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The relationships between nitrogen use efficiency and nitrogen input in crop production in Poland

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Abstract. The study attempted to characterize Nitrogen Use Efficiency (NUE), nitrogen yield (Yn), and N balance (Nb = N surplus) depending on the dose of the total N fertilization (F = N dose in mineral fertilizers, natural fertilizers, or N from deposition). The study included basic crops in Poland in the years 1999–2014. The determination of the relationships between Yn, NUE, Nb, depending on F was performed using the elements of the methodology proposed by Lassaletta et al. (2014). The evaluation of differences between the optimal NUE and the NUE obtained in this study was carried out using the lower limits of the optimal NUE = 70–90%, as proposed tentatively by the EU NEP (2014). The study indicates that in the period of 1999–2014, NUE of basic crops in Poland increased, achieving the weighted average value of 55%. This value was significantly decreased by low NUE of permanent grasslands (42%), which have the largest share (20.3%) in the structure of land use in Poland. It would, therefore, be recommendable to increase NUE on grasslands. The omission of permanent grassland in the analysis increased the weighted average NUE for basic crops on arable lands to the value of 60%. There were no differences found in the weighted average NUE values in the case of more intensive (60%) and more extensive (60%) crops. Assuming that there is a need to increase NUE to the lower level of the optimal value (70%), we concluded, on the basis of our results and discussion, that the most effective way to achieve it would be to improve the NUE of more intensive crops, especially of wheat, triticale and barley. These plants achieve higher grain yields, Yn, Ymax, and Yn gap. They also have a larger share in the crop structure in comparison with more extensive crops.

Keywords: crops, Nitrogen Use Efficiency (NUE), improvement possibilities

INTRODUCTION

The forecasted growth of the world population will increase the demand for food. Covering this demand will require intensifying agricultural production. It is estimated that the annual increase in the yield of crops, the current average being currently 0.9%/year, should rise to 2.4%/year to meet the growing demand for food (Ray et al., 2013). Achieving this goal will require a more efficient use of resources and means of production. Nitrogen (N), which remains one of major yield-forming factors in the crop production, is of particular importance in this situation. Recently, the effectiveness of its use throughout the entire food chain has been widely calculated using Nitrogen Use Efficiency (NUE) ratio, defined as N output/N input ratio (Billen et al., 2014; Lassaletta et al., 2014; EU NEP, 2014; Norton et al., 2015). If this ratio is lower than 70% (EU NEP, 2014; a tentative value which needs to be examined in practice further), it means that a certain amount of N is unproductively lost, which contributes to water pollution, air pollution, and more severe climate changes, thereby degrading the quality of the environment and human health (Erisman et al., 2013; Galloway et al., 2008).

The increase of the non-productive burdening of the environment with reactive N has caused the urgent need to enhance NUE by increasing plant productivity or lowering the amount of N used in mineral fertilizers. Objectifying the decisions in this matter requires developing efficient methodologies for estimating NUE in the entire food chain, which are currently being intensively worked on in Europe (EU NEP, 2014) and worldwide (Norton et al., 2015). Recently, Lassaletta et al. (2014) applied NUE, Yn, Nb and F to characterize NUE trends in 124 countries around the world, including Poland. These trends, presented for the entire crop production of arable land, provide an overall picture that allows for comparing NUE among different countries as well as for grouping them according to the obtained values. Our study aimed to characterize NUE trends for basic crops in Poland during the last sixteen years (1999–2014). The study used the elements of the methodologies proposed by Lassaletta et al. (2014) and EU NEP (2014), which made it possible to estimate the value of NUE, Yn and Nb for major crops in Poland and

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to identify relationships between Yn, NUE, Nb and F value for all the crops in total, as well as for intensive and extensive crops separately. The aim of this study is to extend the analysis presented for Poland by Lassaletta et al. (2014), indicating which crops require improving their NUE in order to, above all, increase the average value of this indicator for the entire production.

MATERIALS AND METHODS

The study took into account major crops in Poland, divided into two groups. The first group included intensive crops, which are usually located on medium and heavy soils of higher fertility and water capacity (winter and spring wheat, barley, maize for grain, triticale, oil seed rape, and sugar beet). The second group included extensive crops, located on light soils of lower fertility and water capacity (oats, rye, cereal mixtures, potatoes) and grassland. The listed crops had 82% share of the utilized agricultural area in Poland. The analysis were performed using the series of data from the years of 1999–2014, which included: crop area (million of ha), yields of major products (t/ha) and the total consumption of mineral fertilizers in crop production (t N). These data came from the Polish national statistics (the CSO, 2000–2015). The supply of natural fertilizers (kg N/ha) was estimated based on the number of livestock, according to the methodology adopted in ISSPC, without correction for gaseous N losses during the manure storage. N from deposition was assessed from empirical data and adopted as a constant value for Poland, amounting to 14 kg N/ha. The total N supply (from mineral and natural fertilizers, and deposition) was allocated for each crop according to the methodology adopted in the reporting on the use of N by individual crops (EFMA, 2000–2014). In this way, a dose of N (F, kg N/ha) for each crop was calculated without taking into consideration biological N fixation.

