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Nitrogen relationships in Polish cropping systems

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Abstract: Based on FAO data, the paper presents trends in nitrogen (N) input and output in Poland. As N input (N_{inp}), nitrogen from mineral fertilisers, manure application, biological fixation, and deposition was included. The N outputs (N_{out}) include the N contained in crop harvest (main products and by-products). The trend analyses were carried out for the period before (1961–1989) and after (1990–2018) the changes in the political and economic systems. Additionally, trends in the nitrogen use efficiency (*NUE*) and nitrogen surpluses (N_S) are presented for these periods. In both compared periods, the mean values of N budget indicators in Poland were (kg N·ha^{-1} UAA): N_{inp} 120 and 125, N_{out} 61 and 84, N_S 60 and 41 and *NUE* 53 and 67%, respectively. The estimated Y_{max}, which represents the N_{out} value reached at saturating N fertilisation, reached the values of 127 and 263 kg N·ha^{-1} UAA in these periods. The difference in these values suggests a significant impact of agronomy improvement on N_{out} in the recent period. The trends of nitrogen within 16 regions in period 2002–2019, based on national data, resulted in a significant variation in N indicators. The values found were in the following ranges (kg N·ha^{-1} UAA): N_{inp} 78–167; N_{out} 62–99; N_S 15–83 and Y_{max} 139–317. The *NUE* ranged from 50–81%. The obtained results indicate that in Poland and its regions there is still a need to improve of the nitrogen efficiency.

Keywords: crops, nitrogen, trends, use efficiency, surplus

INTRODUCTION

Nitrogen is a crucial input to food production [FERNANDEZ, ROSIELLO 1995; MARSCHNER *et al.* 1996; MULLER *et al.* 2012] but if used in excess in many parts of the world it contributes to many environmental problems [BOUWMAN *et al.* 2013; CAMERON *et al.* 2013; GALLOWAY *et al.* 2008; JONES *et al.* 2014; KANTER *et al.* 2020; LEIP, UWIZEYE 2019; SUTTON *et al.* 2011]. In this situation, activities dedicated to reducing agricultural nitrogen pollution should be undertaken at farms level and beyond. Both in the case of farms [CHMELÍKOVÁ *et al.* 2021, LÖW *et al.* 2021; REIMER *et al.* 2020], as well as on regional [BASSANINO *et al.* 2011; HÄUßERMANN *et al.* 2020; ÖZBEK, LEIP 2015], country [LASSALETTA *et al.* 2014; ZHANG *et al.* 2021], continental [EINARSSON 2020; KLAGES *et al.* 2020] and global scales [HEFFER, PRUD'HOMME 2016; KALTENEGGER *et al.* 2021; KALTENEGGER, WINIWARTER 2020; LASSALETTA *et al.* 2016; MUELLER *et al.* 2014; ZHANG *et al.* 2021], nitrogen budget is a frequent tool for assessing nitrogen management.

The OECD [1993] suggested the gross nitrogen budget (GNB) as an appropriate method to calculate comparable indicators at the regional and national scale. The OECD approach was later adopted by Eurostat [KREMER 2013]. According to Eurostat/OECD [KREMER 2013], the term "nitrogen budget" is more comprehensive and appropriate than the term "nitrogen balance", as the former includes a summary of all major N flows between the major compartments of agriculture and the environment. Over the years, the calculated budgets have provided valuable data. Due to that, spatiotemporal patterns of crop N budget have important implications for agricultural N management and environmental policy.

In recent years, publications on time series cropland N budgets characterising the evolution of N input-yield response functions at global [HEFFER, PRUD'HOMME 2016; MUELLER *et al.* 2014; MUELLER *et al.* 2017], country [EINARSSON *et al.* 2021; LASSALETTA *et al.* 2014; SUŠIN, VERBIČ 2021; ZHANG *et al.* 2021], and regional [LASSALETTA *et al.* 2021] scale have become more numerous. They clearly imply that we should strive to increase nitrogen use efficiency (*NUE*) and reduce N surplus (N_S). Possibilities recognised in this regard indicate that levels of cereal production could be achieved with ~50% less nitrogen application and ∼60% less excess nitrogen [MUELLER *et al.* 2014]. If current global nitrogen applications were held constant but spatially redistributed, production could increase by ∼30% [MUELLER *et al.* 2014]. It has also been proven possible to feed the global population in 2050 with moderate animal protein consumption but with much less N pollution, and less international trade than today [LASSALETTA *et al.* 2016]. Optimal allocation of N inputs among regions to maximise *NUE* would further decrease pollution but would also require increased levels of N trade.

However, the current situation may lead to an issue where sustainably feeding 10,000,000,000 people by 2050 will require more fundamental changes in the global food system [BILLEN *et al.* 2015; BODIRSKY *et al.* 2014; IATP 2021]. In addition, the rising costs of synthetic nitrogen fertilisers, triggered by a spike in natural gas prices, have governments panicking about a catastrophic global food crisis. At the same time, new research shows that synthetic N fertilisers are a major driver of the climate crisis, responsible for 1 out every 40 Mg of GHG's currently pumped into the atmosphere [IATP 2021]. Sometimes the literature asks whether N is not a second carbon dioxide due to its impact on the climate [BATTYE *et al.* 2017]. As the 26th UN Climate Change Conference gets underway, now is the time for the world to kick its addiction to synthetic N fertilisers and urgently transition to farming without fossil fuels and chemicals.

When analysing the current and future conditions, it can be concluded that one of the "grand challenges" of this age is the anthropogenic impact exerted on the nitrogen cycle. Issues of concern range from an excess of fixed nitrogen resulting in environmental pressures for some regions, while for other regions insufficient fixed nitrogen affects food security and may lead to health risks. To address these issues, nitrogen needs to be managed in an integrated fashion, at a variety of scales (from global to local).

The article aimed to present the time trends: N input (N_{inp}), N output (N_{out}), nitrogen use efficiency (*NUE*), and N surplus (N_S) and the trajectories of N_{out} versus N_{inp}. The trajectories followed from 1961 to 1989 (the period before political and economic changes in Poland) and from 1990 to 2018. Regional analysis was carried out for the years 2002 to 2019. It was hypothetically assumed that the economic changes in Poland could have had an impact on the improvement of the efficiency of N management in the country and its regions.

