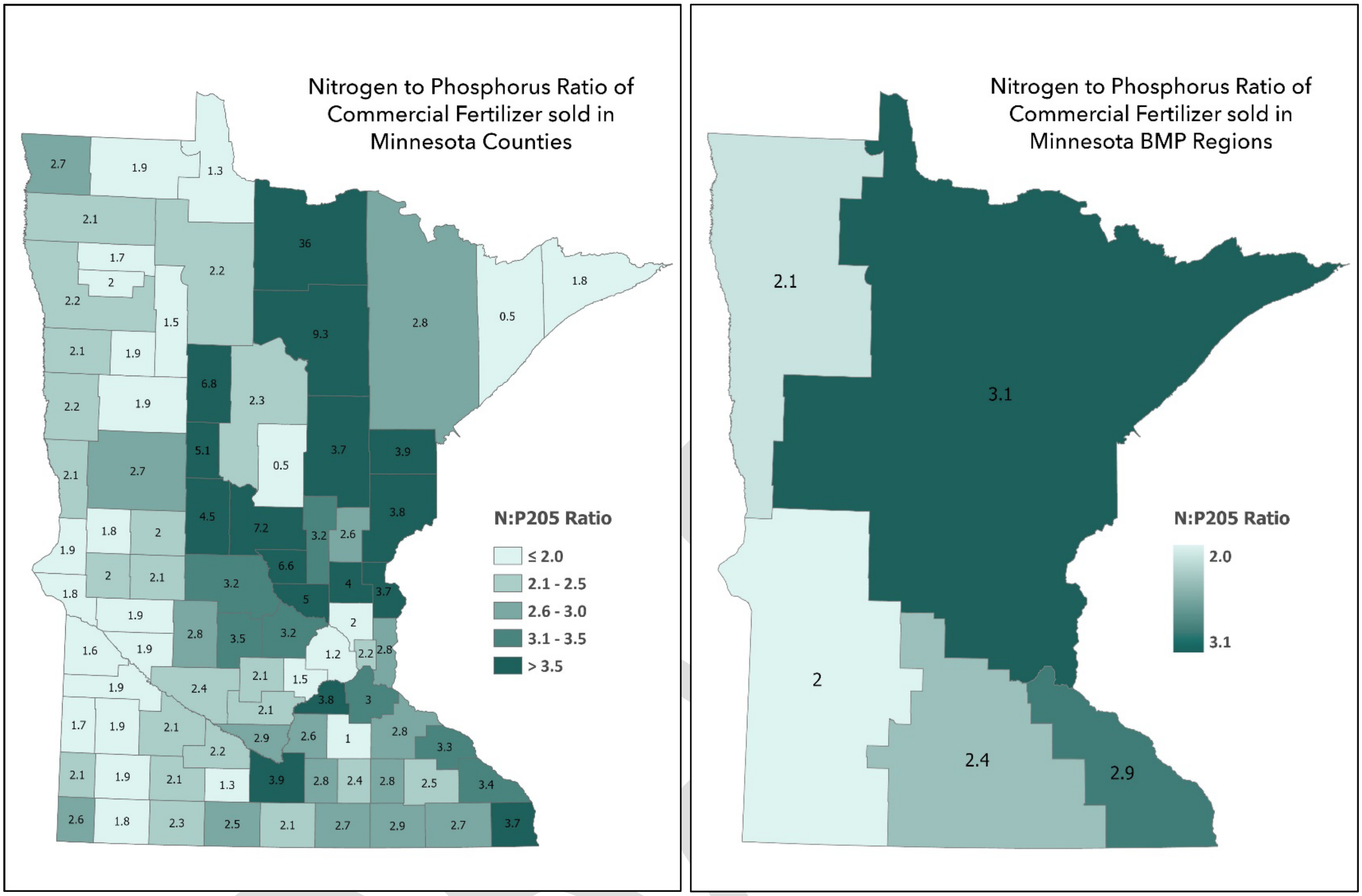


Figure 9. N to P205 ratios of fertilizer sold in Minnesota. Left: All county N sold divided by all county P205 sales. Right: Summed county N sales of BMP region divided by summed county P205 sales of BMP region. These ratios were used to determine the distribution of commercial P205 fertilizer.

There is notable variation in the N to P205 ratio of commercial fertilizer sold among counties and regions in Minnesota (Figure 9). Differing N:P205 ratios between regions of the state follow patterns that are expected based on soil properties and the dominant manure sources in each region. The eastern part of the state has natively higher levels of P205 in the soil; but these soils also tend to be more acidic which can make phosphorus less available to plants. Central Minnesota has a disproportionately high number of poultry feedlots which are associated with high P205 manure, potentially reducing the amount of P205 purchased by farmers using poultry manure.

The N:P205 ratios for each Best Management Practice (BMP) region were calculated by dividing the sum of all county N sales in each region by the sum of all P205 county sales in the same region. The comparison of BMP region N:P205 sales ratios indicates a clear trend that the Northwest and Southwest regions have a lower N:P205 ratio than South Central, Southeast and Irrigated and Non-Irrigated Sandy Soils regions.

