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Research article

Waste nutrients from U.S. animal feeding operations: Regulations are inconsistent across states and inadequately assess nutrient export risk

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ABSTRACT

Livestock production in the United States has been transformed over the past several decades, largely as a result of widespread development of industrial-scale mass production facilities, termed Animal Feeding Operations (AFOs). These facilities generate massive amounts of animal waste that can concentrate in small areas. Animal wastes from AFOs have led to high levels of nutrients and other pollutants in nearby surface waters, as well as groundwater. The environmental problems associated with these disposal practices have led to federal and state modifications to the rules and regulations governing waste practices. We summarize the federal guidelines for AFO nutrient management, focusing on swine, and compare the regulations of four AFO-rich states in different regions of the USA. Furthermore, we discuss inconsistencies among regulations and regulatory gaps, and identify issues with waste nutrient management practices that lead to environmental degradation in watersheds hosting AFOs. Finally, we address these shortcomings and the need to implement policy updates that would alleviate some of these environmental and human concerns.

1. Introduction

1.1. Livestock production in the US

Livestock production in the United States has changed greatly over the past several decades. Small-scale production by many individual farms has given way to mass production of swine, poultry and cattle by industrialized animal feeding operations (AFOs) that are often owned by or contracted with large corporations (Fig. 1a–e). Such facilities grow hundreds to many thousands of animals in buildings in which they are fed *ad libitum* using carefully formulated grain-based feeds and excrete large quantities of wastes, including feces, urine, and spilled feed. There are approximately 450,000 AFOs in the USA, the large majority concentrated in relatively few states (USDA, 2020.). However, AFOs are not limited to the USA; they also occur in Mexico, South America, China, and Southeast Asia (Thu and Durrenberger, 1998).

1.2. Livestock waste disposal practices and excess nutrient loading

The raw or partially-decomposed animal waste is largely disposed of on the nearby landscape (Burkholder et al. 1997, 2007; Mallin, 2000), known as sprayfields. Manure has *value* as a fertilizer and soil conditioner because its contents of nitrogen (N), phosphorus (P), and potassium (K) are nutrient sources to soils, while the organic component of manures enriches soil characteristics (US EPA, 2004). Manure has *drawbacks* as a fertilizer however, owing to its compositional mismatch with crop plant needs and the need for AFOs to dispose of so much of it within a short distance. Because they are highly concentrated in certain areas of the US, there is well-documented off-site pollution of waterways by nutrients and other pollutants (Weldon and Hornbuckle, 2006; Burkholder et al., 2007; Harden, 2015; Mallin et al., 2015).

Although the effects of excess nutrient loading are well-known for driving the eutrophication process (Boesch et al., 2001), elevated nitrate in particular is known to be damaging to aquatic invertebrate and vertebrate health (Camargo et al., 2005). Nitrate readily enters groundwater from agricultural sources (Liebhardt et al., 1979; Keeney, 1986; Ritter and Chirnside, 1990), where it can impact drinking water. Elevated nitrate in well water is known to cause methemoglobinemia, or blue-baby syndrome (Johnson and Kross, 1990) and there is a growing body of evidence that elevated nitrate is associated with other human health factors including various cancers (Temkin et al., 2019).

Swine waste is particularly troublesome, as swine have not achieved

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the feed conversion efficiencies of poultry (>3 kg and <2 kg feed/weight gain, respectively) and their waste is therefore generated as voluminous wet waste very high in nutrient (N and P) content and containing several added metals (Copper, Manganese, and Zinc; Table 1). Appropriate disposal practices for swine waste have been debated for decades (Barker and Zublena, 1995; Mallin and Cahoon, 2003; Williams, 2004; Vanotti et al., 2007).

1.3. Concerns with current waste disposal practices

Although there is no standard, industry-wide, economically attractive, and environmentally benign treatment and disposal practice within the general land application process for the millions of metric tons of swine waste generated annually, there have been various modifications to federal regulations attempting to define more environmentally-friendly practices. Federal regulations for animal waste disposal, however, remain only vaguely prescriptive, and state regulations vary; consequently, loopholes and imperfect monitoring programs lead to unsavory environmental effects of swine waste, including excess nutrient loading to surface and ground waters.

The utility and problems of land application of animal wastes are a function of having adequate land for disposal/treatment, as well as calculation of appropriate application rates to minimize nutrient export. Specific determining factors include *plant available N* (PAN) from manure, loss of N to the atmosphere as ammonia, and over-application of phosphorus (if managing for N), which can lead to nutrient export. Owing to typically low N:P ratios in manures, managing by P content (as in some states, like Maryland) under-supplies nitrogen, leading to a need to add inorganic N to support cover crops, increasing cost.

The geographic distribution of Concentrated AFOs (CAFOs) encompasses a variety of elevations, soil types, rainfall patterns, air temperature ranges and other environmental factors, posing additional challenges to effective waste nutrient management. Further, sprayfield disposal of liquid waste is *usually* permitted only for the growing season of March–September, leading to significantly higher concentrations of conductivity, nitrate, total nitrogen and fecal bacteria in nearby waterways during the spraying season (Mallin and McIver, 2018).

The objectives of this review are to highlight the disparate waste management practices across the U.S. Furthermore, sampling and analytical disparities can lead to an improper nutrient budget calculation(s) that can ultimately lead to environmental damages to the surrounding waterways. In the following sections, we reviewed federal Guidelines for CAFO waste management, and surveyed CAFO waste management regulations of several US states with large numbers of CAFOs (Table 2) and described the N, P, and K content of swine manure specifically in depth. Finally, we investigated the potential shortcomings

Fig. 1. A. Swine in AFO, eastern NC; B. Polluted runoff from swine waste sprayfield to public (waters of the US) roadside ditch; C. Massive poultry CAFO on VA eastern shore; D. Drainage from poultry CAFO entering waterway along public road; Duplin Co, NC; E. Cattle CAFO in eastern Washington State (all photos M. Mallin).

Table 1
Comparison of the nutrient content of the common forms of swine manure on South Carolina farms (as-sampled or wet basis) (Chastain et al., 2003).

