Estimation of nitrogen leaching load from agricultural fields in the Puck Commune with an interactive calculator

Dawid Dybowski Corresp., 1 , **Lidia Dzierzbicka-Glowacka** 2 , **Stefan Pietrzak** 3 , **Dominika Juszkowska** 3 , **Tadeusz Puszkarczuk** 4

1 Physical Oceanography Department, Ecohydrodynamics Laboratory, Institute of Oceanology of the Polish Academy of Sciences, Sopot, Poland

2 Physical Oceanography Department, Ecohydrodynamics Laboratory, Institute of Oceanology Polish Academy of Sciences, Sopot, Poland

3 Department of Water Quality, Institute of Technology and Life Sciences in Falenty, Raszyn, Poland

4 Municipality of Puck, Puck, Poland

Corresponding Author: Dawid Dybowski
Email address: ddybowski@iopan.pl

Background: Nutrient leaching from agricultural fields is one of the main causes of pollution and eutrophication of the Baltic Sea. The amount of nitrogen leached from a particular field can be very different from the amount of nitrogen leached from other fields in a given region or even within a single farm. Therefore, it is necessary to estimate the amount of nitrogen leaching for each field separately.

Methods: An opinion poll has been conducted on 31 farms within the Puck Commune, which is approximately 3.6% of all farms in this Commune. Farmers provided data on the manner of fertilizing and cultivating crops on all their farms. For each field individually, on the basis of collected data, an estimated amount of the nitrogen leaching from the field has been determined.

Results: An interactive calculator to assist farmers in determining the amount of nitrogen leaching from the field has been developed. The influence of factors shaping the amount of nitrogen leaching from a single field has been analyzed and it has been determined that autumn ploughing (specifically its absence) and the type of cultivated soil had the greatest average influence on this value in the studied sample.

Discussion: Due to the possible ways of reducing nitrogen leaching from fields, most of the studied fields were fertilized in an appropriate manner. However, in the studied sample there are fields for which the fertilization intensity significantly exceeds the recommended doses. In this context, a tool in the form of an interactive, easy-to-use nitrogen leaching calculator should help farmers to select appropriate doses and optimal fertilization practices.

Estimation of Nitrogen Leaching Load from Agricultural Fields in the Puck Commune with an Interactive Calculator

Dawid Dybowski[1], Lidia Dzierzbicka-Glowacka[1], Stefan Pietrzak[2], Dominika Juszkowska[2], and Tadeusz Puszkarczuk[3]

[1]**Physical Oceanography Department, Ecohydrodynamics Laboratory, Institute of Oceanology Polish Academy of Sciences, Sopot, Poland**
[2]**Department of Water Quality, Institute of Technology and Life Sciences in Falenty, Raszyn, Poland**
[3]**Municipality of Puck, Puck, Poland**

Corresponding author:
Dawid Dybowski[1]

Email address: ddybowski@iopan.pl

ABSTRACT

Background: Nutrient leaching from agricultural fields is one of the main causes of pollution and eutrophication of the Baltic Sea. The amount of nitrogen leached from a particular field can be very different from the amount of nitrogen leached from other fields in a given region or even within a single farm. Therefore, it is necessary to estimate the amount of nitrogen leaching for each field separately.
Methods: An opinion poll has been conducted on 31 farms within the Puck Commune, which is approximately 3.6% of all farms in this Commune. Farmers provided data on the manner of fertilizing and cultivating crops on all their farms. For each field individually, on the basis of collected data, an estimated amount of the nitrogen leaching from the field has been determined.
Results: An interactive calculator to assist farmers in determining the amount of nitrogen leaching from the field has been developed. The influence of factors shaping the amount of nitrogen leaching from a single field has been analyzed and it has been determined that autumn ploughing (specifically its absence) and the type of cultivated soil had the greatest average influence on this value in the studied sample.
Discussion: Due to the possible ways of reducing nitrogen leaching from fields, most of the studied fields were fertilized in an appropriate manner. However, in the studied sample there are fields for which the fertilization intensity significantly exceeds the recommended doses. In this context, a tool in the form of an interactive, easy-to-use nitrogen leaching calculator should help farmers to select appropriate doses and optimal fertilization practices.

INTRODUCTION

The aim of agriculture, as well as any human economic activity, is to maximize efficiency. On the one hand, there is an attempt to maximize income (from the sale of plant and animal products). On the other hand, there is a try to reduce costs (fertilizers, equipment, activities). Modern large-scale agriculture cannot be imagined without fertilizers and pesticides. Each plant needs a certain amount of nutrients to grow. Increasing fertilizing intensity may increase the potential yield. However, this yield reaches its maximum at some point and further increases in fertilizing intensity do not increase the yield but causes additional costs. Beside the obvious costs of fertilizer and all fertilizing-related activities of the farmer, there is an additional cost to the environment (Álvarez et al., 2017; Heisler et al., 2008; Howarth, 2008). Nutrient leaching from agricultural fields is one of the main causes of pollution and eutrophication of the Baltic Sea (Elofsson, 2003; Ning et al., 2018; Voss et al., 2011; Savchuk, 2018). In 2012, approximately 48,600 tonnes of nitrogen (45.2% of total riverine nitrogen load from Poland) was delivered to the Baltic Sea as a result of farm activities in Poland (Sonesten et al., 2018).

The amount of nitrogen leached from a particular field can be very different from the amount of nitrogen leached from other fields in a given region or even within a single farm. Therefore, it is necessary to estimate the amount of nitrogen leaching for each field separately. The factors shaping magnitude of nitrogen leaching are climate, soil type and management system. Each of these factors (except the climate) may vary for different fields within a given region. Main factors related to agriculture influencing the nitrogen leaching are:

- cultivation of inter-crops,
- the time of soil tillage,
- application of natural fertilizers, especially in autumn,
- annual doses of natural and mineral fertilizers.

The Puck Commune is located in the north-eastern part of the Pomeranian Voivodeship (northern Poland), on the western shore of the Puck Bay which consists of the inner part called Puck Lagoon and the outer part of Puck Bay (see Figure 1). The boundary between them runs from the Rybitwia Sandbank to the Cypel Rewski and has two straits within which there is an intensive water exchange between the Puck Lagoon and the outer part of the Puck Bay. Watercourses from Puck Municipality flow directly into the Puck Lagoon. Special attention should be paid to the quality of freshwater entering the Puck Lagoon. Geomorphological separation of the Puck Lagoon from the rest of the Puck Bay and the fact that the area of the Puck Lagoon is 30% of the entire Puck Bay and only about 6% of the water volume of the entire Puck Bay is located within Puck Lagoon makes this water body very sensitive to pollution. The ecohydrodynamic model of the Puck Bay called EcoPuckBay, whose hydrodynamic part has been validated (Dybowski et al., 2019), is in the final stage of preparation and is the high-resolution model describing the quality of the Puck Bay waters.