As a way of capturing patterns in the MDA sales data that may be unique to phosphorus, the BMP N:P205 ratios were used to allocate county P205 fertilizer to each county using the N:P205 ratio in that BMP region and the redistributed county N fertilizer as described in the previous section. For each county, the redistributed N fertilizer was divided by the assigned BMP N:P205 ratio to get a redistributed county P205 fertilizer amount. This resulted in a sum of county redistributed P205 that was slightly lower than the statewide P205 sales reported by MDA, and the difference (i.e. remaining P205) was allocated to each county using the same proportion of statewide P205 sales already allocated to each county.

This method builds off the perceived reliability of the NASS COA expenditure data as a proxy for each county's proportion of N sales. While it is not ideal that the ratios are averaged at a BMP scale, the county data appeared sporadically distributed, perhaps based on where fertilizer co-ops are located. Although coarse, BMP regions are the most logical scale to aggregate the data because they are formed by county boundaries and are based on agroecological traits.

Once statewide P205 sales were redistributed to counties using the approach described above, county commercial P205 sales were distributed to agricultural (ACPF) fields within each county, using the proportion of each field's P205 removal relative to the county total P205 removal. This step enabled the aggregation of inputs (commercial fertilizer plus manure P205) to the watershed rather than the county scale, as all nutrient inputs are ultimately allocated to each agricultural field in the state. In contrast to N, for which we assumed a 70% credit on first year manure N, we assumed that 95% of manure P205 was credited on each field. This assumption was guided by communication with MPCA and MDA staff regarding commercial fertilizer usage on manured fields with respect to P205.

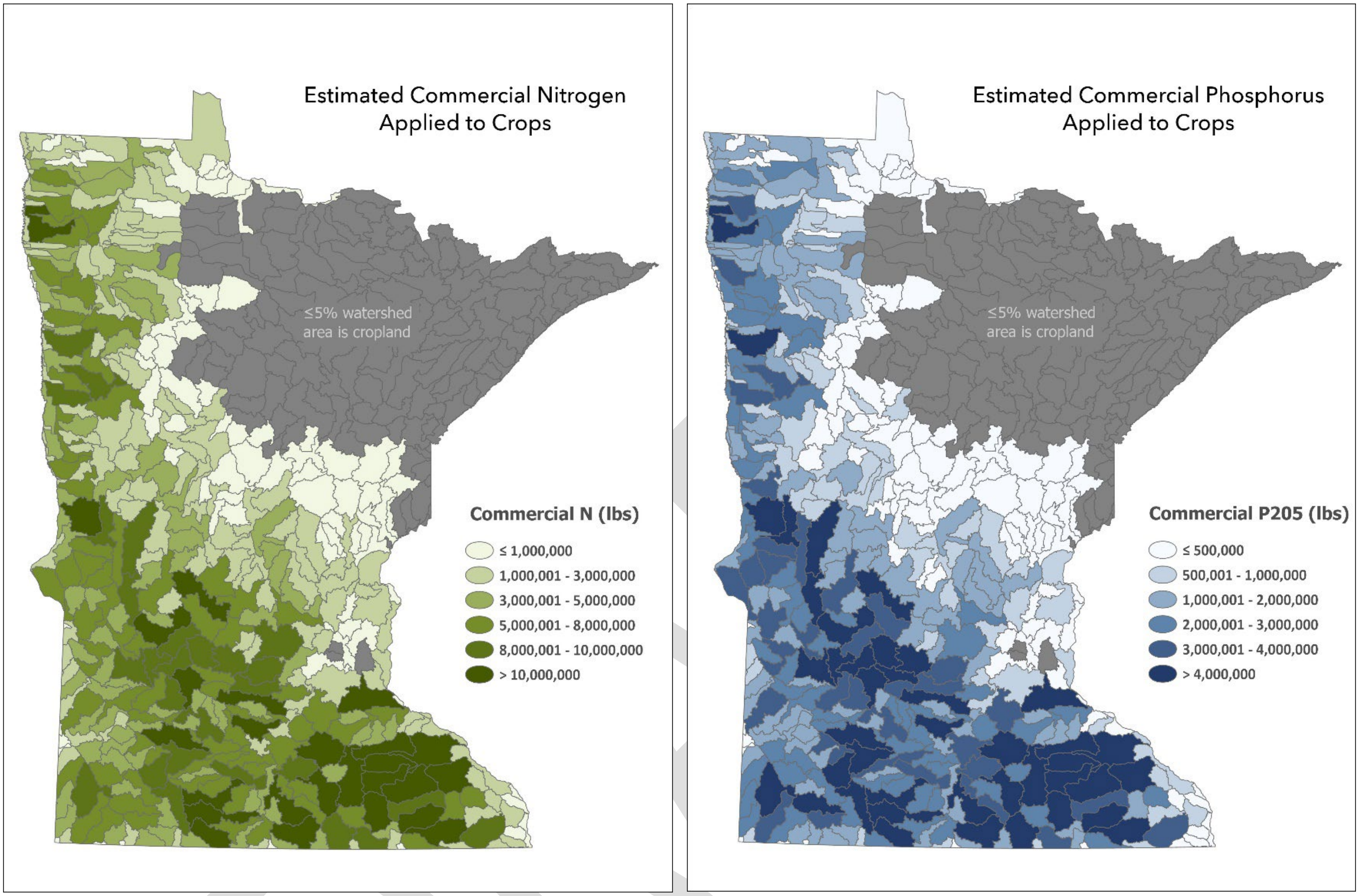


Figure 10. Results of redistributed statewide commercial fertilizer N (left) and P205 (right) at HUC10 watersheds.

