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Use of manure nutrients from concentrated animal feeding operations

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ABSTRACT

Over the past few decades, there has been a nationwide trend away from small livestock farms and toward large Concentrated Animal Feeding Operations (CAFOs). This shift results in concentrated manure production and introduces potential problems associated with its disposal. We analyzed data from 13 permitted CAFOs in southeastern Michigan, including 1187 occurrences of manure application from 12 of the CAFOs with available field-level data. CAFOs applied excess manure nutrients to cropland by applying to fields with soil phosphorus test levels >50 ppm (42% of all cases), applying to soybeans (7% of all cases), over-estimating crop yields in calculating plant nutrient requirements (67% of all cases), and applying beyond what is allowed by state permits (26% of all cases). This represents significant potential for redistribution of manure nutrients. The total amount of manure from all instances of over-application could be redistributed to fertilize over 4775 ha (11,800 acres) per year. Significant barriers to redistribution of manure exist, however, including cost, land availability, crop and soil need, transport logistics, and farmers' reluctance to use manure instead of inorganic fertilizer due to its variable composition. These findings are relevant to the harmful algal bloom and hypoxia issues in Lake Erie, which are driven by excess nutrients, and can be used to better inform science, modeling, and policy in the region.

Introduction

Over the past few decades, there has been a nationwide trend toward large animal operations and away from small farms (Kellogg et al., 2000; Gollehon et al., 2001). While the total number of livestock has remained relatively stable, the number of livestock farms has decreased, resulting in more livestock kept in larger operations and in confinement. Concentrated Animal Feeding Operations (CAFOs) are defined by the United States Environmental Protection Agency (EPA) as operations that confine animals for >45 days a year and either meet a certain size threshold (e.g., 1000 beef cattle, 700 dairy cows, 2500 swine weighing >55 pounds) or discharge manure or wastewater directly into a waterway (USEPA, 2008). The shift from traditional smaller farms to CAFOs results in concentrated manure production and introduces potential problems associated with its disposal. There has been growing public concern about the environmental effects of CAFOs, particularly regarding potential contamination of surface water and groundwater with nitrogen (N) and phosphorus (P), the primary nutrients in manure. Excess inputs of N and P can lead to eutrophication of surface water, resulting in harmful algal blooms (HABs) and depleted dissolved oxygen concentration (hypoxia). The Clean Water Act and other federal and state laws regulate CAFOs to minimize environmental impacts, but uncertainty remains regarding the effect of CAFOs on nutrient inputs to surface water and the success of policies designed to protect against water contamination.

The manure produced in CAFOs can be used to fertilize cropland, but there may be agronomical, logistical, and economic constraints on these large operations because there may not be enough nearby cropland in need of nutrients to receive all of the manure. In these cases, manure may be applied far from CAFO barns or transferred to another operation (both of which can be expensive), stored on site, or potentially over-applied on nearby cropland. Nutrients applied above crop requirements can accumulate in the soil (especially P), denitrify (in the case of N), or wash off fields and then contaminate surface water. Studies have suggested that the amount of land needed to use CAFO manure nutrients is often underestimated (Kellogg et al., 2000; Jackson et al., 2000; Gollehon et al., 2001; Ribaudo et al., 2003a), so there is an opportunity to spread manure on more land, and potentially reduce inorganic fertilizer applications. Those studies, however, use literature-based manure nutrient composition and assumed application rates and do not consider the effect of inorganic fertilizer applications at CAFOs. Herein, we address these shortcomings by using detailed, field-level manure application data reported by CAFOs to further understanding of manure management at these operations.

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We analyzed data from 13 southeastern Michigan CAFOs that are within a 15 km (9.3 mi) radius of each other in the River Raisin and Maumee River watersheds, both of which discharge to western Lake Erie (Fig. 1). This includes six of the seven CAFOs in the River Raisin Watershed and seven of about 80 CAFOs in the Maumee River Watershed, which has most of its land area and CAFOs in Ohio and Indiana (IDEM, 2017; MDEQ, 2017; OEPA, 2017b). While this area is relatively dense with CAFOs compared to the rest of the Maumee River Watershed, it is not unique. There are over 30 CAFOs within a 30 km (18.6 mi) radius in southern Mercer County, Ohio, and CAFOs in other areas throughout mid-Michigan are even more dense. In recent years, harmful algal blooms and hypoxia in Lake Erie have increased in extent and intensity due to elevated P loadings from watersheds that drain to the lake, particularly from the Maumee River watershed. Farm fertilizers and manure are primary sources of the Maumee River's P load (Scavia et al., 2014, 2017), and it has been estimated that about 12% of phosphorus applied to cultivated cropland throughout western Lake Erie basin (WLEB) watersheds is from manure (USDA, 2017a). Policymakers have set a goal of reducing the P input to Lake Erie by 40% (GLWQA, 2012), and meeting the goal will require a better understanding of the relative contributions and the spatial distribution of nutrient sources, including manure. While a majority of the critical WLEB watershed area is in Ohio, only Michigan has publicly-available, detailed field-level data on CAFO manure nutrient application. We chose our study area because we can address key questions about CAFO practices in this region using the data provided publicly by Michigan. Our primary objectives were to 1) develop a baseline understanding of manure produced and applied at CAFOs in a critical watershed area and 2) examine agronomic and logistic potential for redistributing manure nutrients to land with greater nutrient needs.

