Restructuring the P Index to Better Address P Management in New York

Quirine M. Ketterings,* Sebastian Cela, Amy S. Collick, Stephen J. Crittenden, and Karl J. Czymmek

Abstract
The New York Phosphorus Index (NY-PI) was introduced in 2001 after the release of the state’s first Concentrated Animal Feeding Operation (CAFO) Permit that required a nutrient management plan developed in accordance with NRCS standards. The stakeholder-based approach to development of the NY-PI, combined with a requirement for all regulated farms to determine a NY-PI score for all fields, ensured widespread adoption. While P management greatly improved over time, the initial NY-PI overemphasized soil-test P (STP), allowing for P addition if STP was low, even if the risk of P transport was high. Our goal was to develop a new PI approach that incentivizes implementation of best management practices (BMPs) where P-transport risk is high, building on feedback from certified planners (survey), analysis of a planner-supplied 33,000+ field database with NY-PI information, and modeling of the impacts of specific BMPs on P runoff using data from a central NY CAFO farm. We propose a new NY-PI structure that identifies landscape-driven P-transport risk if P is surface applied when crops are not actively growing to reach a raw PI score that is multiplied by credits (factors ≤ 1.0) for implementation of BMPs effective in reducing the risk of P transport. In this “Transport x BMP” approach, STP is used as P application cutoff. This approach could reduce barriers to regionalization of PIs, as states can identify landscape risk factors, soil-test cutoffs, and BMPs while maintaining the same management categories (no manure, P-removal-based rates, or N-based management).

Core Ideas
• Stakeholder engagement is essential to develop improved Phosphorus Indices (PIs).
• A “Transport x BMP”-based PI incentivizes BMP use where risk of P transport is high.
• In a “Transport x BMP”-based PI, soil-test P sets rate limits to enhance P balances.
• A “Transport x BMP”-based PI can reduce barriers to regionalization of PIs within watersheds.

The first New York Phosphorus Index (NY-PI), released in 2001, aimed to reduce P runoff risk by scoring fields for relative risk of P runoff to meet the NRCS 590 standard and to incentivize best management practices (BMPs) that are effective in reducing P runoff across the farm (Czymmek et al., 2003). In New York, the Concentrated Animal Feeding Operation (CAFO) Permit requires regulated farms to have a comprehensive nutrient management plan (CNMP) addressing fertilizer and manure management, prepared in accordance with the NRCS 590 standard (USDA-NRCS, 2013). As a result, all CAFOs, as well as animal feeding operations receiving state or federal cost-share funds for a nutrient management plan (NMP), have been required to have a NY-PI score for all fields on the farm since 2001.

The original PI, devised by Lemunyon and Gilbert (1993), was an applied assessment tool used to identify agricultural fields most vulnerable to P loss by accounting for the major source and transport factors controlling P movement. The short-term objectives included (i) development of a procedure to assess the risk for P leaving “the landform site” and traveling toward a water body, (ii) development of a method that allows users to identify critical parameters that most strongly influence the PI, and (iii) to select management practices that could significantly reduce P loss (Lemunyon and Gilbert, 1993). Primary users were envisioned to be NRCS field staff and resource planners working with farmers. As such, the PI was designed to be used by planners to affect field-based manure and P fertilizer management.

The original PI assigned a weighing factor to eight “landform site characteristics,” including soil erosion (1.5), irrigation erosion (1.5), runoff class (0.5), soil-test P (STP, 1.0), P fertilizer application rate (0.75), P fertilizer application method (0.5), organic P source application rate (1.0), and organic P source application method (1.0). Each site characteristic was described in terms of “level” using a rating system with a base of 2, with low = 1, medium = 2, high = 4, and very high = 8. The final PI score was obtained by selecting a level for each site characteristic, multiplying the score for that specific level by the weighing factor for the site characteristic, and then adding all scores. Site vulnerability ratings were low (<8), medium...
Table 1. The New York Phosphorus Index (NY-PI) approach (Source × Transport) as introduced in 2001 (Czymmek et al., 2003). The summation of scores for P sources (soil-test P [STP], fertilizer and manure P application rate, timing, and method) is multiplied by a score for particulate P transport to obtain the particulate NY-PI, and by a score for dissolved P transport to obtain the dissolved NY-PI. Transport scores are capped at one. Nitrogen (N)-based management implies that N application rates are limited to no more than the equivalent of 1 yr of crop removal of N. Phosphorus-based management implies that P application rates are limited to no more than the equivalent of 1 yr of crop removal of P. Zero means that no addition of manure or fertilizer P can take place.

