The Concept of Phosphorus Index for Identification of Phosphorus Loss Risk

II. Application of Phosphorus Index to Estimate the Risk of Off-site Agricultural Phosphorus Loss to Water Bodies

Fosfora indekss fosfora noplūdes riska noteikšanai

II. Fosfora indeksa pielietojums virszemes ūdeņu piesārņojuma riska novērtēšanā

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Abstract. Phosphorus index (PI) as a field-level assessment tool has been developed particularly for ranking the relative potential of off-site movement of phosphorus from the landscape due to increased attention on environmental risk assessment in agricultural production areas. The paper presents the results of testing the modified PI version to evaluate agricultural fields' vulnerability of P loss to surface water sources. The reliability of the PI was tested within agricultural areas in the central part of Latvia within two catchments at the field scale based on input data that could be easily derived from soil analysis and field observations. The final indices were represented as ranking of fields according to the relative risk of P losses. The PI values were compared with surface water quality monitoring results. The study found an acceptable relationship between PI rating and P concentrations in the nearest water sources monitored over the study period. Additionally, the PI can be used to identify nutrient management practices that reduce high P losses and that contribute to soil conservation and water quality. The presented PI is, however, the first version adapted to Latvia conditions.
Key words: phosphorus index application, phosphorus loss, surface water quality.

Introduction

Many factors are identified to have an impact on phosphorus (P) export from agricultural land to surface water. Two major factors influencing P movement to water body can be categorized into those that influence the source of P and those that influence its transport (McDowell, Sharpley, Folmar, 2001; McDowell, Biggs et al., 2004). Source factors that contribute to P loss include soil P concentration and the rate, timing, method and form of applied P (as fertilizer and/or manure) to soil (Shigaki, Sharpley, Prochnow, 2007; Hart, Quin, Nguyen, 2004). In general, P sources can be natural (indigenous soil P and atmospheric deposition) and anthropogenic (fertilizers applied to the soil); however, the major sources of P in the soil are mentioned inorganic and organic fertilizers, also plant residues and rock weathering. It is strongly admitted that prolonged inputs of P to soil can result in the P accumulation in topsoil and create the potential for an increase of P transfer to the wider environment (Haygarth, Condron et al., 2005). Transport factors are those mechanisms causing P movement within the landscape, such as erosion, runoff and leaching (Shigaki, Sharpley, Prochnow, 2007; Haygarth, 2004). Phosphorus index (PI) helps to identify the risk level of areas that contribute to P losses within agricultural catchments by using available data and allows making judgements of the likelihood that water bodies will meet the defined environmental objectives (Djodjic, Bergstrom, 2005). However, approaches of PI design have become rather complicated, and PI needs to be modified to local or regional conditions in order to incorporate all potential P loss pathways. A detailed literature review about PI framework is presented in the first part of this article (Bērziņa, Sudārs, 2010). The main objective of the article is to demonstrate the results of modified PI application to prioritize fields at the catchment scale based on P loss vulnerability. The calculated PI results are linked with the surface water quality measurements to analyse how the index ratings correspond to actual P losses from a site.

Table 1

Characteristics of research sites

Characteristic feature	Auce	Bauska
Catchment area	105 ha	740 ha
Median of a single field area	3.4 ha	14.9 ha
Median for a field slope	4%	<1%
Maximum for a field slope	13%	2.8%
Median of a single field pH KCl	7.2	7.3
Median of organic matter	2.8% (3 fields are located on peat with organic matter of up to 50%)	3%
Median of the soil P concentration	47 mg kg^{-1}	106 mg kg^{-1}
Drainage	Partly drained by tile drains and partly by separate drains	Tile drains
Soil cover type, % of total area	Dominating winter crops (44%) and alfalfa (37%), also pastures, idle land, cereal grasses	Dominating spring crops (58%) and winter crops (37%), also pastures, idle land, cereal grasses