Statewide Nutrient Balance

Nitrogen

When combining the contribution of manure N with commercial N sales we find a statewide surplus ranging from 15.0% (low scenario) to 18.2% (intermediate scenario) to 21.4% (high scenario) above crop N fertilizer recommendations of 792,111 tons.

Table 6. Nitrogen statewide balance summary table			
	Low	**Intermediate**	**High**
Manure N applied (tons)	123,564	**149,136**	174,494
Commercial fertilizer N applied (tons)	787,155	**787,155**	787,155
Total N inputs (tons)	910,719	**936,291**	961,649
N recommendations (tons)	792,111	**792,111**	792,111
Overall N Surplus (tons)	118,608 (15.0%)	**144,180**	169,538
Percent N surplus	15.0%	**18.2%**	21.4%

Figure 11 (left) illustrates *area-normalized* N surplus (N surplus divided by total land acreage) summarized by HUC 10 watershed. This visualization approach highlights watersheds with predominantly agricultural land use that have the greatest nitrogen demands in the state. In these regions where agricultural pressure is high, slight N overapplication on a field-by-field basis can have large impacts when considered in aggregate across the landscape.

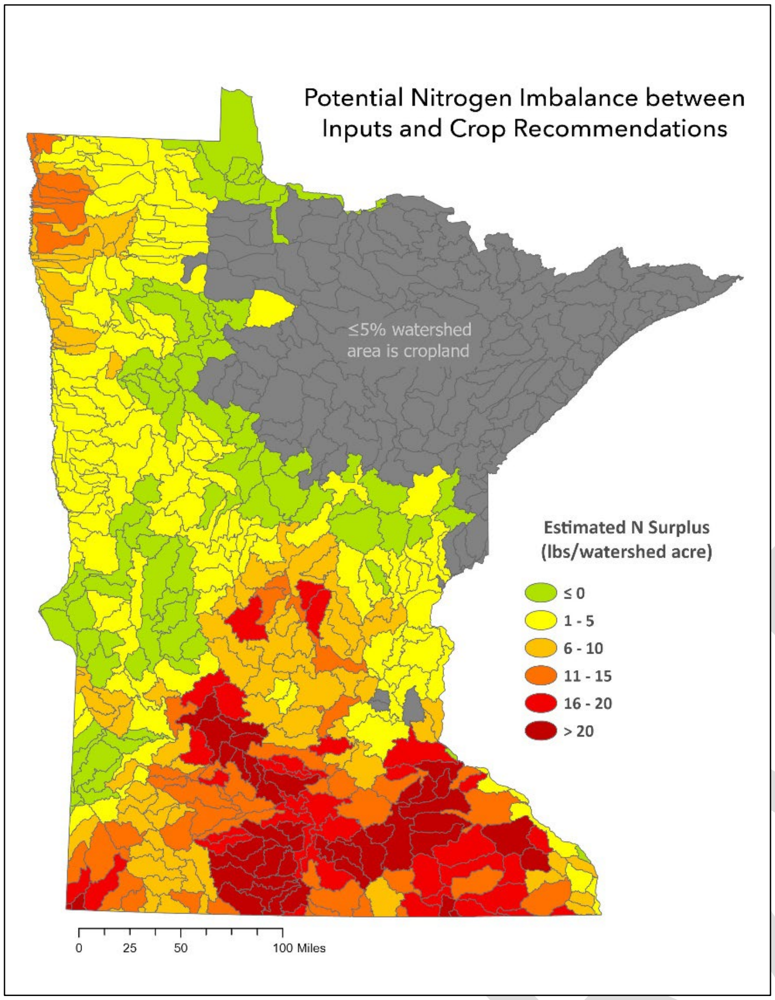
Figure 11 (right) illustrates *per-cropland-acre normalized* N surplus (N surplus divided by harvestable cropland acreage) summarized by HUC 10 watershed. This visualization approach highlights watersheds that may have higher rates of N over application on a per cropland acre basis. The southeast region of the state is identified as a region of concern as well as the central portion of the state and around the Twin Cities metro; The karst and sandy soils of the southeast and central regions of the state make the groundwater particularly vulnerable to nitrogen contamination.

Both maps in Figure 11 highlight the south-central region of the state as an area of particular concern. Many of the watersheds in this region have consistently elevated nitrate levels in surface waters and have been identified as “Nitrogen Priority” watersheds in the 2014 Nutrient Reduction Strategy (Anderson et al., 2016) as well at the draft 2025 Nutrient Reduction Strategy Update.

The identification of watersheds with a high N surplus is the result of several interacting variables. First, the N recommendation for a given watershed is driven by the crop intensity and N demand of the crops grown within it. Watersheds with high N intensity crops (such as corn or potatoes) or high N intensity rotations (such as a higher frequency of corn following corn) will have a higher N need based on UMN recommendations. N recommendations are initially calculated at a field-scale and directly define watershed N “output”, providing the baseline for determining where surplus N exists.

Statewide commercial N sales (provided by MDA in tons) are distributed to each county using the proportion of each county’s COA fertilizer expenditures relative to the statewide total. Because this method of distributing commercial fertilizer N does not directly consider N recommendations, some counties where expenditures are greater than expected (as compared to baseline N recommendations) will receive a disproportionately higher share of the commercial N sales and are likely locations of N surplus. The presence of manure N is not considered when allocating commercial N to the county level. COA expenditures are therefore a primary driver of where N surplus is identified.