Manure Type	Fresh[a] Manure	Manure[b] from Building	Lagoon Surface Water	Lagoon Sludge	Agitated Water and Solids[g]	Storage Pond Surface Water
lb/1000 gallons						
NH_4^+ - N	28.6	11.4	3.4	6.1	3.9	4.3
Organic - N	22.7	5.6	1.4	15.5	4.1	2
Total - N[c]	51.3	17	4.8	21.6	8	6.3
Estimates of Available Nitrogen[d]						
Incorporated	36.5	12.5	3.6	14.2	5.6	4.6
Surface	27.9	9.1	–	12.3	4.4	–
Direct Injection	–	14.8	4.2	–	6.4	5.5
P_2O_5[e]	40.4	13.4	2.8	47.3	11.3	3.6
K_2O[f]	34.5	14.2	6.1	6.3	6.1	7.9
Ca	32.6	3.7	0.86	32.3	6.8	1.1
Mg	6.9	2.4	0.46	11	2.5	0.57
Zn	0.49	0.28	0.03	1.8	0.37	0.04
Cu	0.12	0.26	0.02	0.75	0.16	0.03
Mn	0.19	0.12	0.01	0.65	0.13	0.02
S	7.5	1.3	0.31	6.6	1.5	0.39
Na	6.6	2.5	1.8	1.6	1.8	2.2

[a] Nutrient content of manure as excreted (from ASAE Standard D384.1, 1998). All other values based on database compiled by the authors.
[b] The total solids content from flush and pit-recharge buildings will vary from 1.5% to 2.6% depending on building design and animal weight. A mean value of 2% is shown.
[c] Total-N = Organic-N + (NH_4^+ - N).
[d] Estimates based on recommendations from the Clemson University Agricultural Services Laboratory.
[e] Total phosphorus expressed as P_2O_5. Elemental P = 0.44 x [P_2O_5].
[f] Total potassium expressed as K_2O. Elemental K = 0.83 x [K_2O].
[g] Use these values as an estimate of the nutrient content of agitated liquid storage structures and lagoons.

of these waste management practices. Suggestions on how to mitigate these shortcomings are included in the conclusion.

2. Results

2.1. The federal guidelines for CAFO waste disposal

Any AFO that discharges manure or wastewater into a natural or man-made ditch, stream or other jurisdictional waterway (Fig. 1b,d) is defined as a CAFO, regardless of size. Livestock and poultry CAFOs that land-apply manure are federally regulated under the National Pollutant Discharge Elimination System (NPDES) permitting program, in both the 2003 and 2008 versions of the "CAFO" rule. This program regulates the discharge of pollutants from point sources to waters of the US as defined by the Clean Water Act (CWA). CAFOs from which discharges are proposed or reasonably expected must have an NPDES discharge permit. Most CAFOs, however, are generally permitted as non-discharge operations (US EPA, 2003).

The U.S. EPA updated original CAFO rules of the 1970s in 2003 to address changes in animal agriculture, commonly referred to as the '2003 CAFO Rule.' It focused on the 5% of the nation's animal feeding operations that presented the highest risk of impairing water quality and public health (Federal Register (FR) 70418). This rule required CAFOs to seek coverage under an NPDES permit unless they demonstrated no potential to discharge to jurisdictional waters. The requirements of this permit are standard: name and location of the owner/operator of the CAFO, a topographic map of the geographic area, data on the number and types of animals and how they are housed, data on containment and storage for manure and wastewater, number of acres under control of the applicant available for land application of waste, estimated amounts of waste, and a nutrient management plan (NMP). If the applicant proposes to discharge, they must also indicate the receiving stream(s) (Final Rule, July 30, 2012). The U.S. EPA again updated these rules in 2008 in response to a 2005 decision by the U.S. 2nd Circuit Court of

Table 2
Comparison of lagoon waste and soil testing in four different CAFO-rich states.

State	Permit type	Soil testing/limits	Lagoon waste testing	Software used to create Nutrient Management Plan
NC	NC General Permit	Standard Soil Fertility Analysis, including pH, P, Cu, Zn every 3 years, Mehlich-3 extractant process	N, P, Zn, Cu within 60 days (before or after) date of application. Manure Analyses must include Total N, ammonium N, total P, total K, percent solids, Cu, Zn (NRCS, 2014)	NC Phosphorus Loss Assessment Tool (NC PLAT), Nitrogen Loss Estimation Worksheet (NLEW) for Neuse and Tar-Pamlico River TMDLs
CA- Colorado River Valley	General Waste Discharge Permit	1 sample set per Conservation Treatment Unit (CTU) per year, (from CAFO permit: 1/5 years for P)	Liquid Manure: 1 sample per irrigation during the irrigation event for the first year, then quarterly; use "quick test" to evaluate for Ammonium N (ppm) and Organic N (ppm); Lab test for other parameters. Manure/wastewater should be analyzed 1/year for N and P	CA Central Valley Nutrient Management Plan, Manure Management Planner (MMP)
MD	State: (1AFA) and Federal (MD G01A)	Regulations require soil testing for pH, P and N, most cropping farms also test for K, Magnesium, and Calcium	yes	NuMan MD Pro 3.0, NuMan MD Reporter 2.0, MMP
WI/CAFO applications and P-based NMP	NR 243 and WPDES	Soil Test Phosphorus Strategy or PI strategy, Phosphorus, K, % OM, pH	yes	SNAP Plus, MMP

Appeals (WaterKeeper Alliance et al. v. EPA, 2005, 73 FR 70418). This update expanded the number of operations covered by the CAFO regulations and included requirements to address the land application of manure from CAFOs (EPA summary of the 2nd Circuit's decision of the CAFO litigation).

The 2003 CAFO rule included a "duty to apply' provision that required CAFOs to apply for NPDES permits, as well as a process for CAFOs to seek a "no potential to discharge" determination from the permitting authority. The U.S. EPA in 2008 created a set of three revisions regarding this 'duty to apply.' A CAFO operator now has no duty to apply for an NPDES permit if the permitting authority determines that a CAFO has no potential to discharge manure, litter, or process wastewater to waters of the U.S., based on information supplied by the CAFO operator. It eliminates the procedures for a 'no potential to discharge' determination and it establishes a voluntary option for unpermitted CAFOs to certify that they do not discharge or propose to discharge. Furthermore, assuming the CAFO produces (and abides by) a management plan that applies CAFO manure onto crops at an 'agronomic rate,' then the storm water runoff of manure from a CAFO's crop fields qualifies as 'agricultural storm water,' which is exempt from regulation. The U.S. EPA also leaves the regulation of groundwater discharge (to surface waters) up to the permitting agency per individual case (EPA summary of the 2nd Circuit's decision of the CAFO litigation).