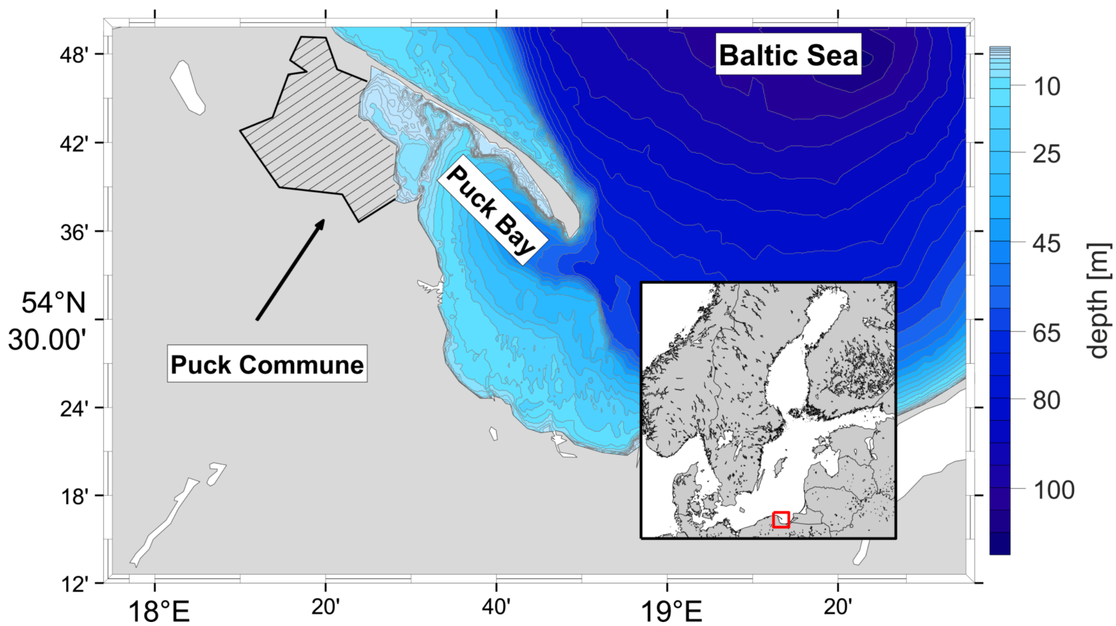

Figure 1. Localization of the Puck Commune and the bathymetry of the Puck Bay as a part of Gdańsk Basin.

The research presented in this paper was conducted as part of the project on modelling of the impact of the agricultural holdings and land-use structure on the quality of water in the Bay of Puck—Integrated information and forecasting Service "WaterPUCK" (Dzierzbicka-Głowacka et al., 2019). The aim of the research presented in this paper is to determine the approximate total nitrogen leaching from fields located in the Puck Commune. In the previous stage of work, an integrated agriculture calculator for establishing the balance of nutrients using the "At the farm gate" method was developed (Dzierzbicka-Glowacka et al., 2019).

METHODS

The method for estimating the amount of leached nitrogen from the field used in this paper has been adapted to Polish conditions by a scientific team from the Institute of Technology and Life Sciences in Falenty (Ulén et al., 2013).

We assume that the growing season lasts from 1 September of the previous year to 31 August of the current year. Nitrogen leaching begins at the beginning of autumn, immediately after harvest, and continues throughout the winter until the start of the plant growing season (see Figure2). The amount of leaching is a result of all the activities undertaken in the previous crop season, and the main factors are:

- the type of crop grown in the summer before the start of the current season,
- methods of plant fertilization and soil tillage after harvesting.

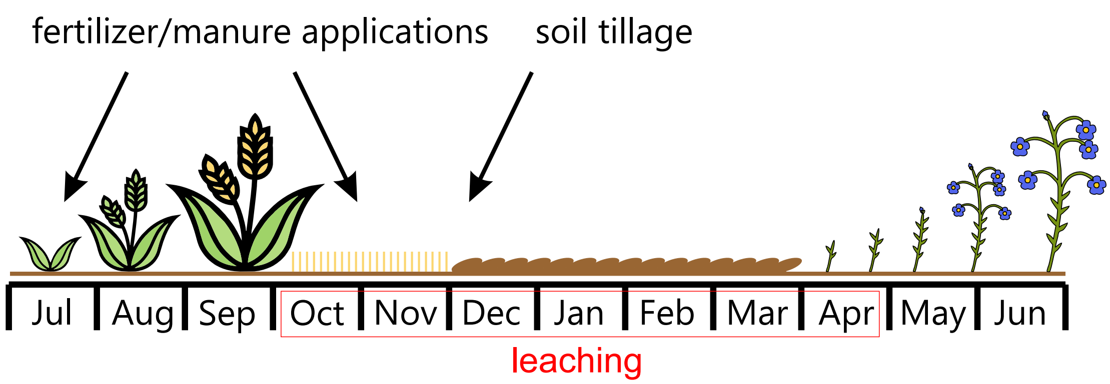

Figure 2. Nitrogen leaching period.

Factor A - soil type and the impact of the climate

In soils with high sorption capacity, the nutrients supplied with fertilizers (e. g. ammonium nitrogen, potassium, magnesium) are not leached into the soil profile and groundwater but are activated from the sorption complex during plant development. The sorption capacity is also of key importance for limiting the migration and bioavailability of trace metals. In soils with excessive metal contamination (e.g. cadmium or lead), a high sorption capacity reduces the leaching and transfer of metals to the food chain.

The total nitrogen content of the soil is most dependent on humus content, mineralization conditions shaped by water conditions of the soil and climate, the type of bedrock, the direction and degree of advancement of the soil-forming process. In soils used for agricultural purposes, an important factor shaping the nitrogen content is the level of organic and mineral fertilization and crop rotation, especially the share of legumes binding free nitrogen from the air (Lityński and Jurkowska, 1982). The vast majority of the nitrogen in the soil is incorporated into the organic part of the solid phase of the soil. Nitrogen occurs in soil in the form of mineral and organic compounds and as molecular nitrogen in soil air. It comes either from fertilization or from microbiological processes - ammonification and nitrification. On average, inorganic compounds in the topsoil represent about 5-6% of the total N content. The most easily accessible form of nitrogen for plants is inorganic nitrogen from $N\text{-}NH_4$. It varies considerably during the year depending on the weather conditions, the intensity of uptake by the plants and the amount of fertilizer applied. The content of these compounds decreases with depth.

The majority of N transformations are determined by the activity of soil microflora. The transformations of nitrogen compounds in the soil have a significant influence on the overall natural nitrogen cycle. The balance of these transformations determines the conditions of nitrogen nutrition of plants and also determines the extent to which they use nitrogen fertilization. Nitrogen mineralization consists of a set of processes leading to the formation of ammonia or ammonium nitrogen. This is essential for plants, as ammoniacal nitrogen is a form directly absorbed by their root system and is easily converted into nitrates, which are even more easily used by plants. Nitrogen losses in the soil are caused by crop cultivation, water and wind erosion and denitrification processes. Nitrogen in nitrate form can be denitrified or leached if it is not taken up by the plants. Because nitrate ions are highly mobile in soil, they move like water, i.e.

both upward (~~if precipitation is more intense than transpiration~~) and downward (otherwise). Therefore, a real threat of nitrate leaching occurs only during the winter half-year, because in the summer half-year, i. e. when the temperature exceeds 5°C, ~~evaporation~~ dominates and water ~~soaks~~ from deeper layers to the surface. Therefore, in the summer half-year nitrate leaching is recorded only in the situation of inflammable or prolonged precipitation. Nevertheless, with high nitrate content in the soil, there is a risk of eutrophication of surface and groundwater (especially the first layer) and therefore rational fertilizer management should be applied in accordance with the guidelines of the Code of Good Agricultural Practices or the Nitrate Directive.