Methods

CAFO data and manure application records

The state of Michigan requires all CAFOs to submit to the Michigan Department of Environmental Quality (MDEQ) Comprehensive Nutrient Management Plans (CNMPs) and Annual Reports that include field-level manure application records. These data are available through Michigan's MiWaters online database (MDEQ, 2017). We compiled the most recent CNMPs and three years (2013–2015) of annual reports for 11 dairy CAFOs and two swine CAFOs in southeastern Michigan (Fig. 1). The annual reports have two main components: general operation data and field-level manure application data. The general data include average and maximum number of animals confined, estimated total waste generated, estimated total waste transferred off-site to another operation, total number of acres available for land application, and total number of acres used for land application for each calendar year. The field-level application data include field size, soil P level, date of soil test, planted crop, yield goal, actual yield, manure application rate, manure N application rate, available N, N credit, manure P application rate, fertilizer N application rate, fertilizer P application rate, total N, total P, and the basis for rate calculation (e.g., N-based, 1 year P-based, 2 year P-based) for every field to which manure was applied during the crop year. Fields must be 40 acres or smaller. Data are not provided for fields that received only inorganic fertilizer or were not fertilized. After omitting the field-level information from one CAFO due to reporting errors (R. Burns, MDEQ, pers. comm., February 13, 2017), we compiled a database of 1187 manure application records from the remaining 12 CAFOs. The annual reports' general data described above were retained and analyzed for all 13 CAFOs.

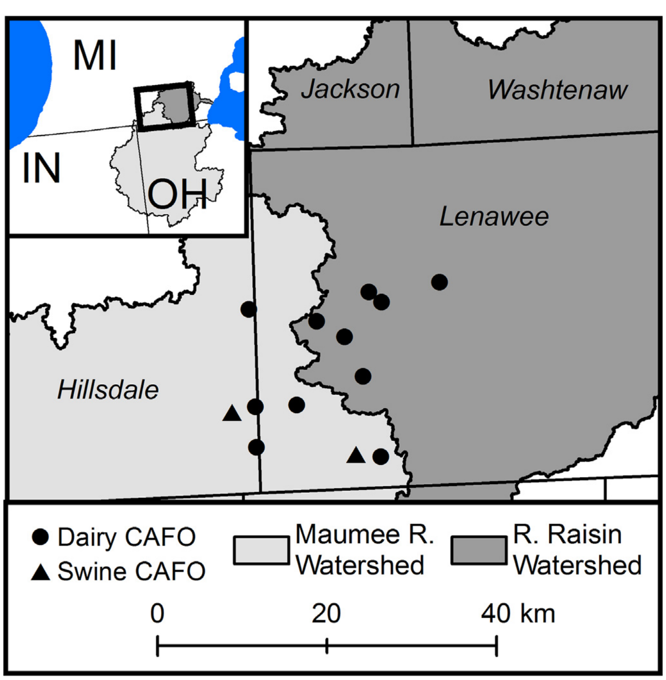

Fig. 1. Locations of CAFOs included in this study.

Missing data and data calculations

There were some inconsistencies in reporting among CAFOs, and records were occasionally missing information. When a field's size was not reported (8% of records), we used the average size of all other fields fertilized with manure by the given operation in calculations. Other cases of missing data are described below when relevant. The CAFO permits require that soil P tests use the Bray P1 method unless an alternate method is approved (MDEQ, 2015). Because no exceptions were noted on any reports, we assumed Bray P1 tests were used in all cases. When applicable, units for P application were converted from P to P_2O_5 and units for soil P test levels were converted from lb./acre to ppm using conversion factors from Warncke et al. (2004) and assuming a 16.96 cm (6.67 in) soil depth. All other data were used as reported. Herein, "P_2O_5" (phosphate) is used instead of "P" for discussion of phosphorus application rates and manure composition in accordance with U.S. agricultural convention. Unless otherwise noted, manure N refers to first-year plant-available N, which can be less than total manure N applied, as this is what is reported as the final rate in the CAFOs' annual reports.

Total liquid and solid manures applied by each CAFO each year were calculated by multiplying application rates by field areas. Total manure accounted for was this amount plus manure transferred off site. Manure N and P_2O_5 contents for each reported field application were calculated by dividing the total manure N and P_2O_5 application rates by rates of total manure applied.

Recommended and allowed application rates

The maximum allowed manure nutrient application rates for CAFOs in Michigan are based partially on Tri-State Fertilizer Standards established in 1995 by Michigan, Ohio, and Indiana (Warncke et al., 2004). P_2O_5 recommendations are based on soil P level and yield goal, and it is recommended to apply no P_2O_5 when soil P levels are >40 ppm (for corn and soybeans) or 50 ppm (for wheat and alfalfa). In Michigan, CAFOs are allowed to apply at 1, 2, or 4 times the Tri-State recommended P_2O_5 rate, depending on soil P levels, and application is allowed on soils with P levels up to 150 ppm (MDEQ, 2015). The MDEQ allowances follow the Tri-State N recommendations, which are based on previous crop and yield goal, except they allow application on soybeans and alfalfa, which the Tri-State Standards do not recommend.