Finally, the presence of manured fields within a county will also impact where N surplus is identified. Redistributed county commercial N (using the COA fertilizer expenditures) is allocated to individual fields within each county based on the proportion of each field's remaining N need (after manure application) relative to the county total, where N need is defined as the N recommendation of the field minus a standard 70% manure credit. For example, fields already meeting their full N recommendation from manure will still have a 30% N recommendation that is used for calculating its proportion of N recommendation relative to the county total. The result is that watersheds with a higher proportion of manured fields will receive a greater share of any N surplus. This impact is minimized in the sense that it only affects how commercial fertilizer N is allocated from the county to individual fields within that county. If a county has lower than expected COA fertilizer expenditures (relative to N recommendations), then the commercial N allocated to that county will be lower. However, watersheds with a higher amount of manured fields will still receive a proportionately greater share of whatever N surplus exists within that county.



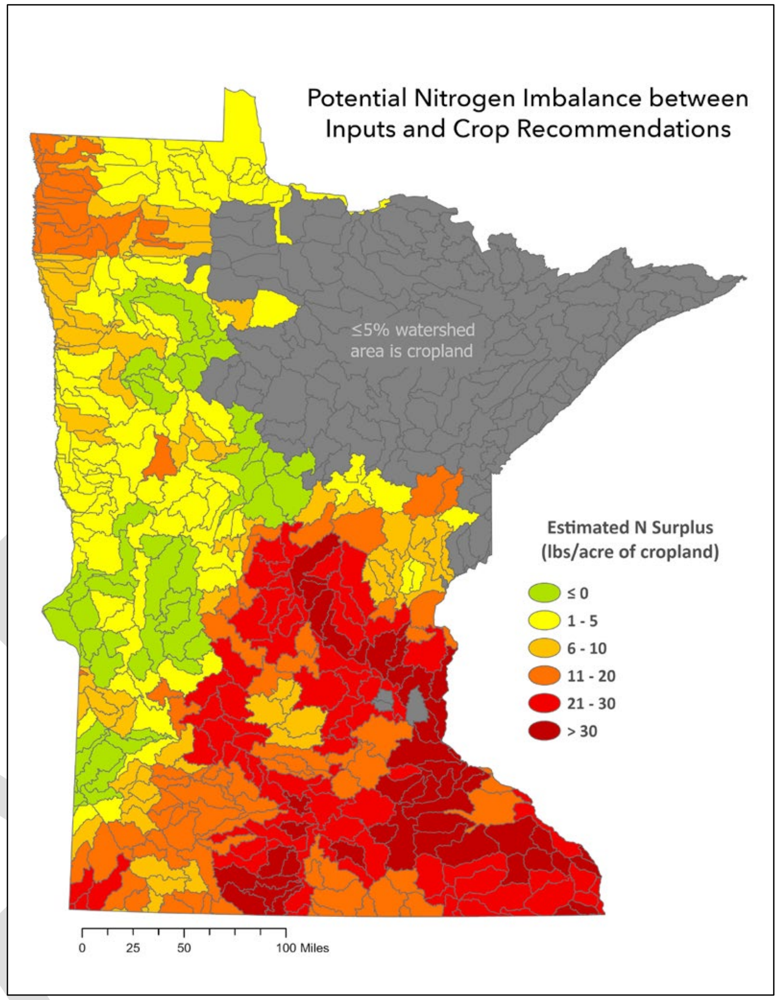


Figure 11. Results of nutrient balance for nitrogen at HUC10 watersheds in Minnesota using the intermediate manure scenario. Areas of greatest surplus when normalized to watershed acre are in south central Minnesota (left map). When the surplus is normalized to the amount of cropland in the watershed, the greatest surpluses are in southeast Minnesota (right map). Both maps show that most of the state is in a nitrogen surplus. Note that surplus nutrients are rounded to the nearest whole number, which may cause a watershed deficit on the left map (where the surplus was rounded to zero) and a surplus on the right map.