<table>
<thead>
<tr>
<th>P-loss risk</th>
<th>Source factors (P source score = STP + fertilizer P + organic P)</th>
<th>Transport factors (dissolved P = D + F + FLD; particulate P = R + F + FLD + CF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>&lt;50</td>
<td>N-based</td>
</tr>
<tr>
<td>Medium</td>
<td>50–74</td>
<td>N-based</td>
</tr>
<tr>
<td>High</td>
<td>75–99</td>
<td>P-based</td>
</tr>
<tr>
<td>Very high</td>
<td>&gt;100</td>
<td>Zero</td>
</tr>
</tbody>
</table>

Source factors (P source score = STP + fertilizer P + organic P):

- Soil-test P score = 2.5 × Morgan STP (mg P kg⁻¹) + Fertilizer P × P × P × P + Manure P × P × P
- P application rate (Pa) = 0.89 × kg P₂O₅ ha⁻¹ (if fertilizer); 0.67 × kg P₂O₅ ha⁻¹ (if manure)

Transport factors (dissolved P = D + F + FLD; particulate P = R + F + FLD + CF):

- Soil drainage (D): Well or excessively well drained, Moderately well drained, Somewhat poorly drained, Poorly or very poorly drained
- Soil erosion (R): 0.224 × RUSLE⁺ erosion rate (Mg ha⁻¹)
- Flooding frequency (F): Rare or never, Occasional, Frequent
- Flow distance (FLD in feet) to blue line stream as depicted on topographic map (or equivalent): Intermittent stream, Intermittent stream, Intermittent stream

- Concentrated flow (CF) present?: No, Yes

† RUSLE, Revised Universal Soil Loss Equation.
balance declined accordingly, resulting in a much smaller P surplus (Swink et al., 2009). Assessment of whole-farm P balances (P imports with feed, fertilizer, animals, and/or bedding minus P exports through sales of milk and crops, as well as exports of animals and manure; Soberon et al., 2013) in New York and in the New York portion of the Upper Susquehanna Watershed (USW), headwaters of the Chesapeake Bay Watershed (CBW), are consistent with these trends; whole-farm P balances per hectare declined over 10 yr by 41% (statewide) and 51% (for the USW dairies), while milk production remained constant in both regions (Cela et al., 2017). Reduced P balances resulted primarily from reductions in nutrient imports (source reduction), particularly feed nutrients, reflecting increased efficiency of production over time (Cela et al., 2014, 2015, 2017; Soberon et al., 2015). These results reflected stakeholder willingness and ability to make changes that reduced the P footprint of animal agriculture in New York.

At the national level, in response to perceived lack of improvement in reduction of P loadings to many of the nation’s surface waters since introduction of the PI in 1999, as well as to criticism that some state PIs do not result in changes in P management practices, NRCS required states to evaluate and, where needed, improve PIs across the United States to better reflect site vulnerability to offsite P loss (Sharpley et al., 2011, 2012, 2013; USDA-NRCS, 2011). Title 190 (National Instruction) stated that all “NRCS P-Index tools must be calibrated,” and that, if increases in STP are expected, the NMP shall document “the soil P levels at which it is desired to convert to a P-based planning” and document when no P would be allowed (USDA-NRCS, 2011). In addition, “States must establish an upper limit of STP above which manure cannot be applied regardless of P-Index results” and “Manure P can be applied at a rate to meet the recommendation for multiple crop years as long as crop N recommendations are not exceeded” (USDA-NRCS, 2011).