NUE (%) for each crop was calculated according to the formula:

$$NUE = (Yn/F) * 100 \quad [1]$$

whereas: Yn (kg N/ha) – N yield (= N nitrogen uptake by major products = N output), F – dose N (input).

NUE defined in this way for each plant is usually interpreted as the efficiency of N uptake.

Yn (kg N/ha) was calculated according to the formula:

Yn = the yield of a major product * average N concentration [2]

The average N concentrations in major products were taken from the databases of ISSPC.

N balance (Nb = N surplus, kg N/ha) was calculated as:

$$Nb = F - Yn \quad [3]$$

It has to be underlined that Nb remains directly related to NUE and Yn in accordance with:

$$Nb = Yn * (1/NUE - 1) \quad [4]$$

Nb is usually interpreted as a partial N balance.

In the crops on arable lands, 80–100% of Nb can leach into waters (Billen et al., 2014). Nb from grassland leaches in smaller quantities and therefore should not be interpreted in terms of nitrogen losses (Billen et al., 2014). According to the formulas 1–3, Yn, NUE and Nb were estimated for each tested crop and the results were presented as medians and ranges for the analyzed time series. The preliminary assumption taken for the data interpretation was that optimum NUE should be in the range of 70–90% (EU NEP, 2014). According to this assumption, NUE > 90% means overexploitation of the soil, while < 70% – the risk of excessive pollution of the environment.

The dependencies among Ymax, NUE, Nb and F were assessed for all the crops jointly and for the two distinguished groups of crops according to the methodology of Lassaletta et al. (2014). Ymax was calculated as follows:

$$Yn = Ymax*F/(Ymax+F) \quad [5]$$

The parameter Ymax, representing the maximum N yield at saturating N inputs, as well as the fertilization rate providing half the maximum yield, is characterizing the cropping system including crop varieties, technical management (besides the rate of fertilization) and pedo-climatic context (Billen et al., 2014; Lassaletta et al., 2014). As a result of the curvilinear nature of the Yn vs F relationship, NUE is expected to decrease, and surplus to increase, with increasing fertilization rate, at constant technical conditions. Only an improvement of Ymax can lead to increased NUE at constant fertilization rate (Billen et al., 2014).

The dependencies among NUE, Nb and F were assessed according to the formulas:

$$NUE = 1/(a + b*F) \quad [6]$$

$$Nb = b*F^2 \quad [7]$$

where a and b are equation coefficients.

A gap in Yn (Yng) was calculated as:

$$Yng = (Ymax - Yn)/Ymax \quad [8]$$

The higher Yng, the higher possibility and necessity to enhance NUE.

The methodology used in this work is a compilation of elements of the methodology proposed by Lassaletta et al. (2014), EU NEP (2014) and earlier works of the experts of EU NEP (2014). The final methodology of EU NEP, which could be recommended for use in EU in the future, may differ from the one applied in this study.

RESULTS

The studied variables were described using medians and ranges of their values, as data distribution was skewed (Table 1). Data analysis led to the conclusion that, despite the significant statistical differences of Yn and F in the compared crop groups, there were no significant differences in the values of NUE and Nb. With the

Table 1. Medians and ranges of yield (Yd; t/ha), nitrogen use efficiency (NUE; %), nitrogen yield (Yn; kg/ha), nitrogen balance (Nb; kg/ha) and nitrogen fertilization rate (F; kg/ha) for the studied crops.