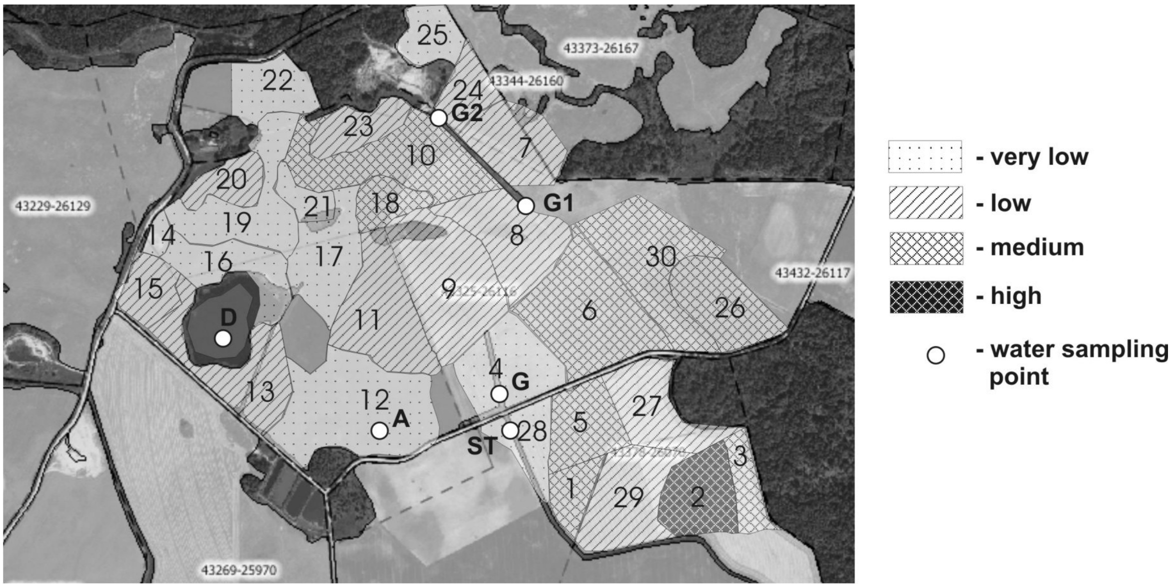

Fig. 1. Field risk classes calculated by PI and water sampling points in Auce site.

Materials and Methods

Case Study

Data for PI design evaluation were collected from 2 sites: Auce (Auce rural muinicipality) and Bauska (Gailīši rural municipality) located in the central part of Latvia with intensive agricultural production. The research site in Auce rural municipality is located in Austrumkursa highland on Carboniferous dolomite, which is covered by sandy loam and loamy sand. Glaciofluvial material has mixed layers of different permeability and forms 8–15-m-thick Quaternary deposits. Slightly undulating and somewhere rolling moraine with high slopes in the upper part of the catchment is typical for this area, with an altitude of 97–123 m above the sea level. Some layers in the parent material have high groundwater transport capacity. Springs and drainage runoff throughout the year is common for Auce area. Stagnic Cambisols (according to FAO) is the dominating soil type in the Auce site. Due to the relatively steep slopes, the soil in some parts of the catchment is eroded.

The research site in Bauska is located in Zemgale lowland. The territory of Bauska is characterized by flat relief with an average altitude of 25 m. The Upper Devonian bedrock surface is covered by a thin, 7–8 meters, cover of Quaternary deposits. Same layers of parent material have poor groundwater transport capacity. Soils in the catchment are not linked to erosion processes. Gleyic Luvisols (according to FAO) is the dominating soil type, and the main determined soil textures are loam, sandy loam, and loamy sand (according to FAO) in the Bauska site. Detailed characteristics of fields in the study sites are listed in Table 1.