In New York, while the NY-PI contributed to statewide improvements in P management (Ketterings and Czymmek, 2012), it was realized that further improvement in the NY-PI could be made, as the initial NY-PI allowed for manure and fertilizer P application that exceeded crop removal even in high-transport-risk scenarios as long as the STP was low or medium. Thus, the initial NY-PI overemphasized STP for high-risk fields. Furthermore, the Source × Transport approach resulted in an iterative process for manure and BMP allocation (setting of an initial application, evaluation of PI score and interpretation, adjustment of rates, timing, or method, reevaluation of PI score, etc.) that was time consuming and did not lend itself to clear identification of most effective BMPs for farmers. Furthermore, New York certified nutrient management planners with clients in neighboring states had voiced a desire for more unification in PI assessment across state lines, similar to feedback in other states with land area within the CBW. Thus, the states with agricultural land within the CBW started to evaluate the feasibility of PI assessments and recommendations within physiographic regions (Kleinman et al., 2012), an improvement that would be welcomed by certified planners with clients in multiple states, as documented for New York and Pennsylvania in Cela et al. (2016).

Here, we present the guiding principles, role of planner feedback (both in survey and farm data), and modeling in designing a new directionally correct PI approach. On the basis of findings and experiences with the initial NY-PI, we now propose a shift from the original Source × Transport approach to a more explicit, intuitive, and incentive-driven “Transport × BMP” approach that address the National Instruction (USDA-NRCS 2011) and is expected to be more effective (i) in implementation of BMPs in situation of high risk of P transport from farmer fields and (2) in reducing whole-farm P balances.

**Materials and Methods**

**Guiding Principles for PI Development**

A survey among certified planners, 10 yr after the implementation of the initial NY-PI, illustrated the key ingredients for success: (i) statewide awareness of environmental challenges through both regulations and extension programming; (ii) science-based, user-friendly tools that allow for farm-specific responses to the challenge of environmental sustainability; (iii) risk assessment of management alternatives through on-farm research; (iv) enforcement of regulations; and (v) existence of economically feasible farm and field management (Ketterings and Czymmek, 2012). A PI should not include assessment of factors that are (i) difficult or impossible to determine with some level of accuracy by farmers or farm advisors, (ii) unimportant in determining relative risk of P loss, and/or (iii) cannot be affected by a change in management. Instead, to meet the original objectives of the PI proposed by Lemunyon and Gilbert (1993) and the current objectives of NRCS, as documented in the National Instruction (USDA-NRCS, 2011), a PI should assess the relative risk for P leaving an agricultural field and traveling toward a water body and aid in selection of management practices that could significantly decrease the risk of P loss while also enhancing whole-farm P-use efficiency. Our primary guiding principle was that stakeholder engagement is essential when developing field-based tools that aim to affect farm management for improvement of the environment (Ketterings and Czymmek, 2012).

**Planner Survey**

Building on the importance of a stakeholder-driven process already employed with the development of the initial NY-PI, a second survey was developed to specifically request feedback on the NY-PI, while a very similar survey was conducted in Pennsylvania with focus on the Pennsylvania PI (Weld et al., 2007) to enable comparisons across state boundaries. These surveys, conducted in 2014 to 2015, showed that the current versions of each PI were well accepted in their respective states, documented the type of management practices that planners experienced as high risk, and identified overreliance on STP as an issue in high-risk scenarios (Cela et al., 2016). Lessons learned from the survey were used to guide development of a new NY-PI approach and to identify transport factors and BMPs to be included in the new NY-PI.

**Phosphorus Index Data from CNMPs**

The survey conducted in 2014 to 2015 also requested that planners share NY-PI information for farm fields, contributing to a larger statewide database of field information. Planners were eager to contribute (with approval from their clients), resulting in a statewide dataset of 33,327 farm fields from NMPs collected between 2009 and 2014. This dataset allowed us to: (i) document the statewide distribution of fields in various STP
Results and Discussion
Lessons Learned from Feedback, Database, and Modeling

The feedback from the planners indicated a high ranking for relevance of all transport $P$ factors in the initial NY-PI. They did, however, suggest that a new NY-PI could more strongly discourage manure application during winter and to fields near streams and could more strongly promote manure incorporation or injection, establishment of cover crops, maintenance of ground cover with crop residues, and implementation of setbacks within production fields and vegetated buffers outside of fields (Cela et al., 2016). This feedback was consistent with findings that the NY-PI allows for relatively high manure application rates when STP is low, even if the risk of transport of the manure to streams is high.