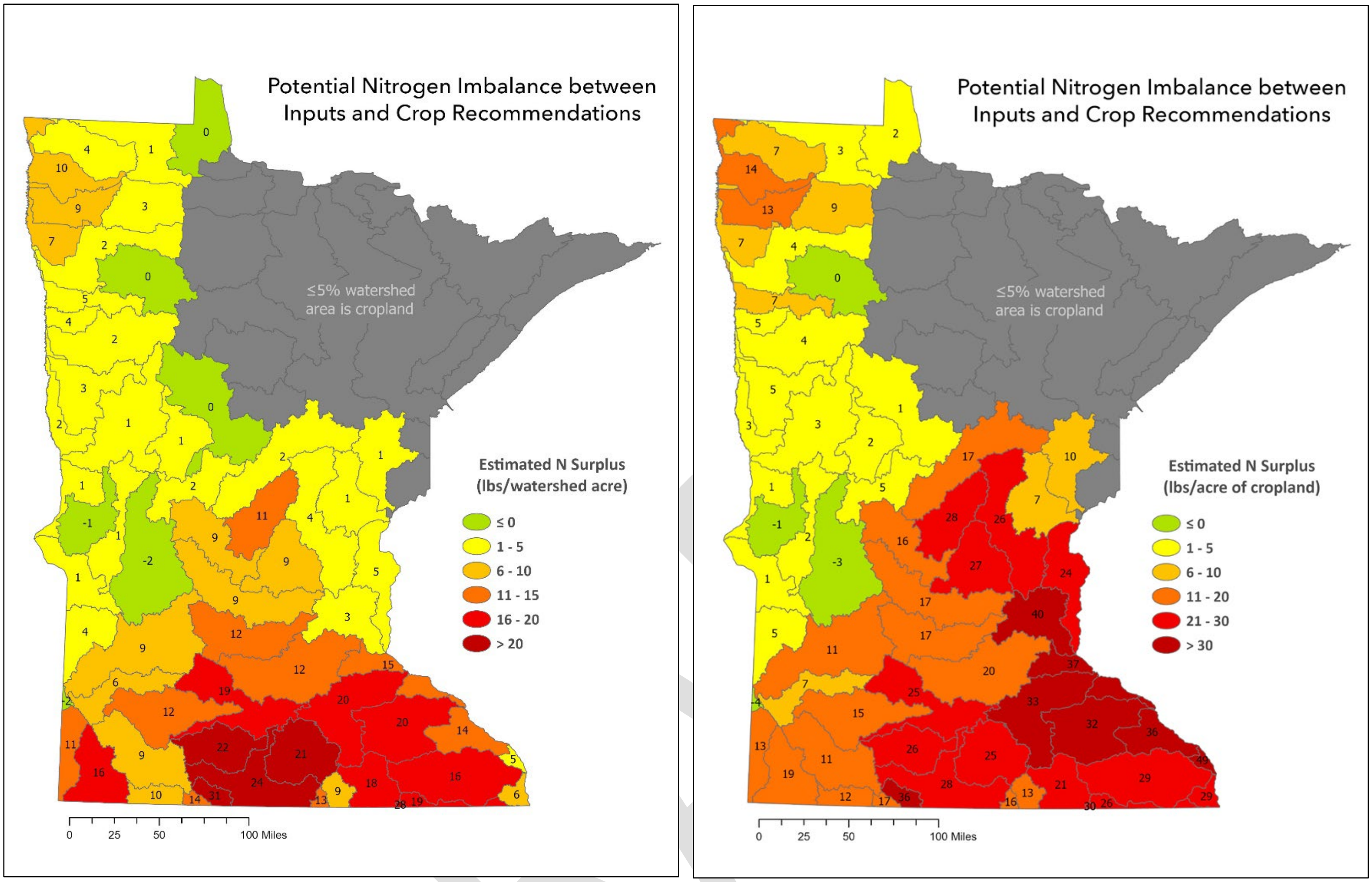


Figure 12. Results of nutrient balance for nitrogen in Minnesota at HUC08 watersheds using intermediate manure estimates. Each watershed is labeled with its unique estimated nitrogen surplus or deficit in pounds per acre. Note that surplus nutrients are rounded to the nearest whole number, which may cause a watershed deficit on the left map (where surplus was rounded to zero) and a surplus on the right map.

Phosphorus

When combining the contribution of manure P205 with commercial P205 sales, the statewide balance ranges from a 4.5% deficit (low scenario) to a .7% surplus (intermediate scenario) to a 5.9% surplus (high scenario) of the statewide P205 removal.

Table 7. Phosphorus statewide balance summary table			
	Low	**Intermediate**	**High**
Manure P205 applied (tons)	99,421	**123,621**	147,821
Commercial fertilizer P205 applied (tons)	341,496	**341,496**	341,496
Total P205 inputs (tons)	440,917	**465,117**	489,317
P205 removal (tons)	461,877	**461,877**	461,877
Overall P205 Surplus (tons)	-20,960	**3240**	27,440
Percent P205 surplus	-4.5%	**0.7%**	5.9%

These results suggest an overall balance between P205 inputs and outputs at a statewide scale, a finding supported by stable trends in median soil phosphorus levels in Minnesota over time (IPNI, 2015). Results do suggest, however, the existence of concentrated regions in the state where surplus phosphorus may be occurring. These regions primarily coincide with manured regions where P205 tends to concentrate, such as in central Minnesota where there is a higher density of poultry operations (Figure 13).

As with N, the identification of watersheds with a high P2O5 surplus is a result of several interacting variables. The process is different for P205, as COA fertilizer expenditures are used only to drive the redistribution of commercial fertilizer N to each county. Statewide commercial P205 sales (provided by MDA in tons), in contrast, are redistributed to each county based on both the amount of redistributed commercial N and the average N:P2O5 ratio of commercial fertilizer sold (from MDA six-year average sales) within the BMP region where that county is located. Therefore, a county receiving a disproportionately higher amount of commercial fertilizer N (based on COA fertilizer expenditures) may still receive a lower-than-expected share of commercial P205 if it is in a region with a high N:P2O5 ratio, such as the IRR or SE BMP regions.

The presence of manure only impacts the allocation of commercial fertilizer from the county to the individual field scale. Redistributed county commercial P2O5 is allocated to individual fields within each county based on the proportion of each field's remaining P2O5 need (after manure application) relative to the county total, where P2O5 need is defined as the P2O5 removal rate of each field minus a standard 95% manure credit. Therefore, fields already meeting their full P2O5 removal rate from manure will still have a 5% P2O5 need that is used for calculating its proportion of P2O5 need relative to the county total.