Regardless of the NPDES requirements, the US Department of Agriculture (USDA) Soil, Plants, Air, and Water (SPAW) and Agriculture Water Management (AWM) models can be used to conduct the 'no potential to discharge' studies. In order to manage manure and process wastewater properly, applicators must know how much manure is produced, its composition, and the composition of the soil where the manure is to be land-applied. The rate and method of application should consider the soil holding capacity, the nutrient requirements of the crops, slope of the field, other nutrient inputs, and potential leaching and runoff of any pollutants.

2.2. Federal guidelines for animal waste and receiving field sampling

General federal guidelines state that 1) application rates should be based on the more restrictive crop phosphorus requirements, 2) application should be timed to provide maximum benefits for cover crops, 3) manure should not be spread on land in winter where the ground is frozen, 4) incorporation should occur within 24 h of application (no application during or immediately before rain, to limit runoff), and 5) there must be soil management to minimize erosion to mitigate runoff problems (US EPA, 2004).

The federal 2003 CAFO rule *requires* that samples of manure be collected and analyzed for Total Kjeldahl Nitrogen (TKN) + nitrate/nitrite-N (= total N), total P and soluble P a minimum of once per year (US EPA, 2004). These samples should represent the average composition of the material that will be applied to the field, with representative sampling methods that vary according to manure type. Although the 2003 CAFO rule requires that manure be analyzed only for N and P, the U.S. EPA suggests analyzing for percentage of dry matter, ammonium-N, calcium, manganese, magnesium, sulfur, zinc, copper, pH and electrical conductivity. A CAFO operator may use a 5-year manure analysis average as long as the average includes a manure analysis taken within the past 12 months (US EPA, 2012).

The 2008 CAFO rule states that soil must be analyzed a minimum of once every 5 years for P content (ELG 40 CFR 412.4). The USDA Natural Resources Conservation Service (NRCS) issued a Conservation Practice Standard Nutrient Management Code 590 adopted by the states, which states that "current soil tests are those that are no older than 3 years, but may be taken on an interval recommended by the land-grant university or as required by the state code." Traditional soil test analyses are conducted for pH, N, P, K, soil organic matter, and electrical conductivity (as required for *large* dairy, beef, poultry, swine, and veal calf CAFOs; ELG 40 CFR 412.4), yet the U.S. EPA considers this the *minimum* necessary to properly manage soil nutrient levels. CAFOs are required to sample each field where manure is applied, as different fields have different soil types, past cropping histories, or different production potentials. Conservation Management Units (CMUs), fields with similar soils, cropping, and irrigation management that receive very similar nutrient applications, should be tested once per year. All samples are tested for pH, nitrate-N (parts per million, ppm and mass/0–0.46 m soil depth), ammonium-N (ppm and mass/0–0.46 m depth) when taken less than two weeks after application of liquid manure, plant-available P (ppm-P and mass/0–0.46 m depth), exchangeable K (ppm-K and mass/0–0.46 m depth), electrical conductivity (to evaluate salt accumulation), and salinity diagnostics for salt-affected soils. The NRCS Code 590 also states that *manure* (waste) testing must include the aforementioned analyses plus total K or K_2O, and percent solids, "or follow land-grant university guidance regarding required analyses".

State permitting authorities can use the NRCS Code 590 as guidance for developing technical standards for the land application of manure. The purposes of these standards are to guide development of CAFO-specific NMP. This enables agricultural users of manure nutrients to minimize pollution of surface and groundwater resources, to budget and supply nutrients for plant production, and to maintain or improve the physical, chemical, and biological condition of the soil. The development of specific NMPs is based on field risk assessment, determination of land management units, nutrient application rate development, timing, and methods, and operation and maintenance practices (US EPA, 2004).

The NRCS Code 590 describes three field-specific risk assessment methods to determine whether the manure application rate is to be based on N, P or whether land application of manure is to be avoided. These three methods are: 1) Soil Test P Level (agronomic soil-test interpretation), 2) Soil P Threshold Level (environmental interpretation of soil-test P), and 3) P index (site-specific assessment of P availability). Soil test-P levels (Table 3) identify the level above which crop yield would not increase with additional P applied, and therefore no additional fertilizer or manure P would be recommended. A soil-test P threshold requires establishing the relationship between soil-test P level and runoff P concentration. Because of the variation in climate, crops, cropping systems, and soil types (etc.) use of a P index is also an option. State permitting authorities have the discretion to determine which of these methods is to be used.

The objectives of determining a nutrient application rate are to match the amount of plant-available nutrients in animal manure with the amount required by the cover crop and to avoid over-applying nutrients. The basic elements are:

- Agronomic application rate (crop nutrient requirement minus nutrient credits, those values that account for soil nutrient levels prior to application and available in the soil),

Table 3
Key characteristics of commonly used soil P extraction methods (Elrashidi, 2000; Wuenscher et al., 2015). 'SRP' = soluble reactive phosphate (including adsorbed phosphate), 'Fe-P' = iron-bound phosphate, 'Al-P' = aluminum-bound phosphate, 'Ca-P' = calcium-bound phosphate.

Method	Extractant	P forms extracted	Comments
Bray P-1 (Bray and Kurtz, 1945)	HCl/NH_4F	SRP, Fe-P Al-P	California, Wisconsin; acid-soluble P forms
Mehlich I (Nelson et al., 1953)	HCl/H_2SO_4	SRP, Fe-P, Al-P	Maryland; acid-soluble P forms
Olsen P (Olsen et al., 1954)	$NaHCO_3$	SRP, AL-P, Ca-P	California, specific for calcareous, alkaline, and neutral soils
Mehlich 3 (Mehlich, 1984)	HNO_3/HOAc/ NH_4F/NH_4NO_3/ EDTA	SRP, Fe-P, Al-P, Ca-P	North Carolina, useful for broad range of soils

- crop nutrient requirement (crop nutrient uptake x crop yield), and
- nitrogen credits (legume nitrogen credits + nitrogen residual from past manure applications + nutrients from commercial fertilizer applications + irrigation water nitrate nitrogen + crop residues + other nitrogen credits)

The Nitrogen Leaching Index (NLI) in an NMP developed by USDA Agricultural Research Service assesses the risk of nitrogen leaching loss. This index estimates the amount of precipitation that infiltrates a crop field and percolates to below the root zone (1 m). It is calculated using the fall and winter seasonal rainfall, the annual rainfall, and the runoff curve number for the hydrologic soil group of the soil on the field (Hurley and Stewart, 2013). The NLI presumes the highest risk of percolation is in October to March, owing to low plant utilization and seasonally elevated groundwater levels.