We compared the reported CAFOs' N and P_2O_5 application rates to the Tri-State Standard recommended rates and to MDEQ-allowed rates. The MDEQ-allowed rates were calculated using equations from the Tri-State Standards bulletin (Warncke et al., 2004) and the MDEQ allowance guidelines (MDEQ, 2015), and the rates were confirmed when possible using annual report reviews completed by MDEQ staff and available on MiWaters (MDEQ, 2017). Of the 1187 compiled records of manure application, allowed P_2O_5 rates were calculated for 1109 (93%) and N rates were calculated for 1123 (95%). The omitted records either had a crop other than corn, wheat, soybeans, or alfalfa; were planted with a combination of crops; or lacked reported soil P level or yield goal. In cases where alfalfa was reported without specifying hay or haylage, we assumed hay if the yield goal was ≤11.2 tonnes/ha (5 tons/acre) and haylage if the yield goal was ≥13.5 tonnes/ha (6 tons/acre). In addition to calculating the maximum allowed rates using the CAFOs' reported yield goals, we calculated maximum allowed rates using each CAFOs' own actual average crop yields as yield goals.

Spatial data and land use

To examine the distribution of manure application relative to CAFO barn locations, we digitized field boundaries reported in the CNMPs in ArcGIS for all CAFO-managed fields that are used to spread manure. The MDEQ also provided ArcGIS field maps to supplement and confirm the digitized boundaries. The National Landcover Dataset (NLCD) (Homer et al., 2015) was used to determine area of cropland when considering potential redistribution of manure.

Results

Livestock totals, total manure, and annual manure utilization

The total number of cattle in the 11 dairy CAFOs increased from 15,478 to 23,524 between 2013 and 2015, with the majority in Lenawee County (14,310 in 2013 and 19,345 in 2015). The National Agricultural Statistics Service reported 32,114 cattle in Lenawee County in 2012 (USDA, 2012), suggesting that about 50% are in the county's eight dairy CAFOs. The swine CAFO in Lenawee County reported 4000 animals each year; in 2012, there were 6016 hogs and pigs in 35 farms in the county, suggesting that the one swine CAFO in the county contained approximately 66% of its swine. Out of about 70,000 swine in 48 farms in Hillsdale County, the swine CAFO averaged 7000 swine per year (10% of total county swine). These percentages suggest that a substantial portion of the manure nutrients applied to cropland in this area may be from CAFOs.

Over the study period, 314 to 644 million liters (83 to 170 million gallons) of liquid waste and 64 to 335 thousand tonnes (71 to 369 thousand tons) of solid waste were generated by the 13 CAFOs annually. These totals include water added to liquid manure and bedding and compost added to solid manure. Approximately 20% of the liquid manure was transferred to other operations, but it was only reported as transferred in 18 out of the 33 annual reports when it was produced. When liquid manure was transferred to other operations, an average of 30% of the generated waste was transferred, ranging from <10% to 80%. Approximately 12% of all solid manure was transferred to other operations, but in the 11 transfers of solid manure reported (out of 26 reported instances when solids were produced), about 35% of what was generated was transferred, ranging from <5% to 100%. The CAFO reports did not indicate how far transferred manure traveled or how it was subsequently managed and applied. Manure that was not transferred is assumed to be kept on site and either applied to cropland managed by the CAFO or kept in storage.

It has generally been assumed in studies of land available for manure application (e.g., Jackson et al., 2000; Ribaudo et al., 2003a; Kaplan et al., 2004) and in watershed models studies (e.g., Han et al., 2012; Luscz et al., 2015; Scavia et al., 2017) that all of the manure generated at a CAFO is applied on site each year. However, over our study period, there were five CAFOs where the amount of liquid manure applied and transferred was less than the amount generated each year, suggesting some was stored for more than three years. Conversely, there were 12 occurrences at seven CAFOs where more manure was applied and/or transferred than was generated, suggesting stored manure was applied to fields at those CAFOs. While over time these deficits and excesses may balance, this year-to-year variability may be important when analyzing or modeling dynamic manure application.

Manure composition

Michigan CAFOs' CNMPs include annual animal nutrient production based on published "book values" from the MidWest Plan Service (Lorimor et al., 2004) for as-excreted manure. The CAFOs are also required to test their stored manure annually to determine its nutrient content. The composition of manure as applied to fields varied greatly among the CAFOs, as well as within individual CAFOs (Fig. 2). On average, the applied liquid dairy manure had only 0.72 g P_2O_5/L and 1.15 g N/L (6.0 lb. P_2O_5 and 9.6 lb. N per 1000 gal), compared to as-excreted book values of 1.88 g P_2O_5/L and 4.23 g N/L (15.7 lb. P_2O_5 and 35.3 lb. N per 1000 gal) for milking cows and 0.97 g P_2O_5/L and 2.41 g N/L (8.1 lb. P_2O_5 and 20.1 lb. N per 1000 gal) for heifers (Lorimor et al., 2004; James et al., 2006). In contrast, applied solid dairy manure often contained more nutrients than as-excreted manure, averaging 2.90 g P_2O_5/kg and 4.00 g N/kg (5.8 lb. P_2O_5 and 8.0 lb. N per ton), compared to as-excreted book values of 2.20 g P_2O_5/kg and 4.95 g N/kg (4.4 lb. P_2O_5 and 9.9 lb. N per ton) for milking cows and only 1.10 g P_2O_5/kg and 2.65 g N/kg (2.2 lb. P_2O_5 and 5.3 lb. N per ton) for heifers.