MATERIALS AND METHODS

DATA

The research for Poland used FAO data for the years 1961–2018, which included N inputs (N_{inp}) from the following sources: mineral fertiliser, manure application, biological fixation, and deposition [FAO 2022]. Nitrogen from sources such as mineralisation, seed, and decomposition to inorganic material is excluded. Crop residues are also excluded, as they are assumed to stay within the system. The N outputs (N_{out}) include the N contained in crop harvest (main products and by-products). N_{inp} and N_{out} are expressed in kg N·ha^{-1} UAA.

Data for 16 NUTS 2 (Classification of Territorial Units for Statistics – from Fr. Nomenclature des unités territoriales statistiques) occurring in Poland for the years 2002–2019 came from national statistics (Fig. 1). They include the same inputs as for the whole country and, in addition, the amount of nitrogen brought in with the seeds. The outputs include the N contained in crop harvest. Nitrogen inputs and outputs are expressed in kg N·ha^{-1} utilised agricultural area (UAA).

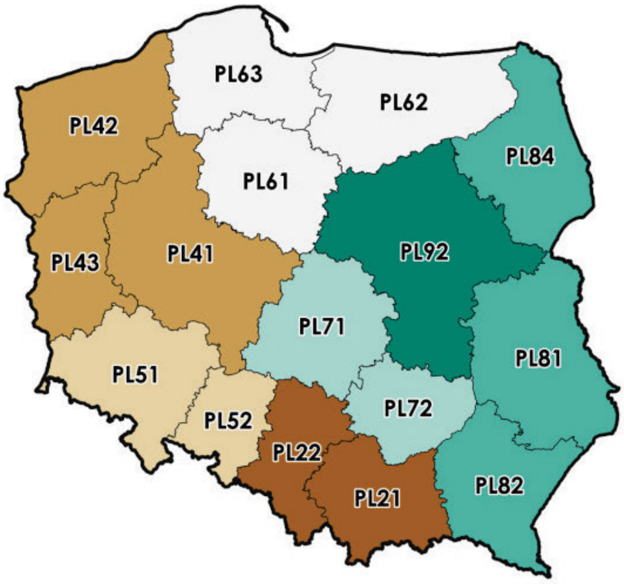

Fig. 1. Codes of Classification of Territorial Units for Statistics (NUTS 2) for 16 regions in Poland (NUTS 1 macroregions are marked with the same colours); source: own elaboration

QUALITY CHECK

The data for Poland was checked by counting a regression between N_S according to FAO data [FAO 2022] and N_S according to OECD [OECD undated] from 1985–2018. A statistically significant ($P \leq 0.001$) linear regression 1:1 was obtained with the equation: N_S *FAO* = 0.928 N_S *OECD*; R^2 = 95.6% (n = 34). Based on this analysis, it was concluded that the quality of FAO data qualifies them for further analysis.

CALCULATIONS AND STATISTICS

Following the method proposed by the EU Nitrogen Expert Panel, *NUE* and N_S were calculated [EU Nitrogen Expert Panel 2015]. According to the approach, *NUE* calculations based on N_{inp} and N_{out} provide information about resource use efficiency, the economy of food production (N in harvested yield), and the pressure on the environment (N_S).

Nitrogen use efficiency (*NUE*, %) was calculated according to the formula by EU Nitrogen Expert Panel [2015]:

$$NUE = \frac{Y_n}{F} 100 \tag{1}$$

where: Y_n = nitrogen output (kg N·ha^{-1} UAA); F = nitrogen input (kg N·ha^{-1} UAA).

The term N_{out} is equivalent to the term N yield (Y_n) and N_{inp} is equivalent to the term fertiliser rate (F).

N surplus (N_S, kg N·ha^{-1} UAA) was calculated according to the Equation (2) acc. to EU Nitrogen Expert Panel [2015]:

$$N_s = F - Y_n \tag{2}$$

Based on the country and regional data trajectories were assessed Y_n versus F as a hyperbolic function of the form [Lassaletta *et al.* 2014]:

$$Y_n = \frac{Y_{\max} F}{(F + Y_{\max})} \tag{3}$$

The parameter $Y_{\max}$ represents the Y_n value reached at saturating N fertilisation, as well as the value of fertilisation at which a definite fraction of this maximum yield is reached (this fraction is 0.5) [Lassaletta *et al.* 2014]. This parameter characterises the cropping system including crop varieties, technical management, and pedo-climatic context. As a result of the curvilinear nature of the Y_n vs F relationship, *NUE* is expected to decrease, and N_S to increase, with increasing fertilisation rate, at constant technical conditions. Only an improvement of *Ymax* can lead to increased *NUE* in the constant fertilisation rate.

The degree of N limitation (N_l) of current agricultural N yields is characterised by an indicator in the form of [Lassaletta *et al.* 2014]:

$$N_l = \frac{Y_{\max} - Y_n}{Y_{\max}} \tag{4}$$

Nitrogen limitation is a dimensionless indicator of the degree of current agricultural yields. The values of this indicator >0.75 indicate margins for increasing yields by increasing N fertilisation. On the other hand, values <0.3 indicate no benefit in terms of yield to be expected from a simple increase of N fertilisation in the absence of radical agronomical improvement of the cropping system.

Calculations for the entire country were made for the period before (1961–1989) and after (1990–2018) the changes in the political and economic systems. The command-and-distribution economy that prevailed in the first period was replaced in later years by the market system. State Farms that applied unreasonably high fertilisation were liquidated and the land was handed over to farmers. Cropping and technical management on farms have improved since. The trajectory N_{out} to N_{inp} depending on the Standardized Precipitation Index (*SPI*) was carried out for the whole data set for the country. *SPI* is a widely used index to characterise meteorological drought on a range of timescales. Positive *SPI* values indicate greater than median precipitation (i.e. wet conditions), and negative values indicate less than median precipitation (i.e. dry conditions). On the other hand, calculations for 16 NUTS 2 were made for the period of 2002–2019.

Statistical analyses were performed in the Statgraphics 19 Package (Statgraphics Centurion, Rockville, USA) [STATGRAPHICS®]. Confidence intervals for the means were estimated using the Arbitrarily Censored Data procedure at a number of bootstrap subsamples 10,000. Comparison of Regression Lines and Nonlinear Regression were also used. Variance analyses were performed as one-way ANOVA. Cluster Analysis according to Ward's method was used to compile the results for NUTS 2.