Group	Crops	Yd		NUE		Yn		Nb		F	
		Me	Range	Me	Range	Me	Range	Me	Range	Me	Range
I	Winter wheat	4.20	3.40–5.15	65	56–79	80	64–97	40	22–58	118	101–144
I	Spring wheat	3.19	2.46–3.93	59	52–61	67	52–82	45	32–60	109	94–139
I	Barley	3.24	2.54–4.05	60	48–69	55	43–68	38	28–49	93	81–105
I	Maize	6.07	4.16–7.35	55	37–61	94	65–114	81	71–111	181	165–187
I	Triticale	3.32	2.68–4.02	61	51–73	60	48–72	37	24–47	96	88–103
I	Oil seed rape	2.62	1.86–3.44	54	42–74	88	63–116	73	36–103	169	130–191
I	Sugar beet	45.4	33.8–68.3	39	36–56	77	57–116	113	92–132	203	160–219
I	Median significantly different	*				*				*	
II	Oats	2.52	1.89–3.05	52	40–64	41	30–49	38	27–46	78	74–87
II	Rye	2.45	1.88–3.15	50	43–64	39	30–49	36	22–49	76	64–93
II	Cereal mixture	2.82	2.09–3.32	71	55–86	47	34–55	20	9–28	66	63–72
II	Potatoes	19.4	15.0–27.8	66	52–90	60	47–86	32	9–44	91	75–98
II	Meadows & pastures	45.4	33.8–68.3	42	35–46	45	36–51	64	50–80	109	93–136
II	Median significantly different	*				*				*	

* $p<0,05$

exception of cereal mixtures, NUE values for all the tested crops were lower than 70%. Nb values higher than 50 kg N/ha were recorded only for the most intensive crops: sugar beet, grain maize and oil seed rape. Permanent grasslands (Nb = 64 kg N/ha) were the exception to this rule, however, due to the specificity of N leaching from the soils of these areas, the obtained Nb value could not be interpreted. The average NUE value weighted on the crop areas amounted to 55% for all the tested plants, which would indicate the need to increase it by 15% in order to achieve the lower range of the optimal values (70%).

This value was decreased by low NUE for grassland (42%) which has 20.3% share in the utilized agricultural area. The weighted average NUE calculated for plants grown only on arable land, amounted to 60%. The values of the Yn, NUE and Nb significantly depended on the total N dose (F). Ymax assessed for all the crops jointly amounted to 166 kg N/ha (Fig. 1). This is the maximum Yn which can be achieved under current production conditions, mostly yields and fertilizing.

The relationship between NUE and F was statistically significant, but weaker than the one previously discussed (Fig. 2). A higher NUE variability was recorded for the crops fertilized with lower N doses (F). Due to the fact that the estimated relationship was statistically weak, a better assessment was sought for the group of more extensive and intensive crops.

The relationship between Nb and F was fairly well adjusted (Fig. 3). It is notable that some crops (sugar beet, maize and oil seed rape) had Nb > 50 kg N/ha (Table 1).

The presented drawings (Figures 1-3) show a clear segregation of the variance of the tested variables into two groups. Therefore, an attempt was made to find better fitting regressions by dividing the data into two groups: crops grown intensively and extensively. Both these types of crops were estimated in terms of the previously discussed regression functions. Ymax values differed for the both groups of plants, amounting to 179 kg N/ha for crops grown more intensively (r^2 = 46,4%) and 103 kg N/ha for crops grown more extensively (r^2 = 7,3%) (Fig. 4). In the latter group, Yn variance depending on F was still large, which can be explained by the fact that these plants were grown on light soils with lower water capacity. This caused the yields to be frequently reduced by droughts, which occurred in Poland once every two years during the period of the study. The crops grown more intensively were usually set up on the soils of higher water capacity, where droughts reduce yields and Yn to a lesser extent.

Diversification of Ymax in these plant groups causes a diversification of the gap in Yn, which amounted to 0,603 for intensive, and 0,563 for extensive crops. It means that intensive crops have a further distance to achieving Ymax compared to the extensive ones. For this reason, it is recommended to either increase the Yn of these crops, or reduce their N fertilization in a way that would not reduce their yields.

Calculating the regression between NUE and F for the two groups ensured their better fit, as was indicated by the increase of the coefficients of determination (r^2). Analyses showed that r^2 for the entire set of data was 12.3% (Fig. 2), for the intensive cultivation – 39,7%, while for the extensive cultivation – 33.6% (Fig. 5). The obtained function images are typical – NUE decreases together with the increase of F. This decrease is larger in the case of extensive

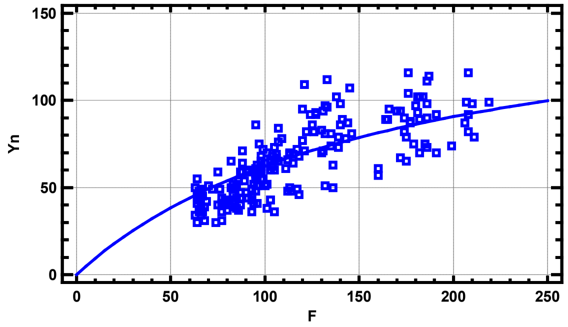

Fig. 1. The relationship between nitrogen yield (Yn, kg N/ha) and the total N dose (F, kg N/ha) (Ymax = 166 kg N/ha, r^2 = 61,3%)