The method used in this article defines the concept of so-called basic leaching as the equivalent of N leaching losses in conventional cereal cultivation, under conditions of sustainable mineral fertilization and mid-autumn ploughing, but without the use of natural fertilizers. When determining the basic leaching value, the soil type and average precipitation in the region have been taken into account (see Table 1).

Precipitation [mm]	sandy soil	loamy soil	clay soil	organic soil
500-700	30	20	15	30
700-1000	40	30	20	40

Table 1. Basic leaching [kg N ha^{-1}] with different amounts of precipitation and from different soil types.

It should be emphasized that basic leaching does not determine the exact amount of nitrogen leaching from a given field, because it does not take into account variations of temperature, amount of precipitation and other quantities influencing nitrogen leaching from a specific measurement year. Despite these simplifications, basic leaching calculations can help farmers better understand what factors affect nitrogen leaching and what actions they can take to reduce it.

Factor B - ~~a~~ type of crop grown in the previous season

The highest nitrogen leaching occurs in autumn and winter, i.e. at the beginning of each crop year. It is mostly determined by the way in which the field was used in the previous crop year. Thus, crops grown in the previous crop rotation also influence the level of nitrogen leaching in the current crop cycle (see Table 2.

Crop in the previous year	Factor
Cereal	1.0
Cereal followed by winter wheat	0.9
Cereal followed by winter oilseed	0.8
Cereal and oilseed with undersown catch crops	0.7
Cereal and oilseed with catch crops sown after	0.9
Cereal with undersown ley (grass and legumes)	0.7
Oilseed	1.2
Oilseed followed by winter wheat	1.1
Oilseed with undersown catch crops	0.7
Oilseed with catch crops sown after	0.9
Finalising ley without ploughing	0.6
Ley ploughed in early autumn	2.0
Ley ploughed in mid-autumn (October-December)	1.9
Potato	1.7
Potato followed by catch crop	1.2
Beet	0.9
Legumes	1.3
Flax	1.3

Table 2. Factor affecting basic leaching depending on the crop in the previous year.

So if new crops are sown in the autumn, nitrogen leaching will decrease, which must be taken into account when estimating the losses. Where temporary grassland is ploughed in spring before a new crop is introduced, particular attention should be paid and the relevant coefficient in Table 2 **should**

be multiplied by 1.5. Data from Table 2 cannot be treated only as crop-specific leaching values. For example, leaching rates in cases such as fodder crops, fallow land, sugar beet and postharvest crops include corrections (adjustments) related to other factors contributing to the reduction of nitrogen leaching, e.g. late ploughing, plough-less tillage.

Factor C - soil tillage

Frequent tillage and the associated soil mixing stimulate the release of nitrate-nitrogen from the soil, especially if the tillage is carried out at the beginning of autumn. In case of delay or failure to carry out cultivation operations in autumn, nitrate leaching is reduced. Therefore, a coefficient from Table 3 must be used, taking into account the date of ploughing in the previous year. If a perennial crop is grown in the field for fodder, the coefficient from the row 'No ploughing in the autumn' must be used. In the case of potatoes, beet and root crops, it should be assumed that harvesting means the same as soil tillage in late autumn.

Soil tillage	Factor
In early autumn (August-September)	1.0
Late autumn (October-December)	0.8
No ploughing in the autumn	0.7

Table 3. Factor estimating effect of soil tillage on nitrogen basic leaching.

Factor D - application of ~~natural~~ fertilizers

If manure is applied in autumn, some of its nitrogen content will be leached. Moreover, with fertilizer, both nitrogen available to plants (mineral) and organic nitrogen not available to them are introduced into the soil, and the release of mineral nitrogen from the latter is not always synchronised with the uptake cycle of the plants. This means that the risk of nitrogen leaching increases slightly even after spring application. As shown in Table 4, under the spring application of manure and liquid fertilizers, nitrogen leaching is only slightly higher than when only mineral fertilizers in balanced doses are applied. After the application of ~~natural~~ fertilizers in autumn, the leaching is greater than after the application of mineral fertilizers. Manure (livestock urine with a possible small amount of faeces and/or water; contains on average 1-3% of dry matter) consists mainly of ammonium nitrogen available to plants, so its fertilizing effect can be compared to that of nitrogen mineral fertilizers. Manure, on the other hand, contains almost exclusively nitrogen in organic form. Therefore, the release of mineral nitrogen from manure can be slower than from other natural fertilizers, both solid and liquid. Probably the most favourable way to use manure for nitrogen leaching is in autumn rather than in spring. There are discrepancies in the permissible date of application of fertilizers, but the provisions in this respect should be strictly observed (natural and organic fertilizers in liquid and solid form should be applied in the period from 1 March to 30 November, except for fertilizers used in crops under protection, i.e. in glasshouses, inspectorates, foil tents).

Type of manure	Autumn	Spring
Solid manure	1.15	1.10
Slurry	1.30	1.10

Table 4. Factor for additional nitrogen leaching losses compared with basic leaching depending on manure type. Based on an application rate of 20–40 tonnes ha^{-1}.

Factor E - ~~Extra~~ nitrogen leaching

When the field is fertilized with natural or mineral fertilizers at doses appropriate to the nutritional requirements of the crops grown, nitrogen leaching may be considered to be low. If too much fertilizer is applied, the leaching will increase, although an overdose of fertilizer is not intentional. Such a situation is possible during the summer drought when small plants cannot fully benefit from the nitrogen introduced with the fertilizers in spring and early summer. When estimating whether, and if so, too much nitrogen was applied on the field, it is appropriate to start by estimating the amount of nitrogen available for the crop that remained from the previous growing season, i. e. the total amount of mineral nitrogen supplied by mineral and/or natural fertilizers, and to add the amount of predicted additional leaching losses due to exceeding the optimum fertilizer application rate for average yields on different soils (expressed in kg N ha^{-1}). In this way, a sum of leaching is obtained. The amount of nitrogen applied should be compared with the recommended nitrogen dose needed to obtain planned yield of cultivated plants. A good source of information on nutrient requirements of plants is Programme of measures to reduce pollution of waters with nitrates from agricultural sources and to prevent further pollution (Ministry of Agriculture and Rural Development of Poland, 2018).

The nitrogen load applied is the sum of the amount of nitrogen from mineral fertilizer and the expected (approximately) amount of nitrogen contained in the natural fertilizers used for cultivation. If the actual amount of nitrogen is greater than the recommended amount, refer to Table 5 for the additional nitrogen leaching rate.