RESULTS

NITROGEN INDICATOR TRENDS AND N_{out} VERSUS N_{inp} TRAJECTORIES FOR POLAND

When comparing the N budget indicators it was found that N_{out} and *NUE* were lower and N_S higher in the period of 1961–1989 than in the period of 1990–2018 (Fig. 2). These indicators had average values: 61 and 84 kg N·ha^{-1} UAA, 53 and 67%, and 60 and 41 kg N·ha^{-1} UAA, respectively. ANOVA analyse showed that the differences in these parameters were statistically significant ($P < 0.05$). In both periods, the N_{inp} (120 and 125 kg N·ha^{-1} UAA) did not differ significantly.

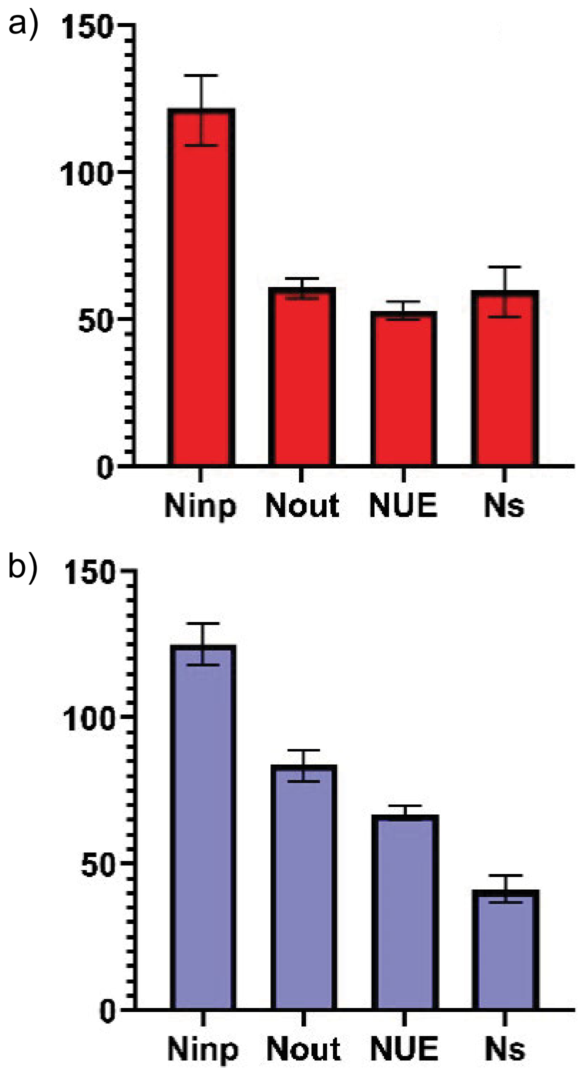

Fig. 2. Mean values of nitrogen indicators: a) in 1961–1989, b) in 1990–2018; N_{inp} = nitrogen input, N_{out} = nitrogen output, *NUE* = nitrogen use efficiency, N_S = nitrogen surplus; source: own study

N_{inp} grew in the analysed periods by 3.44 and 2.19 kg N·ha^{-1} UAA·y^{-1}, respectively (Fig. 3).

The growth dynamics of N_{out} were 1.01 and 1.45 kg N·ha^{-1} UAA·y^{-1}, respectively (Fig. 4).

The differentiation of the N_{inp} and N_{out} trends was reflected in the dependence between these variables (Fig. 5). In 1961–1989 N_{out} did not exceed the desired value of 80 kg N·ha^{-1} UAA. In the period 1990–2018, the N_{out} were larger.

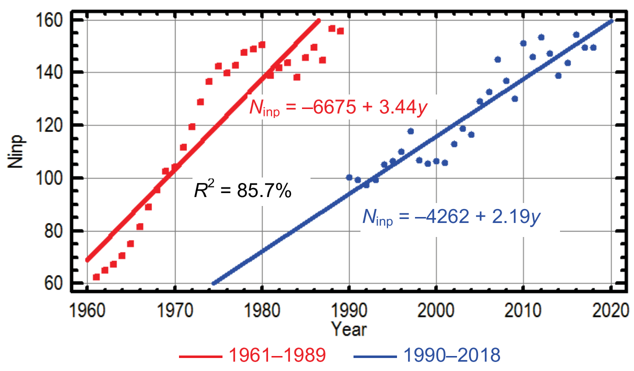

Fig. 3. Nitrogen input (N_{inp}) time trends in the periods 1961–1989 and 1990–2018; source: own study

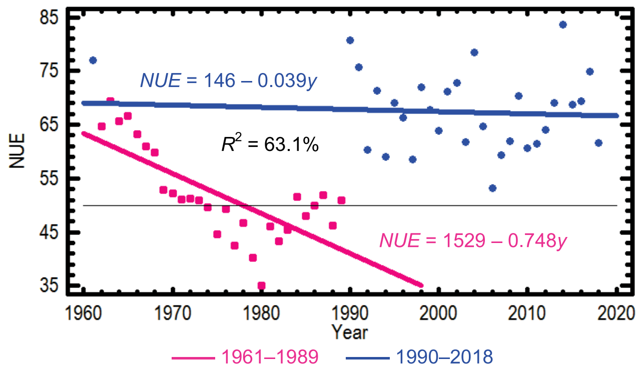

Fig. 6. Nitrogen use efficiency (*NUE*) time trends in the periods 1961–1989 and 1990–2018; the horizontal line indicates the lower value (50%) of the desired *NUE* [EU Nitrogen Expert Panel 2015]; source: own study

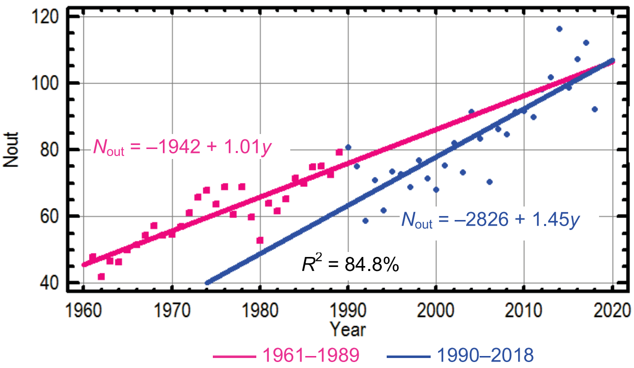

Fig. 4. Nitrogen output (N_{out}) time trends in the periods 1961–1989 and 1990–2018; source: own study