2.3. N, P, and K ratios of swine manure

The N:P:K ratios in swine manure vary depending on the age of the animals, feed content, temperature, methods used to collect and store manure, and the moisture content. A typical finishing hog manure (liquid manure from mature adult pigs) might test 2 N: 1.4 P (as P_2O_5):1 K (as K_2O) (Ag Decision Maker, 2007). The NPDES Permit Writers' Manual for CAFOs (2012) denotes a manure ratio of 1.35 N: 1 P. The Confined Animal Manure Managers (CAMM) program through South Carolina's Clemson University, for example, developed and continuously updates species-specific training manuals to aid in the certification of CAFOs under State (SC) regulation R.61-43. In this CAMM Swine Training Manual, Chastain et al. (2003; Table 1) addresses the variability in nutrient content of swine manure. Manures are inherently labile, so their nutrient content, especially of N, can change during handling and storage. Total N:P:K for *fresh manure* is roughly 1.43 N: 1.14 P: 1 K. Depending on storage type, that ratio can change to an *average* of 1.45 N: 1.98 P: 1 K, indicating relative P enrichment with aging. Swine CAFO NMPs require calculations considering several parameters to determine appropriate volumes and rates of N, P, and K to land apply to fields. Lagoon liquid nutrient content (as 'plant available' nutrients), soil nutrient parameters and cover crop type are used in determining the agronomic rate of application/use. The aforementioned EPA guidelines provide general considerations when determining application rates (and standards) for swine manure.

2.4. North Carolina: NRCS 590 - NC

North Carolina (NC) is 2nd among the top national producers of swine (Fig. 1a and b) and turkeys (Fig. 1c), and 4th in broiler chickens (USDA, 2018). The majority of swine and turkey production is in the central Coastal Plain (Mallin and Cahoon, 2003) but chicken CAFOs are more broadly distributed across the state (Patt, 2017). As of November 6, 2019, NC Department of Environmental Quality reported a list of 2, 105 unique permitted farm names, owned by 1,496 owners producing cattle, swine, and/or poultry, most of these falling under the general state or NPDES permit. Dry litter-producing chicken and turkey operations (Fig. 1c and d) are deemed permitted. This means that while these operations *are not required to apply for permits,* they must follow general requirements, including developing and following a NMP.

Swine and some cattle and poultry CAFOs in NC use wet waste management systems. Waste is washed from confinement structures into an open-air cesspit or 'lagoon', where anaerobic processes slowly degrade the organic contents. Excess supernatant is then sprayed onto nearby cropland as fertilizer (Burkholder et al., 1997; Mallin, 2000; Mallin and McIver, 2018). Application of sludge that builds up in lagoons is also allowed under NMP guidelines but must consider the relatively high sludge content of P, as well as copper and zinc in swine waste.

The approach to nutrient management in North Carolina consists mainly of developing certified animal waste management plans (CAWMP) for regulated animal operations in order to qualify for the non-discharge general permit. As previously mentioned, land application rates are dependent on soil type and cover crop varieties. This allows individual CAFOs to create a nutrient budget for N, P and K that considers all potential sources of nutrients. Application rates must consider crop/cropping sequence, current certified soil test results, NC Realistic Yield Expectations (RYEs, established for each NC county based on soil productivity information, yield data, and research with NC soils and cropping systems) for each cover crop, crop yield response to applied nutrients, nutrient risk assessment results, and producer management objectives and capabilities. If established RYE values do not exist for a certain crop, a nitrogen fertilization rate recommended by North Carolina State University (NCSU) or NC Department of Agriculture (NCDA) and NRCS agronomy and nutrient management specialists may be developed in coordination with the NC Interagency Nutrient Management Committee. In the absence of this recommendation, the nutrient management planner may infer a realistic yield from a similar crop on soil with similar physical and chemical features. Manure application rates are typically based on the N required by the target crop, but the P applied in the manure is often 2–5 times greater than the crop requires. To assess the risk of nitrogen leaching loss the Nitrogen Leaching Index is used, giving field specific soil loss calculations based on USDA maps (NRCS NC, 2014). The NC Phosphorus Loss Assessment Tool (PLAT) is a soil P-Index tool that is used to assess P loss risk (Table 4). These evaluations are applicable to fields that meet either of the following conditions:

The PLAT determines the Total Soil P Loss using the Mehlich 3 soil P test (Table 3) to estimate the amount of bioavailable P in soils. The PLAT analyzes 4 major pathways of P loss from fields to waters: soil-attached P erosion (particulate P), soluble-P runoff (dissolved P), soluble-P leaching (P in subsurface drainage), and source-P loss (fertilizer and/or animal waste). As mentioned, the NRCS Code 590 requires management of P; an NC state interagency group chose to develop a *site-specific index* because both the agronomic soil test and the environmental threshold approaches were too strict and not scientifically defensible, as other factors are known to affect actual P export from agricultural fields (Osmond et al., 2014). The manure P application rating and criteria are listed in Table 4. The total application rate (when using the PLAT) must be calculated using the *most erosive project crop in the P application planning period.* The soil erosion data are also derived from USDA maps as mentioned above.

2.5. Maryland: NRCS 590 - MD

The state of Maryland ranks 8th in broiler chicken production (USDA, 2018), but most of the state's poultry CAFOs are confined to drainages close to the Chesapeake Bay, a water body that provides

Table 4
North Carolina PLAT application rating, consequence, and equivalent NRCS Code 590 P loss risk category.

1. The P-application rate for manure *exceeds* soil test report rate guidelines for the planned crops, or
2. The planned area is within the watershed for a 303(d)-listed water body (impaired) and the agriculture-related P loss is identified by the North Carolina Division of Environmental Quality (NCDEQ) as a likely contributor to the impairment.