Excess over the recommended fertilizer intensity [kg N ha^{-1}]	sandy soil	loamy soil	clay soil	organic soil
10–20	3	2	2	3
20–30	6	4	4	6
30–40	10	5	5	10
40–50	16	7	7	16
50–60	22	8	8	22

Table 5. Estimated extra nitrogen leaching [kg N ha^{-1}] for different soil types and the amount by which the recommended fertilizer doses have been exceeded

Calculations - total nitrogen leached from field

The first step in calculating the total nitrogen leached from the field (see Figure 3 is to determine the extra nitrogen leaching from Table 5.

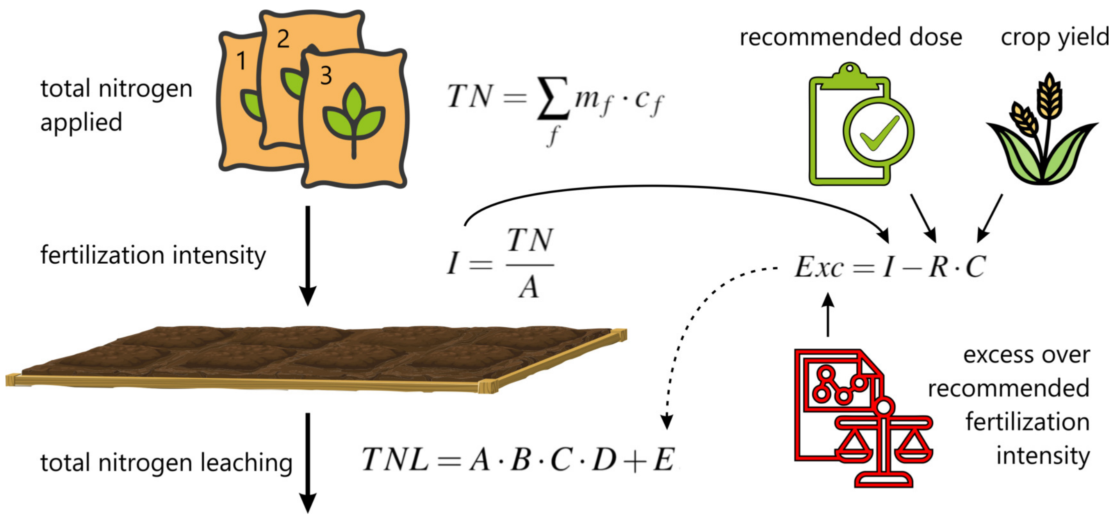

Figure 3. Scheme of total nitrogen leaching from the field calculations.

It is necessary to calculate the fertilizer intensity first as:

$$I = \frac{TN}{A}, \quad TN = \sum_f m_f \cdot c_f,$$

where I is the fertilizer intensity [kg N ha^{-1}], TN is the total nitrogen load applied to the field [kg N], A is the area of the field [ha], m_f and c_f are mass of fertilizer [kg] and nitrogen content in specific fertilizer respectively, f f indexes the fertilizers used in the field. In the next step, the excess over the recommended fertilizer intensity should be calculate as:

$$Exc = I - R \cdot C,$$

where Exc is the excess over the recommended fertilizer intensity [kg N ha^{-1}], R is the recommended nitrogen load per tonne of product [kg N tonne^{-1}], C is the crop [tonnes ha^{-1}]. Depending on the value of Exc, for a given soil type, the appropriate value of estimated extra nitrogen leaching E is now selected from Table 5. Finally, the total nitrogen leaching from the field is calculated as:

$$TNL = A \cdot B \cdot C \cdot D + E,$$

where TNL is the total nitrogen leaching from field [kg N ha^{-1}], A is basic leaching [kg N ha^{-1}] from Table 1, B is the factor affecting basic leaching depending on the crop yield in the previous year from Table 2, C is the factor estimating effect of soil tillage on nitrogen basic leaching from Table 3 and D is the factor for additional nitrogen leaching losses compared with basic leaching depending on manure type from Table 4.

Opinion poll

An opinion poll was conducted on 31 farms within the Puck Commune, which is approximately 3.6% of all farms in this Commune. Farmers provided the following data for all their fields in the survey:

- soil type (determination of factor A)
- type of crop (determination of factor B)
- date of ploughing (determination of factor C)
- information on manure (determination of factor D)
- mass of the product (determination of factor E)
- field area (determination of factor E)
- types and ~~masses~~ of mineral fertilizers applied on the field (determination of factor E)

RESULTS

Nitrogen leaching calculator

Within the WaterPUCK project, a website in the form of an interactive calculator to assist farmers in determining the amount of nitrogen leaching from the field was developed. Access to the calculator is through the main website of the project www.waterpuck.pl through the "Services" tab on navigation bar (see Figure 4).

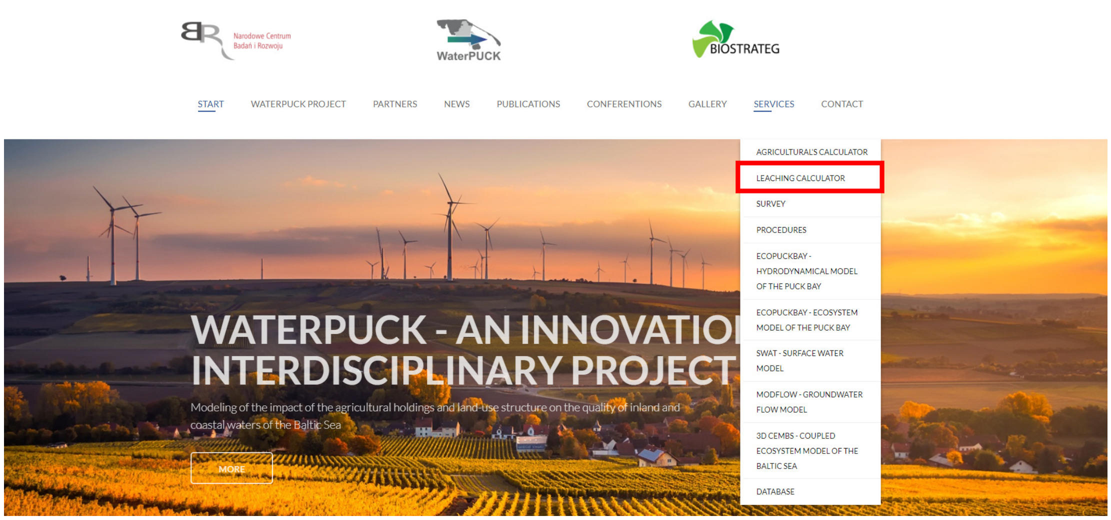

Figure 4. The selection page of the nitrogen leaching calculator.

The method of calculating nitrogen leaching from a field described in this paper has been implemented as a website's back-end. After entering the correct input data, the result is refreshed immediately. The user can easily enter the same information as collected in opinion polls into the leaching calculator (see Figure 5). Entering data is very intuitive and the result is refreshed on the fly. As a result, the farmer, agricultural adviser or other interested parties can quickly and easily obtain information about:

- basic nitrogen leaching [kg ha^{-1}],
- total mass of nitrogen applied [kg],
- modified nitrogen leaching [kg ha^{-1}],
- crop yield [tonnes ha^{-1}],
- fertilization intensity [kg ha^{-1}],
- extra nitrogen leaching [kg ha^{-1}],
- total nitrogen leaching [kg ha^{-1}],
- total nitrogen leached [kg].