The result is that watersheds with a higher proportion of manured fields will receive a greater share of any P205 surplus. As with N, this impact is minimized in the sense that it only affects how commercial fertilizer P2O5 is allocated from the county to individual fields within that county.

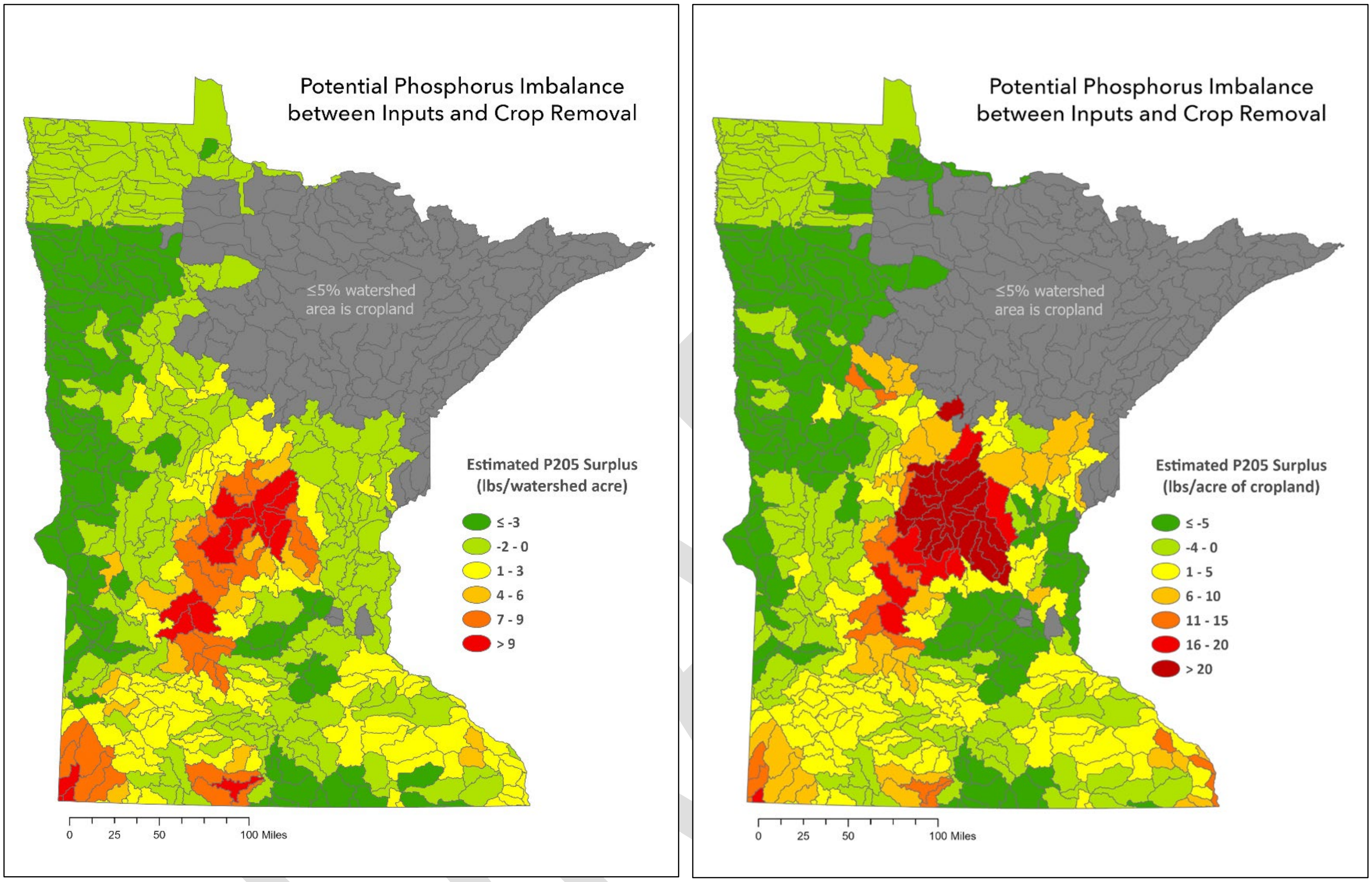


Figure 13. Results of Nutrient balance for Phosphorus in Minnesota at HUC10 watersheds using intermediate manure estimates. Areas of greatest surplus are in areas with large amount of manure (refer to figure 5) and this pattern holds regardless of whether the surplus is normalized to watershed size (left map) or amount of crop area in the watershed (right map).