PLAT rating	Equivalent National 590 P-loss risk category	NC Manure Nutrient Application Criteria
Low (0–25)	Low	N-based manure application
Medium (26–50)	Low	N-based manure application
High (51–100)	Moderate	P-based manure application
Very High (>100)	High	No additional manure or starter P

abundant seafood resources yet is very sensitive to nutrient pollution (Boesch et al., 2001). The state of Maryland's Department of the Environment (MDE) Animal Feeding Operation (AFO) Division issues a federal permit (MD G01A) and a state permit (14AFA) for AFOs. Generally, medium or large animal feeding operations that propose to discharge pollutants to waters of the state are required to apply for a CAFO permit; large AFOs that *do not* propose to discharge pollutants are required to apply for a Maryland Animal Feeding Operation (MAFO) permit. Farmers must also notify the MDE if they plan to construct an animal waste or manure storage structure. The majority of the animal feeding facilities (90%) are CAFOs (pers. communication, Pamela Harris, MDE). Nutrient applications for N are based on crop needs and the N credits from previous applications. However, organic nutrients that contain both N and P (such as manure) are applied based on P maxima.

The agronomic plant nutrient recommendations are based on the cumulative knowledge derived from decades of soil fertility research (MD Nutrient Management Manual, 2016). The Maryland Cooperative Extension Soil Testing Laboratory employs the Mehlich 1 (double acid) procedure for determining the levels of soil test phosphorus, potassium, calcium, magnesium, manganese, copper, and zinc. A hot water soil extract is used for boron determination and an acidic mono-calcium phosphate solution is used to extract sulfate-sulfur (SO_4-S). All nitrogen recommendations are based on crop nitrogen requirements and yield goals (MD Nutrient Management Manual, 2016).

Soil tests are required to be taken every three years or sooner for each management unit (land application field). It is recommended that soil sampling be conducted consistently at the same time of year, and sampling depth for P and K shall be 20 cm (pH testing depth for no-till soils is only 10 cm). As stated above, soil test results (per nutrient) are grouped into four categories: Low, Medium, Optimum, and Excessive (Table 5). Maryland uses an alternative method for expressing the relative level of plant available nutrients (N and P) in the soil by using a Fertility Index Value (FIV). This operates on a scale that is calculated from the concentration of extractable nutrients, where the highest concentration within the "optimum" range is set equal to FIV = 100. If the FIV-P is above 150, there is an additional assessment that calculates the Phosphorus Site Index (PSI). Developed in 1990, this P index uses available information to evaluate 2 categories of factors that contribute to the potential for P loss from agricultural land: 1) P loss potential due to site and transport characteristics (erosion, runoff, subsurface drainage, leaching potential distance from edge of field to surface water, and priority of receiving water), and 2) P loss potential due to management and source characteristics (soil test FIV-P, method and rate of P fertilizer application, and method and rate of organic P application). Also, when manure application rates are P-based "Application shall result in an application rate of plant available nitrogen not exceeding 56 kg/ha (50 lbs/acre)" (Maryland Department of Agriculture, 2016)

Table 5
Maryland P loss rating and management implications (Steinhilber and Salak, 2010).

P loss rating/Category	Management Implication
0-50/Low potential for P movement from this site given current management practices and site characteristics	N-based nutrient recommendations are acceptable; soil P levels and P loss potential may increase in the future due to continued N-based recommendations
51-75/Medium	N-based nutrient recommendations 1 year in 3; P-based nutrient recommendations 2 years in 3; P applications limited to amount expected to be removed from field by crop harvest or soil test-based P application recommendations, whichever is greater
76-100/High	P-based nutrient recommendations for this site; P applications limited to amount expected to be removed from field by crop harvest or soil test-based P application recommendations; all BMPs for reducing P losses by erosion, runoff or leaching should be implemented
>100/Very High	No P should be applied to this site; Active remediation techniques should be implemented in an effort to reduce the P loss potential from this site

2.6. *Wisconsin: NRCS 590 - WI*

Wisconsin (WI) ranks 8th in cattle (Fig. 1e) inventory and 2nd in milk cow population in the U.S. (USDA, 2018). Permits issued to CAFOs require practices to minimize P delivery to surface waters. These permits allow operations to use either the Soil-Test Phosphorus Strategy *or* the PI Strategy on a field-by-field basis. WI permits require additional practices that are more stringent than the federal regulations, using a P-Index under various circumstances; i.e. fields with soil test P levels <50 ppm and not at optimum.

"Soil tests are required to be taken every 4 years at a density of 1 sample/5 acres minimum. Also, CAFOs are required to sample their manure and process wastewater at the rate provided in the permit. These results are used for the nutrient management plans in both past and future years. Soil nutrients tested are generally P, K, % Organic Matter, and pH (Table 6). Nutrient limits are based on multiple criteria that are found in the UW publication A2809 (Laboski and Peters, 2012). These criteria include nutrient content of the soil, type of crop, type of fertilizer/manure/process wastewater, etc." (pers. communication Aaron O'Rourke, WI DNR).

The two strategies adopted by the WI State Legislature (NR 243.14 (5)) reference NCRS WI Code 590. The Soil Test P Strategy is based on soil test P, where operations using this strategy shall have "a conservation plan addressing all soil erosion that is consistent with the current crops and management or use the erosion assessment tools included with the P Index model. The PI Strategy averages PI values for up to 8 years. Most importantly, P applications from all sources shall be based on soil test P values via the Bray P-1 test, when:

1) less than 50 ppm soil test P – nutrient application rates allowed up to the N needs of the following crop or the N removal of a following legume crop,
2) 50–100 ppm soil test P – P application shall not exceed the total crop P removal for crops to be grown over a maximum rotation length of 8 years, and
3) Greater than 100 ppm soil test P – total P application from all sources shall not exceed guidelines from UWEX Publication A2809 (Laboski and Peters, 2012). If manure applications above the guidelines are necessary due to lack of suitable application sites, P applications shall be 25% less than the cumulative annual crop removal over a maximum rotation length of 8 years (NCRS WI Code 590).

It is important to acknowledge that the above code states that manure *may still be applied if there is no other suitable application site.*

The land application criteria for N are based on nutrient limitation criteria found in UW publication A2809 as follows: soil characteristics,

Table 6
Analytical Procedures for soil tests (Laboski and Peters, 2012).