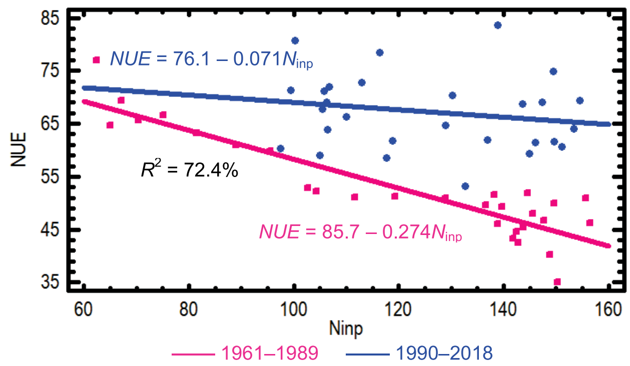

Fig. 7. The relationship between nitrogen use efficiency (*NUE*) and N input (N_{inp}) in the period 1961–1989 and 1990–2018; source: own study

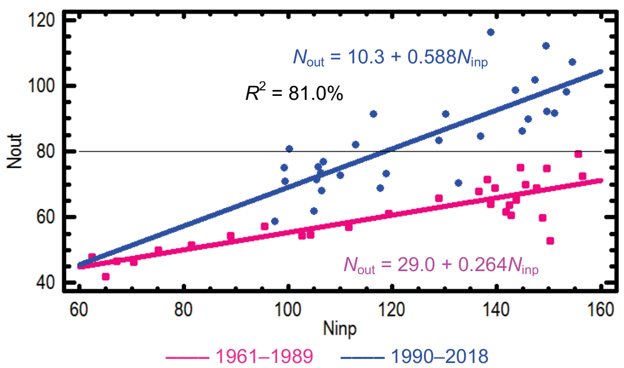

Fig. 5. The relationship between nitrogen output (N_{out}) and input (N_{inp}) in the period 1961–1989 and 1990–2018; the horizontal line indicates the lower value (80 kg N·ha^{-1}) of the desired N_{out} [EU Nitrogen Expert Panel 2015]; source: own study

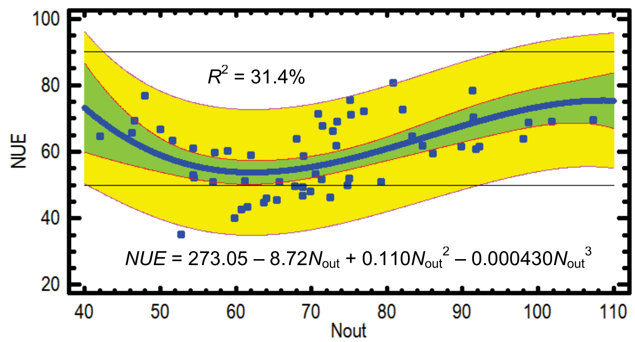

Fig. 8. The relationship between nitrogen use efficiency (*NUE*) and N output (N_{out}) in the period 1961–2018; yellow – upper and lower 95% confidence interval, the horizontal lines define the range of desired *NUE* values of 50 and 90% [EU Nitrogen Expert Panel 2015]; source: own study

The disproportionate increases in N_{out} with N_{inp} resulted in a clear differentiation of *NUE* trends. In the years 1961–1989, *NUE* decreased by 0.75%·y^{-1}, and in the period of 1990–2018 only by 0.04%·y^{-1} (Fig. 6).

The differences in *NUE* confirmed the relationship of *NUE* vs N_{inp}. Typically, *NUE* decreases as N_{inp} increases. In the first study period, *NUE* decreased sharply compared to the second study period (Fig. 7).

The relationship between *NUE* and N_{out} enables a better understanding of the dynamics of NUE (Fig. 8). It is described by a third-degree polynomial.

Initially, *NUE* decreases quite sharply with a moderate increase in N yields until the minimum functions is reached. This regularity, described in the literature, is the result of a disproportionately small increase in the nitrogen yield in relation to the large increase in the N dose. This usually occurs when the yield is also limited by factors other than nitrogen fertilisation. From the *NUE* minimum point yield have risen synchronously. This increase was attributed to an improvement in farming technique which decreased the occurrence of yield limiting and reducing factors.

As could be expected from the results presented so far, the N_{out} vs N_{inp} trajectories differed significantly. The estimated Y_{max} for the studied periods were 127 and 263 kg N·ha^{-1} UAA, respectively (Fig. 9).

The value of Y_{max} depended to a small extent on the *SPI* (Fig. 10). In the years with rainfall close to the long-term norm, in

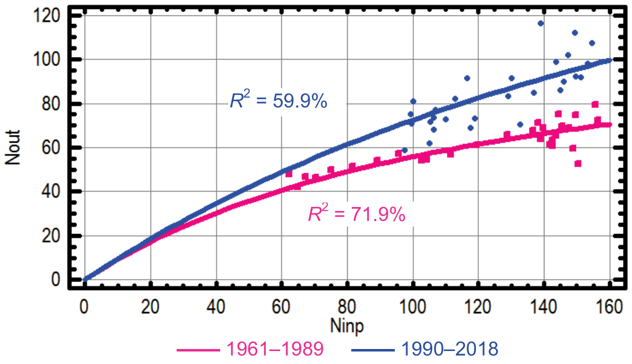

Fig. 9. Trajectories in nitrogen yields (N_{out}) vs N input (N_{inp}) for the periods 1961–1989 and 1990–2018; source: own study

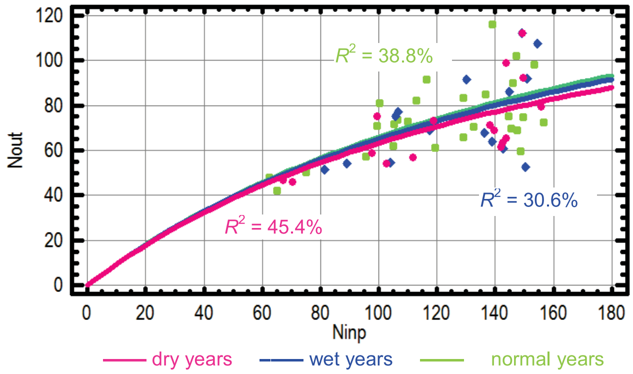

Fig. 10. Trajectories in nitrogen yields (N_{out}) vs N input (N_{inp}) depending on the Standardized Precipitation Index (*SPI*); source: own study

wet and dry years, Y_{max} was 193, 186, 171 kg N·ha^{-1} UAA, respectively.

The N limitation index (N_l) decreased over time in both analysed periods (Fig. 11). In the years 1961–1989, it reached an average value of 0.52 and a minimum value of 0.37. The latter was close to the value of 0.35, below which increasing fertilisation would be ineffective until other agronomic constraints were removed. In the years 1990–2018, N_l had an average value of 0.68 and a minimum value of 0.56 (Fig. 11). In this case, other agronomic factors limited the nitrogen yield to a lesser extent.