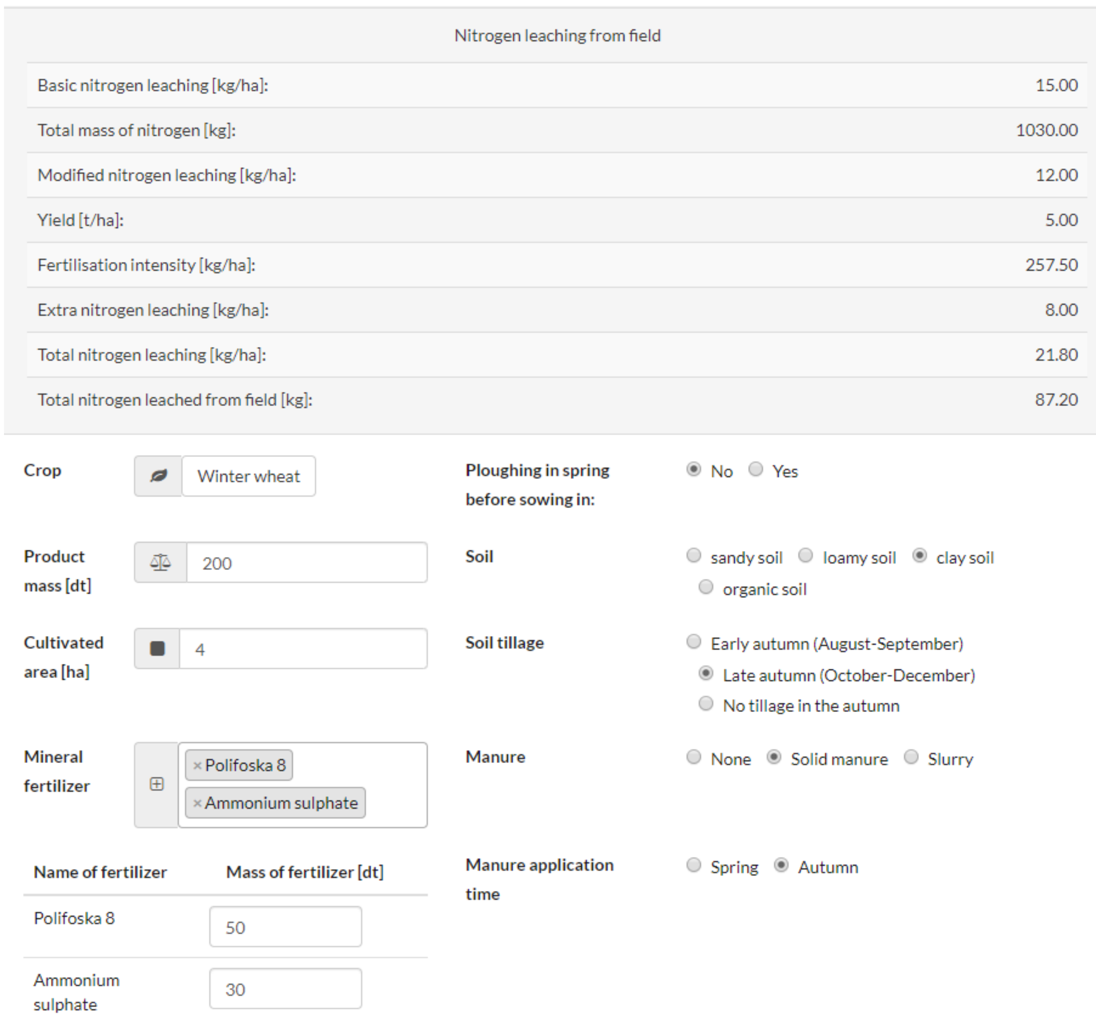

Figure 5. Calculating load of nitrogen leaching from cultivated field (website snapshot).

Using the nitrogen leaching calculator described here should help farmers to choose the right dosage of nitrogen-containing fertilizers to be applied on the field. In addition, the user of the calculator can check what effect the use of natural fertilizers will have on the nitrogen leaching. It also informs which fertilization practices increase the risk of excessive leaching of nitrogen.

Surface area of the studied fields

The Puck Commune has the area of 24 266 ha (242.6 km^2), which is 1.33% of the area of Pomeranian Voivodeship. Agricultural land is 61% of the Commune's area, including 72.7% of arable land, 19.2% of meadows, 0.2% of orchards and 4.4% of pastures. Forests are 31.2% of the Puck Commune's area. The area of 291 studied fields varies from 0.1 to 25 ha with a median of 2.3 ha. The distribution of the size of the fields according to the type of crop is shown in a box diagram (see Figure 6). On the vast majority of fields (n=182) cereals are grown and a median area of these fields is equal to 2.25 ha. The second crops with the highest number of fields are fodder crops (n=55) with a median area equal to 2.5 ha. Oilseeds are grown on 30 fields with a median area of 2.32 ha, root crops on 19 with a median area of 0.6 ha, legumes on 4 with a median area of 4.59 ha and textile crops are grown on only one field of 5 ha.

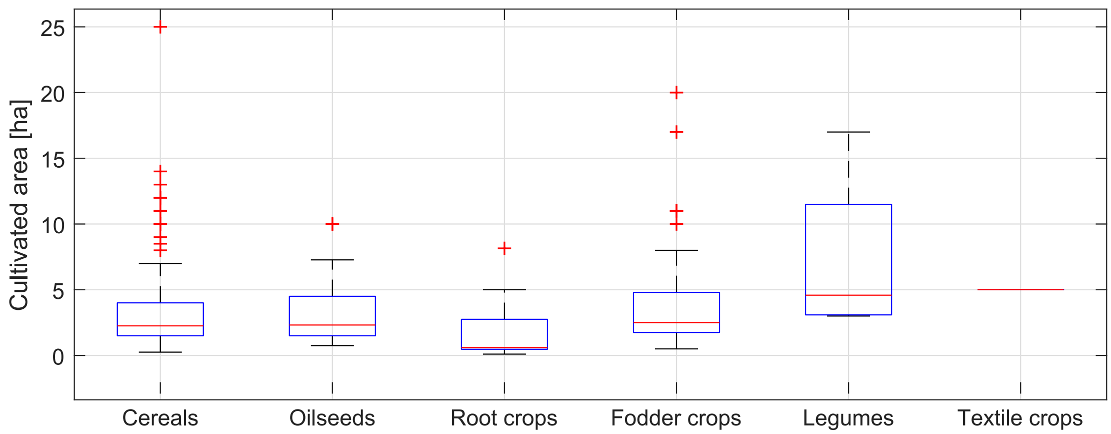

Figure 6. Box plot of the fields' area of cultivated crops on the studied farms in the Puck Commune in 2018.

