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4R Water Quality Impacts: An Assessment and Synthesis of Forty Years of Drainage Nitrogen Losses

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Abstract

The intersection of agricultural drainage and nutrient mobility in the environment has led to multiscale water quality concerns. This work reviewed and quantitatively analyzed nearly 1,000 site-years of subsurface tile drainage nitrogen (N) load data to develop a more comprehensive understanding of the impacts of 4R practices (application of the right source of nutrients, at the right rate and time, and in the right place) within drained landscapes across North America. Using drainage data newly compiled in the "Measured Annual Nutrient loads from AGricultural Environments" (MANAGE) database, relationships were developed across N application rates for nitrate N drainage loads and corn (*Zea mays* L.) yields. The lack of significant differences between N application timing or application method was inconsistent with the current emphasis placed on application timing, in particular, as a water quality improvement strategy (p = 0.934 and 0.916, respectively). Broad-scale analyses such as this can help identify major trends for water quality, but accurate implementation of the 4R approach will require site-specific knowledge to balance agronomic and environmental goals.

Core Ideas

- Analyzed nearly 1,000 site-years of cropping and drainage N load data.
- Neither N timing nor method treatments had significantly different drain N loads.
- Broad-scale analyses such as this can help identify major trends for water quality.

Changing global diets, intensified climate variability, and increasingly degraded land and water resources have created an urgent need to revisit agriculture's approach toward sustainability. This mounting complexity now requires agricultural producers to undertake new and redefined roles as integrated landscape managers, directors of natural capital, and ecosystem service suppliers, beyond their more overt responsibilities as providers of food, fiber, and fuel. It is critical to provide comprehensive and useful information to producers, industry stakeholders, and government and regulatory agencies on the impacts of recommended on-farm management practices.

In most agronomic systems, nutrient additions are used to enhance crop productivity when soil nutrient supply is deficient. The 4R Nutrient Stewardship approach to nutrient management is an integrated strategy developed to foster achievement of agricultural production goals while minimizing associated negative environmental, economic, and social effects. This approach advises the application of the 4Rs: the right source of nutrients, at the right rate, at the right time, and in the right place (4R Nutrient Stewardship, 2015). Despite the simplicity of and increasing momentum behind this concept, accurate implementation of the 4Rs requires site-specific knowledge of any given field's biophysical constraints in tandem with associated economic and production goals.

Artificial agricultural drainage networks are used in many areas of North America to meet production goals (Blann et al., 2009; Skaggs et al., 1994; Skaggs and van Schilfgaarde, 1999). Unfortunately, the intersection of agricultural drainage and nutrient mobility in the environment has led to multiscale water quality concerns (David et al., 2010; Shirmohammadi et al., 1995; Thomas et al., 1995). Nitrogen (N) management within drained landscapes is particularly vexing due to the mobility of nitrate within the soil profile and volatilization and denitrification gaseous losses. Variation in soil type, weather, climate, drainage system, and management practices, among other factors, affects drainage N losses (Randall and Goss, 2008; Skaggs and van Schilfgaarde, 1999). Individual N management practices will have differing effectiveness and differing compatibility with

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Abbreviations: UAN, urea-ammonium nitrate.

farm management and profitability goals in any given location and year.

While studies of the agronomic and environmental impacts of N management practices have been conducted, there is a need to assemble and further analyze these previous works to develop a more comprehensive understanding of their effects within drained landscapes. To this end, nearly 1300 site-years of drainage N and phosphorus (P) studies have recently been compiled in a free, publically available database. This new Drain Load table in the existing "Measured Annual Nutrient loads from AGricultural Environments" (MANAGE) database provides comprehensive N and P load data from peer-reviewed studies across North America. The addition of drainage studies complements the more than 1800 existing agricultural and forest runoff watershed-years in this database, hosted by the USDA-ARS Grassland, Soil, and Water Research Laboratory in Temple, TX (USDA-ARS, 2015; Harmel et al., 2006, 2008).

This work used the new MANAGE Drain Load database to better identify and define the consequences of the 4R N management strategies. Specifically, the analysis asked the questions: (i) How do the 4R practices affect N losses from artificially drained agricultural fields? and (ii) How do the 4R N practices affect crop yield in drained agronomic systems?

Materials and Methods

The MANAGE Drain Load table was based on a comprehensive literature review of more than 400 studies performed between April and October 2014. The total database of 1279 N and P site-years (91 total N and P studies) contained 987 and 162 site-years with dissolved N and total N loads from 73 and 7 studies, respectively; note that some individual site-year records contained both N and P loads or dissolved and total N loads. Studies suitable for MANAGE must be peer-reviewed, be from study areas of at least 0.009 ha with a single land-use in North America, not be a rainfall simulation or lysimeter study, and include data from at least 1 yr. When necessary, data were extracted from graphs using Data Thief software (Tummers, 2006). Other relevant database fields included study location, tillage type, soil type, precipitation, drainage discharge, fertilizer application, drainage system (surface/subsurface, drain depth and spacing), and cropping (crop, rotation, yield) information. The literature review methods and the development of MANAGE's Drain Load table were fully described in Christianson and Harmel (2015) (as were hydrology, crop rotation, tillage, and drainage systems impacts on drainage N loads), and MANAGE was previously described in Harmel et al. (2006) and Harmel et al. (2008).