As-applied swine manure generally had less P_2O_5 than as-excreted book values, averaging 2.3 g P_2O_5/L (19.3 lb./1000 gal) compared to as-excreted values of 4.5 g P_2O_5/L (37.9 lb./1000 gal). N content of applied swine manure was similar to the content of as-excreted manure, averaging 5.2 g N/L (43.1 lb./1000 gal), compared to as-excreted book values of 5.5 g N/L (45.5 lb./ton).

Land area and field distribution for manure application

The 13 CAFOs are located within a 15 km (9.3 mi) radius, and together they reported between 10,623 and 13,615 ha (26,249 and 33,643 ac) available for manure application in 2013–2015, with between 3918 and 5792 ha (9682 and 14,313 ac) (37% to 43%) used each year. Although the CAFOs are near a watershed boundary (Fig. 1), 94% of fields used for manure application were within the same watershed as their CAFO. Approximately 25% of field acreage used for manure application was within 2 km (1.2 mi) of CAFO barns, 51% was within 5 km (3.1 mi), and 95% was within 15 km (9.3 mi). The median distance to a field from the CAFO barns was 5.7 km (3.5 mi), and the maximum distance was 33 km (20 mi). These distances are for on-site application of manure; distances traveled in transfers off-site were not reported.

Actual nutrient application rates vs. recommended and allowed rates

On average, total P_2O_5 application rates at CAFOs were similar to the Tri-State recommendations for all crops (Fig. 3), although there was substantial variability with several extreme outliers. The mean reported total N rates were lower than the Tri-State recommended rates for corn but higher for wheat, alfalfa, and soybeans. The Tri-State Standards recommend no N be applied to soybeans or alfalfa and no P be applied to soils where the soil P level is >40 or 50 ppm, depending on the crop. Between 2013 and 2015, there were only 80 occurrences (7% of all records) of manure applied to soybeans, but 495 occurrences (42% of all records) of manure applied when the soil P test was >50 ppm. Assuming an average rate of 34 kg P_2O_5/ha (30 lb./ac), manure applied to soybeans could have been redistributed to fertilize an average of 730 ha (1800 ac) per year, and the manure applied to fields with soil P levels >50 ppm could have fertilized an average of over 4025 ha (9945 ac)

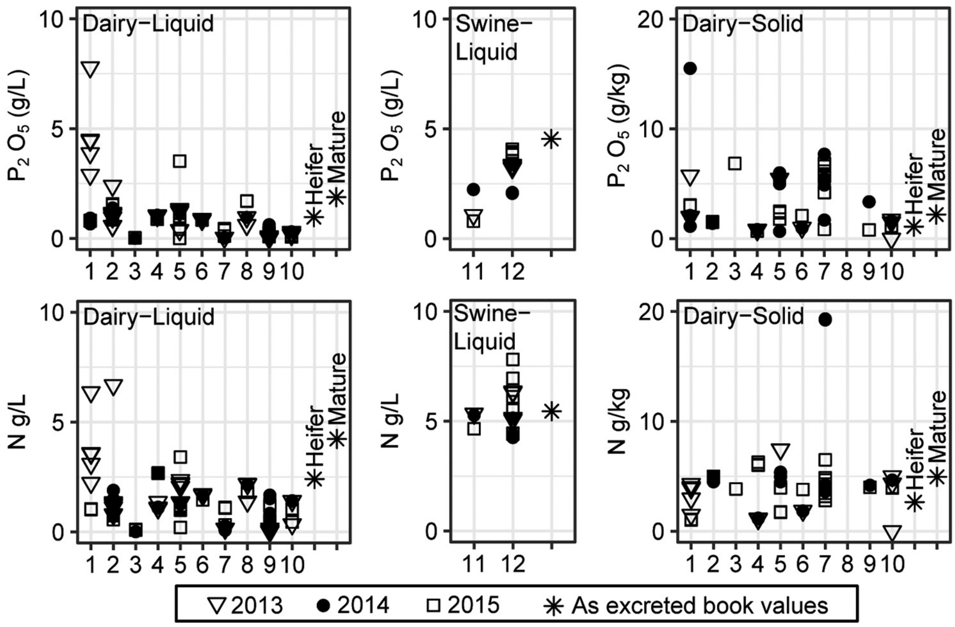

Fig. 2. Reported P (top row) and N (bottom row) content of as-applied liquid dairy manure (first column), liquid swine manure (second column), and solid dairy manure (third column) from 12 CAFOs over three years. Asterisks represent book values of nutrient content of as-excreted manure for heifers, mature dairy cows, and swine (Lorimor et al., 2004; James et al., 2006).

per year (Fig. 4). Using application rates based on N needs would cover less land because of the low N:P ratio in manure.