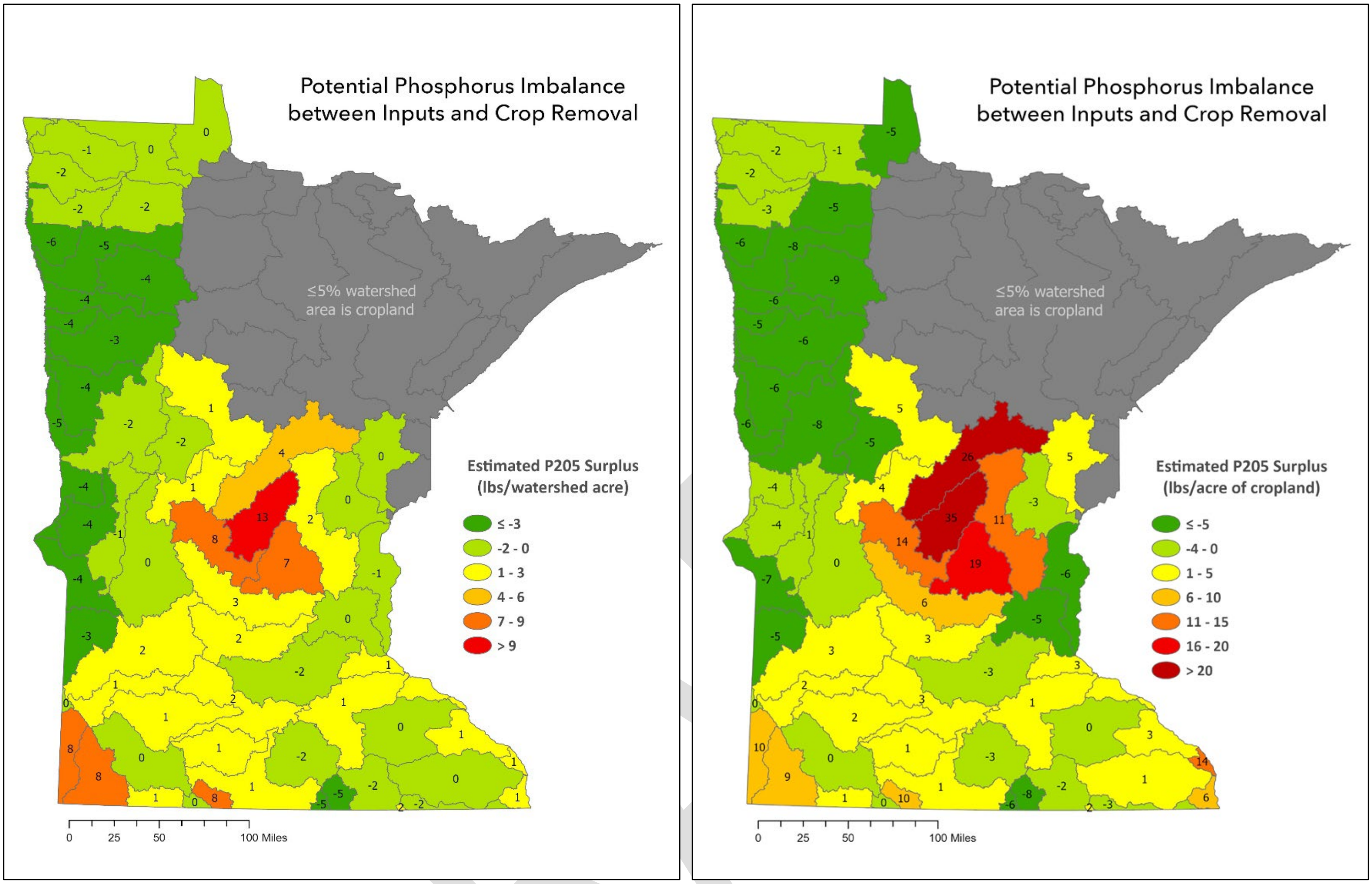


Figure 14. Results of nutrient balance for phosphorus in Minnesota at HUC08 watersheds using intermediate manure estimates. Each watershed is labeled with its unique estimated P205 surplus or deficit in pounds per acre.

Limitations

Perhaps the largest limitation of this work is related to data availability and the translation of data across multiple spatial scales.

The detailed animal feedlot database provided by MPCA plays a key role in this analysis to enable field-scale modeling of potential manure spreading. It is important to note, however, that this analysis still requires simplifying assumptions regarding animal counts, manure recoverability and nutrient losses; these assumptions contribute to uncertainty around manure estimates. Additionally, the idealized nature of the modeling approach (manure applied to the nearest agricultural fields) may not accurately reflect patterns of actual manure transfer at a field and watershed scale. This is particularly evident with poultry manure, which has been shown to travel distances beyond the scope of what a spatial model may be able to predict.

Less confidence can be placed in the spatial distribution of nutrients from commercial fertilizers, despite being the dominant source of N and P2O5 inputs statewide. Our results suggest that commercial fertilizer accounts for 84% and 73% of statewide N and P205 inputs, respectively, from manure and commercial fertilizer combined. While MDA provides annual information on commercial fertilizers ***sold*** in each county, these data must first be redistributed to better reflect fertilizer ***use*** in each county. While we utilized the Census of Agriculture fertilizer expenditures for this redistribution, several disadvantages exist to this dataset, including that values are provided in dollars (not the amount of fertilizer) and that expenditures cover all nutrients (N, P, K) as well as lime and soil conditioners. This analysis and related efforts would ideally benefit from improved detail about commercial fertilizer use at a sub-county scale, although options for achieving this are limited and would require either substantive policy changes or self-reporting at an intensive scale. Improved tracking of fertilizer use, in addition to or in lieu of fertilizer sales, would improve spatial estimates of county-level commercial nutrient inputs. While MDA surveys provide a valuable resource for understanding regional and rotational differences regarding commercial fertilizer and manure use in Minnesota, we could not confidently utilize the survey to determine nutrient application rates at a spatial scale that would improve our modeling estimates.