Dissolved N loads in the Drain Load table primarily represented nitrate N, but as this was sometimes reported as "NO_3–N" (922 of 987 site-years), sometimes as NO_3+NO_2–N (44/987), NO_3+NO_2+NH_4^+-N (10/987), or NO_3+ NH_4^+-N (7/987), and as "soluble nitrogen" in one manuscript (4/987), "dissolved N" was deemed the most appropriate classification. The MANAGE Drain Load database was mainly composed of subsurface tile as opposed to surface ditch drainage site-years (1177 vs. 56 site-years, respectively; Christianson and Harmel, 2015). This 4R analysis was most generally considered to be for subsurface drainage, as only 8 of the 987 (0.8%) and 7 of the 162 (4%) dissolved and total N site-years, respectively, were surface drainage systems.

In the Drain Load table, N application source, timing, and placement/method were recorded separately for up to two individual fertilizer products for a given site-year. The time of application was grouped into one of four options: "At Planting, within 1 wk of plant," "Out of Season, >2 mo before plant," "Pre-Plant, 2 mo−1 wk before plant," or "Side/Top Dress, >1 wk after plant." Nutrient placement was also grouped into four categories. "Surface applied" included a publication's reference to surface applications and applications specified as broadcast (no incorporation noted); "incorporated" included applications specified as such, as well as those that were broadcast incorporated; "injected" included both knifed and injected; and "banded." One N application rate (i.e., the summed total of each reported formulation's application rate) was reported for a given site-year.

Nitrogen loads in the Drain Load database were analyzed using graphical methods including box plots and regression analyses. To aid in comparisons particularly with drainage discharge and N application rate, the large dataset was binned into "wet" and "dry" years. The approximate mean (846 ± 219 mm) and median (828 mm) across all precipitation values in the Drain Load table (n = 889) were used as separation points, with precipitation values <820 mm or >850 mm considered "dry" or "wet" site-years, respectively. Dissolved N loads were regressed against N application rate using three parameter exponential growth models following Bergström and Brink (1986) and Guillard et al. (1999); these data were also modeled using linear regressions (following Hallberg et al. [1986] and Baker and Laflen [1983]), but such models generally had lower R^2 and did not improve the relationship significance. Corn (*Zea mays* L.) yields were regressed against N application rate using a two-parameter exponential rise to maximum model to capture the well-known "diminishing returns" plateau at N rates beyond the optimum (Sigma Plot 12.5; Systat Software, 2015). The data were generally non-normally distributed and thus were analyzed using Kruskal–Wallis one-way ANOVA tests based on rank, which uses median values (Sigma Plot 12.5; Systat Software, 2015).

Results and Discussion

The greatest dissolved N load reported in the MANAGE Drain Load database was 245 kg N/ha, with 19 site-years reporting nitrate loads >90 kg N/ha^{-1} (Baker et al., 1975; Bjorneberg et al., 1996; Gast et al., 1978; Kladivko et al., 2004; Lawlor et al., 2008; Miller, 1979; Nash et al., 2014; Randall and Iragavarapu, 1995; Randall et al., 1997). Site-years reporting dissolved N and total N loads spanned 1969 to 2012 and 1961 to 2005, respectively (Christianson and Harmel, 2015). Iowa and Illinois contributed 60% of the dissolved N site-years (472 and 123, respectively), although contributions were made from a total of 17 US states and Canadian provinces (Fig. 1). Only five states and provinces presented total N load data, with Ontario and North Carolina dominating (90 and 62 site-years, respectively; Fig. 1). Regionally, precipitation was greatest in the American southeast and lowest in the western Midwest states (Iowa, Illinois, and Minnesota) and eastern Canadian provinces (New Brunswick, Nova Scotia, Ontario, and Quebec) (Table 1). Drainage discharge was not significantly different between eastern Canada provinces and American Midwest states, with median values of 166 to 173 mm. The western Midwest states had significantly greater drainage N