The NY-PI database with 33,327 farm fields showed that, under the existing NY-PI, 87, 8, 3, and 2% of all fields were classified as low, medium, high, or very high PI categories, respectively (Cela et al., unpublished data, 2016). The source factor was the main driver of the NY-PI, with STP and manure application as the main drivers of the source factor. The dissolved $P$ score tended to be greater than the particulate PI score, reflecting the fact that saturation excess is the dominant mechanism for runoff generation in New York. Flow distance to the stream was the main driver among the transport factors of the NY-PI. Increasing the weights of manure rate, timing, and method of application affected the distribution of fields across the NY-PI categories, but as a result of rounding of the transport score to a maximum of 1.0, only minor changes in the NY-PI scores were obtained by increasing the weight of transport factors (Cela et al., unpublished data, 2016).

The modeling exercises using a fixed amount of applied $P$ predicted a 34% reduction in dissolved $P$ loss with incorporation and a 69% reduction with injection across the 54 corn fields (Table 2). The impact on particulate $P$ was predicted to be much smaller, 5% for incorporation and 15% for injection (Table 2). When applications were adjusted to supply the same amount of $N$ with surface application versus incorporation or injection, relative $P$ loss was predicted to result in a much larger reduction in $P$ loss, in part reflecting the lower application rate when manure is incorporated or injected in the spring (Table 2). Implementation of cover crops in the corn rotation was predicted to slightly increase the risk of dissolved $P$ loss while considerably reducing the loss of particulate $P$, resulting in an overall reduction in $P$ runoff risk.

Proposed New PI Structure

Taking into account the findings of the planner survey (Cela et al., 2016), the analyses of the 33,327 farm fields, and the TopoSWAT modeling of BMP scenarios, we designed a new PI structure and set initial coefficients. In this new PI approach, we first identify inherent landscape risk of $P$ transport if $P$ is surface applied to bare soil, to reach a raw PI score determined by transport risk. The score is then multiplied by a BMP credit factor (factor $\leq 1.0$) for implementation of BMPs considered effective in reducing $P$-transport risk if manure were to be applied. This is a shift from the original Source $\times$ Transport approach to a more explicit, intuitive, and incentive-driven Transport $\times$ Source.
BMP approach. In this Transport × BMP approach, we propose the use of STP as a modifier of a P cutoff, recognizing the need to improve whole-farm P-use efficiency to obtain whole-farm P balances in the optimum operational zone over time (Cela et al., 2014, 2015; Soberon et al., 2015) that are consistent with the National Instruction (USDA-NRCS, 2011).

Transport Score

The landscape-driven transport factors in the proposed NY-PI structure include soil erosion, flow distance to a stream or ditch, flooding frequency, presence or absence of an untreated concentrated flow, presence or absence of a vegetated buffer outside of the field, drainage class, and subsurface drainage (Table 3). These factors are consistent with the initial NY-PI as requested by the planners (Table 1), expanded with a recognition of the importance of vegetated buffers outside of the cropped land and subsurface drainage within fields, as pointed out by planners (Cela et al., 2016). A major shift in proposed PI approach is that the transport factor reflects the anticipated risk of transport of P applied outside of the growing season to bare soil without any form of incorporation (“worst-case scenario”). Soil annual erosion rate is estimated using the Revised Universal Soil Loss Equation (USDA-ARS, 2008) as stated in the National Instruction (USDA-NRCS, 2011). The soil drainage classification is determined from a soil survey, as currently done in the NY-PI. The flooding frequency is also determined from the soil survey or from flood hazard boundary maps, when available. The flow distance is the length of the “path that excess water takes as it leaves a field and finds its way downhill to a watercourse,” as originally defined in Czymmek et al. (2003). Flow distance can be estimated by field observation or determined from topographic maps, whereby flow path is perpendicular to the contour lines.

The division in particulate and dissolved PI in the initial NY-PI was retained in the new structure as well. This was done to reflect differences in P-loss patterns and management practices to reduce dissolved versus particulate P loss (Table 3), consistent with planner feedback (Cela et al., 2016). The particulate P component of the proposed NY-PI is similar to the dissolved P component in that flooding frequency and the predominant water flow distance to a stream are included, but particulate P-loss potential is influenced by soil erosion as well. The two factors that were added on the basis of planner feedback are: (i) the presence or absence of a vegetated buffer strip outside of the production area (for both the dissolved and particulate PI transport scores), and (ii) subsurface drainage for the dissolved PI transport score. The raw PI transport score is the sum of coefficients for each of the options within landscape factors listed in Table 3.