Sample Collection and Processing

Soil samples from 30 fields in Auce site and soil data from 41 fields in Bauska site were analyzed. Random sampling was used to make one composite soil sample (5 subsamples) per field. Top soil samples in Auce site were taken in May, 2008, at the depth of 10 cm. The soil sampling in Bauska site was done in April, 2007. Additionally, grab water samples at 6 sampling points were collected from draining-ditches every second week during August–November of 2008 in Auce site. Surface water sample collecting was done according to guidelines of LVS ISO 5667-6:2005 and LVS ISO 5667-4:1987 A. The water sampling strategy was designed and sample sites located in order to cover a possibly wide range of runoff origin (Fig. 1). All information about surface water quality results from Bauska site makes part of Latvia agricultural runoff monitoring.

Analysis of water samples for $P_{tot.}$ and PO_4-P was carried out in the accredited laboratory “Vides audits” with standard testing methods LVS EN ISO 15681-1 ($P_{tot.}$) and LVS EN ISO 15681-1 (phosphates). Plant available soil phosphorus was determined by the Egner-Riehm method (extraction with 0.02 M calcium lactate, buffer solution pH 3.5, colorimetric determination). Soil organic carbon was determined by Tyurin method (wet oxidation using $K_2Cr_2O_7$ + H_2SO_4, spectrophotometric determination). Organic matter in soils higher than 15% was determined by loss on dry combustion at the temperature of 525 °C. Soil pH was measured potentiometrically in 1 M KCl suspension, soil/solution – 1:2.5.

Index Parameters

Parameters for PI were selected from the P indexes already used in USA and Europe to get the best characterization of their influence on P availability, movement, and management. Each parameter included in PI was evaluated taking into account Latvia conditions. The following information was available for index calculation of each field: soil P content, soil pH KCl and content of organic matter in soil, land use (dominant crop), inputs of P in fertilizers and manures, soil type, texture and field slope, field area. Data on land use and inputs of P were achieved from land users and direct on-field observations. Soil types, field slopes and drainage options were derived from drainage maps (Department of Environmental Engineering and Water Management, LLU). Firstly, the individual risk indices were calculated and applied at field scale on 30 fields in Auce site. The indexing results were validated with data from 41 samples in Bauska site.

Statistical Analyses

All fields were scored using the index model (Formula 1), and the resultant score was compared to water quality data downstream of particular fields. Relationships between calculated PI and water quality data were investigated using Spearman correlation coefficient. Nonparametric statistical analysis (Kruskal-Wallis test) was used to compare medians for P concentrations in water sampling points. The success of classification of fields for P loss was verified by discriminant analysis. All statistical analyses were made in SPSS and EXCEL, where the risk of rejecting a true hypothesis or confidence level was set at 5% (α=0.05).

PI Calculation Methodology

The tested PI consists of the two major factors: sources of P, and transport promoters of P loss. Multiplicative approach was accepted for PI calculation as:

$$PI = SF \times TF,$$
$$SF_{(1...8)} = \sum SP, AP,$$
$$TF_{(1...8)} = \sum E, R, L, D, W, B, \quad (1)$$

where

SF – source factor;
TF – transport factor;
SP – soil P status;
AP – application of P fertilizers;
E – erosion;
R – runoff;
L – leaching;
D – drainage;
W – filter wells;
B – buffers.

The source and transport factors were multiplied in order to account for evident interaction effects. Rating values of index parameters were collected in Table 2.

Table 2

Parameter values for PI calculation

P source characteristics	P loss rating value				
	Very low (1)	Low (2)	Medium (4)	High (6)	Very high (8)
1. Soil test P (mg kg^{-1} P)	<13	13–30	31–60	61–122	>122
2. Application of P fertilizers (for cultivated crop requirements)	no additional P	pastures	winter and spring crops	alfalfa, rape grassland	potatoes, beets, vegetables
P transport characteristics	**P loss rating value**				
	Very low (1)	Low (2)	Medium (4)	High (6)	Very high (8)
3. Risk of erosion (field slope)	<6%	6–9%	10–14%	15–20%	>20%
4. Risk of runoff (field slop, % and soil texture class)	– slope <0.5 and sand	– slope <0.5 and loamy sand, sandy loam – slope 0.6–3.0 and sand	– slope <0.5 and clay – slope 0.6–3 and loamy sand, sandy loam – slope >3 and sand	– slope 0.6–3 and clay – slope >3 and loamy sand, sandy loam	– slope >3 and clay
5. Risk of leaching (soil texture class)	clay	loam	sandy loam	sand	peat
6. Artificial drainage	no drainage	single tile drains	systematic tile drainage		
7. Filter wells	no filter wells on field	filter wells on field			
8. Buffers	at least 4 m wide buffer zone from field edge with perennial grassland	at least 1.5 m wide unploughed and grassed zone	no protective zone		