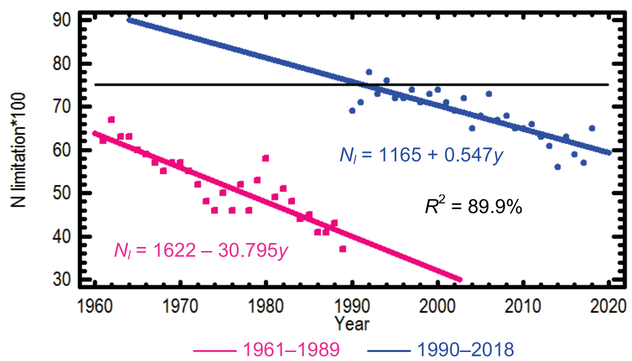

Fig. 11. Nitrogen limitation (N_l) time trends in the periods 1961–1989 and 1990–2018; the horizontal line indicating margins for increasing yields by increasing N fertilisation acc. to LASSALETTA *et al.* [2014]; source: own study

Nitrogen yield limitations, especially in the period 1961–1989 (Fig. 5) and the deteriorating *NUE* with the increase of N_{inp} (Fig. 7), had an impact on the amount of N_S (Fig. 12).

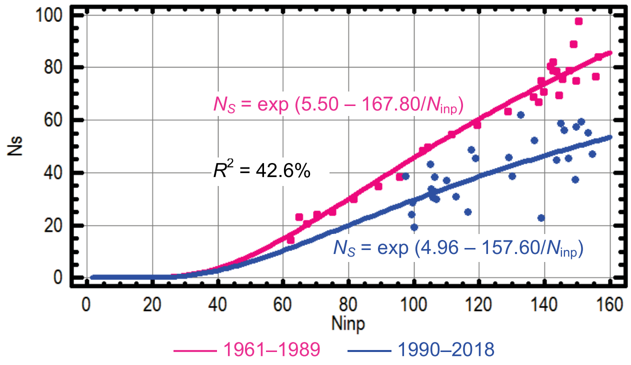

Fig. 12. The relationship between nitrogen surplus (N_S) and N input (N_{inp}) in the period 1961–1989 and 1990–2018; source: own study

Precipitation had no significant effect on the magnitude of the N_S (Fig. 13), although, the highest N_S occurred in dry years, smaller in wet years, and the lowest in years with normal precipitation.

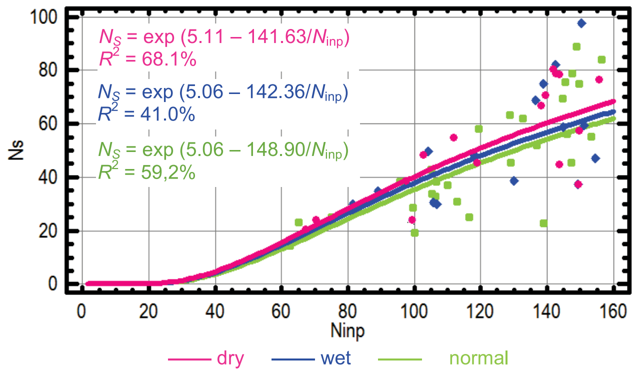

Fig. 13. Relation between N surplus (N_S) and N input (N_{inp}) in dry, wet, and normal years; source: own study

Throughout the period covered by the research, three decades particularly draw attention (Tab. 1). In the years 1980–1989, the average N_{inp} reached its maximum value before the political and economic changes. In the next decade, the value of this indicator decreased statistically significantly by 28%. In the final decade of 2009–2018, N_{inp} achieved the same value as before the political and economic transformations. The N_{inp} changes did not result in significant N_{out} differences in the first two decades compared.

Table 1. Average values of N indices in three selected decades

Decade	N_{inp}	N_{out}	*NUE* (%)	N_S (kg N·ha^{-1} UAA)
	kg N·ha^{-1} UAA			
1980–1989	146	69	47	78*
1990–1999	105*	71	68*	34*
2009–2018	146	100*	68*	46*

Explanations: N_{inp} = nitrogen input, N_{out} = nitrogen output, N_S = nitrogen surplus, *NUE* = nitrogen use efficiency, * = statistically significant differences ($P < 0.001$).
Source: own study.

In the third of them, N_{out} increased statistically significantly by 43%. The very low *NUE* in the first decade increased statistically significantly in the second and third by the same value of 31%. This resulted in a statistically significant decrease in N_S in the second and third decade by 57 and 40%, respectively.

NITROGEN INDICATOR TRENDS AND N_{out} VERSUS N_{inp} *F* TRAJECTORIES FOR REGIONS IN POLAND

Nitrogen input trends were increasing in all NUTS 2 regions except PL21 and PL82 (Fig. 14). The latter are regions with a large share of fragmented farms, where there are socio-economic limitations.

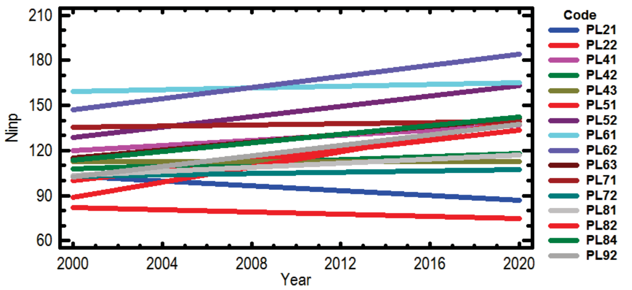

Fig. 14. Nitrogen inputs (N_{inp}) trends in 16 NUTS 2 regions (R^2 = 85.6%); NUTS codes as in Fig. 1; source: own study

Growing N_{out} trends were found in all studied regions (Fig. 15). The maximum values of this variable were less than 80 kg N·ha^{-1} UAA in the PL72 and PL82 regions.

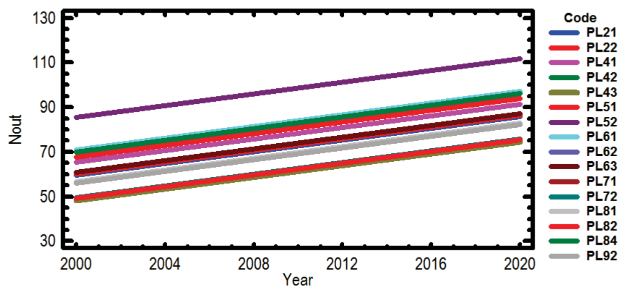

Fig. 15. Nitrogen output (N_{out}) trends in 16 NUTS 2 regions (R^2 = 69.3%); NUTS codes as in Fig. 1; source: own study

Nitrogen use efficiency trends were increasing except for PL51 and PL92 (Fig. 16).