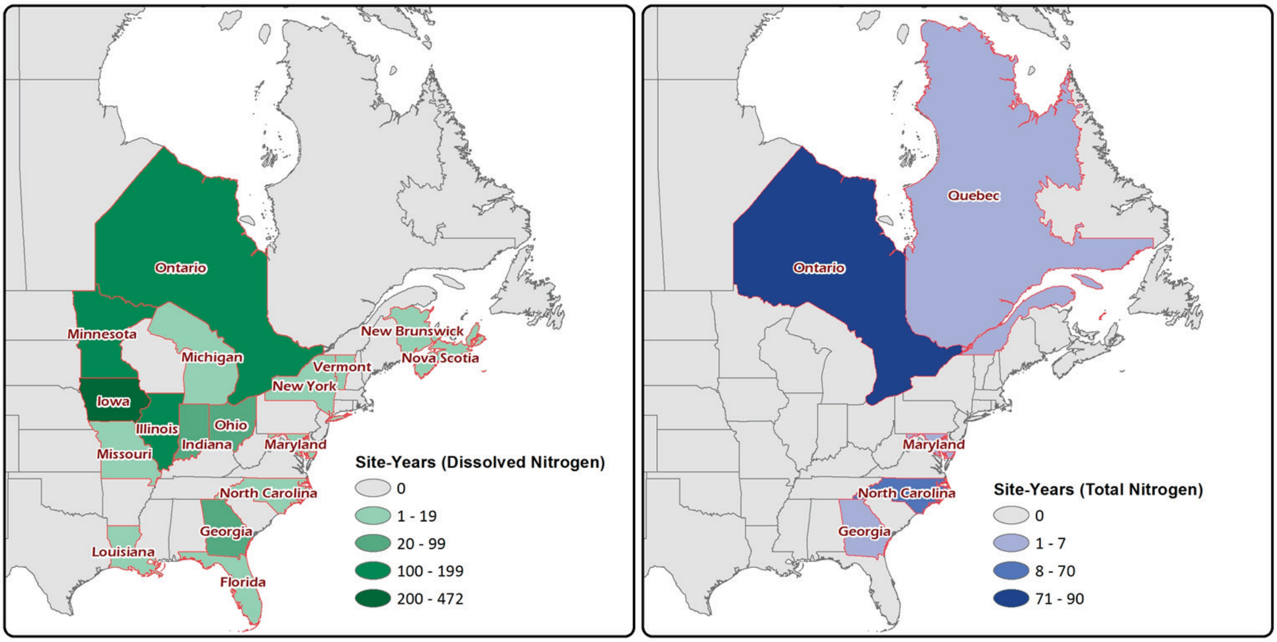

Fig. 1. Locations of dissolved (left) and total (right) N load site-years in the Drain Load database.

loads than eastern Canadian provinces, although the mean values ranged from 24.0 to 27.4 kg N ha^{-1} for all four regions (Table 1; means not shown). Corn and soybean [*Glycine max* (L.) Merr.] dominated the reported cropping systems in Iowa, Illinois, and Minnesota compared with the eastern provinces (93% [Iowa, Illinois, and Minnesota] vs. 54% [eastern provinces] of site-years were for corn and soybean, respectively).

Nitrogen Application Rate

The prevalence of corn cropping systems in North American agriculture means corn is one of the largest single users of N fertilizer (Ribaudo et al., 2012). The exact application rate required to maximize profitability at a given site in a given year, however, is highly variable and continues to pose challenges to farmers and scientists (Kladivko et al., 2004; Sawyer et al., 2006). Traditionally recommended application rates are known to impair subsurface drainage water quality (Jaynes et al., 2001; Tan et al., 2002). Even when no N is applied (e.g., a "0" control plot or during a soybean year), drainage may contain elevated nitrate N concentrations and/or loads (Gupta et al., 2004; Lawes et al., 1882; Lawlor et al., 2008). Fine-tuning N application rates would help reduce "insurance" N applications, which have ranged, for example, from 22 to 67 kg N ha^{-1} in one watershed in Minnesota (Legg et al., 1989; Mitsch et al., 2001). While application of the optimal N rate is thought to be the most important and most accessible of the 4R N management strategies (Lawlor et al., 2011), optimizing application rates will likely not be sufficient alone to meet water quality goals (Kaspar et al., 2007).

Increasing N fertilization rates correspond with increased drainage nitrate N concentrations (Angle et al., 1993; Baker and Johnson, 1981; Bergström and Brink, 1986; Chichester, 1977; Drury et al., 2009; Gast et al., 1978; Hallberg et al., 1986; Helmers et al., 2012; Jaynes and Colvin, 2006; Jaynes et al., 2001; Lawlor et al., 2011; Miller, 1979) and losses (Andraski et al., 2000; Baker and Johnson, 1981; Bergström and Brink, 1986; Bolton et al., 1970; Gast et al., 1978; Guillard et al., 1999; Hallberg et al., 1986; Jaynes et al., 2001; Lawes et al., 1882). Likewise, decreased application rates (in combination with other practices) can reduce nitrate N in drainage waters over time (Kladivko et al., 2004). This strong rate effect on drainage N concentrations has been observed regardless of N source (e.g., manure vs. inorganic fertilizer; Bakhsh et al., 2009; Evans et al., 1984). This rate effect was significant across the Drain Load continuous corn site-years under wet and dry conditions, but not for the corn soybean rotation (Fig. 2a and b, Table 2; $\alpha = 0.10$). At a given N application rate, the regression relationships indicated the continuous corn wet years produced higher dissolved N loads than did the dry years (Table 2). The effects of N fertilization rate may be confounded by precipitation (e.g., dry conditions, rainfall timing relative to application) and drainage flow trends (Guillard et al., 1999; Jaynes, 2013; Zwerman et al., 1972). This variability may explain why some authors did not

Table 1. Regional evaluation showing median (count) of precipitation, drainage discharge, and drainage dissolved N loads from the MANAGE Drain Load database.

