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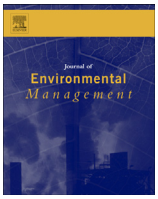

Research article

Beyond the nutrient strategies: Common ground to accelerate agricultural water quality improvement in the upper Midwest

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ABSTRACT

Nutrients in drainage waters from the Upper Mississippi River Basin states have been a well-documented contributor to the Gulf of Mexico hypoxic zone for decades, and in response, twelve states have developed strategies to address this issue, with Iowa, Minnesota, and Illinois performing rigorous science assessments which estimated nitrogen and phosphorus reduction effectiveness for numerous agricultural non-point source conservation practices. The practices identified in these strategies were compared to identify areas of consensus and discord on nutrient load reduction potentials. Additionally, each practice was assessed for (1) the suitability to stack or be layered with other practices (stackability), (2) the ability to track implementation within a state or regionally (trackability), and (3) the level of production system change required to implement the practice. Overall, there was general consensus among the state strategies in the nutrient load reduction effectiveness of most practices with the exception of cover crops (10%–31% nitrogen reduction) and bioreactors (13%–43% nitrogen reduction). The most effective water quality-improvement practices (i.e., land-use change practices) required relatively more production system changes to agronomic management and were the most trackable (scores: 5, 1–5 scale), although they were also less stackable with other practices (scores: 1 to 1.8; 1–5 scale) and were the least cost effective on a unit area basis (generally $15 to $964 per ha). The most cost effective practices tended to be highly stackable (e.g., nitrogen management: (−)$49 per ha and stackability of 4.7), which indicated that stacking a variety of practices may be the most cost effective use of conservation dollars. The practices that were most difficult to track had relatively lower nitrogen loss reduction effectiveness, but these practices were less costly to implement and required relatively less production system change to agronomic management, two factors of importance to many producers.

1. Introduction

The hypoxic zone in the Gulf of Mexico, documented since 1985 (Dale et al., 2007), has been linked to nutrients from states in the upper Mississippi River basin, and particularly to agricultural activities in those states (Alexander et al., 2008; David et al., 2010; Jacobson et al., 2011). To accelerate progress towards nutrient loading reduction goals, twelve states within the basin were tasked with developing nutrient loss reduction strategies (Stoner, 2011; Arkansas, Indiana, Illinois, Iowa, Kentucky, Louisiana, Minnesota, Mississippi, Missouri, Ohio, Tennessee, Wisconsin). Of these states, Iowa, Illinois, and Minnesota invested considerable effort from scientists to develop state-specific science assessments that provided science-based rationale for implementation of conservation practices associated with strategy goals. The work invested by the scientist team in each state was highly novel as well as extremely relevant and timely for a variety of audiences (e.g., policy makers,

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agricultural advisors and professionals, conservation planners) in that a state-relevant consensus was developed for the nutrient loading reduction effectiveness values' of a range of recommended agricultural conservation practice. While each of these assessments necessarily accounted for state-specific differences (e.g., climate, agricultural practices), the underlying assumptions and methods used to develop conservation practice effectiveness and nutrient loading reduction scenarios should align to ensure consistency and positive cumulative impact across the upper Midwestern states.

The major objective with this work was to identify areas of consensus and discord among the Iowa, Illinois, and Minnesota nutrient strategies to help guide implementation and tracking of water quality improvement practices in the upper Midwest. The goal was not to identify if a given strategy was “better” than another, but rather to open a dialog that might promote more consistent evaluation and lead to consensus on assumptions, data sources, and methodologies that can make basin-wide efforts more robust. Perhaps most importantly, in addition to the comparison of state-based practice effectiveness, this work's assessment of (1) each conservation practice's ability to be stacked or layered with other practices and (2) the ability to track implementation of each practice provides a particularly practical assessment of options to increase practice adoption and aid state and federal efforts in monitoring progress towards Gulf of Mexico hypoxia goals.

1.1. State strategy development

Iowa, with a population of 3.1 million (US Census Bureau, 2016), ranks highly in the production of corn (Zea mays) and soybeans (Glycine max), with greater than 11.8 million total cropland ha (including pasture and hay) (Han et al., 2014; NASS, 2014), which represents 82% of the state. Additionally, approximately 3.6 million ha of this cropland has artificial subsurface drainage (Sugg, 2007) (Figs. 1 and 2). The Iowa Nutrient Reduction Strategy (NRS; IDALS, IDNR, and ISU, 2013), developed by the Iowa Department of Agriculture and Land Stewardship, the Iowa Department of Natural Resources, and Iowa State University College of Agriculture and Life Sciences, underwent public comment in early 2013 and was released in final form in 2013 with updates in 2014. The Iowa science assessment that supported the strategy was developed by a science team comprised of 23 scientists from six organizations. Major Land Resource Areas (MLRAs; ten total), or areas of similar climate, soil, and water resources, were used for the development of statewide scenarios that consisted of combinations of conservation practice implementation with estimated N and P reductions. This level of spatial aggregation was also necessary given limited fertilizer and manure application rate data at finer scales and particularly considering inter-county fertilizer sales. Iowa's N load estimates were determined using a long-term average water yield