The coefficients for various options within landscape factors (Table 3) were set to obtain NY-PI scores >100 when fields are closer than 33 m (100 feet) from a stream or ditch. In other words, the coefficients signal that manure and fertilizer P application BMPs have to be considered when manure application within 33 m is desired. This approach addresses the issue that the current NY-PI allows for surface application of manure close to streams as long as the STP of the field is low, an issue recognized by many of the planners. The initial coefficients also greatly increase the PI scores (limit manure application) when untreated concentrated flows are present, and they reward farmers for creating a vegetated buffer outside a field (Table 3).

Best Management Credits

Planners identified the calendar-based categorization of risk in the initial NY-PI as a major issue (Cela et al., 2016). They frequently remarked that, in some years, April is a safe month to apply manure, while in other years, applications would have resulted in direct runoff, hence decisions should not be based on a firm calendar date (Cela et al., 2016). Using this feedback, the list of potential BMPs was narrowed down and reorganized into two main categories: (i) timing or ground coverage condition at time of application (combined), and (ii) method of application (Table 3). Scores from these two broader categories (timing or ground coverage and method) are multiplied to obtain the BMP score for a specific field. The coefficients for each of the BMPs are set to incentivize manure incorporation and injection over surface application, application of manure to hay fields over bare ground, application close to planting, use of setbacks, and implementation of overwintering cover crops (Table 3).
The final recommendations in the new NY-PI structure (Table 3) are grouped in three categories: (i) nitrogen (N)-based applications of manure is allowed, (ii) applications of manure and fertilizer cannot exceed the annual P removal with harvest (P-based), or (iii) no manure or fertilizer P can be applied, identical to the current NY-PI (Table 1). We also retained 100 as the PI score beyond which no more manure or fertilizer P should be applied, for consistency of PI interpretations in the region.

An addition to the current structure is the use of STP to place fields in categories based on manure application cutoff (compare Tables 1 and 3). When soils test higher than a specific resource threshold, initially set at 80 mg P kg\(^{-1}\) (160 lbs P acre\(^{-1}\) on the Cornell Morgan (1941) test, equating to ~35% P saturation (Crittenden et al., 2017; Table 3), no more manure or fertilizer P should be applied. When soils test between 51 and 80 mg P kg\(^{-1}\) (100–160 lbs P acre\(^{-1}\); ~20–35% P saturation; Crittenden et al., 2017), manure can only be applied at P-based rates when P-transport risk is low. In all other situations, drawdown of STP levels by not adding manure or fertilizer P is the recommended BMP. When soils test at or below the threshold that would result in an agronomic P recommendation (20 mg P kg\(^{-1}\) [40 lbs P acre\(^{-1}\)] for the Cornell Morgan soil test; Ketterings et al., 2003), applications can be N-based if the P-transport risk is low or medium, can be P-removal-based if the transport risk is high, and are not permitted when the transport risk is very high. For all other STP levels, the recommendation is to apply up to annual P-removal rates when transport risk is medium or high and N-based rates when transport risk is low. No P application is permitted when the transport risk is very high, regardless of STP level (Table 3). The STP cutoff is included as a recognition that there is a point above which the risk of P loss from a field is too great to warrant application of P in any form, either from an environmental or finite resource conservation perspective (Sharpley et al., 2012), or where further addition of P to fields

| Overall interpretation (landscape factor score × BMP score × 10) |
|-----------------|-----------------|-----------------|------------------|
| P-loss risk     | PI score        | Cornell Morgan soil-test P† |
|                 |                 | <20 mg kg\(^{-1}\) | 20–50 mg kg\(^{-1}\) | 51–80 mg kg\(^{-1}\) | >80 mg kg\(^{-1}\) |
| Low             | <50             | N-based          | N-based          | P-based          | Zero             |
| Medium          | 50–74           | N-based          | P-based          | Zero             | Zero             |
| High            | 75–99           | P-based          | P-based          | Zero             | Zero             |
| Very high       | ≥100            | Zero             | Zero             | Zero             | Zero             |