	Precipitation	Drainage discharge	Dissolved N load
	mm	mm	kg N ha^{-1}
Southeast (FL, GA, LA, NC)	1290 (20) a†	332 (89) a	27.1 (38) ab
Western Midwest (IA, IL, MN)	787 (577) c	170 (627) b	23.0 (701) a
Eastern Midwest (IN, MI, MO, OH)	1020 (79) b	166 (92) b	20.6 (92) ab
Eastern Canada (NB, NS, ON, QC)	882 (180) c	173 (178) b	14.4 (142) b

† Medians with the same letters are not statistically significantly different

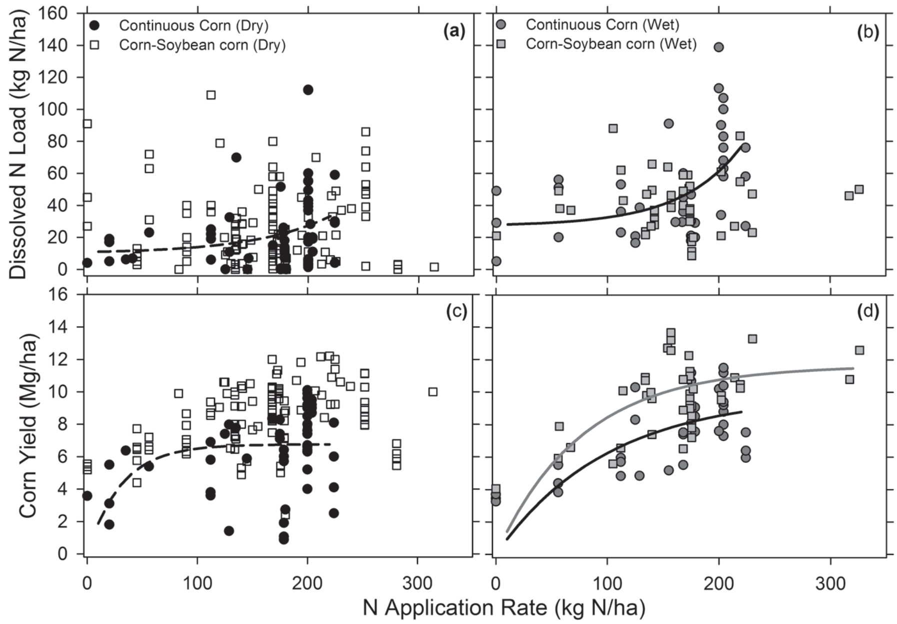

Fig. 2. (a and b) Dissolved N load and (c and d) corn yield versus N application rate for continuous corn (black line) or corn in a corn–soybean rotation (gray line) for dry (dashed line; a and c) and wet years (solid line; b and d); three outliers at a 448 kg N/ha application rate were removed; dry: precipitation < 820 mm, wet: precipitation > 850 mm.

observe a relationship between N rate and drainage N concentrations or losses (Cambardella et al., 1999; Hanway and Laflen, 1974; Schwab et al., 1980).

While a relationship exists between N application rate and drainage nitrate N concentrations/loads, the positive fertilization impact on the yield of corn and other crops is equally well established (Andraski et al., 2000; Chichester, 1977; Helmers et al., 2012; Jaynes et al., 2001; Lawlor et al., 2008; Stevens et al., 2005; Vetsch et al., 1999). This important effect was shown here for both continuous corn (wet and dry years) and corn–soybean cropping systems (wet years) (Fig. 2c and d). Regression analysis indicated corn following soybean had greater yields than continuous corn systems in wet years at any given N rate. At application rates between 170 and 220 kg N ha^{-1} (i.e., the maximum extent of the continuous corn regression), the yield difference between the two cropping systems was consistently very close to 2.25 Mg ha^{-1}. While comparing the two systems across the same N application rate may lead to spurious conclusions even when the lower recommended application rate for corn following soybean was considered, the rotation corn's yield was still higher than yields from a continuous corn system at its recommended application rate. For example, at university-recommended application rates of 154 and 213 kg N ha^{-1} for the rotation and continuous corn, respectively (Corn Nitrogen Rate Calculator at a 0.1 price ratio; Sawyer et al., 2006), the regressed corn grain yields were 10.1 and 8.7, respectively, in wet years. Helmers et al. (2012) and Kanwar et al. (1997) both observed this yield benefit, and suggested a corn–soybean rotation may be the better cropping system of the two for the Midwest. A broader analysis, independent of N rate, by Christianson and Harmel (2015) reported no significant difference in drainage discharge or N loads between continuous corn and corn–soybean cropping systems, although corn in rotation showed significantly greater yields.

Percentage of Applied Nitrogen Lost in Drainage

Across the literature, drainage N loss in context of the amount of N applied in a given year generally ranges from just under 10 to roughly 40%, although it could extend much higher (e.g., Gentry et al., 1998; Kanwar et al., 1988; Fig. 3). However, Jaynes et al. (1999) made an important caveat about basing interpretations too deeply on a percentage-of-N-applied basis: "...we do not wish to imply that fertilizer is the only source of nitrate . . . nor that only the current year's chemical applications contributed to losses during that year." An average of 20% of N applied to corn was lost in drainage in the Drain Load dataset (median: 15%; n = 495), although it should be reiterated that this N loss will include some soil-derived N in addition to N applied as fertilizer or manure. Separating these values based on precipitation revealed a similar

Table 2. Dissolved N load and corn yields regressed against N application rate for four cropping/precipitation combinations from the Drain Load database.