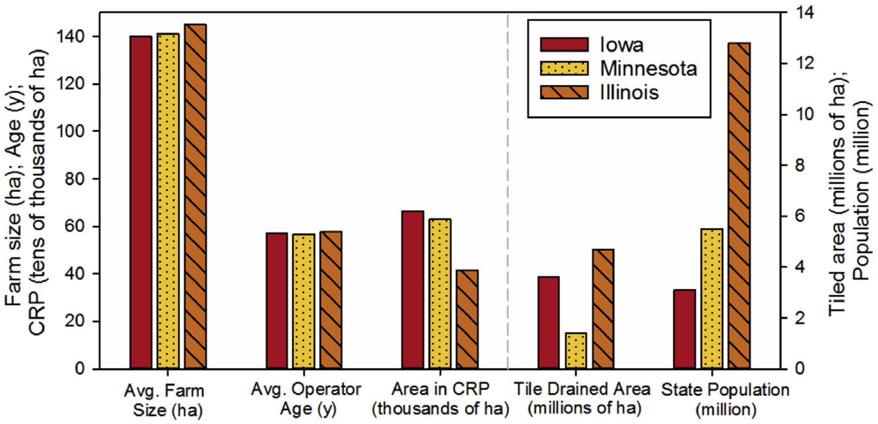

Fig. 1. Iowa, Illinois, and Minnesota average farm size and farmer age, area of subsurface agricultural tile drainage and Conservation Reserve Program (CRP – all types, cumulative), and state population (NASS, 2012; Sugg, 2007; US Census Bureau, 2016).

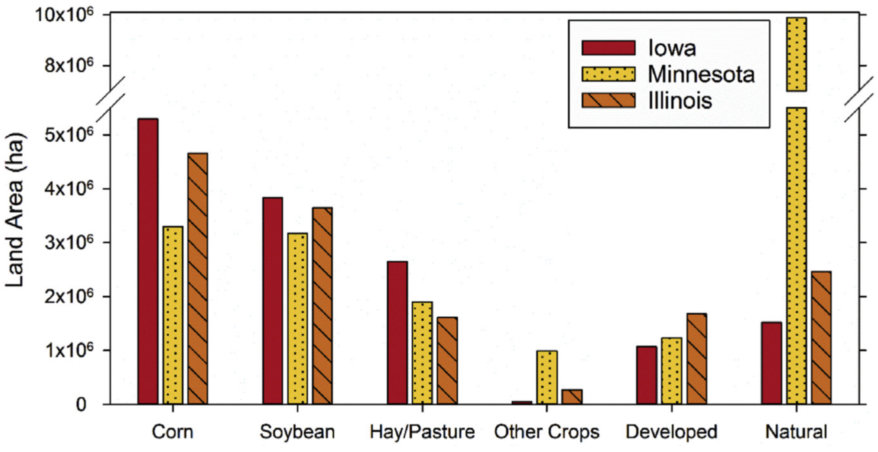

Fig. 2. 2014 Land use and cropping information for Iowa, Illinois, and Minnesota (Han et al., 2014; NASS, 2014).

using US Geological Survey (USGS) Water Watch data coupled with projected nitrate concentrations associated with N application rates (Lawlor et al., 2008). Phosphorus load estimates were made using a modified Iowa P Index calculation based on tillage, soil test phosphorus (STP), and slope combinations representing conditions in each MLRA.

Like Iowa, Illinois (population: 12.8 million) also ranks highly in the production of corn and soybeans (71% of the state is used for agriculture), activities which are heavily underpinned by the 4.7 million ha of artificial subsurface drainage in the state (Sugg, 2007) (Figs. 1 and 2). The Illinois Nutrient Loss Reduction Strategy (NLRS; IEPA and IDOA, 2015) was released in summer 2015 jointly by the Illinois Department of Agriculture (IDOA) and the Illinois Environmental Protection Agency (IEPA). The science assessment was conducted by a five-member team at the University of Illinois, and a key feature of the Illinois strategy was estimation of point source contributions, primarily from the Chicago metropolitan area, one of the largest metropolitan areas in the US. Like Iowa, the Illinois science team used MLRAs for data aggregation; however, another key feature of the Illinois plan was to identify priority watersheds for nutrient loss reduction. Additionally, Illinois included provisions for coordinating water quality monitoring and improving collaboration among agencies and non-government organizations (NGOs) focused on nutrient losses. The Illinois nitrate and total P loads for 1980–1996 and 1997–2011 were calculated using streamflow data and N and P concentrations provided by the IEPA and the USGS. Point source contributions were estimated from data provided by IEPA and the Illinois Association of Wastewater Agencies. Non-point source load contributions were determined by subtraction of point-source loads from total riverine loads.

The Minnesota NRS (MPCA, 2014) was unique in its necessary consideration of the state's contribution to three major drainage basins: the Lake Winnipeg, Lake Superior, and Mississippi River basins (6%, 34%, and 60% of the state, respectively). The state also notably differed from Iowa and Illinois in its more than 9 million ha of natural land use such as forest and wetlands (Fig. 2; Han et al., 2014; NASS, 2014). The Minnesota strategy was published in 2014 (MPCA, 2014), and was a multi-organization effort consisting of more than 75 individuals who evaluated literature reviews, modeling, and monitoring data. The strategy was based heavily on a 2013 report by the Minnesota Pollution Control Agency (MPCA) and a spreadsheet tool for assisting with cost effective watershed-scale N planning (MPCA, 2013; Lazarus et al., 2014). Rather than dividing the state using MLRAs, the strategy focused on individual watersheds (eight-digit Hydrologic Unit Code [HUC] or smaller) using an adaptive management approach and the Lazarus et al. (2014) tool was based on soil, landscape, climate, and agricultural management data for 39 agroecoregions. This method encourages targeting of higher nutrient loading rate areas, and aligns with Spatially Referenced Regression on Watershed (SPARROW) model attributes. The SPARROW model was used to estimate overall N and P loads. Minnesota also has a unique online agricultural conservation practice tracking tool supported by the Minnesota Board of Water and Soil Resources (BWSR), eLINK (BWSR, 2016), which takes into account local information when estimating the benefits of agricultural best management practices (BMPs) and is used for tracking all conservation practices funded by BWSR and MPCA.

2. Methods

The Iowa, Illinois, and Minnesota strategies were reviewed in summer/fall 2016 with clarification questions posed to key science team members either over the phone or during in-person interviews during fall 2016 (personal communications: M. David, G. McIsaac, L. Gentry, L. Christianson, M. Helmers, R. Christianson, and D. Mulla).