The total area of all studied fields is equal to 956.74 ha which is about 6.5% of total agricultural land of the Puck Commune. Share of individual crops in the total studied area is presented in Figure 7. Cereals are grown on more than 60% of the studied area, fodder crops on 22.5%, oilseeds on 10.5%, root crops on 3.4%, legumes on 3% and textile crops on 0.5%.

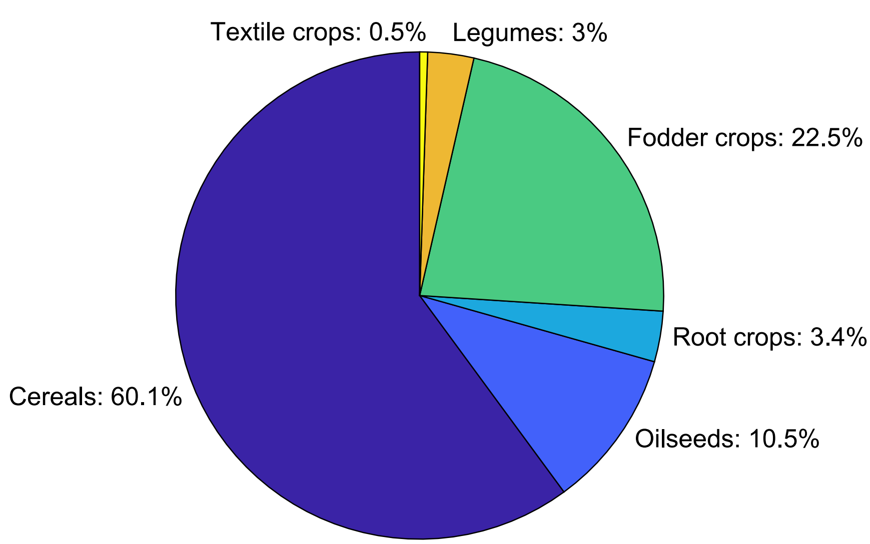

Figure 7. Share of individual crops area in the total cultivated area in 2018.

Basic leaching and its modifications

Clay soils with 15 kg N ha^{-1} of basic leaching (see Table 1) are 47.5% (n=140) of the surface area of all studied fields, loamy soils with 20 kg N ha^{-1} of basic leaching are 45.7% (n=134) and sandy together with organic soils (15 kg N ha^{-1} of basic leaching) are 6.8% (n=17) of the surface area of all studied fields. Table 2 shows that the type of crop cultivated in the previous year may have the greatest influence on the change in basic leaching and its modifications may range from -40% to 100% of the original value. The number of fields with a specific modification of base leaching is presented in Table 6.

Basic leaching modification	-30%	-20%	-10%	0%	+10%	+20%	+30%	+70%	+100%
Number of fields	1	25	26	170	23	10	16	15	5

Table 6. Number of fields with a specific modification of base leaching caused by the type of crop from the previous year.

Another factor that may influence the basic leaching is the soil tillage time. According to Table 3, the ploughing time can change the basic leaching even up to -30% (if no ploughing is done at all). Table 7 shows the number of fields depending on the ploughing time.

Soil tillage (basic leaching modification)	Number of fields
Early autumn (0%)	32
Late autumn (-20%)	98
No ploughing in the autumn (-30%)	161

Table 7. Number of fields according to soil tillage time.

The third and last factor influencing the basic leaching rate is the application of natural fertilizers. In the case of spring natural fertilizer application, basic leaching is modified by +10% regardless of the type of fertilizer. In the case of natural fertilization in autumn, the use of solid manure increases the basic leaching by 15%, while the use of slurry increases the basic leaching by 30%. The categorisation of fields by natural fertilization type is shown in Table 8.

Application time and type of manure (basic leaching modification)	Number of fields
No manure application (0%)	182
Spring - solid manure and slurry (+10%)	63
Autumn - solid manure (+15%)	43
Autumn - slurry (+30%)	3

Table 8. Number of fields with specified natural fertilization.

It should be emphasized that the change in basic leaching is the product of all three factors analyzed above. Lack of autumn ploughing or late autumn ploughing can only reduce the amount of basic leaching. However, both the type of crop cultivated in the previous year and the use of manure can potentially increase this value. Thus, the total change in basic leaching due to these factors can range from -51% to even + 160% of its initial value resulting from soil type and average annual precipitation in a given region.

Fertilization intensity

The average value of mineral fertilization intensity calculated as the sum of the total load of nitrogen applied to the fields divided by the total area of all fields is equal to 110.94 kg N ha^{-1}. The mineral fertilization intensity for each type of crop is shown in the box plot (see Figure 8). The highest average intensity of mineral fertilization was applied to oilseeds fields (140.87 kg N ha^{-1}) and the lowest to legumes and textile crops fields (32 and 34 kg N ha^{-1} respectively). The most intensively fertilized fields (about 340 kg N ha^{-1}) were cultivated with fodder crops (see Figure 10).

It should be noted that a large variation in the intensity of fertilization within a given type of crop does not necessarily mean that the intensity of fertilization deviates strongly from the recommended dose, but may result from the different nitrogen demand of plants included in a particular crop group.

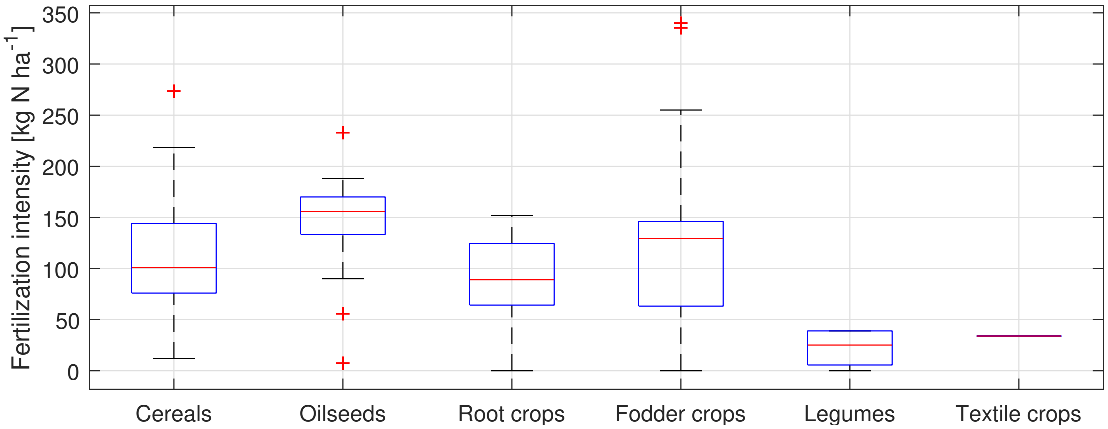

Figure 8. Box plot of the fertilization intensity of studied fields in the Puck Commune in 2018.