	Crop	N load regressions from Fig. 2a and b				Yield regressions from Fig. 2c and d			
			R^2	p	n		R^2	p	n
Dry	Continuous corn	$y = 10.0 + 0.94e^{0.015x}$	0.076	0.089	69	$y = 6.76 \times (1\text{-}e^{-0.033x})$	0.075	0.045	59
	Corn–soybean rotation corn	ns†	–	–	129	ns†	–	–	125
Wet	Continuous corn	$y = 27.1 + 0.84e^{0.019x}$	0.245	0.004	43	$y = 9.89 \times (1 - e^{-0.010x})$	0.336	0.0002	37
	Corn–soybean rotation corn	ns†	–	–	61	$y = 11.66 \times (1 - e^{-0.013x})$	0.331	< 0.0001	57

† Regression not significant at α = 0.10.

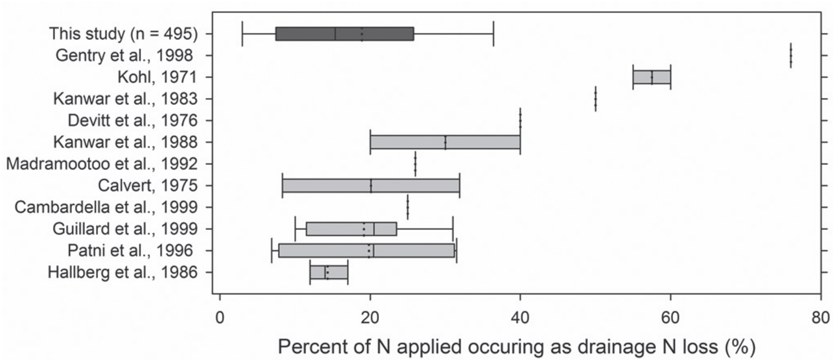

Fig. 3. Percentage of N applied lost as dissolved N in drainage as reported in literature and from corn site-years in the Drain Load database (*n* = 495); note that this N loss will include some soil-derived N in addition to N applied as fertilizer or manure. The box boundaries represent the 25th and 75th percentiles, the solid line represents the median, the dotted line represents the mean, and the whiskers show the 10th and 90th percentiles.

trend between wet and dry years (Fig. 4a). The percentage lost in drainage decreased at increasing N application rates for both, with convergence of the trends at application rates >300 kg N/ha. At lower application rates, a relatively greater percentage of the application would be lost in drainage in a wet versus a dry year, but at higher application rates, the impact of annual precipitation may be overshadowed by excessive applications. Regressing these loss percentages against precipitation seemed to indicate a precipitation change point existed, below which increasing annual precipitation increased the percentage of N lost in drainage, but above which no notable increase occurred (Fig. 4b). This may mean that increased annual precipitation poses an increased risk of drainage N loss, but only to a point at which a relatively consistent percentage of a given year's application will be lost.

Nitrogen Application Timing

Because multiple nutrient products are often applied in a given site-year, the MANAGE framework allowed recording of up to two fertilizer products for each record; that is, each site-year had the option to contain information on a Fertilizer 1 and Fertilizer 2, each of which included details on the product, timing, and placement method. The total annual N application rate was entered as one summed value for each record. If a N application rate was reported for a site-year, the timing of Fertilizer 1 was generally at planting or preplant (31 and 36% of Fertilizer 1's site-years, respectively; $n = 530$; Fig. 5a), whereas if a second fertilizer was reported, it was, not surprisingly, often a side-dressed application (50% of Fertilizer 2; $n = 210$; Fig. 5a). The most common source/timing combinations for corn (the most prevalent crop in the Drain Load database) were urea-ammonium nitrate (UAN) applied at planting, preplant anhydrous ammonia, preplant ammonium nitrate, and out-of-season liquid swine manure (Fig. 5b).

Across many watersheds, fall application is more common than spring preplant (e.g., 51% vs. 35%, respectively, in the Lake Bloomington watershed; Smiciklas and Moore, 1999), and the widespread trend of increasing farm size may result in its increasing prevalence (Gentry et al., 2000). Spring N application is generally recommended to reduce N leaching losses and to improve profitability (Malone et al., 2007; Randall et al., 2003b; Vetsch and Randall, 2004). Studies from Minnesota showed an approximately 13% reduction in drainage nitrate N loss for spring preplant anhydrous ammonia application compared with fall and found that yields and corn N uptake were higher from spring application (Randall and Vetsch, 2005a, 2005b; Randall et al., 2003a, 2003b). Nevertheless, it is possible drainage N loading impacts of changing applications from the fall to the spring will be minimal compared with the effect of annual precipitation, as some studies have observed no difference in nitrate N concentration or grain yield when the same N rate was applied in the fall and spring (Lawlor et al., 2011). Analysis of fertilizer timings (only corn site-years where only one fertilizer was reported to avoid confounding effects of Fertilizer 1 vs. Fertilizer 2) showed no significant difference in dissolved N load between the four application timings (Table 3). Out-of-season fall N applications were not statistically different from pre-preplant or from at planting applications in terms of application rate or corn yield (Table 3).