P risk class rating values were attached to the following intervals: very low risk (1–70), low risk (71–120), medium risk (121–170), high risk (171–300), and very high risk (>300).

Results and Discussion

PI Calculation and Risk Class Identification

Observations as well as calculation and validation of the first version of the PI for Latvia were carried out at 2 sites to reach the differences between fields regarding soil type, field slope, and soil P status that make data set suitable for a PI performance testing. Soil chemical properties showed that pH for fields were within the range of 5.5–8.1. The organic matter in these soils ranged from low to high. In Auce site, 34% of soils had less than 2.5% of organic matter, which is insufficient for sandy loam soils; 33% of soils had acceptable (2.5–3.0%) values of organic matter, and 22% of soils had high organic matter value (3.1–10%). Whereas in Bauska site, only 0.02% of soils had insufficient amount of organic matter, and 67% of soils were considered as soils with high organic matter content. According to Timbare and Reinfelde (2002), high organic matter content is within the range of 2.6–10% for loamy sand, and 2.1–10% for sand. Soil P values showed a wide range for both research sites: from 3 to 285 mg kg^{-1} of P in Auce site, and 42–535 mg kg^{-1} of P in Bauska site. According to Timbare and Reinfelde (2002), the samples from both research sites should be classified as very high in P content. It is defined that soils with very high soil P level are indicated by values of up to 96 mg kg^{-1} of P for sandy loam, up to 81 mg kg^{-1} of P_5 for loamy sand, and up to 68 mg kg^{-1} of P for sand. Excessively high concentrations of P in some agricultural soils could be linked with intensive application of swine manure on fields in the research sites. It is important to include fields with such high concentration of soil P in the environmental research, because agricultural runoff monitoring results show that P in surface water increases rapidly at higher levels of soil P concentrations. Knowledge on timing of P inputs and methods made the greatest uncertainty because these data were based only on the landowner statement. Uncertainty of fertilizer application rates consequently contributed most to the output uncertainty. Details about calculated PI summary statistics to identify fields with a high potential for P losses are presented in Table 3.

Results of fields testing with PI and P loss risk class identification in Auce are graphically presented also in Fig. 1. The median of calculated PI for Auce site reaches value 96, which, in general, shows Auce site as a low risk example of P loss, while PI median value for Bauska site reaches value 140, which falls in a medium risk class of P loss. Table 4 summarizes and compares the first results of PI scores calculated by PI approach using formula (1) for ranking fields

Table 3

Summary statistics for the PI of experimental fields

Site	Median of PI	Mode of PI	Range of PI	Minimum of PI	Maximum of PI	Median of source factor	Median of transport factor
Auce	96	72	180	1	180	6	18
Bauska	140	140	160	96	256	10	16

Table 4

Summary of risk classes for experimental fields

Site	Indicator	Risk class				Total
		1 – very low	2 – low	4 – medium	6 – high	
Auce	count	10	11	8	1	30
	% of total	33.3	36.7	26.7	3.3	100.0
Bauska	count	0	4	26	11	41
	% of total	0	9.8	63.4	26.8	100.0
Total	count	10	15	34	12	71
	% of total	14.1	21.1	47.9	16.9	100.0