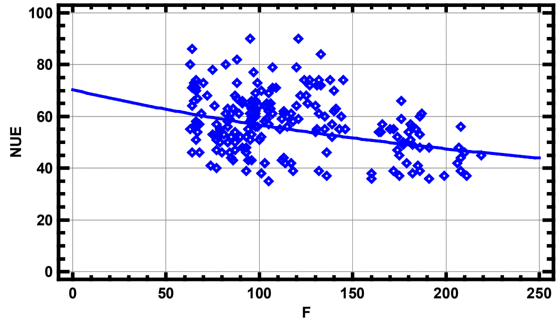

Fig. 2. The relationship between NUE (%) and the total N dose (F, kg N/ha) (r^2 = 12,3%)

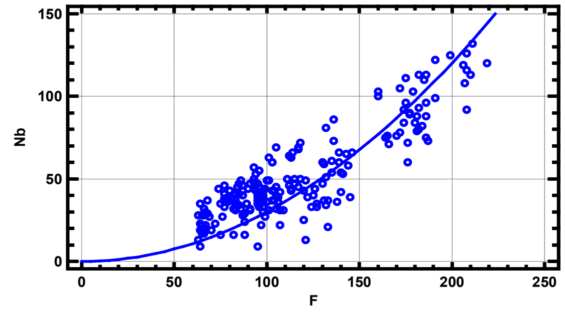

Fig. 3. The relationship between Nb (kg N/ha) and the total N dose (F, kg N/ha) (r^2 = 64,9%)

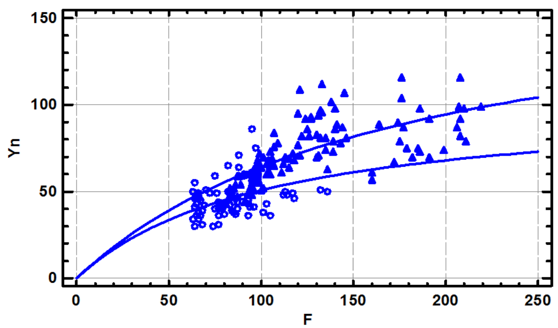

Fig. 4. The relationship between the N yield (Yn, kg N/ha) and the total dose of N (F, kg N/ha) for intensive crops (upper curve and triangles; Ymax = 179 kg N/ha, r^2 = 46,4%) and extensive crops (lower curve and circles; Ymax = 103 kg N/ha, r^2 = 7,3%).

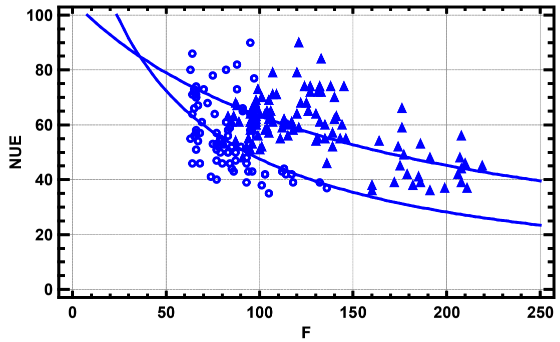

Fig. 5. The relationship between NUE (%) and the total N dose (F, kg N/ha) for intensive crops (the upper curve and triangles; r^2 = 39,7%) and extensive crops (the lower curve and circles; r^2 = 33,6%).

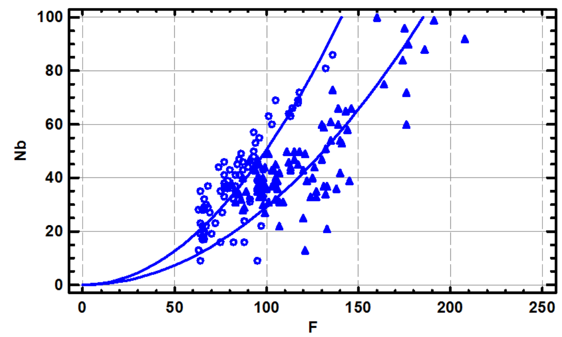

Fig. 6. The relationship between Nb (kg N/ha) and the total N dose (F, kg N/ha) for intensive crops (the lower curve and triangles; r^2 = 79,3%) and extensive crops (the upper curve and circles; r^2 = 66,8%).

than intensive cultivation. For both groups of crops, the medians of NUE (%), F (kg N/ha) and Nb (kg N/ha) amounted to 57, 125 and 49, and 54, 82 and 36, respectively.