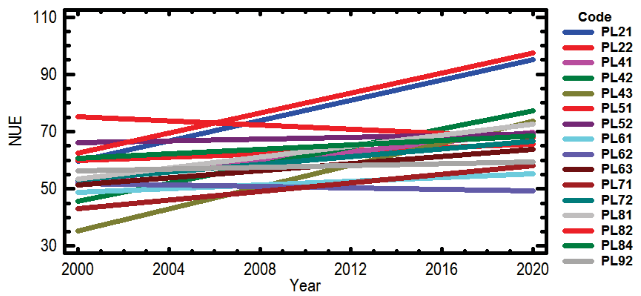

Fig. 16. Nitrogen use efficiency (*NUE*) trends in 16 NUTS 2 regions (R^2 = 68.4%); NUTS codes as in Fig. 1; source: own study

The most diverse trends were found in the case of N surplus (Fig. 17). The value of this indicator decreased in the regions of PL21, PL41, PL42, PL43, PL63, PL71, PL72, PL81, and PL82. In some years, N soil mining was found in the regions of PL21 and PL82. N surplus grew in the remaining regions.

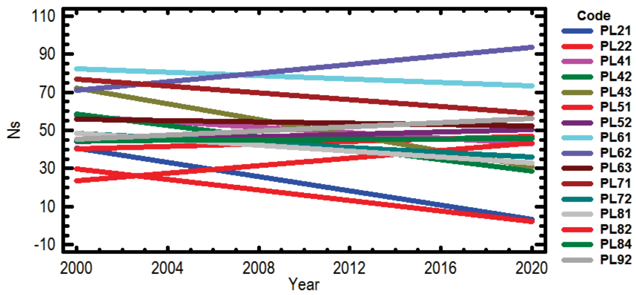

Fig. 17. Nitrogen surplus (N_S) trends in 16 NUTS 2 regions (R^2 = 75.9%); NUTS codes as in Fig. 1; source: own study

The regional differentiation of the mean values of nitrogen indicators was quite large (Tab. 2). The values found were in the following ranges (kg N·ha^{-1} UAA): N_{inp} 78–167; N_{out} 62–99; N_S 15–83 and Y_{max} 139–317. The *NUE* ranged from 50 to 81% and the N_l range was 0.50–0.80. It was found that in 11 regions the mean N_{out} was below the desired value of 80 kg N·ha^{-1} UAA [EU Nitrogen Expert Panel 2015].

Table 2. Values of nitrogen indicators for 16 NUTS 2 regions in 2002–2019

NUTS code	N_{inp} (kg N·ha^{-1} UAA)	N_{out} (kg N·ha^{-1} UAA)	*NUE* (%)	N_S (kg N·ha^{-1} UAA)	Y_{max} (kg N·ha^{-1} UAA)	N_l (–)
PL21	95	73	78	21	317	0.77
PL22	118	74	63	44	203	0.64
PL41	129	79	61	50	206	0.62
PL42	113	70	62	43	187	0.63
PL43	113	62	55	51	139	0.55
PL51	115	81	71	34	275	0.70
PL52	147	99	68	47	310	0.68
PL61	162	85	52	78	177	0.52
PL62	167	84	50	83	170	0.50
PL63	129	75	58	54	181	0.59
PL71	137	70	51	67	143	0.51
PL72	105	63	60	42	160	0.60
PL81	110	70	64	40	195	0.64
PL82	78	63	81	15	310	0.80
PL84	129	84	65	45	243	0.66
PL92	121	70	58	51	168	0.58

Explanations: mean values are given in the Table except Y_{max}, NUTS-2 codes as in Fig. 1, N_{inp} = nitrogen input, N_{out} = nitrogen output, *NUE* = nitrogen use efficiency, N_S = nitrogen surplus, Y_{max} = N_{out} at saturating N_{inp}, N_l = nitrogen limitation.
Source: own study.

NUTS 2, due to the examined features, can be divided into four relatively homogeneous groups (clusters), as shown by the cluster analysis (Fig. 18). The differentiation of the examined features in the separate groups was quite significant (Tab. 3).

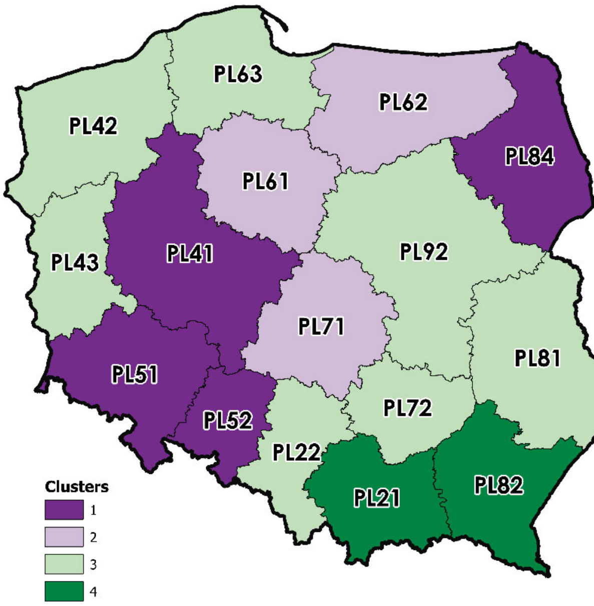

Fig. 18. NUTS 2 clusters based on the studied characteristics; source: own study

Table 3. Values of examined features in selected clusters

Cluster	N_{inp}	N_{out}	*NUE* (%)	N_S	Y_{max}	N_l (–)
	kg N·ha^{-1} UAA			kg N·ha^{-1} UAA		
1	130	86	66	44	259	0.67
2	155	80	51	76	163	0.51
3	116	69	60	46	176	0.60
4	87	68	80	18	314	0.79

Explanations: clusters and NUTS 2 in clusters as in Fig. 17, N_{inp}, N_{out}, *NUE*, N_S, Y_{max}, N_l as in Tab. 2.
Source: own study.

DISCUSSION

Historic and current N_{out} and N_{inp} relationships, *NUE*, and N_S are calculated to monitor the evolution of nitrogen management over time. They were presented for Poland and 16 NUTS 2 regions.