Because the MDEQ allowed rates are higher than the Tri-State recommendations, Tri-State exceedances described above were often within MDEQ permitted limits. Over the three-year period, there were 256 exceedances (23% of all records) of the MDEQ allowed N rates and 111 exceedances (10%) of allowed P_2O_5 rates on fields fertilized with manure (Fig. 5). Assuming an average rate of 34 kg P_2O_5/ha (30 lb./ac), the excess manure nutrients from these cases could be redistributed to fertilize an average of over 481 ha (1190 ac) of additional cropland every year (Fig. 4). Many of these exceedances were due to application of supplemental inorganic fertilizer (Fig. 5), which is further discussed below.

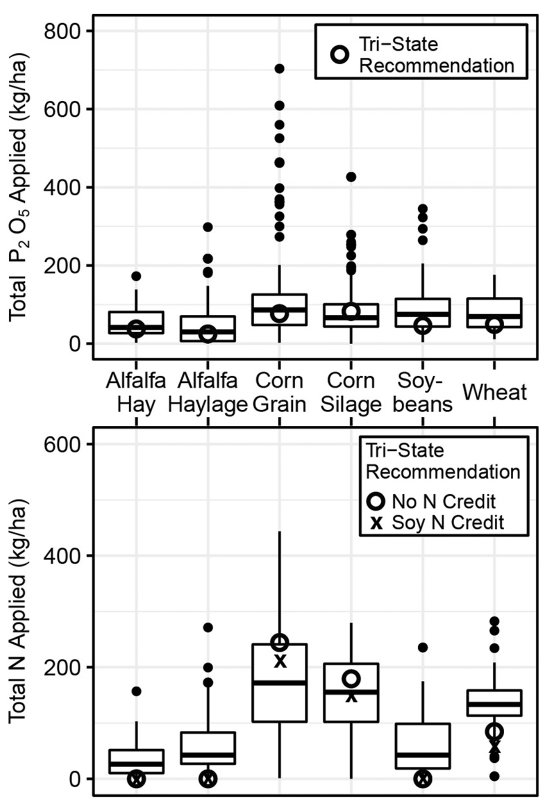

Fig. 3. Total nutrient application rates reported by CAFOs for different crops compared to Tri-State standard recommended rates. Reported rates are total N and P including manure and inorganic fertilizer. Tri-State rates assume maintenance soil P levels and average yields across all CAFOs in our dataset for yield goals.

There is broad interest in knowing if the nutrient exceedances are systemic or if only select operations are in violation. Not all CAFOs in this study violated MDEQ allowance limits. Considering both manure and supplemental inorganic fertilizer applications, four CAFOs exceeded the MDEQ N allowance on fewer than five field applications over three years; four of them averaged six or seven exceedances per year; three averaged 11 or 12 exceedances per year; and one averaged 20 exceedances per year (29% of all their applications) (Electronic Supplementary material (ESM) Table S1; see ESM Table S2 for exceedances summarized by crop). P_2O_5 exceedances were less frequent. Three CAFOs never exceeded P_2O_5 allowances, and six had fewer than 10 total exceedances over three years. But one had 40 P_2O_5 exceedances (19% of all their applications) (ESM Table S1).

Crop yield goals

Recommended application rates for both N and P_2O_5 are based on crop yield goals. A higher yield goal allows for a higher nutrient application rate, and CAFO operators set their own yield goals. We found that the stated yield goals were higher than actual yields 67% of the time. For alfalfa hay, wheat, and soybeans, yield goals were not met in 85%, 58%, and 57% of cases, respectively (Fig. 6). Conversely, actual yields were greater than goals in 72% of cases for alfalfa haylage and in 61% of cases for corn silage. Corn grain yields were above and below goals in roughly equal proportions. We determined the average actual yield for each crop at each CAFO and calculated the MDEQ's allowed N and P_2O_5 application rates using those as yield goals instead of the CAFOs' stated yield goals. In cases where the application rate exceeded the recommended rate calculated using average yields as goals, using the lower rate would have made available enough manure to fertilize an additional 438 ha (1083 ac) every year at an average rate of 34 kg P_2O_5/ha

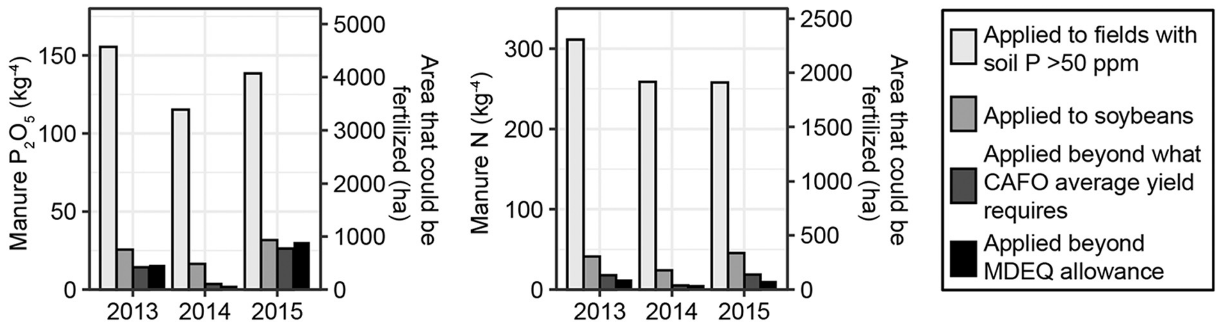

Fig. 4. Thousands of kilograms of excess manure P_2O_5 and N applied by CAFOs (left Y axis), and area which those nutrients could fertilize (right Y axis). Each bar represents one way that nutrients were under-utilized. Bars are not cumulative (e.g., the same field may have had both soil P >50 ppm and be in soybeans). N amounts applied beyond MDEQ allowances and beyond average yield requirements represent only first-year plant-available manure N, as this is how exceedances are determined in those cases; total manure N could be much greater. Areas are calculated based on application rates of 34 kg P_2O_5/ha and 135 kg N/ha.