† Morgan (1941). The Cornell guidelines for P addition to corn becomes zero when the soil-test P is 20 mg kg\(^{-1}\) (40 lbs P acre\(^{-1}\)) or higher (Ketterings et al., 2003).
that are already high in P becomes an issue of inefficient use of a limited resource. In fields with little transport risk, however, a discontinuation of P application to already excessive P soils does not have a direct impact on water quality, and setting of soil-test-based cutoffs can initiate a search for better uses of the P over time, aiding in improvement of overall P balances on farms. Thus, the structure presented in Table 3 is designed to incentivize both BMP implementation on high-risk fields and evaluation and improvements in whole-farm P management so that excessive STP levels can be avoided and/or addressed.

As designed, the new PI approach meets the National Instruction that states that (i) if increases in STP are expected, the NMP shall document “the soil P levels at which it is desired to convert to a P-based planning” and document when no P would be allowed; (ii) states must establish an upper limit of STP, above which manure cannot be applied regardless of PI results; and (iii) “manure P can be applied at a rate to meet the recommendation for multiple crop years [...] as long as crop N recommendations are not exceeded” (USDA-NRCS, 2011). The proposed NY-PI approach is more intuitive for farmers and farm planners, as it allows for ranking of all fields on a farm on the basis of inherent risk of P transport if manure was applied, and this has the added advantage of being a suitable approach to select fields for emergency spreading plans (“worst-case scenario fields”). In addition, this approach incentivizes implementation of BMPs for manure application and makes it easy to add BMPs if deemed appropriate for a specific region.

Next Steps

The proposed NY-PI structure, initial factors, and coefficients (Table 3) were introduced to New York stakeholders as a concept at a certified crop advisor conference in the fall of 2015 and were discussed with planners via a series of 4-hr meetings held at four different locations in the spring of 2016. Planners were invited to evaluate the approach, initial categories, and coefficients in more detail over the year and to share their feedback through a new set of stakeholder meetings. They were given a spreadsheet that enabled them to derive the newly proposed PI for individual farms and to adjust initial scores to evaluate ranking of fields and ability of BMPs to reduce scores. A second round of stakeholder meetings is ongoing to collect and document more detailed feedback and to evaluate the impact of changes in the NY-PI on whole-farm manure management and whole-farm N and P balances. Software tools for whole-farm P balance assessment have been developed (Soberon et al., 2013; Van Almelo et al., 2016) to aid in assessment of P-use efficiency on dairy farms.

It is understood by all that a rigorous evaluation of the proposed NY-PI is needed to determine if it flags the appropriate fields on the basis of transport risk and is directionally correct and incentivizes effective BMPs. Currently, seven New York case study farms are involved in this evaluation funded by the New York Department of Environmental Conservation, and this effort will be expanded with additional farms, aided by a new multistate Conservation Innovation Grant of USDA-NRCS. It is fully expected that the factors and scores, as initially set (Table 3), will be adjusted over time after field evaluations, more detailed literature review, comparison with PIs from different states with similar agricultural landscapes and soils, further planner feedback, and modeling of additional scenarios similar in scope to those presented in Table 2.

Parallel to efforts in New York, collaboration among states in the Northeast has been initiated to evaluate the potential for regionalization of PIs. The use of a Transport × BMP approach with agreed-on interpretation (low, medium, high, very high) is easier to regionalize than current PIs. Results of the PI surveys in New York and Pennsylvania suggested common experiences and viewpoints among stakeholders in each state, supporting the development of a single-format, physiographic-region PI over time (Crito et al., 2016). One challenge with regionalization is differences in soil-test methodologies. For example, in New York, the Cornell Morgan test (Morgan, 1941) is the main agronomic soil test, while in Pennsylvania, the Mehlich-3 test (Mehlich, 1984) is used. However, recent work on use of P saturation to determine equivalency among these two soil tests (which are not linearly correlated; Ketterings et al., 2002) shows promise that these issues can also be resolved (Crito et al., 2017). For states where Mehlich-3 and Bray-1 (Bray and Kurtz, 1945) analyses are used, setting application cutoffs will be easier since, for high-P soils, results of these two soil extraction methods are typically linearly correlated (Ketterings and Flock, 2005).

Acknowledgments

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References