Table 5

Classification results

Indicator	Risk class	Predicted risk class membership				Total
		very low	low	medium	high	
Count	very low	10	0	0	0	10
	low	0	11	4	0	15
	medium	0	0	33	1	34
	high	0	0	1	11	12
%	very low	100	0	0	0	100
	low	0	73.3	26.7	0	100
	medium	0	0	97.1	2.9	100
	high	0	0	8.3	91.7	100

according to their vulnerability to the potential of P loss. The majority of low PI index values were found in Auce site; however, most of fields in Bauska site were ranked to higher risk classes. Only one field in Auce has PI, which is defined as high, while 21 fields have PI below 120 indicating a very low or low risk of P transfer. Quite different results show data from Bauska site. There are no fields identified in the very low risk class – most of them fall in the medium and high risk of P loss.

Risk classes that represent very low and low risk for P losses refer to fields with very low indices for P source factor; however, there are fall fields with comparatively high transportation factor estimation. The class that represents medium risk of P loss includes fields with comparatively high P source factor estimation and prevalence of leaching and runoff as transportation factors, there are also fields with filter wells. The high risk class includes fields with an approximately similar evaluation of transportation factors, but very high estimations of P source, and, by reference to previous statement, fields with very high risk class were not identified within the investigation. Assuming PI values, they show that the majority of calculated PI values for fields with intensive agriculture fall in medium risk class of P loss. Generally, the source factor explained 60% of the variation in the PI, which implies that the source factor was more important for the identification of high-risk areas than the transport factor. The high P source factor for fields in Bauska site (67% of total PI variation explained by source factor) was due to high soil P status as well as a high fertilizer application rate. Due to high source factors and the uniformity of transport factors within the catchment there was a smaller variation in the PI values in Bauska site, in fact, these data resulted in comparatively high PI scores. However, regarding transport factors, the observations in Auce site showed greater variability (53% of total PI variation explained by transport factor). Overall results of the research pointed that P source factors had a decisive role for field classification.

The success of classifying was verified with discriminant analysis. Discriminant analysis is a multivariate statistical technique commonly used to build a predictive model of group discrimination based on observed predictor variables, and to classify each observation into one of the groups. The dependent variable was set as a risk class (1 – very low, 2 – low, 4 – medium, 6 – high, 8 – very high), and 8 predictor variables were utilized to predict category membership of these groups. A classification result gives a simple summary of the number and percent of subjects classified correctly and incorrectly. The output includes cross-validation table presented in Table 5.

Values in the classification table reflect the correct classification of individuals into groups based on their scores on the discriminant dimensions. As the results of analysis show, the most evident uncertainty to predict risk class is associated with the low and medium risk class group; all cases to predict very low or high risk group were correct. In general, 91.5% of originally grouped cases are supposed to be correctly classified. Overall, the study showed that the greatest uncertainties in PI estimates were for the fields with the lowest levels of soil P.

The performance of the PI was initially tested by comparing the calculated PI values with measured P concentration in surface water near to experimental fields. To test links of PI with surface water quality

Table 6

PI and P in water samples close to experimental fields

Bauska	PI	Risk class	PO_4-P, mg L^{-1}
B-1	128	medium	1.79
B-2	144	medium	0.07
B-3	196	high	2.04

there were collected water samples in six points in Auce site (Fig. 1):

- G1 – draining-ditch (eroded soils);
- G2 – draining-ditch (eroded soils);
- G – draining-ditch;
- ST – draining-ditch (peat and sandy soils);
- A – well;
- D – pond (soils with high P concentrations).