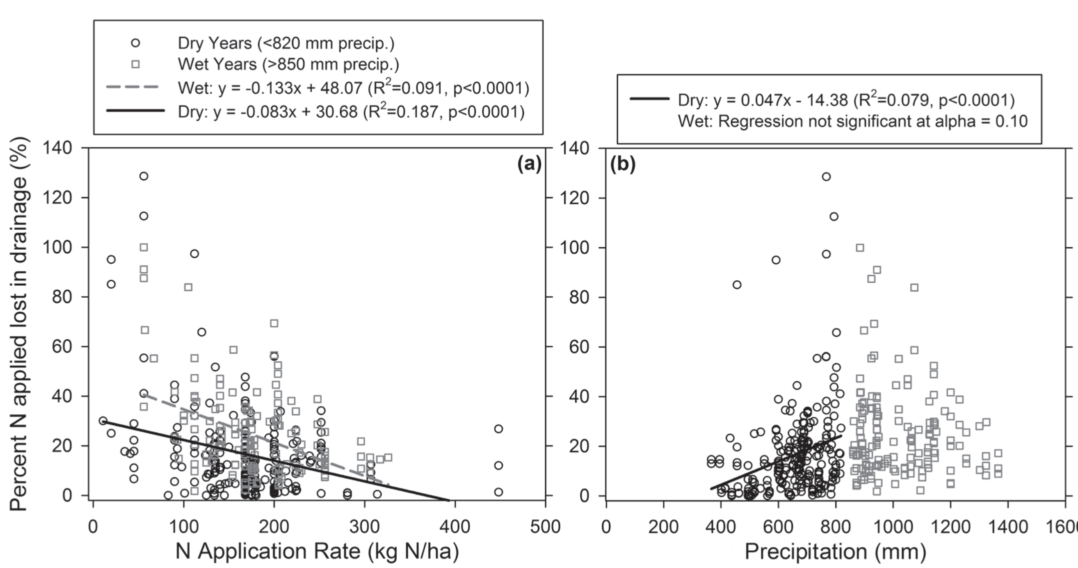

Fig. 4. Percentage of a given site-year's annual N application lost in drainage across corn site-years in the Drain Load database shown against (a) N application rate and (b) annual precipitation.

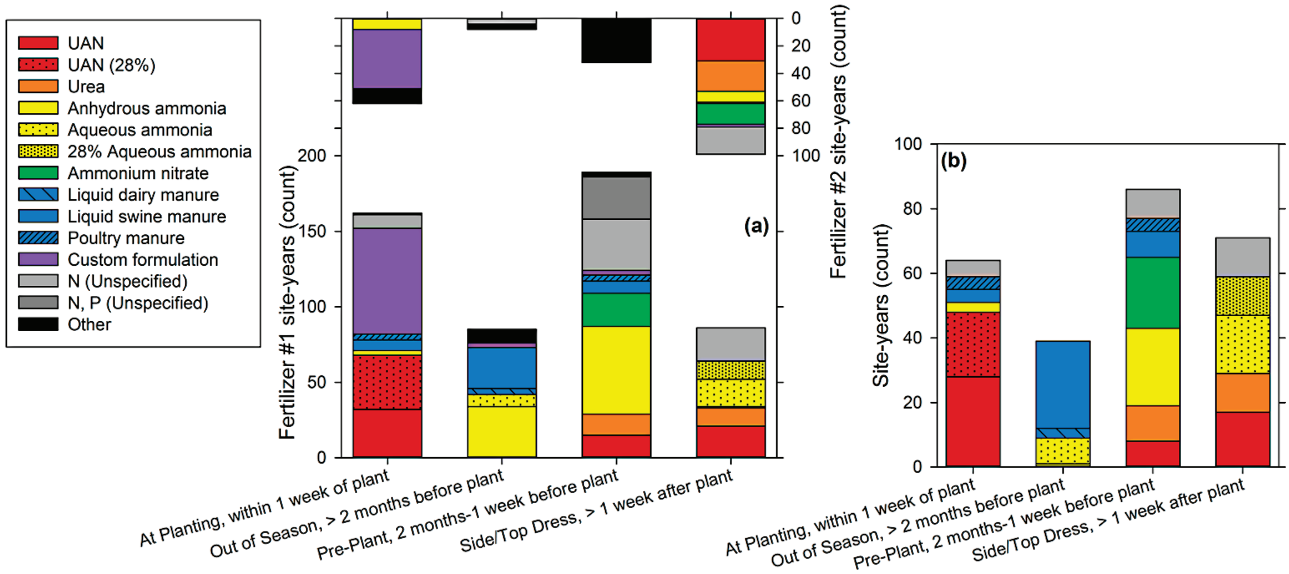

Fig. 5. Nitrogen application timing by product for Drain Load (a) Fertilizer 1 site-years (bottom) and Fertilizer 2 site-years (top), and (b) when only one application was reported in a corn site-year. UAN, urea-ammonium nitrate.