2.1. Conservation practice comparison

The three strategies each included conservation practice tables detailing nutrient loss reduction effectiveness (i.e., percent nutrient loss reduction compared to a baseline without the practice in place) of the recommended practices in each state. Reported reductions influence loads through reductions in concentration, water volume or both. Two of the strategies also included cost effectiveness of many of the practices. Ranges in cost effectiveness were due to variations in conservation practice implementation scenarios, differing loading rates across the states, and varying land values. Cost effectiveness for Minnesota N and P reduction practices reside in the science based software tools for N and P reduction (Lazarus et al., 2014). Total costs of N and P reduction strategies for Minnesota depend on user specified practice adoption rates in the software.

Beyond the comparison of nutrient loss reduction and cost effectiveness of each practice presented in the three strategies, the stackability, trackability, and relative production system change of each practice was evaluated. The ability to pair practices (i.e., practice “stackability”) will likely be an essential component of meeting basin-wide water quality goals. Additionally, the ability to track practice implementation (i.e., “trackability”) is necessary for states and federal agencies to quantify progress towards Gulf of Mexico hypoxia goals given the lag time required for water quality improvement downstream.

Stackability of practice combinations were quantified by evaluating the compatibility of each practice with each of the others. For example, in-field and edge-of-field practices are often highly compatible, but a bioreactor and a wetland would generally not treat the same drainage outflow, at least at the field scale. Each potential practice combination was assessed using a 1–5 scale, where a rating of “1” indicated complete incompatibility of the two practices (often due to competing land uses; e.g., land retirement x the practice of N management on corn: rating of 1), and a rating of “5” not only indicated practice compatibility, but a synergistic water quality effect of using the two practices simultaneously. A rating of “2” indicated the two practices could potentially be paired, but likely would not due to conflicting agronomic goals or overlap in treatment (e.g., perennial energy crops used with controlled drainage: 2). A rating of “3” was used for two practices that may be paired depending on practice nuances; for example, use of a nitrification inhibitor would be reasonable for early spring N fertilizer application, but not for a later season side-dressed application (inhibitor x N management: 3). A rating of “4” indicated the two practices were not in competition and could easily be used together. After each practice had been assigned a rating against every other practice, the ratings were summed for each practice. This overall stackability score for each practice was scaled to between 1 and 5 to assess this metric against trackability and production system changes scores (see below). In other words, the practices with the lowest and highest stackability summed scores (land retirement: 17; buffers, controlled drainage, and soil test P: 48) were assigned a 1 and 5, respectively, and all other practices were linearly assigned a value between 1 and 5. Although some practices can be easily stacked more than two-deep (e.g., improved N management x cover crop x bioreactor), this assessment only evaluated two-way practice pairings for simplicity. Moreover, while many practices can be stacked within a given watershed, this “stackability” metric focused a farmer-level view of practice pairing (i.e., field-scale perspective). It should be noted, however, that optimization tools that evaluate stacking practices at the watershed-scale can allow cost effective targeting by recognizing the variety of site-specific characteristics within a watershed, and that a diversity of practices could singly be applied to many different fields.

Each practice was quantitatively ranked along a five-point trackability scale based on availability of implementation data. A ranking of “5” was assigned to practices for which data to track implementation was easily accessible (e.g., free of charge, publicly available data), whereas a ranking of “1” indicated implementation of the practice was difficult to track with certainty. Private implementation of practices (i.e., practices implemented without the use of federal incentive payments) is particularly difficult to track, and was thus taken into account by assigning practices that were more likely to be privately implemented lower ratings on the 1–5 scale. Mid-range rankings were reflective of practices that could be tracked via conservation program data (e.g., United States Department of Agriculture Natural Resources Conservation Service Environmental Quality Incentives Program [USDA NRCS EQIP] or USEPA 319 projects) that may be available to state officials/Hypoxia Task Force members.

Production system change was also assessed using a five-point scale where a “5” represented a wholesale change in on-farm management and production, and a “1” represented a small change in management practices that may have been done regardless of water quality or conservation efforts. The general idea here was that as a producer's level of thought, effort, and/or financial commitment required for a practice's implementation increased, the production system change ranking of that practice also increased. For example, shifting from row-crop agriculture to perennial energy crops requires a completely different business model and was scored a 5. Since the basis of the state strategies was improvement of water quality, the 1–5 scale used generally indicates increased water quality benefits with greater production system change.

3. Results and discussion

3.1. Practice nutrient loss reduction comparison

Practices were generally divided into in-field, edge-of-field, and land-use-change categories in the three strategies, and all the strategies contained more practices for reducing N loss than P loss (Table 1). For a detailed description of the practices themselves, please refer to the state strategy documents (IDALS, IDNR, and ISU, 2013; MPCA, 2014; IEPA, and IDOA, 2015). The Iowa strategy included at least eight practices not included in the other strategies, and thus not discussed here (N: living mulch, extended rotation, shallow drainage, changing from spring applied commercial fertilizer to poultry manure, changing from spring applied commercial fertilizer to liquid swine manure, and saturated buffers; P: changing from commercial fertilizer to beef, dairy, poultry or liquid swine manure, changing from no incorporation of broadcasted fertilizer to broadcast fertilizer with incorporation within one week, terraces, and sedimentation basins). There were many nuances and details present in the scientific assessment of each practice in each of the three strategies, which were condensed here for the sake of comparison.