Extra nitrogen leaching from field

For all 291 studied fields, on the basis of calculations of exceeding the recommended fertilization intensity and data from Table 5, an estimated value of the extra nitrogen leaching was determined. For almost half of all fields (49.8%) the extra nitrogen leaching is equal to 0 kg N ha^{-1}. For 37.8% of the fields, the extra nitrogen leaching value is between 2 and 7 kg N ha^{-1}. In the remaining 12.4% of the fields, the value of the extra nitrogen leaching exceeds 7 kg N ha^{-1}. The amount of extra leaching due to the type of plant was presented as a bar chart (see Figure 9).

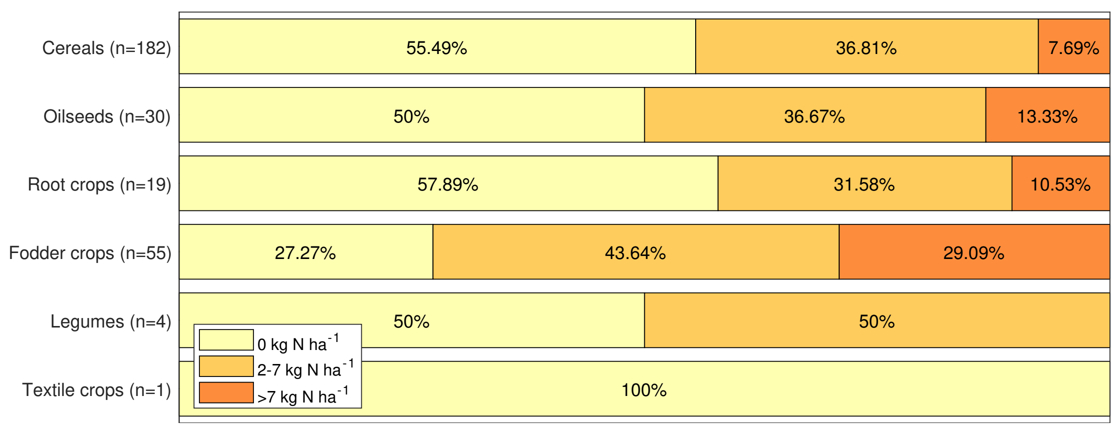

Figure 9. Extra nitrogen leaching from studied fields in the Puck Commune in 2018.

The extra leaching of nitrogen depends on the excess over recommended fertilization intensity and the soil type on which the plant is cultivated. The higher the excess of the actual fertilizer intensity over the recommended fertilizer intensity, the greater the extra nitrogen leaching from the field is (see Table 5). It is also worth comparing how the extra nitrogen leaching from the field varies due to the soil type (i. e. whether farmers apply higher than recommended doses on specific soil types). This comparison is presented in Table 9 and shows that such a relationship does not exist (i. e. the distribution of extra nitrogen leaching depending on the soil type is similar to the collective distribution for all fields).

Extra nitrogen leaching	loamy soil	clay soil	sandy and organic soils
0 kg N ha^{-1}	60	74	11
2-7 kg N ha^{-1}	57	49	4
>7 kg N ha^{-1}	23	11	2

Table 9. Number of fields with specified extra nitrogen leaching according to different soil types.

Total nitrogen leaching from field

The total estimated nitrogen leaching from studied fields varies from 4.0 to 68.2 kg N ha^{-1} with a median of 19.8 kg N ha^{-1}. The distribution of the total nitrogen leaching from field according to the type of crop is shown in a box diagram (see Figure 10).

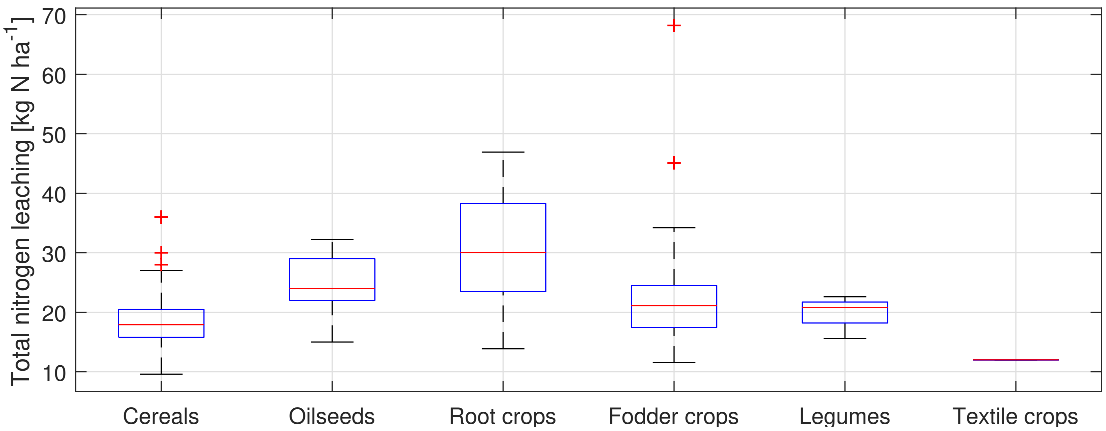

Figure 10. Box plot of the total nitrogen leaching from study fields in the Puck Commune in 2018.

The highest average total leaching of nitrogen (weighted by fields' surface areas) is for fields cultivated with root crops (about 33 kg N ha^{-1}) and the lowest for the field cultivated with textile crop (12 kg N ha^{-1}).

DISCUSSION

In the examined sample of fields, the highest percentage are fields cultivated with cereals (over 60%) while the lowest percentage are fields cultivated with legumes and textile crops (3% and 0.5% respectively). Taking into account all three factors that influence the basic leaching, i.e. the type of crop cultivated in the previous year, the time of soil tillage and the application of natural fertilizers, we can see that the most dominant factor in the examined sample is the time of soil tillage which decreases basic leaching by 30% for more than half of the studied fields. For nearly 60% of the fields, the basic leaching is not changed by the crop type in the previous year, nor is it changed for more than 60% when it comes to natural fertilizer application. Furthermore, a change of basic leaching due to no ploughing or late autumn ploughing reduces the average basic leaching of nitrogen from the fields by approximately 26% which points to very good agricultural practices on soil tillage in the studied region. The amount of basic leaching increases on average by about 12.5% by applying natural fertilizers and, on average, less than 6% by the type of crop cultivated in the previous year.

The average value of mineral fertilization intensity in the studied sample (about 110 kg N ha^{-1}) is higher than Poland's average (80 kg N ha^{-1}) while in other countries of the Baltic Sea region these values are around 30 kg N ha^{-1} in Sweden and Estonia, over 100 kg N ha^{-1} in Norway, c.a. 80 kg N ha^{-1} in Denmark and around 75 kg N ha^{-1} in Germany (European Environment Agency, 2018). A recent study conducted by Wojciechowska et al. (2019) aimed at examining loads of N and P released into the Puck Bay from three small first-order agricultural watersheds showed that the mean total nitrogen concentrations in the analysed watercourses were similar to other rivers in central Europe with medium-intensive agricultural land use in the catchments. In mentioned paper correlation were confirmed between precipitation and concentrations of nutrients in watercourses, pointing out the need for measures counteracting nutrient losses through leaching and erosion.