Split N applications are thought to reduce N leaching and increase plant uptake and/or yield by synchronizing application with plant growth (Kanwar et al., 1988; Waddell et al., 2000). Bakhsh et al. (2002) reported a 25% reduction in nitrate N leaching and a 13% corn yield increase with a side-dressed N application versus a single application. Economically, Randall et al. (2003a) determined the highest profitability in their study resulted from a split N application and the lowest from a fall application without the use of a nitrification inhibitor ($239.40 ha^{-1} yr^{-1} versus $166.70 ha^{-1} yr^{-1}, respectively). However, the water quality benefits of side-dressing may be variable, as Tan et al. (2002) observed a spike in tile drainage nitrate N concentrations coincident with the timing of such an application (at the six-leaf stage). Several studies noted a yield benefit of split N application but no significant difference in drainage nitrate N loads (Bjorneberg et al., 1998; Jaynes and Colvin, 2006), and other studies reported no consistent yield benefit (Guillard et al., 1999; Jaynes, 2013; Karlen et al., 2005). Jaynes and Colvin (2006) went as far as to note that the "reactive strategy" (Jaynes, 2013) of split N applications should not be considered a water quality improvement practice. Analysis of the Drain Load database revealed no significant water quality or corn yield benefit of a side-dressed application (Table 3).

Nitrogen Application Method

Injected N was the most predominant application method across Drain Load site-years (256 of 394 Fertilizer 1 site-years; 18 of 86 Fertilizer 2 site-years; Fig. 6a). In records where more than one fertilizer was applied, surface application was the predominant method for the second application (50 of 86 site-years for Fertilizer 2; Fig. 6a) likely due to its occurrence later in the season (i.e., most second applications were side-dressed; Fig. 5a).

When sorting similar to the N fertilizer timing analysis was done (i.e., data were sorted to exclude site-years using more than one application method to ensure the entire reported rate was applied using one method), injected UAN was the most prevalent N source/method combination for corn site-years, followed by injected ammonia products and injected liquid swine manure (Fig. 6b). From this selected dataset, application rates for surface-based N applications were significantly greater than the rate when injected (Table 4). However, these data were skewed by one study with a relatively high site-year count where broadcasting was used (Randall and Iragavarapu, 1995); removing this study, there was no significant difference in application rates between methods, although the population became relatively small (surface applied median: 156 kg N ha^{-1} applied, $n = 15$; $p = 0.070$). Injection and incorporation resulted in the highest yields.

Nitrogen Source

There was no predominant N source when all Drain Load site-years were evaluated (Fig. 7). Nitrogen application rate was reported in 784 site-years, within which a Fertilizer 1 was reported 746 times with a site-year having a second application in 242 records. Across both Fertilizer 1 and 2, the most prevalent

Table 3. Median (count) N application rate, corn yield, and dissolved N load by N application timing for corn site-years where only one application was reported in the Drain Load database.

N application timing	N application rate	Corn yield	Dissolved N load†
	kg N ha^{-1}	Mg ha^{-1}	kg N ha^{-1}
Out of season, > 2 mo before plant	168 (39) ab‡	8.7 (34) ab	29.5 (39)
Pre-plant, 2 mo-1 wk before plant	200 (86) a	9.4 (69) a	30.5 (86)
At planting, within 1 wk of plant	152 (64) b	7.5 (56) b	27.0 (63)
Side/top dress, > 1 wk after plant	160 (71) b	8.4 (62) b	27.9 (71)

† No significant difference between treatments ($p = 0.934$).

‡ Medians with the same letters are not statistically significantly different.

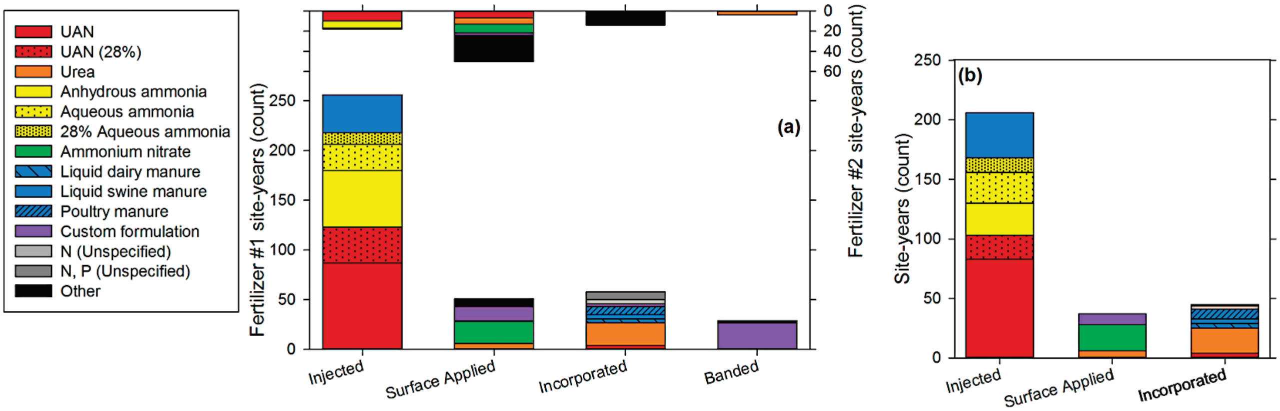

Fig. 6. Nitrogen application method by product source for Drain Load (a) Fertilizer 1 site-years (bottom) and Fertilizer 2 site-years (top), and (b) when one application was reported in a corn site-year. UAN, urea-ammonium nitrate.

Table 4. Median (count) N application rate, corn yield, and dissolved N load by N application method for corn site-years where only one application was reported in the Drain Load database.