(30 lb./ac) (Fig. 4). While many factors affect yields, some CAFOs consistently used yield goals that they did not achieve; seven of 12 CAFOs achieved yield goals <50% of the time. This finding is consistent with Jackson et al. (2000) who found that CAFOs in Iowa were underestimating the area required for manure application by projecting above-average crop yields.

Use of supplemental inorganic fertilizer

During our study period, 36% of fields received inorganic P_2O_5 fertilizer and 63% received inorganic N fertilizer in addition to manure. A majority of the exceedances for both N and P_2O_5 were on fields which received supplemental inorganic fertilizer (Fig. 5). We found that 23 of the 111 fields (21%) that exceeded the MDEQ P_2O_5 allowance and 197 of the 256 fields (77%) that exceeded the N allowance would have been below the allowed rates if inorganic fertilizer was not added. So, while we have considered only excess manure nutrients when calculating additional cropland areas that could be fertilized through redistribution (e.g. Fig. 4), recorded use of excess inorganic fertilizer would increase these amounts.

The average P_2O_5 application rate on fields that were fertilized with only manure was 64.8 kg/ha (57.8 lb./ac), while on fields that were

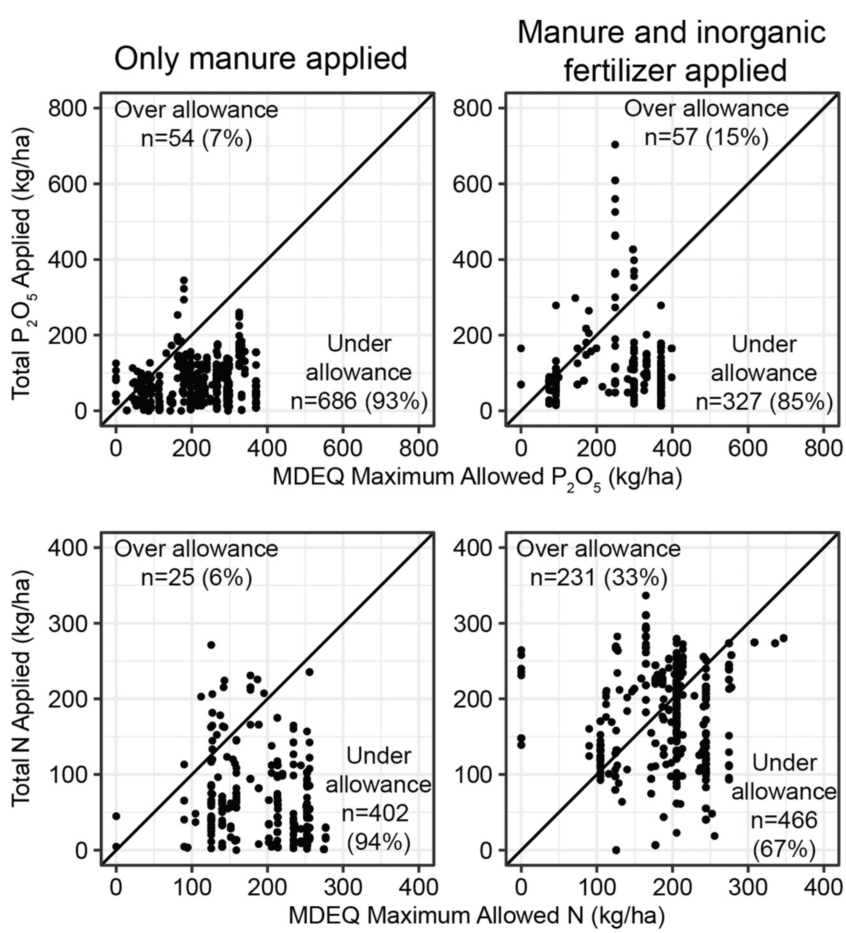

Fig. 5. Maximum P_2O_5 (top row) and N (bottom row) application rates allowed by the MDEQ compared to reported P_2O_5 and N application rates. Plots in the left column are for fields where only manure was used as fertilizer; plots in the right column are for fields where manure and additional inorganic fertilizer were used. Any point above the 1:1 line is an exceedance of the MDEQ allowed rate.