For almost half of all fields (49.8%) the extra nitrogen leaching is equal to 0 kg N ha^{-1} which means that for the crops grown on these fields the recommended fertilizer doses have not been exceeded. However, there are fields (12.4%) where the extra nitrogen leaching exceeds 7 kg N ha^{-1} and here is a possibility for the agricultural advisers to take action to improve the situation by consulting with the farmers cultivating these fields.

The average (weighted by the surface area of the fields) of the basic leaching of nitrogen for the studied sample resulting from the type of soil and precipitation is equal to 18.3 kg N ha^{-1}. While analogical average of basic leaching of nitrogen modified by factors resulting from the type of crop cultivated in the previous year, the time of soil tillage and the application of natural fertilizers is equal to about 17.5 kg N ha^{-1} which suggests good agricultural practices due to mentioned factors. However weighted average of total nitrogen leaching for the studied field sample is about 20.3 kg N ha^{-1} (it is greater than the median of the sample, which suggests slightly higher nitrogen leaching from relatively larger fields). Therefore, the average total nitrogen leaching is about 16% higher than the average modified basic leaching from field and it is caused by exceeding the recommended doses of mineral fertilizers.

CONCLUSIONS

The interactive nitrogen leaching calculator presented at work is a tool that allows farmers to enter data on their agricultural practices in a simple and intuitive way and that displays the results of calculations of the estimated amount of nitrogen leaching in real time. By using a calculator, farmers can also simulate the impact that a change in their current practices will have on nitrogen leaching, and thus on soil quality and potentially higher yields in the future. At a time when agriculture is aimed on a massive scale crop cultivation where fertilization and plant protection techniques are extensively used to maximize production efficiency, particular attention should be paid to the risks associated with nutrient leaching. Among these threats, the potential risk of water pollution is particularly important. Further research should be carried out and as simple to implement as possible solutions should be created for farmers, which will ensure a significant reduction in the amount of nutrient leaching from agricultural fields. Forward-looking implementations and perspectives that can improve the quality of surface runoff receivers from fields and prevent erosion include all kinds of Green Infrastructure applications such as constructed wetlands and buffer strips along river beds.

ACKNOWLEDGMENTS

The authors of this article would like to thank all the farmers who agreed to take part in the research.

REFERENCES

Dybowski, D., Jakacki, J., Janecki, M., Nowicki, A., Rak, D., and Dzierzbicka-Glowacka, L. (2019). High-Resolution Ecosystem Model of the Puck Bay (Southern Baltic Sea)—Hydrodynamic Component Evaluation. *Water*, 11(10):2057.

Dzierzbicka-Glowacka, L., Pietrzak, S., Dybowski, D., Białoskórski, M., Marcinkowski, T., Rossa, L., Urbaniak, M., Majewska, Z., Juszkowska, D., Nawalany, P., Pazikowska-Sapota, G., Kamińska, B., Selke, B., Korthals, P., and Puszkarczuk, T. (2019). Impact of agricultural farms on the environment of the Puck Commune: Integrated agriculture calculator—CalcGosPuck. *PeerJ*, 7:e6478.

Dzierzbicka-Głowacka, L., Janecki, M., Dybowski, D., Szymczycha, B., Obarska-Pempkowiak, H., Wojciechowska, E., Zima, P., Pietrzak, S., Pazikowska-Sapota, G., Jaworska-Szulc, B., Nowicki, A., Kłostowska, Z., Szymkiewicz, A., Galer-Tatarowicz, K., Wichorowski, M., Białoskórski, M., and Puszkarczuk, T. (2019). A New Approach for Investigating the Impact of Pesticides and Nutrient Flux from Agricultural Holdings and Land-Use Structures on Baltic Sea Coastal Waters. *Polish Journal of Environmental Studies*, 28(4):2531–2539.

Elofsson, K. (2003). Cost-effective reductions of stochastic agricultural loads to the Baltic Sea. *Ecological Economics*, 47(1):13 – 31.

European Environment Agency, . (2018). Agricultural land: nitrogen balance.

Heisler, J., Glibert, P. M., Burkholder, J. M., Anderson, D. M., Cochlan, W., Dennison, W. C., Dortch, Q., Gobler, C. J., Heil, C. A., Humphries, E., Lewitus, A., Magnien, R., Marshall, H. G., Sellner, K., Stockwell, D. A., Stoecker, D. K., and Suddleson, M. (2008). Eutrophication and harmful algal blooms: A scientific consensus. *Harmful Algae*, 8(1):3 – 13.

Howarth, R. W. (2008). Coastal nitrogen pollution: A review of sources and trends globally and regionally. *Harmful Algae*, 8(1):14 – 20.

Lityński, T. and Jurkowska, H. (1982). *Soil fertility and plant nutrition*. PWN, Warsaw.

Ministry of Agriculture and Rural Development of Poland, . (2018). Ordinance of the Council of Ministers of 5 June 2018 on the adoption of the "Programme of measures to reduce pollution of waters with nitrates from agricultural sources and to prevent further pollution".

Ning, W., Nielsen, A. B., Ivarsson, L. N., Jilbert, T., Åkesson, C. M., Slomp, C. P., Andrén, E., Broström, A., and Filipsson, H. L. (2018). Anthropogenic and climatic impacts on a coastal environment in the Baltic Sea over the last 1000 years. *Anthropocene*, 21:66 – 79.

Savchuk, O. P. (2018). Large-Scale Nutrient Dynamics in the Baltic Sea, 1970–2016. *Frontiers in Marine Science*, 5.

Sonesten, L., Svendsen, L. M., Tornbjerg, H., Gustafsson, B., Frank-Kamenetsky, D., and Haapaniemi, J. (2018). Sources and pathways of nutrients to the Baltic Sea : HELCOM PLC-6. Technical Report 153, Helsinki Commission.

Ulén, B., Pietrzak, S., and Tonderski, K. S. (2013). *Farms' self-evaluation in the fields of: nutrients' management and the environmental conditions' analysis*. Institute of Technology and Life Sciences in Falenty, Falenty.

Voss, M., Dippner, J. W., Humborg, C., Hürdler, J., Korth, F., Neumann, T., Schernewski, G., and Venohr, M. (2011). History and scenarios of future development of Baltic Sea eutrophication. *Estuarine, Coastal and Shelf Science*, 92(3):307 – 322.

Wojciechowska, E., Pietrzak, S., Matej-Łukowicz, K., Nawrot, N., Zima, P., Kalinowska, D., Wielgat, P., Obarska-Pempkowiak, H., Gajewska, M., Dembska, G., Jasiński, P., Pazikowska-Sapota, G., Galer-Tatarowicz, K., and Dzierzbicka-Głowacka, L. (2019). Nutrient loss from three small-size watersheds in the southern Baltic Sea in relation to agricultural practices and policy. *Journal of Environmental Management*, 252:109637.

Álvarez, X., Valero, E., Santos, R. M. B., Varandas, S. G. P., Fernandes, L. F. S., and Pacheco, F. A. L. (2017). Anthropogenic nutrients and eutrophication in multiple land use watersheds: Best management practices and policies for the protection of water resources. *Land Use Policy*, 69:1 – 11.