While there was a great deal of similarity in the effectiveness values among the states, appreciable differences also existed. To ensure the use of the most accurate science for regional agricultural conservation practice effectiveness, a recommended consensus reduction for many of the practices was created by the authors to spur the discussion of tracking comparable benefits across the region (Table 1 “Rec. Consensus”). Though recommendations were included in Table 1, obvious exceptions to a consistent value

Table 1
Overall practice comparison among state strategies for nitrogen and phosphorus reduction percentage with the recommended consensus nutrient loss reduction value (“Rec. Consensus”). Reductions were attributed to concentration, water volume, or a combination.

Practice Type	Practice	Nitrogen				Phosphorus			
		IA	MN	IL	Rec. Consensus	IA	MN	IL	Rec. Consensus
Edge-of-Field	Constructed Wetlands	52%	50%	50%	***50%***	0%	0%	0%	***0%***
Edge-of-Field	Buffers[a]	91%	95%	90%	***90%***	58%	58%	50% (25%[b])	***55%***
In-Field	Cover Crops	31% (28%[c])	51% (10%[d])	30%	***30%***	29%	29%	30% (50%[e])	***30%***
Land-use-Change	Perennial Energy Crops	72%	95%	90%	***90%***	34%	34%	90% (50%[b])	***35%***
Land-use-Change	Land Retirement	85%	83%	NI	***85%***	75%	56%	NI	***65%***
Land-use-Change	Grazed Pasture or Hayland	85%	95%	90%[f]	***90%***	59%	59%	NI	***60%***
Edge-of-Field	Controlled Drainage	33%	33 to 44%	NI	***35%***	NA			
Edge-of-Field	Bioreactor	43%	13%	25%	***27%***				
In-Field	Nitrification Inhibitor	9%	14%	10%	***10%***				
In-Field	Nitrogen Management			[g]	***15%***				
	→ Timing & rate reduction	NI	26%	NI	NR				
	→ Timing	6%	NI[h]	15 to 20%	NR				
	→ Sidedress	5%	NI[h]	NI	NR				
	→ Split application	NI	NI	15 to 20%	NR				
In-Field	Maximum Return to Nitrogen (MRTN)	10%	16%	10%	***10%***[i]				
In-Field	Conservation Tillage	NA				33% (90%[j])	63%	50%	***60%***
In-Field	Soil Test Phosphorus (STP)					17%	17%	7%	***15%***
In-Field	Phosphorus Banding					24%	24%	NI	***25%***

NI = Not included in strategy.
NA = Not applicable.
NR = No recommendation.

[a] Some settings have limited shallow subsurface flow through buffer root zone.
[b] Reduced effectiveness on tile drained land.
[c] Oats have a slightly lower effectiveness than rye.
[d] For cover crops planted after corn or soybeans grown for grain.
[e] Used with extended rotation (corn-soybeans-wheat).
[f] Equated to "Perennial Energy Crop" due to energy crop numbers being based on alfalfa.
[g] The larger number is applicable to central and southern Illinois, versus northern.
[h] Included in the combined “Timing & rate reduction” value.
[i] Ultimately depends on initial N application rate.
[j] If moving to no-till from chisel tillage.

included cover crops, N management, and bioreactors, because nuances of the practice were defined differently in each state or due to different calculation methods (see below discussion). While such methodological differences could be resolved through evaluation and discussion, there will also be differences in practice effectiveness within the region due to climate with, for example, a bioreactor or a cover crop working better in slightly warmer east-central Illinois compared to northern Minnesota. Regional differences should be highlighted and noted, as no consensus would be appropriate in these situations. Further research is needed to evaluate differences in practice performance across the region.

3.1.1. Practices to reduce N loss

The land-use-change practices (perennial energy crop, grazed pasture/hayland, and land retirement) were consistently rated highly across the three strategies (72–95% N loss reduction; Table 1). Buffers were also rated highly for N loss reduction (>90%), although this carried the caveat that the reduction was only for water that interacts with the active root zone below the buffer or applied only to the actual buffer footprint. In tile-drained landscapes, this would be a relatively small fraction of the flow. The most consistently rated practice, constructed wetlands, was assessed at approximately 50% N loss reduction. However, wetland design and implementation was targeted at different scales for Iowa and Illinois, with constructed wetland promotion in the latter focused on field-scale treatment.

The in-field N management practices also tended to be rated similarly between the three strategies, with Iowa and Illinois both considering shifts towards spring and in-season applications at 5–20% N loss reduction. The Minnesota strategy evaluated a combination of timing modification and rate reduction, which accounts for their slightly greater reduction effectiveness of 26% (Lazarus et al., 2014; MPCA, 2013). Rate reduction to the maximum return to nitrogen (MRTN; Sawyer et al., 2017) for all three strategies was fairly consistent at 10–16% N loss reduction, though the actual benefit would depend on starting (current) application rates. Nitrification inhibitors were rated at 9–14% N loss reduction.

The evaluation of cover crops was slightly more dissimilar between the three states with Iowa and Illinois both rating grass-based cover crops at approximately 30% N loss reduction (with Illinois' values based on Iowa's earlier assessment), while Minnesota assessed the practice at 10% reduction effectiveness. This difference was due to the relatively shorter cover crop establishment period and limited germination in more northern climes. Minnesota included a 51% N loss reduction for a cover crop planted after short season crops (i.e., sweet corn or peas).

The practice of controlled drainage, or drainage water management, was assessed at N loss reduction effectiveness of 33% (Iowa) to 44% (Minnesota). While research on controlled drainage has been ongoing in Illinois for nearly two decades (Cooke et al., 2008), this practice was not included in the Illinois strategy due to concerns about measured nutrient loss through surface runoff, lateral seepage and loss through other pathways (Ross et al., 2016).

Denitrifying bioreactor's had a large range of N loss reduction effectiveness at 43% in Iowa compared to 13% in Minnesota. The 43% used in the Iowa strategy was from a study of four in-state bioreactors which based load reductions on both water bypassing and water treated. The Minnesota strategy applied the same 43% reduction effectiveness but added an assumption that much less water was being treated, which reduced overall effectiveness to 13%. Regardless of the resulting reduction effectiveness, the Minnesota assumption highlights the highly engineered nature of bioreactors, and how specific design criteria (or lack thereof) can dictate actual and perceived performance.