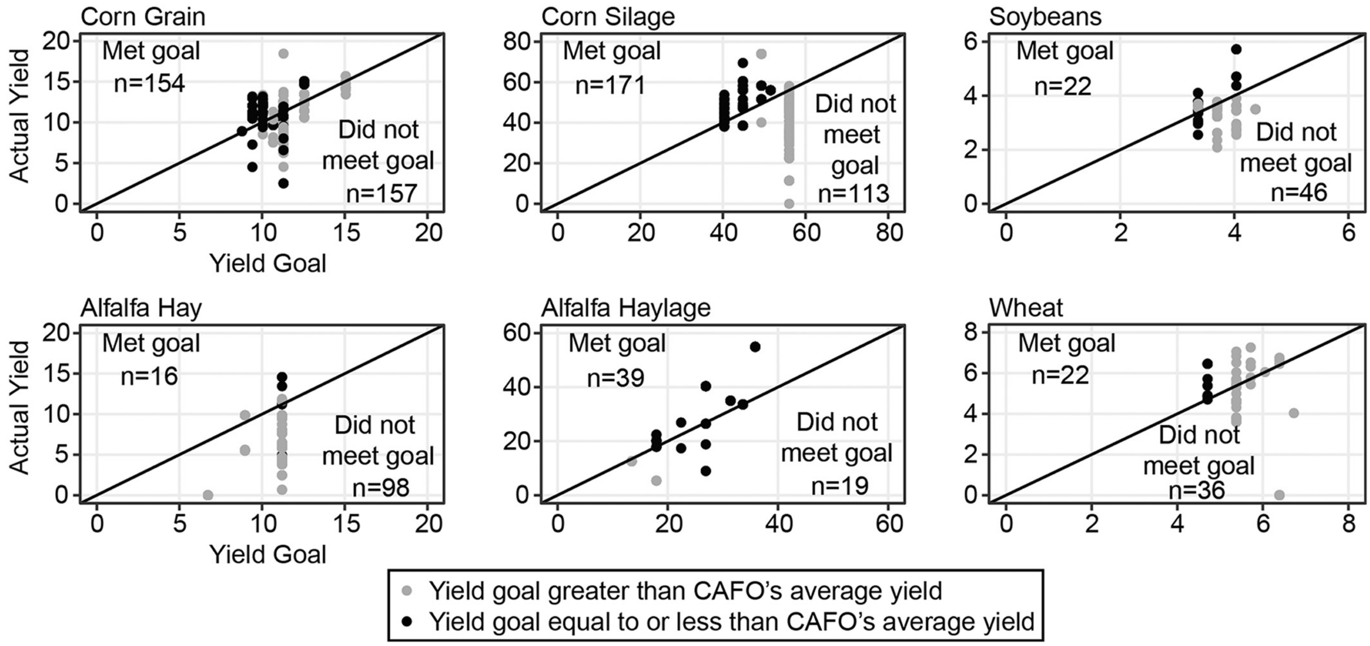

Fig. 6. Yield goals compared to actual crop yields for major crops at all CAFOs. Units are kg/ha for corn grain, wheat, and soybeans, and tonnes/ha for corn silage, alfalfa hay, and alfalfa haylage.

fertilized with both manure and inorganic fertilizer, the average total P_2O_5 application rate was 111.1 kg/ha (91.1 lb./ac), about 72% greater. The regional average total P_2O_5 application rate for fields to which manure is applied (with or without inorganic fertilizer as well) is 85.0 kg/ha (75.8 lb./ac) (USDA, 2017b). The rates at the CAFOs are higher than the regional average P_2O_5 application rates for fields to which only inorganic fertilizer applied, which is 50.1 kg/ha (44.7 lb./ac) (USDA, 2017b). As previously stated, no data were available for fields fertilized with only inorganic fertilizer at the CAFOs. It is worth noting that these regional rates are for most of MI, IN, IL, IA, WI, MN, and OH and parts of MO, SD, KS, NE, and OK, an area much larger than our study area.

Discussion

Manure composition and application rates

The wide range of manure nutrient content that we found is to be expected because different animal feeds, animal species, manure storages, storage duration, sampling techniques, and application methods all influence nutrient content (O'Dell et al., 1995; Petersen et al., 1998; Lorimor et al., 2004; Griffin et al., 2005). Our results emphasize the importance of using recent manure composition data because as-excreted literature values may lead to over- or under-estimation of nutrient availability (Fig. 2). As-applied liquid dairy manure often had lower nutrient content than as-excreted manure due to dilution and nutrient losses during storage. However, as-applied solid manure often had higher nutrient content than as-excreted manure, likely due to additions of compost materials and loss of water content. This wide range of nutrient composition also demonstrates that using published or average values to estimate nutrient loss (e.g., Kellogg et al., 2000) may still result in errors because the nutrient content is sensitive to many variables. The variability in manure composition may be one reason for nutrient exceedances.

Because more manure is generally produced by a CAFO than can easily be used, it is often treated as waste rather than as a valuable replacement for inorganic fertilizer (Hoag and Roka, 1995; Fleming et al., 1998). In 42% of records in our dataset, manure was applied to fields with soil P levels >50 ppm, even though the Tri-State Standard recommends no P_2O_5 application is needed in these cases. That amounted to 406,000 kg (895,000 lb.) of excess P_2O_5 and 818,000 kg (1,800,000 lb.) of excess N applied to over 5600 ha (13,800 ac) over three years. Thus, there are opportunities for better nutrient use, not only in southeastern Michigan, but potentially in other Midwestern states that have CAFOs and that allow nutrient application beyond what is recommended in the Tri-State Standards. Indiana allows CAFOs to apply manure on land with soil P levels up to 300 ppm (IDEM, 2014), reducing it to 200 ppm in 2018. In Ohio, CAFOs can apply manure to land with soil P levels up to 150 ppm. Adhering to the Tri-State Standard recommendations could result in improved nutrient use throughout the region and would also decrease the risk of nutrient runoff and contamination of surface water with excess N and P. The Tri-State recommendations are based on maintaining a soil P where crop yield will be 95–97% of maximum so that economic return on added nutrients is optimized (Warncke et al., 2004). So, adhering to Tri-State recommendations should not negatively impact yields and could be economically beneficial. While these data demonstrate the potential for improved manure use, there are barriers to manure redistribution, which are discussed in more detail in the next section.