Input–output estimates of nitrogen on cropland are essential for improving nitrogen management and better understanding the nitrogen cycle [Zhang *et al.* 2021]. It was found that in Poland in the period before the political and economic transformation (1961–1989), N_{inp} grew dynamically from 62 to 156 kg N·ha^{-1} UAA, reaching an average value of 120 kg N·ha^{-1} UAA (Figs. 2a, 3). The new economic conditions after the transformation (1990–2018) initially resulted in a radical decrease in N_{inp}, which however, grew over time (98–154 kg N·ha^{-1} UAA) reaching the average value of 125 kg N·ha^{-1} UAA (Figs. 2b, 3). The presented average values were lower than the average N_{inp} for Europe, which is 145 kg N·ha^{-1} [de Vries *et al.* 2021]. They were also significantly below the value of 227 kg N·ha^{-1} UAA found in neighbouring Germany [Häußermann *et al.* 2020]. The N_{out} found for the first period of research fluctuated within the limits of 42–79 kg N·ha^{-1} UAA, reaching the mean value of 61 kg N·ha^{-1} UAA (Figs. 2a, 4). These values are lower than 80 kg N·ha^{-1} which is considered a minimum desirable value for N_{out} [EU Nitrogen Expert Panel 2015]. Such low nitrogen yields were the result of agronomic neglect in that period. The situation slightly improved in the second period of the study, when N_{out} ranged between 59 and 116 kg N·ha^{-1} UAA with an average of 84 kg N·ha^{-1} UAA (Figs. 2b, 4). This was achieved thanks to the agronomic improvements in recent years (e.g. new varieties, better technical equipment, more efficient plant protection, more balanced fertilisation).

The average crop N_{out} in the EU for the year 2010 is 92 kg N·ha^{-1} UAA [de Vries *et al.* 2021]. The N_{out} for Germany, amounting to an average of 149 kg N·ha^{-1} UAA, is higher than the values recorded for Poland and EU due to the higher N_{inp} [Häußermann *et al.* 2020].

NUE is an indicator of nutrient management performance, which reflects the efficiency of uptake by crops of the N_{inp} to a crop production system. These indicator levels and trends vary widely between regions and countries because of the diversity of soils, crops, climate, farmers access to technology and knowledge, and policy priorities. However, *NUE* tends to follow a typical trend concerning yield over time, with different countries being at different points on the curve [Heffer, Prud'homme 2016]. When N application rates are low, N yield is usually low but *NUE* levels can be relatively high. As fertiliser application rates increase, yield rises while *NUE* contracts up to a certain point. Beyond that point, *NUE* and yield increase in synchrony, reflecting adoption of fertiliser best management practices. This typical evolution of *NUE* was confirmed in our research (Fig. 8).

The mean *NUE* and its ranges in the compared periods reached the values of 53% (35–77%) and 67% (53–84%), respectively (Fig. 6). For the second period of our research, they are comparable with the mean *NUE* values for the EU and Germany, which were 63% and 66%, respectively [de Vries *et al.* 2021; Häußermann *et al.* 2020]. The *NUE* for the world has been estimated at 40–53% of fertiliser N recovered by the crop [Zhang *et al.* 2021]. *NUE* of European agriculture has increased, but by far not enough to sufficiently reduce N losses and meet environmental targets [van Grinsven *et al.* 2014]. To achieve surface water quality targets without crop production losses, average *NUE* needs to increase from 64 to 78%, whereas achieving groundwater targets only requires a modest increase from 64 to 67% [Schulte-Uebbing *et al.* 2021]. In hotspot areas, however, crop production and N thresholds can only be reconciled at *NUE*'s of >90%, which is not feasible. Reducing manure NH_3 emission fractions to 0.10 by adopting best-management practices reconciles current crop production and thresholds for agricultural NH_3 emission (given critical deposition) only on a half of the agricultural area. In some regions, technologically feasible improvements in N management are thus insufficient to both maintain current crop production and respect environmental boundaries. Overall, the evaluated measures could reconcile ~80% of current EU crop production with N thresholds. Summing up the considerations on *NUE* so far, it is justified to say that we still urgently need to increase *NUE* on a global, European, and national scale.

Three strategies for increasing *NUE* have been conceptualised by considering the characteristic saturating response function of N yield (N_{out}) to increasing N_{inp}, where the yield response to increasing N_{inp} is near-linear at low N application rates and saturates at high N application rates [Bodirsky, Müller 2014]. These included: i) a reduction in N_{inp} and yield in a cropping system which will tend to increase *NUE* by operating closer to the linear portion of the response function (extensification), ii) changes to agronomic practices that can shift the N input–yield curve, such that greater N yield is achieved at the same amount of N_{inp}, and iii) to increase *NUE* through the more efficient spatial allocation of N_{inp}, where nitrogen is distributed across locations to maximise production for a given total amount of N use. Determining whether these strategies are usable requires estimating the N_{out}–N_{inp} function (see Eq. (3)). Nitrogen budgets do not always include a sufficient range of data to fit multi-parameter models. Therefore, Lassaletta *et al.* [2014] proposed that the optimal functional forms for these data are the one-parameter hyperbolic models. It makes it possible to estimate the parameter Y_{max} represents the N_{out} value reached at saturating N fertilisation (N_{inp}), as well as the value of fertilisation at which a definite fraction of this maximum yield is reached (this fraction is 0.5) [Lassaletta *et al.* 2014]. This parameter is characterising the cropping system including crop varieties, technical management, and pedo-climatic context. As a result of the curvilinear nature of the N_{out} vs N_{inp} relationship, *NUE* is expected to decrease, and N_S to increase, with increasing fertilisation rate, at constant technical conditions. Only an improvement of Y_{max} can lead to increased *NUE* in the constant fertilisation rate.

The one-parameter hyperbola as the N input–yield response model has been used in nitrogen management analyses on global [Mueller *et al.* 2017], regional [Lassaletta *et al.* 2021], and 124 country [Lassaletta *et al.* 2014] scales. In the latter studies, Poland was also taken into account, stating that in the years 1961–1980 and 1990–2009 Y_{max} amounted to 73 and 120 kg N·ha^{-1}, respectively. The Y_{max} calculated by us using the same method increased in the years 1961–1989 and 1990–2018 and amounted to 127 and 263 kg N·ha^{-1} UAA, respectively (Fig. 9). As a consequence of this, the *NUE* values also increased, as previously discussed (Fig. 8). Y_{max} values decreased in wet years by 4% and in dry years by 11% as compared to the years with normal rainfall (Fig. 10). These changes were small when compared with those found for Mediterranean conditions [Lassaletta *et al.* 2021].