3.1.2. Practices to reduce P loss

All three state strategies assigned similar reduction percentages to the practices of constructed wetlands (0% P loss reduction), cover crops (29–30%), buffers (50–58%), and P management (soil test P management 7–17%). Wetlands were consistently valued at a long-term P loss reduction of 0%, as permanent P removal is questionable unless sediments are removed and/or vegetation harvested. Phosphorus loss reduction mechanisms for buffers is different than N loss reduction mechanisms, as the water does not have to pass directly through the root zone. The Illinois strategy assigned a value of 50% P loss reduction for a 10.7 m (35 ft) buffer in non-tiled areas and a different value for tiled areas (25% reduction) which would have less surface runoff interaction.

The land-use-change practices tended to have dissimilar P loss reduction effectiveness among the three states. Perennial energy crops (i.e., for biofuels; 34–90% P loss reduction) and land retirement (56–75%) both provided notable, but variable, P reduction benefit. A point of consensus between scientists was that additional benefits may be expected when making this cropping change in steeply sloping land; this corroborated the Illinois assessment that valued perennials less on tile drained land (90% versus 50% on tiled land), which tend to be flatter. The practice of conservation tillage was also somewhat variable in P loss reduction between the three strategies (33–90%). This stemmed from the variety of tillage practices (moldboard, chisel, ridge, strip, etc.) and the perception of what is considered “conventional tillage”.

3.2. Practice cost comparison

As with comparisons of nutrient reduction effectiveness, there were many nuances and details in the economic analyses of the three strategies that were condensed here. Economic comparisons of practices were complicated by continuously fluctuating commodity, input, and land prices, preferences and demand for commodities and forages, and changes in insurance and policy structures, not to mention varying methodologies used by each state. Nevertheless, the most cost effective N loss reduction practices were the in-field N management practices which had negative implementation cost (i.e., cost savings) or a relatively low cost per ha (Table 2; nitrification inhibitor, N management, MRTN rate: (−)\$64.30 to \$44.50 ha^{-1} y^{-1}). The in-field P loss reduction practices also tended to represent a cost savings with soil test P management at (−)\$27.20 to (−)\$18.50 ha^{-1} y^{-1} and conservation tillage valued at (−)\$42.00 to \$29.70 ha^{-1} y^{-1}. Use of N and P management practices in areas where nutrient over-application or build-up in the soil is present provide a cost savings to producers; however, such conditions are limited to high or very high STP situations.

The constructed or structural practices of controlled drainage, bioreactors, and wetlands were also fairly cost effective at \$14.80 to \$44.50 ha^{-1} y^{-1}, with the exception of the Illinois assessment of wetlands at \$151 ha^{-1} y^{-1}. This was likely due to higher land costs in Illinois and the scale of wetlands common in Illinois versus Iowa (i.e., field-scale versus up to 800 ha treatment, respectively) and a different planning horizon used to spread initial capital costs. Note, for bioreactors and wetlands, “\$ ha^{-1} y^{-1}” reflects dollars per ha treated, not dollars per surface area footprint of a bioreactor or wetland. These “targeted” conservation practices also had low costs per kg of nutrient removal (\$0.40 kg N^{-1} to \$1.80 kg N^{-1}; Table 2), which was due to the relatively high N reduction effectiveness of these practices.

Cover crops were slightly less cost effective than the consensus around the structural practices at approximately \$71.70 to \$131 ha^{-1} y^{-1} (considering seed, seeding, and termination costs). The Iowa assessment was the only one that considered the economics

Table 2
Conservation practice spatial costs ($ ha^{-1} y^{-1}) reported by the three strategies and load-based cost effectiveness ($ lb N^{-1} or lb P^{-1} loss reduction y^{-1}) reported by the Iowa and Illinois strategies. Negative values indicated with a negative (−) represent a financial benefit. Values from the state strategies have been converted to metric and have been standardized for significant figures. MRTN is Maximum Return to Nitrogen.

Practice	$ ha^{-1} y^{-1}			$ kg N^{-1} reduction		$ kg P^{-1} reduction	
	IA	MN	IL	IA	IL	IA	IL
Constructed Wetlands	37.10	14.80 to 44.50	151	0.60	1.80	–	–
Buffers	571	74.10 to 741	726	0.90	0.70	6.40	5.40
Cover Crops	111 to 121	131	71.70	2.70	1.50 to 5.00	27.20 to 68.00	11.10 to 59.20
Perennial Energy Crops	964	74.10	213	9.70	1.40 to 4.20	108	18.30 to 113
Land Retirement	474	14.80 to 272	–	4.10	–	54.40	–
Grazed Pasture/Hayland	474	14.80 to 272	213[a]	4.10	–	54.40	–
Controlled Drainage	24.70	22.20	–	0.60	–	–	–
Bioreactor	24.70	44.50	42.00	0.40	1.00	–	–
Nitrification Inhibitor	−7.40	−7.40	17.30	−0.70	1.10	–	–
Nitrogen Management	−49.40 to 0.00	−17.30 to −64.30	42.00 to 44.50	−128 to 0.00	1.40 to 2.80	–	–
MRTN Application Rate	−4.90	−37.10 to −47.00	−19.80	−0.30	−1.90	–	–
Conservation Tillage	−2.50 to 29.70	−2.50	−42.00	–	–	−0.90 to 6.50	−7.50
Soil Test Phosphorus	−27.20	–	−18.50	–	–	−49.90	−22.10
Phosphorus Banding	37.10	37.10	–	–	–	321	–

[a] Equated to "Perennial Energy Crop" due to energy crop numbers being based on alfalfa.

of corn yield impacts with an estimated 6% yield decrease for corn following a cereal rye cover crop.