Additionally, water quality monitoring results from Bauska site were analyzed. Analysis of surface water samples clearly showed increased concentrations of P in Bauska site water samples, and P indices values were also calculated higher than for fields in Auce catchment. Mean of PO_4 concentration in the water samples taken during the investigation period close to experimental fields reached 0.013 mg L^{-1} in Auce site, and 0.9 mg L^{-1} in Bauska catchment correspondingly the average PI peak – the value 91 in Auce site, and the value 159 in Bauska site. Spearman correlation coefficient showed the potential of PI for P transfer from the agricultural catchments by describing the relationship between the P-PO_4 concentrations in surface waters and the PI at the catchment scale at the level of r=0.58 (*p*-value 0.10). This result indicates that the PI successfully ranked two catchments noting that the highest P concentrations in surface waters are close to the highest P indices. However, the objective of the PI is to define high risk areas within a catchment. In that context, it must recognize that the PI is developed for field scale risk assessment and the catchment scale testing does not directly show the applicability of the PI at field scale. Subsequently, the PI was evaluated closer to the scale for which it was developed. However, it was not possible to find statistically significant correlations between particular fields PI and P concentrations in surface water near to these fields. Moreover, it should be noted that statistically different P concentrations among water samples taken in Auce site at presented sites by Kruskal-Wallis test (Chi-Square 4.49; Asymp. Sig. 0.340) were not found. Despite the conclusion that the relationship between the P concentrations at the field scale and the PI for subsequent field had very low correlation and coefficients were nonsignificant in Auce site, individual testing of each case showed the same evident tendencies. Comparatively higher P concentrations were observed in the draining ditch next to most eroded soil. Similarly, the fields with the high ranks of runoff potential were these near the elevated P concentrations in the waters accrued. The considerable mean of P concentration (0.017 PO_4-P) in water was observed in a sampling point A (well), which could be explained by high rank of runoff risk for the field No. 12; however, the total PI value for the field shows very low risk of P loss. At the same time, it is important to note that presence of a well plays a significant role in collection of surface runoff. Research has documented that even 0.1 mg L^{-1} of total P in waters is associated with eutrophic criteria (McDowell, Sharpley, 2001). Such value of total P in water samples during investigation period occurred in water sampling points D, A, and G2, and possibly was influenced by very high P transportation factor values and prevalence of erosion, runoff and drainage risk for belonging fields. However, these fields are defined as very low and low risk class examples of P loss. The presence of drains can significantly alter the flow of nutrients, as they are designed to move the water quickly from the soil surface to recipient streams. The highest mean of P (0.022 PO_4-P) for Auce site water sampling sites was observed in sampling point G1, where 0.1 mg L^{-1} of total P in a single sample was not observed. This sampling point was located next to a field representing medium risk of P loss with maximum value (22) of transport factor sum within the investigation. The water sample analysis was also done for Bauska site. Statistically significant differences (Chi-Square 36.24; *p*-value. 0.000) were found in water samples collected from draining ditches in 3 observation points in the catchment by Kruskal-Wallis test. Furthermore, remarkable differences in P concentrations in water samples were found near fields with similar PI risk class evaluations (Table 6).

However, it is important to admit that the field next to observation point B-1 is located close to manure storage lagoons. Possibly these high concentrations result form accidental runoff from manure storage lagoons that are not considered by PI parameters. Anyway, precise interpretation about nutrient losses from agricultural areas must be considered also by pollution of point sources. If to exclude point B-1 from the analysis, the relationship between PI and P concentrations in surface water becomes statistically significant. Moreover, all collected water samples in Bauska site sampling point B-1 exceeded 0.1 mg L^{-1} of total P, for sampling points B-2 and B-3 the relative frequency of exceeding reached accordingly 0.25 and 0.88. Consequently, these results are very demonstrative to show that PI is not a P loss quantification tool but rather a P loss risk-assessment tool. The potential for P losses estimated with risk assessment tools may not always be realized in the field, especially since calculations of PI values do not cover all processes influencing P losses. There should be admitted several reasons for the low correlation for PI and P concentrations in waters within field level. Firstly, the lack of appropriate weighting of PI factors according to their relative impact on loss of P remains a weak point of the adopted index for Latvia. The first testing of the accuracy of PI showed that the index should be improved by increasing the weighting of erosion risk and runoff risk. Moreover, additional analyses could be declared as essential to facilitate PI adjustment in order to explain the influence of the factors weightings on PI scores and sensitivity of nearest water source. However, it became clear that the relative importance of different factors under field conditions and their representation in P indices could be understood after long-term experiments.