Phosphorus output was represented by the amount of P205 removed at crop harvest, with UMN Extension providing 25th percentile, median, and 75th percentile P205 removal rates for corn and soybeans. While these represent small changes in the pounds of P205 removed per unit yield, this had a drastic impact on statewide balances when extrapolated over millions of acres. For example, the use of the median value for P2O5 removal for both corn and soybean resulted in a statewide P2O5 deficit of 11.1%. This compares to our reported .7% excess of P2O5 statewide when using the 75th percentile removal rate, which was the agreed upon approach based on expert judgement as well as a cursory examination of trends in state soil test P levels. This work would benefit from an improved understanding and confidence in P205 removal rates as well as access to data on soil test P levels throughout the state.

Future Work

Below are several potential avenues to expand and build upon the modeling work described in this report.

- Validation of the manure application approach, perhaps by using digitized state manure management plans and/or targeted surveys. This would provide a quantifiable approach for understanding how parameters should be adapted for improved spatial modeling of manure application in the state.
- Comparison and validation of modeling results with nutrient and water quality data, including but not limited to in-field soil test phosphorus data and water quality loads at the outlet of major watersheds. This provides the opportunity to better understand the pathway for surplus nutrients to reach water bodies in different regions of the state, leading to more informed choices regarding conservation options.
- Work with the University of Minnesota, USDA, and MPCA to create visualization tools, interactive maps, and decision support tools to explore results.

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Appendix A1. Manure Nutrient Reference Values

Animal Category	Animal Count Reduction Factor	Weight (lbs.)	% Liquid	% Solid	Excretion (per animal unit per year)				Recoverability Factor (%)
					Tons	Gallons	N (lbs.)	P2O5 (lbs.)	
Dairy cattle > 1000 pounds	.64	1400	.95	.05	18.5	4443	119	52.4	75
Dairy cattle < 1000 pounds	.64	1000	.2	.8	18.5	4443	119	52.4	75
Dairy cattle – heifers	.64	750	.3	.7	11	2536	39	17.2	75
Dairy cattle – calves	.64	250	.1	.9	14.6	3358	24	10.6	75
Veal calves	.64	200	.05	.95	4.8	1153	29	12.7	75
Beef cattle - slaughter/stock	.56	1000	.2	.8	9	2141	39	17.2	80
Beef cattle - feeder/heifer	.56	800	.1	.9	16.8	3982	66	29	80
Beef cattle - cow/calf pairs	.56	1300	.05	.95	16.8	3982	66	29	80
Beef cattle – calves	.56	200	.05	.95	19.5	4591	73	32.1	80
Beef – mature bull	.56	1000	.2	.8	9	2141	39	17.2	80
Swine > 300 pounds	.83	300	1	0	4.1	998	37	16.3	97
Swine 55-300 pounds	.83	170	1	0	9	2166	73	32.1	97
Swine < 55 pounds	.83	25	1	0	13.9	3358	146	64.2	97
Chickens - liquid manure	.51	3	1	0	9.1	2068	97	42.7	95
Chickens - broilers > 5 pounds	.51	6	0	1	17.3	4198	256	112.6	98
Chickens - broilers < 5 pounds	.51	2	0	1	17.3	4198	256	112.6	98
Chickens - layers > 5 pounds	.51	7	0	1	9.1	2068	97	42.7	95
Turkeys > 5 pounds	.7	10	0	1	8.6	2044	285	186	93
Turkeys < 5 pounds	.7	1	0	1	8.6	2044	285	186	93

Dairy cattle (> 1,000 lbs. and < 1,000 lbs.) were assumed to be lactating 305 days and dry 60 days.
Values for gestating sow were assumed for swine greater than 300 lbs.
Values for turkey (female) were assumed for turkeys > 5 lbs. and turkeys < 5 lbs.

Animal Category	Solid Manure (lbs. per ton)		Liquid Manure (lbs per 1,000 gallons)		N Storage Loss (%)	Nutrient Availability		
	N	P2O5	N	P2O5		N Year One	N Year Two	P2O5 Year One
Dairy cattle > 1000 pounds	10	3	31	15	30	50	25	80
Dairy cattle < 1000 pounds	10	3	31	15	35	35	25	80
Dairy cattle – heifers	10	3	32	14	35	35	25	80
Dairy cattle – calves	10	3	31	15	35	35	25	80
Veal calves	10	3	31	15	35	35	25	80
Beef cattle - slaughter/stock	11	7	29	18	35	40	25	80
Beef cattle - feeder/heifer	7	4	20	16	35	40	25	80
Beef cattle - cow/calf pairs	7	4	20	16	35	40	25	80
Beef cattle – calves	7	4	20	16	35	40	25	80
Beef – mature bull	11	7	29	18	35	40	25	80
Swine > 300 pounds	9	7	25	25	20	70	15	80
Swine 55-300 pounds	16	9	58	44	20	70	15	80
Swine < 55 pounds	13	8	25	19	20	70	15	80
Chickens - liquid manure	34	51	57	52	35	55	25	80
Chickens - broilers > 5 pounds	46	53	63	40	35	55	25	80
Chickens - broilers < 5 pounds	46	53	63	40	35	55	25	80
Chickens - layers > 5 pounds	34	51	57	52	35	55	25	80
Turkeys > 5 pounds	40	50	60	38	35	55	25	80
Turkeys < 5 pounds	40	50	60	38	35	55	25	80