On both a spatial and nutrient reduction basis, the land-use-change practices were the least cost effective, although implementation costs varied by more than an order of magnitude between states (perennials: $74.10 to $964 ha^{-1} y^{-1} including production costs and revenue; grazed pasture and land retirement: $14.80 to $474 ha^{-1} y^{-1}). While these practices have very high N reduction potential (Table 1), they are expensive to implement given current cultural, political, and economic drivers.

3.3. Stackability, trackability, and production system change

3.3.1. Stackability

In-field management and edge-of-field practices were generally broadly stackable with each other (i.e., a ranking of 4 was the most common within Table 3), with a few instances of non-stackability (stackability ranking: 1) or of synergetic benefits provided by potential stacking (stackability ranking: 5). In-field N management practices are broadly applicable, but a cover crop that is fertilized may have reduced N loss reduction (a ranking of 4 for N management x cover crops rather than 5), and there are several nuances for N management with perennial crops and pasture. For example, both pasture and a perennial crop may be fertilized (rankings of 3 for their cross with N management), but N inhibitor use with these crops is unlikely (ranking of 2 for perennial crops and pasture x with inhibitor), and the MRTN approach is meaningless since it only applies to corn production (ranking of 1 for perennial crops and pasture x MRTN). Within the N management practices, a N inhibitor, for example, may be unlikely if N is side-dressed after planting (N management x inhibitor: 3). The cover crop practice was less compatible with the practice of no-tillage if tillage is used for incorporation of the cover crop residue (tillage x cover: 3), but use of a cover crop may extend the life of an edge-of-field buffer (buffer x cover: 5). A nuance with cover cropping is that while tillage can be used to terminate the cover, cover cropping is also very compatible with the practice of no-till, thus complicating this assessment. Controlled drainage in tandem with a wetland or a bioreactor could increase the effectiveness through engineering design of both (controlled drainage x bioreactor or wetland: 5), but a bioreactor

Table 3
Stackability matrix showing compatibility between conservation practices from the nutrient loss reduction strategies. Between two practices: a "1" indicated complete incompatibility of the two (often due to competing land uses); a rating of "2" indicated the two could potentially be paired, but likely would not be due to conflicting agronomic goals or overlap in treatment; a rating of "3" was used for two practices that may be paired depending on practice nuances; a rating of "4" indicated the two practices were not in competition and could easily be used together; a rating of "5" not only indicated practice compatibility, but a synergistic water quality effect of using the two practices simultaneously.

Practice	Wetlands	Buffers	Cover Crops	Perennial Energy Crops	Land Retire.	Grazed Pasture	Controlled Drainage	Bioreactor	Nitrification Inhibitor	N Manage.	MRTN	Conservation Tillage	Soil Test P	P Banding
Constructed Wetlands	–	4	4	2	2	2	5	2	4	4	4	4	4	4
Buffers	4	–	5	2	2	2	4	4	4	4	4	5	4	4
Cover Crops	4	5	–	1	1	1	4	4	4	4	3	3	4	4
Perennial Energy Crops	2	2	1	–	1	1	2	2	2	3	1	1	3	2
Land Retirement	2	2	1	1	–	1	2	2	1	1	1	1	1	1
Grazed Pasture	2	2	1	1	1	–	2	2	2	3	1	1	3	2
Controlled Drainage	5	4	4	2	2	2	–	5	4	4	4	4	4	4
Bioreactor	2	4	4	2	2	2	5	–	4	4	4	4	4	4
Nitrification Inhibitor	4	4	4	2	1	2	4	4	–	3	4	4	4	4
N Manage.	4	4	4	3	1	3	4	4	3	–	4	4	4	4
MRTN	4	4	3	1	1	1	4	4	4	4	–	4	4	4
Conservation Tillage	4	5	3	1	1	1	4	4	4	4	4	–	5	3
Soil Test P	4	4	4	3	1	3	4	4	4	4	4	5	–	4
P Banding	4	4	4	2	1	2	4	4	4	4	4	3	4	–
Total	**45**	**48**	**42**	**23**	**17**	**23**	**48**	**45**	**44**	**46**	**42**	**43**	**48**	**44**
1–5 Interpolated Rank	**4.6**	**5.0**	**4.2**	**1.8**	**1.0**	**1.8**	**5.0**	**4.6**	**4.5**	**4.7**	**4.2**	**4.4**	**5.0**	**4.5**

would most often not be paired with a wetland since both are denitrification practices (bioreactor x wetland: 2). The land-use-changes of perennial cropping systems, grazed pasture, and land retirement tended to be much less stackable with the other practices (generally ranked 1 or 2).

The summed stackability rankings ranged from 17 (land retirement) to 48 (buffers, controlled drainage, soil test P) (Table 3), which were equated to interpolated stackability scores of 1 and 5, respectively (Table 3). The overall scores generally fell within three categories: low (1.0–1.8: Grazed Pasture/Hayland, Perennial Energy Crops, and Land Retirement), mid-high (4.2–4.8: Cover Crops, MRTN, Conservation Tillage, Nitrification Inhibitor, P Banding, Wetlands, Bioreactor, N Management), and high (5.0: Buffers, Controlled Drainage, and Soil Test P).