Analytical procedures for soil tests	
Soil pH	Prepare a 1:1 soil to water mixture and measure pH with a glass electrode
Phosphorus	Extract with Bray 1, develop color, and measure colorimetrically
Potassium	Extract with Bray 1 and measure with atomic absorption, flame photometer, or ICP-OES
Organic Matter	Loss of weight on ignition at 360 °C for 2 h
Nitrate-nitrogen (NO_3-N)	Extract soil with 2N KCl and analyze colorimetrically

previous crop, and the N:corn (or wheat) price ratio (an economic consideration) that is applicable to the specific production situation (Laboski and Peters, 2012). The MRTN (maximizing economic return to nitrogen) also affects rate guidelines and is soil-specific due to the fact that corn grown on various soils shows different responses to N fertilization. For other crops, a single N rate suggestion is given regardless of yield level for the crops. This rate is adjusted for soil organic matter content. Analytical procedures are given in Table 6 of A2809.

Two tests are available for soil nitrate to adjust N application rates: a pre-plant nitrate test (PPNT) that is appropriate for corn, sweet corn, and winter wheat, and a pre-side dress nitrate test (PSNT) for corn and sweet corn. The PPNT involves deep soil sampling, to a depth of 0.6 m (~2 ft), before planting the crop. This test measures the amount of residual or carryover nitrate in the soil. The PSNT consists of shallower soil sampling, to a depth of 0.3 m (1 ft), when corn is 0.15–0.3 m (6–12 in) tall. This test is intended to predict the amount of plant-available N that will be released from organic sources during the growing season (Laboski and Peters, 2012).

Soil test P and K categories vary by soil group because soils in each group vary in the amount of P and K they can supply. Each soil's ability to hold P and K along with its P and K buffering capacity (the amount of fertilizer required to change soil test level by 1 ppm) is related to soil texture, mineralogy and organic matter content (Laboski and Peters, 2012). To determine a P (or K) rate one must select the crop demand level for the rotation; the crop with the highest demand is the one that sets the soil test P interpretation categories for the rotation. Secondly, the soil group for the predominant agronomic soil in the field is selected (Table 7). For soils that test at "Optimum," the fertilizer application rate is limited to the amount of P removed in the harvested portion of the crop. For soils that test greater than optimum, the nutrient application guidelines should 1) rely on the soil to supply the bulk of the nutrients needed for crop growth, and 2) reduce the soil test level to optimum. For soils testing High, the P application rate is ½ the rate at optimum. For soils testing Excessively High the application rate is zero (with the exception of potato crops).

Nutrient credits from a manure application should be taken the first crop year after the application. Because the nutrients in manure are not 100% available the first year after application, nutrient credits may also be taken for the second and third years after application for N and Sulfur (Laboski and Peters, 2012). For all nutrients other than P and K, second- and third-year availabilities are assumed to be 10% and 5%, respectively, of the total amount applied in the first year.

2.7. California: NRCS 590 - CA

California ranks 1st in milk cow population, 4th in cattle and 9th in poultry inventory in the U.S. (USDA, 2018). Authority under the federal NPDES Program has been delegated to the State of California for implementation through the State Water Resources Control Board and nine Regional Water Quality Control Boards. NPDES permits are also referred to as Waste Discharge Requirements (WDR).

Soil samples should be collected once every 5 years from each land application area receiving manure and/or process wastewater. A single sample shall represent no more than 10 acres, and be composited for every 80 acres. For solid manure, at least 10 samples shall be collected from various portions of the manure pile, mixed well, and a subsample taken for analyses. Soil samples must be tested for pH, nitrate-N, ammonium-N, bicarbonate-P (Olsen-P, Table 3), exchangeable K, electrical conductivity, and salinity.

Two nitrogen loss risk assessment tools are available for use in CA: The Nitrate Groundwater Pollution Hazard Index and the USDA-ARS Nitrogen Index. The groundwater pollution hazard index works with an overlay of soil, crop, and irrigation information to define an overall potential hazard number; management practices are then suggested where necessary. The USDA-ARS Index integrates data on management practices, weather conditions, soil characteristics and off-site factors.

Analyses of soil samples include nitrate-nitrogen and ammonium-nitrogen using the North American Proficiency Testing (NAPT) program or as accepted by the University of California. The NAPT program is part of the Soil Science Society of America, and develops technical guidelines for effective, consistent analyses of soils. The method for analyzing nitrate-N and ammonium-N in soils for the western region involves the extraction of nitrate from soils using KCl (Miller et al., 2013). Analysis of manure uses the Manure Analyses Proficiency (MAP) Testing Program, or as accepted by the University of California (Colorado River Water Board, 2013), and typically use HCl digestion methods (Peters et al., 2003). Realistic yield goals are established based on soil productivity information, historical yield data, climatic conditions, and manure/organic by-products tests. The California Phosphorus Index (2010) is used to evaluate the risk of P transport (Table 8). Two primary criteria must be met before a field can be assigned risk for P loss: 1) there must be a means to transport available P offsite ("Transport Factors"), and 2) there must be P available for transport offsite in adequate quantities to create risk ("Source Factors"). Transport Factors include soil erosion, irrigation tail-water, hydrologic soil group designation, irrigation-induced soil erosion, and subsurface and discharge drainage. Source Factors include soil P test (the concentration of available P in the top 30 cm (12 in of the soil profile) as determined by the Olsen or Bray methods (Table 3), commercial P fertilizer application rate and method, and organic P source application rate and method (California Phosphorus Index, 2010). Management implications are listed in Table 8.

3. Discussion

3.1. A regulatory patchwork

Several aspects of federal and state regulations concerning CAFO manure nutrient management may allow for excessive nutrient export from land application areas. Moreover, differences in manure nutrient management practices among states create a patchwork of pathways by

Table 7
Wisconsin soil test P interpretation categories (Laboski and Peters, 2012).

	Soil Test Category				
	Very Low (VL)	Low (L)	Optimum (O)	High (H)	Excessively high (EH)
Soil Group[1]	Soil test P ppm[2]; Loamy soils (Sandy, Organic soils)				
Demand Level 1	<10 (<12)	10-15 (12–22)	16-20 (23–32)	21-30 (33–42)	>30 (>42)
Demand Level 2	<12 (<18)	12-17 (18–25)	18-25 (26–37)	26-35 (38–55)	>35 (>55)
Demand Level 3	<15 (<18)	15-30 (18–35)	31-45 (36–50)	46-75 (51–80)	>75 (>80)
Demand Level 4	<100 (<30)	100-160 (30–60)	161-200 (61–90)	>200 (91–120)	(>120)

Table 8
California Risk rating for P loss (CA Technical Notes, 2010).