Method	N application rate	Corn yield	Dissolved N load†
	kg N ha^{-1}	Mg ha^{-1}	kg N ha^{-1}
Incorporated	168 (45) ab‡	9.4 (36) a	19.6 (45)
Injected	167 (206) b	8.4 (198) a	28.0 (206)
Surface applied	200 (37) a	6.7 (31) b	20.0 (37)

† No significant difference between treatments (p = 0.916).

‡ Medians with the same letters are not statistically significantly different.

sources were unspecified N sources, custom formulations, UAN, and anhydrous ammonia (Fig. 7).

Several studies reported a yield boost due to organic fertilizers compared with inorganic N (Lawlor et al., 2011; Malone et al., 2007; Thoma et al., 2005), but this was not exclusively the case (Randall et al., 2000). There was a significant positive corn yield impact due to organic (manure or litter) versus inorganic applications in the Drain Load database ($p < 0.001$; Table 5). Some studies suggested organic N sources may provide a drainage water quality benefit (Bakhsh et al., 2007; Kimble et al., 1972; Malone et al., 2007; Nguyen et al., 2013; Thoma et al., 2005), but here, no significant difference in dissolved N loads occurred between the sources (p = 0.163). Total N loads were also not statistically different between inorganic and organic N sources at α = 0.05 (p = 0.074; Table 5); however, this analysis was complicated by the small population sizes (n = 30 and 7 site-years).

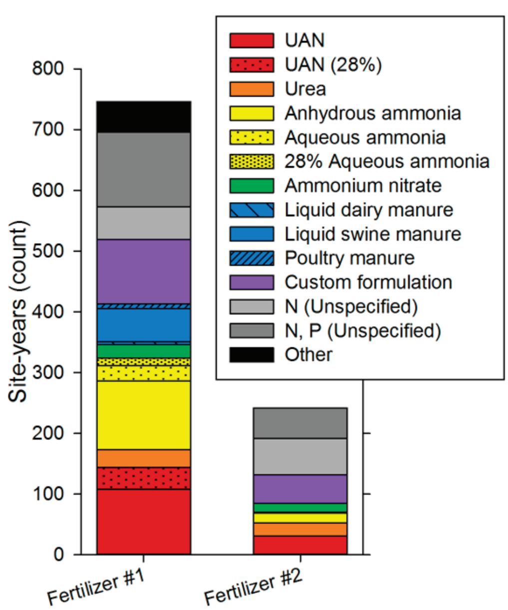

Fig. 7. Nitrogen application sources for Drain Load database Fertilizer 1 and Fertilizer 2 site-years. UAN, urea-ammonium nitrate.

Despite potential benefits of application of organic forms of nutrients (including contribution to soil carbon pools), there are several caveats. First, it is difficult to precisely compare application rates between organic and inorganic N sources because the “available” N in manure or litter is highly variable and requires intensive sampling, analysis, and application procedures for uniformity in application. Moreover, some comparisons do not compensate for the macro- and micronutrients provided with the manure. Second, injection of liquid manures can pose a direct water quality threat; there are several reports of visible contamination of drainage waters immediately following liquid manure injection (Ball Coelho et al., 2007, 2012; Burchell et al., 2005). Lastly, use of organic N sources requires improved management strategies just as inorganic sources do. Mitsch et al. (2001) reported that improved manure management could save 500 × 10^3 t total N yr^{-1} transported through the Mississippi River basin.

Conclusions

Nitrogen, an element essential for life, is particularly vexing as its ubiquity and mutable nature confounds attempts to manage it agronomically. The statistical significance of some of the 4R practices for reduction of drainage dissolved N loads was stronger than for others. Optimizing N application rates will continue to receive primary research and regulatory focus. Across site-years, wetter conditions resulted in greater dissolved N losses than dry from corn-based systems, although at very high

Table 5. Median (count) of Drain Load database precipitation, drainage discharge, corn yield and dissolved and total N loads by nutrient source.

Nutrient source	Precipitation†	Drain discharge	Corn yield†	Dissolved N load	Total N load
	mm		Mg ha^{-1}	kg N ha^{-1}	
Inorganic fertilizer	797 (505)	165 (542)	8.1 (322)	23.6 (571)	14.0 (30)
Organic N Sources	885 (86)	185 (93)	10.4 (55)	18.4 (95)	15.5 (7)

† Indicates significant difference between sources at $\alpha = 0.05$.

N application rates, the impact of annual precipitation may be overshadowed by excessive applications (e.g., Fig. 4). Fine-tuning N rates is clearly important, but it would be short-sighted and unrealistic to focus solely on this practice.

Use of organic N sources could boost corn yields with potentially no increase in dissolved N loads compared with inorganic N fertilizer. However, adherence to 4R strategies is vital regardless of the nutrient source (i.e., organic or inorganic). The lack of significant dissolved N loading differences between N application timing or application method is inconsistent with the current emphasis placed on application timing, in particular, as a water quality improvement strategy. The application timing analysis was complicated by differences in application rates between treatments; the highest application rates resulted in the greatest N losses and yields. Similarly, there was no significant difference in dissolved N losses between application methods. Broad-scale analyses such as this can help identify major trends for water quality, but accurate implementation of the 4R approach will require site-specific knowledge to balance agronomic and environmental goals.

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