3.3.2. *Trackability*

Fertilizer and manure management for N and P, conservation tillage, and cover cropping decisions are often privately implemented and may vary year-to-year, making their implementation the most difficult to track. Producer or co-op surveys or sales records may be the only way to track nutrient management practices, although state level soil testing data (IPNI, 2017) and fertilizer sales data may be useful. Conservation tillage and cover cropping implementation data may be available via federal conservation program contracts (e.g., NRCS EQIP), which slightly increased the tracking score compared to N management practices here (Table 4). Additionally, Conservation Technology Information Center (CTIC) tillage transect data can be purchased (CTIC, 2017), and cover crop seed sales data may be useful. Potential also exists with remote sensing of plant residue cover at planting, which is being developed by researchers in both Iowa and Minnesota. Constructed practices of bioreactors, controlled drainage, and wetlands would generally be less likely implemented privately than in-field practices (i.e., they would be more often installed using incentive payment programs, data from which can be used to track), and tracking of these practices would be aided by their persistence on the landscape. However, proper management of the controlled drainage control structures, which is critical for nutrient loss reduction, is difficult to track (thus, controlled drainage trackability score of 3.0 versus bioreactor and wetland score of 4.0). The National Land Cover Dataset (NLCD; publicly available) can be used to track wetland implementation, but this source does not detail the acres treated by the wetland (i.e., additional watershed delineation may be required). A buffer's multiple benefits mean there are various drivers for implementation apart from water quality improvement, thus private implementation may be common. However, the NLCD or aerial imagery can be used to track buffers, although like wetlands, the area treated would not be known. Aerial imagery and the NLCD can also be relatively easily used to track implementation of grazed pasture, land retirement, and perennial crops, but it may be difficult to distinguish between the three practices in some cases with these data sources. Even with edge of field practices, this seems to highlight the need for reporting of practice implementation and acres treated.

Table 4
Stackability, trackability, and production system change scores for selected N and P loss reduction practices in the state-based strategies. Stackability: low scores mean the practice is relatively more difficult to pair with other practices; trackability: low scores indicate implementation of the practice is more difficult to track for reporting purposes; production system change: lower scores indicate relatively more continuation of status quo agronomic management.

Practice	Stackability	Trackability	Production System Change
Maximum Return to N Application Rate	4.2	1.0	1.0
Nitrification Inhibitor	4.5	1.0	1.0
N Management	4.7	1.0	1.0
Phosphorus Banding	4.5	1.0	1.0
Conservation Tillage	4.4	2.0	3.0
Cover Crops	4.2	2.0	3.0
Soil Test P	5.0	2.0	1.0
Controlled Drainage	5.0	3.0	2.5
Bioreactor	4.6	4.0	2.0
Wetland	4.6	4.0	4.0
Buffer	5.0	5.0	3.5
Grazed Pasture/Hayland	1.8	5.0	4.5
Perennial Energy Crops	1.8	5.0	4.5
Land Retirement	1.0	5.0	5.0

3.3.3. *Production system change*

In-field N and P management and conservation tillage practices were considered smaller changes (actions that are already being taken; annual decisions that were relatively less permanent), although they could include major in-field modifications of agronomic practices (Table 4; nutrient management change ranking: 1.0). Cover cropping similarly was an annual decision that could be relatively less permanent, but would require relatively greater modification to agronomic practices with additional in-field operations (change ranking: 3.0). Bioreactors provide an improvement upon the status quo, but were rated as providing relatively low production system change (ranking: 2.0) since agronomic management would remain unchanged. Controlled drainage would similarly not require a change to in-field management, although there would be slightly increased in-field activity due to control structure management (raking: 2.5). Unlike bioreactors, this practice modifies the hydrology to store water in the landscape. Wetlands and buffers would require a permanent land-use-change meaning their production system change is much greater, but they exert relatively minimal impact on in-field production practices (neglecting the land required). Grazed pastures and perennial crops would be a wholesale, likely semi-permanent change that are often done, at least partially, for economic reasons (change ranking: 4.5), whereas land retirement would provide less economic benefit and was thus rated slightly higher (ranking 5.0).

3.3.4. *Practice comparison*

Illustrating stackability, trackability, and production system change versus the practice N loss reduction effectiveness indicated the most effective water quality-improvement practices required larger production system changes to agronomic management and were the most trackable, although they were also less stackable (Fig. 3a). These land-use-change practices were relatively much more expensive to implement (Table 2; Fig. 3b). All the relationships were statistically significant (at $\alpha = 0.10$) indicating the selected models fit the data very well, but the relatively higher R2 correlation coefficient for the production system change and trackability regressions indicated those models explained the variability in the data relatively better than for stackability. The similarity of trend directionality in Fig. 3a and b was due to the positive correlation between reduction effectiveness and cost effectiveness for N reduction (i.e., a higher N loss reduction effectiveness correlated with a greater \$ ha^{-1} cost effectiveness). The authors recognize that overall the models may be of limited value since the y-axis is a scaled weighting factor, but these relationships nevertheless indicate significant trends. The figure was not necessarily meant to be a decision tool, but rather to show there was no "one size fits all" conservation practice. Clearly, different stakeholders may rank the importance of the effectiveness and metrics differently, and the value here is that these new metrics may aid a variety of unique audiences (e.g., policy makers, agricultural advisors and professionals, conservation planners) in the comparison of