Secondly, there are suggestions that areas greater than 40–50 m from the open stream by using edge-of-field approach are less important for nutrient transfer than near-stream zones. This investigation of the PI, however, uses approach that the connectivity depends on the shape of fields in relation to the stream and not on the actual distance from the areas within the field (Bechmann, Stalnacke, Kværnø, 2007). For this purpose, a framework to identify high-risk areas should be continued in order to investigate field position influence on the P loss to nearest surface water source. Thirdly, evaluation of PI did not include P management factors according to still limited data. However, such factors as P fertilization rate, fertilizer application method, fertilizer type, and fertilization timing are very important factors to control P loss. The amount of P which enters the water body depends also on the intensity of precipitation that was not directly measured by PI.

Overall, the study illustrated the potential of the PI to detect areas with the highest risk of P loss indicating that higher PI values resulted in higher P concentrations in surface waters. Results also showed that the source factor contributed most to the variation between fields and hence were important for the identification of high-risk areas in Bauska site, while importance of transport was shown in Auce site. It was found that the soil P status described 70% of the variation in the source factor. Among the transport variables, it was found that erosion risk, runoff risk, and drainage presence risk had an important influence on the transport factor. The research affirmed that PI is not a tool to quantify how much P will enter in a water body. Instead, PI calculated the rate of movement of P from a field towards the water body, and due to P chemical properties it is possible that P will travel to a water body for a long time.

Conclusions

The first results obtained from evaluation of the first modified version of the PI indicated that the index has potential to rank fields according to the P losses. By means of the PI it was possible to detect fields and catchments with the highest measured P concentrations in surface waters. Using data from field studies in the central part of Latvia with intensive agriculture production, the PI model was validated to predict the possible P loss from a field to the nearest surface water source. PI results totaling 14% of very low risk areas, 21% of low risk areas, 48% of medium risk areas, 17% of high risk areas, and no very high risk areas from the investigated fields were obtained. Discriminant analyses confirmed PI results for successful classification of fields according to the risk class of P loss; however, testing has also shown the week points and potential directions for PI improvement. One of the challenges is to prove that the ranking of fields with the PI actually reflects the risk of P transfer from a given field to the open stream. By considering the limitations of this approach, an objective for the future is to adjust the PI more accurately to site management factors. It is also expected to add weights for each parameter and to rate the relative degree of importance of each factor with respect to the overall risk of nutrient loss. PI could be a valuable decision support tool for nutrient management according to the PI system approach simplicity and low requirements to input data.

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Anotācija

Fosfora indeksa piemērošana noteiktas teritorijas ģeoloģiskajiem, meteoroloģiskajiem un tautsaimnieciskajiem apstākļiem ir jāsaista ar fosfora noplūdes ietekmējošo faktoru izvēli, faktoru gradāciju izveidi, kā arī to ietekmes būtiskuma noteikšanu. Darbā pārbaudīta iepriekšējā pētījumā izstrādātā fosfora indeksa versija, to testējot lauksaimniecības platībās Bauskā un Aucē. Fosfora indekss tika aprēķināts 71 laukam un izvērtēts saistībā ar tuvējos virszemes ūdeņos esošo eksperimentāli noteikto fosfora savienojumu koncentrāciju. Izveidotais fosfora indekss apstiprina, ka, paaugstinoties noteikta lauka riska indeksa vērtībai, tuvējos ūdens objektos palielinās iespējamība novērot salīdzinoši augstas fosfora savienojumu koncentrācijas. Fosfora indeksa aprēķinu precizitāti palielinātu katra faktora ietekmes uz tuvējā virszemes ūdens avota kvalitāti būtiskuma jeb nozīmības svaru noteikšana un iekļaušana indeksa modelī.