Risk Rating	Management implications
Very High (for P loss)	Must not receive manure or other organic forms of P fertilizer. Apply no P from any source if the soil test P exceeds 80 ppm (Olsen) or 120 PPM (Bray).
High	May receive manure at rates to meet crop P requirements based on the P content of manure and anticipated crop yield.
Medium	May receive manure at rates based on the N content of manure and calculated to meet crop N needs based on a N budget. Existing management on these fields will likely lead to higher risk over time; risk should be monitored periodically using P index
Low	May receive manure at rates based on the N content of manure and calculated to meet crop N needs based on a N budget.

which nutrient export may vary, making quantitative analysis and modeling, e.g., creation of comparable state by state nutrient export models for CAFOs, quite challenging. Although the management measures and practices summarized above represent significant improvements over previous management regimes, they do not approach the rigor of point source controls under the CWA's NPDES program. Of course, the effectiveness of even these measures begs questions of compliance and enforcement.

The NPDES permitting provision for CAFOs applies when there is an expected discharge to 'waters of the U.S.', as defined by rule. The U.S. EPA has recently proposed significant alterations to the Clean Water Rule that defines jurisdictional waters, proposing to remove certain wetlands, intermittent streams, and man-made conveyances from federal jurisdiction. That rule change would logically reduce the number of situations in which CAFOs might require an NPDES permit with its more stringent requirements, and increase the number of CAFOs qualifying for a general, non-discharge permit. Note also that when CAFOs apply manure nutrients at an 'agronomic rate' their runoff is then considered as agricultural storm water, which is exempt from regulation.

3.2. Disposal rate calculations are variable and do not reflect bioavailability

The 'agronomic rate' calculations made in Nutrient Management Plans essentially treat the nutrients in manures in the same way as the nutrients in synthetic fertilizers, because they use 'plant available' N (and P) as the basis for subsequent calculations. But 'plant available nitrogen' (PAN) in animal manures and waste lagoon liquids is typically determined to be ~50% of total N (Haering and Evanylo, 2006). This calculation factors in loss of some N by volatilization (mostly as ammonia, NH_3) and less immediate availability of other forms of N (amino acids, peptides and other organic N compounds) to plant uptake. The long term *bioavailability* of nitrogen compounds is, however, almost 100% in soils when one considers the array of decomposers present and their metabolic capabilities. Ammonia volatilized during land application remains in the air shed and may constitute a significant nitrogen export flux, but is ignored in management practices. Moreover, agriculturists are well aware that leaching of N compounds through soils likely limits actual incorporation by plants to about 50% of actual applied PAN.

An example illustrates the quantitative nature of the problem with 'plant available' nutrient calculations. Coastal Bermuda grass is often used in North Carolina to absorb the nutrients contained in the land-applied waste, as it can assimilate a relatively large amount of nitrogen per unit area (up to 300 lb PAN/acre or ~336 kg PAN/ha). Thus, application of 336 kg PAN/ha (approximately the capacity for N utilization by Bermuda grass per year) corresponds to as much as 672 kg total N/ha, minus some lost by aerial transport after volatilization. Use of commercial fertilizer, in contrast, with PAN = 100%, would load half as much N to the same area. Thus manure fertilizers can load very high quantities of nitrogen to a field, almost all of it biologically labile and subject to export.

Phosphorus loading from manure application may be similarly problematic. Actively growing Bermuda grass removes N and P in an approximate ratio of 4N: 1P by weight (Redfearn et al., 2016). In order to supply the appropriate amount of N to fertilize a field of Bermuda grass with manure having an N:P ratio of 0.73 N: 1 P, one would consequently add ~5.5x (4/0.73) the appropriate amount of P (not accounting any contributions from soil). Not surprisingly, ongoing land application of liquid swine manure has caused significant increases in soil test P values on swine CAFO spray fields (Barker and Zublena, 1975; Cahoon and Ensign, 2004; Osmond et al., 2006). Manure P also behaves differently in soils than inorganic fertilizer P. None of the soil P extraction methods cited here (Table 3) extract organic P (Wuenscher et al., 2015), which is likely to be a significant portion of total P in manured soils. Kang et al. (2011) state that degradation of organic P to inorganic P in land-applied liquid manure and reduction of the adsorption capacity of soils receiving large inputs of dissolved organic matter can increase the leaching of P. Thus, standard operating procedures for land application of swine wastes create significant potential for nutrient overloads of soils and potential export of excess nutrients from CAFOs to the surrounding environment (Mallin, 2000; Weldon and Hornbuckle, 2006; Burkholder et al., 2007; Harden, 2015).

3.3. P extraction methods vary and need improvement

One of the issues with P management at a national level is that different states use different soil P extraction and measurement methods (Table 3). They are not always comparable and often yield different values, depending on soil characteristics (Osmond et al., 2006). One study of 50 contrasting agricultural top soils and 14 different extraction methods that compared the magnitude of extractable P found that among the methods regularly used for CAFO soil testing extractable P increased in the order Olsen < Mehlich 3, that an HCl extraction method (similar to Mehlich I) surpassed them all, but that organic P and total P were much higher than the P levels found by any of these methods (Wuenscher et al., 2015). Several factors influence the effectiveness of the various soil P extraction methods, including pH, organic content, $CaCO_3$ content, and soil granularity, so states have adopted different extraction methods for measuring soil P, assuming that one extraction method yields reliable results for soils in that state.

An important consideration in soil P testing is that each extraction method aims to measure 'plant available' P, not total soil P. That presumption arguably fits management of application of commercial, inorganic fertilizers to crops, but does it apply equally well to increasingly widespread use of highly organic manures as fertilizers? It is important to distinguish between 'plant available' P and other soil P fractions that may be *bioavailable* in the soil owing to the metabolic activities of soil bacteria and fungi. In this situation, one must carefully consider the distinction between 'plant available' P and bioavailable P, as the latter has more relevance at ecosystem scale. Thus, measures of soil-test P and soil P thresholds based on extractable (='plant available') P may substantially underestimate risks of P export and ecosystem-scale effects.