Lassaletta *et al.* [2014], in their research over the 1961–2009 period, distinguished four types of trajectory Y_n versus *F*. By adopting this classification, a historical trajectory for Poland, according to our research, can be classified as type II. This type is initially shows regularly increasing fertilisation and yield, fitting the *Y* vs *F* relationship with a definite Y_{max}, then a turning point with a shift of the trajectory to another relationship with a significantly higher Y_{max}. This likely reflects improved agronomical practices in terms of production factors other than nitrogen, together with the pursuit of increasing fertilisation.

Nitrogen limitation decreased over time in both study periods (Fig. 11). However, it was between 0.35 and 0.75. The first value indicates that increasing fertilisation would be ineffective until other agronomic constraints are removed [Lassaletta *et al.* 2014]. The second indicates margins for increasing yields by increasing N fertilisation [Lassaletta *et al.* 2014]. The obtained results indicate that nitrogen limitations were not found in either of the periods, which suggests that the limitations of N_{out}, especially in the first period of the study, were caused by factors other than nitrogen fertilisation. Therefore, the question arises whether the amount of nitrogen doses used was justified. Taking into account the value of Y_{max} amounting to 127 and 263 kg N·ha^{-1} UAA in both periods, a reasonable dose should be 0.5 Y_{max} [Lassaletta *et al.* 2014], that is 64 and 132 kg N·ha^{-1} UAA, respectively. Comparing these values with the mean N_{inp} in both periods (120 and 125 kg N·ha^{-1} UAA) it should be stated that in the first period the dose of N was overstated almost twice. The mean dose in the second period was well adjusted to the existing conditions.

Nitrogen surplus remains directly related to N_{inp} and N_{out}. In the analyses performed, N_S increased with N_{inp} according to the *S*-curve model. N_S gains were significantly greater in the first period of the study compared to the second period (Fig. 12). N_S increased in dry and wet years compared to normal rainfall, although the differences were slight (Fig. 13). The mean values and ranges of N_S were 60 (14–98) and 41 (19–62) kg N·ha^{-1} UAA, respectively. In Europe, the average value of N_S was 53 kg N·ha^{-1} [de Vries *et al.* 2021], while in Germany it was 77 kg N·ha^{-1} UAA [Häußermann *et al.* 2020].

According to Bodirsky and Müller [2014], one of the three strategies to increase *NUE* is a reduction in N_{inp} and yield in a cropping system. The concept was tested for three decades where the greatest N_{inp} was historically (1980–1989) and currently used (2009–2018) compared to the decade (1990–1999) where N_{inp} was reduced by 28% (Tab. 1). It was found that extensification of N fertilisation does not have to lower N yield when the agronomic system is over-fertilised. However, these studies confirmed the second strategy, according to which changes to agronomic practices can shift the N input–yield curve, such that greater N yield is achieved at the same amount of N_{inp} [Bodirsky, Müller 2014]. The third strategy will be analysed in the discussion of the results obtained for NUTS-2 regions.

Regional analyses showed that N_{inp} trends grew in NUTS 2, except for PL21 and PL82 (Fig. 14). N_{inp} should be increased in these regions as N_l enters there, which may lead to N soil mining. N_{out} trends were increasing in all regions (Fig. 15), but in PL72 and PL82 the maximum value of N_{out} did not exceed the desired value of 80 kg N·ha^{-1} UAA [EU Nitrogen Expert Panel 2015]. A deeper analysis is required to explain the reasons for the N_l limitation. In all regions, *NUE* trends were increasing, except for PL51 and PL92 (Fig. 16). The greatest diversification of trends was found in the case of N_S (Fig. 17). Further analyses of growing trends of N_S in PL22, PL51, PL52, PL62, PL84, and PL92 are necessary.

The values of N indicators for NUTS 2 were in the ranges (kg N·ha^{-1} UAA): N_{inp} 78–167, N_{out} 62–99, N_S 15–83, and Y_{max} 139–317. *NUE* and N_l were 50–81% and 0.50–0.80, respectively (Tab. 2). The values of *NUE* and N_S found for districts in Germany were 53–79% and 26–162 kg N·ha^{-1} UAA, respectively [Häußermann *et al.* 2020].

Cluster analysis showed that nitrogen was best managed in NUTS 2: PL41, PL51, PL52, and PL84 (cluster1 – Fig. 18, Tab. 3). N fertilisation in these regions was balanced, as evidenced by good adjustments of the mean N_{inp} and 0.5 Y_{max} values, which were 130 and 129 kg N·ha^{-1} UAA, respectively. NUTS 2: PL61, PL62, and PL71 (cluster – 2 Fig. 18, Tab. 3) were over-fertilised with nitrogen as evidenced by the comparison of N_{inp} (155 kg N·ha^{-1} UAA) with the value of the justified dose of 0.5 Y_{max} (82 kg N·ha^{-1} UAA). Nitrogen fertilisation should be reduced there. Less severe over-fertilisation was found in NUTS 2: PL22, PL42, PL43, PL63, PL72, PL81, and PL92 (cluster 3 – Fig. 18, Tab. 3), in which N_{inp} was 116 kg N·ha^{-1} UAA, and 0.5 Y_{max} was 88 kg N·ha^{-1} UAA. On the other hand, NUTS-2: PL21, and PL82 (cluster 4 – Fig. 18, Tab. 3) were under-fertilised (87 and 157 kg N·ha^{-1} UAA). Bodirsky and Müller [2014] suggest that a third strategy to increase *NUE* is the rational allocation of N. Our research concluded that slightly larger amounts of N should be allocated to PL21 and PL82 to avoid soil N mining. However, it is not certain whether this will improve the efficiency of N use, as these are regions with a significant share of fragmented agriculture, socio-economic constraints and not-N yield limitation.

CONCLUSIONS

The presented research shows that nitrogen management indicators in Poland have improved in recent years. However, it is necessary to increase the nitrogen use efficiency further and lower the nitrogen surplus to achieve surface water quality targets without crop production losses. Research on N indicators on a regional scale made it possible to divide 16 NUTS-2 into four groups. Among them, a group that is close to nitrogen over-fertilisation and a group in which N soil mining may occur were distinguished. In these groups, nitrogen fertilisation should be corrected. In eleven regions and two clusters there is a limitation in nitrogen yields that should be eliminated to further improve the efficiency of nitrogen management.

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