Redistributing manure nutrients: How much is feasible?

Theoretically, it would be possible to redistribute manure to an average of >4775 ha/year (11,800 ac/year) from these CAFOs in southeastern Michigan, based on the amount of manure that was applied to soybeans or to land where soil P test level was >50 ppm, and at rates beyond what is allowed by the state or based on over-estimated crop yield goals. On average, manure produced by the 13 CAFOs in the study area is currently applied to about 5000 ha/year (12,350 acres/year), so this could potentially almost double the land used for application. The median distance from CAFO barns to fields that received manure was just over 5 km (3.1 mi), and there are 33,400 ha (82,500 ac) of cropland within 5 km of the CAFO barns, so applying to an additional 4775 ha seems feasible.

However, there are barriers to redistribution. For example, not all land near the CAFOs could require manure application, and nearby land managed by others may not need additional fertilizer. Other limitations include hauling cost, asynchrony between timing of manure availability and off-site need, public concern about odor and potential public health risks, and farmers' reluctance to substitute manure for inorganic fertilizer due to inconsistencies in manure nutrient content (Risse et al., 2006; Kleinman et al., 2012). More frequent or on-site testing could reduce uncertainty in nutrient content, but additional incentives and changes in insurance programs are likely needed to help address other barriers. The USDA's Environmental Quality Incentives Program (EQIP) can provide financial assistance to CAFOs for storage, treatment, and use of manure, which can lead to more effective on-site use, but it does not address off-site transfer (Ribaudo et al., 2004; USDA, 2017c). Improvements in the integration between the commercial fertilizer industry and manure management agencies could increase substitution of manure for inorganic fertilizer (Kleinman et al., 2012).

In many cases, cost remains a barrier to redistribution because it is expensive to haul manure long distances. This is in addition to potential increased costs associated with application, obtaining more land, and additional tests for soil and manure nutrient content. For example, Ribaudo et al. (2003b) found that production costs for large dairy farms in the northern US would increase by up to 3% to meet a P-based standard of applying P at rates not greater than removal rates. They note, however, that there is a relative abundance of cropland available for manure application in Michigan, Ohio, and Indiana, a finding consistent with our analysis. Willingness of other operators to accept manure greatly influences the cost of distribution (Ribaudo et al., 2003b); addressing uncertainty in manure nutrient content, as discussed above, may increase their acceptance. Models exist to estimate the cost of transporting manure in specific cases (e.g., Fleming et al., 1998; Ribaudo et al., 2003b), and developing them for this region could provide additional valuable information to guide manure management.

Data needs and potential improvements for CAFO reporting

While CAFO data reporting in Michigan is relatively comprehensive, additional information would help improve our understanding of existing manure management. For example, it would be useful to know where CAFOs transfer manure, especially for operations that generate large amounts of solid manure, because hauling this low moisture manure is less expensive and therefore more likely to occur. Without knowing where transferred manure goes, how far it travels, and how it is subsequently managed, it is difficult to complete a comprehensive assessment of the impact that CAFOs have on nutrient loads in a watershed, as noted by Steeves (2002). It would also be useful to know when and how manure is applied, because proper timing and method of application are both critical for reducing nutrient losses (Kleinman et al., 2002).

Despite these shortcomings, the quality and availability of data in Michigan exceeds that in many other Midwestern states. Most states are authorized by the EPA to implement their own CAFO regulatory and permitting programs, and thus program requirements differ among states. All CAFOs are required to obtain NPDES permits in Michigan. In Ohio and Indiana, only CAFOs that discharge manure or wastewater are required to obtain those permits, and field-level reporting is not as detailed as in Michigan (IDEM, 2014; OEPA, 2017a). Uniformity among state reporting systems would be helpful when assessing watersheds that cross state lines, such as the Maumee River watershed that crosses three states and contains over 80 CAFOs (IDEM, 2017; MDEQ, 2017; OEPA, 2017b).

Applications for watershed modeling

Lake Erie watershed models have successfully quantified nutrient sources and delivery rates, but in doing so, broad assumptions had to be made about manure compositions and application rates and locations (Kleinman et al., 2002). Such assumptions likely impact estimates of critical nutrient source areas and perhaps overall nutrient loss rates. Incorporating more precise manure data, as summarized here, will likely improve those estimates. The field-level information described here can also improve models in any region where dairy and swine CAFOs are prevalent. For example, where CAFOs are prevalent, it is more appropriate to assume manure is applied within 15 km (9.3 mi) of CAFOs, to use nutrient compositions reflective of manure that has been stored (e.g., Luscz et al., 2015), and to consider that fields receiving nutrients from manure may also be applied with inorganic fertilizers.

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Appendix A. Supplementary data

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