3.4. P indexing requires adjustment

P Index methods, such as the North Carolina PLAT, for estimating risk of P export from manure land-application fields also depend on soil test P measures (Mehlich 3 in the case of North Carolina). The PLAT incorporates estimates of site-specific characteristics to create an overall index of relative risk of P export. Evaluations of the PLAT-predicted P export risks compare favorably to assessments of areas known to be highly vulnerable to P export based on histories of high P loadings, high densities of animal units, or soil types and topographies (Johnson et al., 2005). Although the NC PLAT was originally formulated with a threshold P export value in surface runoff of 1 mg P/L (Johnson et al., 2005), we are unaware of any quantitative field validations of P export risk estimates derived from the PLAT vs. actual P concentrations and loadings in runoff. Nevertheless Johnson et al. (2005) estimated that 27% of animal manure applicators would exceed P export threshold guidelines and be required to limit manure P applications based on the PLAT. These observations lead to several questions: 1) Does Mehlich 3 soil test P adequately represent the risk of bioavailable P export? 2) Does the 1 mg P/L threshold P value for land-application field runoff adequately protect surface water quality? 3) Are manure applicators managing manure P application rates when risk thresholds are exceeded as PLAT directs?

3.5. Soil sampling varies and needs improved frequency

Soil sampling is a basis for application recommendations, and temporal requirements vary state-to-state from one to five years. CAFOs located on the US East Coast and Gulf Coasts are subject to frequent hurricanes, which cause flooding and erosion and displacement of soils. Likewise, the US Midwest is subject to major river flooding and soil movement. 'Plant available nutrients' are typically those in solution in soil water, so flooding and heavy rain events can have major effects at frequencies greater than the minimal soil sampling schedules currently allowed. The salient point is that a soil sample taken in a given year can be considerably different from one taken three years later, or even a year later due to major storms. Such soil sampling should be conducted at least twice a year for N and P, as well as the EPA-recommended (but not required) parameters noted earlier. Given that operators may have incentives to avoid soil sampling in areas heavily manured, there is potential for biased results.

3.6. Geographic concentration of CAFOs is problematic

Additional factors can contribute to the potential for nutrient export from CAFOs. For example, swine CAFOs are geographically concentrated in a few watersheds in North Carolina, owing to proximity to feed mills and slaughterhouses, primarily in the state's central Coastal Plain, where groundwater levels are usually close to the surface and major rain events can be highly problematic for open-air liquid waste storage systems (Burkholder et al., 1997; Mallin, 2000). Similarly, poultry production in Maryland is highly concentrated in close proximity to Chesapeake Bay, where eutrophication problems are well known (Boesch et al., 2001). The Gulf of Mexico receives heavy nutrient loading that leads to massive benthic hypoxic areas (popularly called 'dead zones'). The massive agriculture in the Mississippi drainage, including swine and cattle in the upper Midwest and poultry in the middle and lower Mississippi region (USDA, 2018) contribute large amounts of nutrients to the watershed (Yang et al., 2016). Close proximity of many CAFOs and their land application fields to drainage features (Wing et al., 2002; Martin et al., 2018) facilitates nutrient loading to surface waters. Furthermore, human errors in soil sampling, manure sampling and manure application, as well as occasional deliberate violation of rules and regulations (e.g. over-spraying) complement the risks from 'acts of God' (e.g. flooding events).

3.7. Runoff and nearby waterways require frequent sampling

Exemption of agricultural runoff from sampling poses clear threats to ecosystem and human health. Land application of CAFO animal manures has been documented to lead to high nutrient and fecal bacterial loading to nearby waterways (Weldon and Hornbuckle, 2006; Harden, 2015; Mallin et al., 2015) especially in the spraying (and growing) season (Mallin and McIver, 2018). Such nutrient loading has led to off-site ecosystem eutrophication problems including algal blooms and high biochemical oxygen demand (Burkholder et al., 1997; Mallin et al., 2015). Loading of elevated nitrate to groundwater poses increased health risks through human consumption, and loading of fecal microbes, especially in concert with nutrients, increases human health risk through exposure to contaminated waterways.

4. Conclusions

- Federal and state regulations governing land application of manure nutrients by CAFOs have lagged behind the growth of the CAFO industry.
- Most CAFOs are regulated as non-discharge operations covered by general permits or 'deemed permitted', thus avoiding the more stringent controls of NPDES permitting for point-source dischargers. Agricultural runoff is not regulated, therefore most CAFOs are under no requirements for monitoring of discharges (as either surface runoff or subsurface movement of nutrients) or nearby waterways, despite known off-site impacts.
- Sampling of manures, waste lagoons and land-application field soils is required relatively infrequently, often once/year to as much as once in five years, creating uncertainty and error in the quantitative development of and compliance with nutrient management plans.
- Use of 'plant available' nutrient measures seriously underestimates total nutrient contents of land-applied manures and in application field soils, thereby under-representing total nutrient throughputs of CAFOs using land application methods.
- P-index methods for estimating P export potential lack empirical data to quantify their accuracy.
- Finally, while scientific evidence clearly demonstrates damaging water quality consequences from CAFO waste disposal practices, there are few, if any, quantitative, empirical federal or state-sponsored analyses of manure nutrient exports.

Implications of these conclusions can be long-lasting and/or controversial. Currently, there are significant sectors of local communities that are fighting against CAFOs in North Carolina and Maryland. Groundwater can be contaminated by CAFOs through runoff from land application of manure; in 2000, the EPA found that 29 states specifically identified AFOs as contributing to water quality impairment (Copeland, 2011), and the concentration of AFOs/CAFOs has increased since then. Surface water contamination from soil erosion, nutrients, and hormones can affect both wildlife and human life, given the proximity of CAFOs to local communities. Furthermore, a reduction in air quality (specifically ammonia, hydrogen sulfide, methane, and particulate matter) have human health risks, ranging from respiratory irritation to global greenhouse effects. Finally, property values have decreased in the areas surrounding CAFOs. Policy changes surrounding CAFO regulations could help to mitigate some of these local effects. Studies have shown that environmental innovation can be an important driver for policy implications concerning waste and land-use strategies; attempting to correct negative environmental impacts can improve existing strategies (Aldieri et al., 2019). Further research into addressing the economic effects of these changes would pair with this analysis in an attempt to balance a regulatory change (to limit environmental impacts of CAFOs) compared with the economic cost (denoted in price of meat) to consumers/public.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Kimberley A. Rosov: Conceptualization, Investigation, Writing - original draft. **Michael A. Mallin:** Conceptualization, Investigation, Writing - review & editing, Supervision. **Lawrence B. Cahoon:** Conceptualization, Investigation, Writing - review & editing, Supervision.

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Appendix A. Supplementary data

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