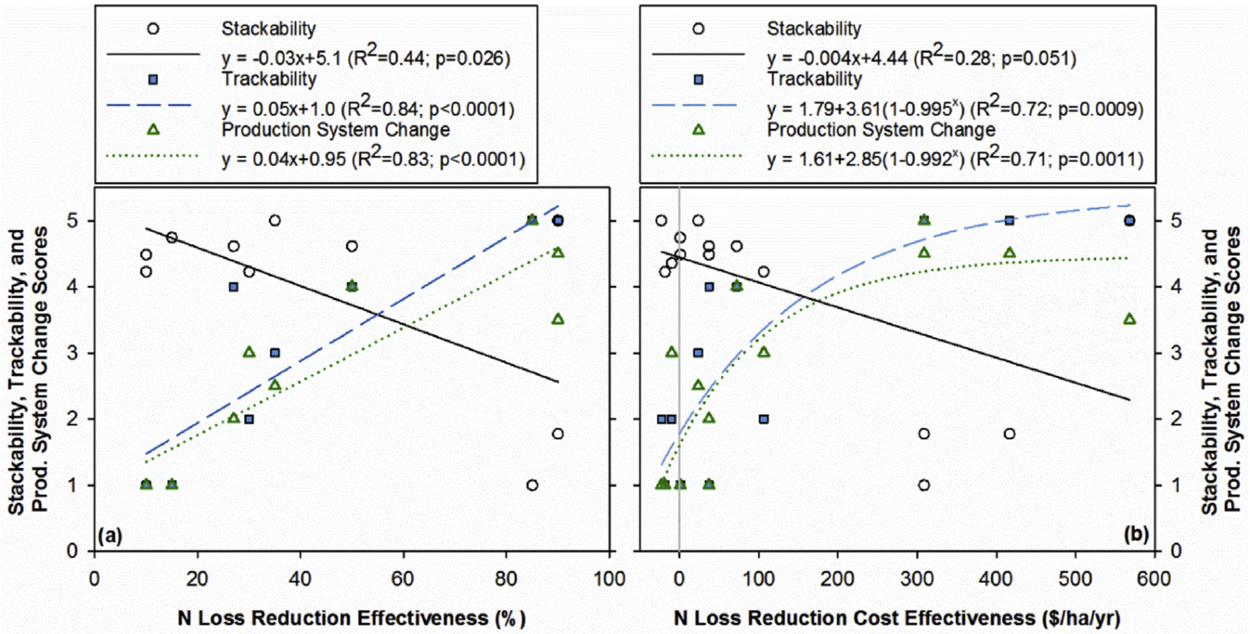

Fig. 3. Conservation practice relative stackability, trackability, and production system change metrics assessed against nitrogen loss reduction effectiveness (a) and cost effectiveness (b). The regressions are shown only for reference and to indicate significance among the trends. The figure does not reflect P loss reduction benefits of practices that can reduce loss of both nutrients due to the increased complexity of adding another factor.

practices in context of each other. For example, one producer might be looking for a low-cost option to reduce nutrient loss on thousands of acres, while another producer might prefer a spatially effective conservation practice to avoid in-field management changes. The “best” practice will be the practice that is spatially suitable for the location, and which the farmer is able to implement.

In terms of cost effectiveness, the least costly practices tended to be highly stackable, yet had a range of trackability and required production system change (Fig. 3b). The cluster of practices with relatively high cost effectiveness is particularly notable (i.e., the cluster of open circles on the upper left of Fig. 3b), compared with practices that were less cost effective. This may indicate that stacking a variety of practices may be the most cost effective use of conservation dollars. However, the N loss reduction effectiveness of stacked practices is not known. For example, stacking N management with a cover crop with controlled drainage and a bioreactor – assuming no negative interactions – cannot physically achieve an additive benefit of 15% + 30% + 35% + 27% = 107% N loss reduction. Calculated another way (multiplicative) yields a more conservative stacked practice load reduction of 72% (100% - (100%–15%)*(100%–30%)*(100%–35%)*(100%–27%) = 72% N loss reduction), but the actual achievable loading reaction is not fully understood. Nevertheless, if the achieved loading reduction was approximately 72%, which is realistic given the variety of practices in this example, the approximately \$125 cost ha^{-1} of this stacked approach would still be substantially less than the >\$250 ha^{-1} cost of a single land-use-change practice, while achieving similar loading reduction and requiring less production system change.

The practices that were the most difficult to track (low trackability scores) had relatively lower N loss reduction effectiveness. However, these practices were less costly to implement per ha and required relatively less production system change to agronomic management, two factors of high importance to many producers (Fig. 3; Table 4). It may be beneficial to develop methods to improve the ability to track practices that have low trackability but provide benefits such as low opportunity cost and less perceived risk (i.e., low production system change). That said, estimates of many of these practices with low trackability could be made with tailored survey questions (Christianson, 2017) or alternative data sources. State-wide strategies are clear that in-field nutrient management practices alone would not result in attainment of water quality goals (e.g., Table 1), but the widespread adoption that might be facilitated by the relative benefits of these practices (low cost, etc.) may not only provide some positive movement of the water quality needle, but may also facilitate the productive industry and landowner engagement. Nevertheless, the potential benefit of tracking these less effective practices accurately would need to outweigh the resources required to implement other practices, as tracking a high number of small scale changes, such as economically-based decisions on improved nutrient management, may not necessarily equate to a significant amount of nutrients reduced (i.e., potentially not worth the effort).

4. Conclusions

Nutrient (loss) reduction strategies and associated science assessments from Iowa, Minnesota, and Illinois were reviewed to help better guide implementation and tracking of water quality improvement practices across the upper Midwest. Stemming from this comparison, three new conservation practice metrics (stackability, trackability, and level of production system change) indicated that stacking a variety of proven practices may provide the most cost effective use of conservation dollars – particularly for interim nutrient reduction goals – without requiring a wholesale production system change. This highlights an important gap in literature: a lack of understanding of either trade-offs or synergies between layered practices. While there was general consensus among the strategies on nutrient removal effectiveness and cost effectiveness for most of the conservation practices evaluated, two of the easiest practices to stack, cover crops (10%–31% N reduction; 29%–50% P reduction) and bioreactors (13%–43% N reduction), had the largest variation in assessed values between states possibly due to climatic and/or methodological differences. The practices that were the most difficult to track implementation of had relatively lower field-scale N loss reduction effectiveness, but were the least costly to implement and required relatively less production system change. Regardless, as practices are implemented across the region, tracking of efforts by the states is crucial for improved understanding of the relationships between conservation efforts and water quality.

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Appendix A. Supplementary data

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