The division of crops into two groups improved also the determination coefficients of the relationship of Nb = f(F) from 64.9% for the total analysis, 79.3% for intensive crops, and 66.8% for extensive crops (Fig. 6).

From the course of the fairly well fitted curves, shown in Figure 5 and 6, the optimum values of F and Nb for NUE = 70% can be assessed. In the case of intensive crops, these values are, respectively, 76 and 17 kg of N/ha compared to the medians for these crops amounting to 125 and 49 kg of N/ha. It means that we either increase the NUE to 70% by increasing Yn, or decrease F from 125 to 76 kg N/ha, thus reducing Nb from 49 to 17 kg N/ha. An analogous analysis performed for extensive crops indicated that obtaining NUE = 70% requires using F = 53 kg N/ha, which would give Nb = 14 kg N/ha. Therefore in the case of these crops, obtaining NUE = 70% F requires reducing F from 82 to 53 kg N/ha, which would reduce Nb from 36 to 14 kg N/ha. An alternative would be to increase Yn, yet it could cause yield reductions of crops due to lower water availability.

DISCUSSION

Polish agriculture, characterized by NUE = 55% in plant production and NUE = 25% in food production (EU NEP, 2014), as well as EU agriculture, for which these indicators are 65% and 35%, respectively, (EU NEP, 2014) requires NUE improvement. It applies especially to mineral fertilization, as the global production of mineral fertilizers consumes approx. 2% of the energy produced (Sutton et al., 2012). Improving the efficiency of the use of these fertilizers has recently become an imperative, not only due energy waste caused by low NUE, but especially due to the effects of non-productive increase of the concentration of reactive nitrogen in the environment (Erisman et al., 2013; Galloway et al., 2008), as well as due to the need to increase food production in this century (Ray et al., 2013). A more efficient use of these fertilizers, constituting non-renewable means of production and being used in a way far from sustainable, is both a challenge and an opportunity to preserve or extend the economic importance of agriculture in the development of the sector of effective bio-economy (Zhang et al., 2015 a,b). Our studies have shown that the weighted average NUE of the production of basic crops in Poland (1999–2014) amounts to 55%, which is consistent with the value obtained by external experts (EU NEP, 2014), but higher than one calculated by Lassaletta et al. (2014) for Poland (medians: NUE = 42% (1961–1980) and NUE = 52% (1990–2009)). In the analyzed series of data, Ymax=166 kg N/ha, which was higher than the values obtained by Lassaletta el al. (2014), that amounted to (kg N/ha): Ymax=73 (1961–1980) and Ymax=120 (1990–2009). In Poland, we are observing a gradual improvement of Ymax and Yn, which, according to Lassaletta et al. (2014), are the main determinants of NUE increase. The recorded growth of these parameters, however, is not sufficient for obtaining the lower tentative optimum border of NUE = 70% (EU NEP, 2014). Permanent grasslands (3.3 million hectares; 20.3% share in utilized agricultural area) with NUE = 42% are the crops which substantially reduce the weighted average value of NUE for major crops in Poland. Improving NUE for this crop is urgently needed. If grasslands were omitted from the analysis, the weighted average NUE for the crops tested would reach a value of 60% for both intensive and extensive crops. It should be noted that in the case of the intensive crops, this result was achieved under higher N fertilization (Table 1). As for the intensive crops, characterized by larger yields, Yn, Ymax, Yn gap and a higher share in the sowing structure, it would be recommended, above all, to improve NUE for individual crops, which, in turn, would increase the weighted average NUE value in plant production. First of all, NUE of the crops with its lowest value, specifically sugar beet> oil seed rape> maize, should be improved. However, the average could be improved rather by increasing NUE in the crops such as: winter wheat > triticale > barley as they have a larger share in the sowing structure.

CONCLUSIONS

The conducted studies show that in the period 1999–2014 NUE for basic crops in Poland increased reaching the weighted average value of 55%. This value was significantly decreased by the low NUE of permanent grasslands (42%), which have the largest share in the land use structure in Poland (20.3%). It is recommended to increase NUE in these areas. The omission of permanent grasslands in the analysis increased the weighted average NUE for basic crops on arable lands to the value of 60%. There were no differences in the weighted average NUE values of the intensive crops (60%) and extensive crops (60%). Assuming that there is a need to increase NUE to at least the lower optimal value (70%), it was concluded on the basis of studies and discussion that the most efficient way to do this would be to improve the NUE of the intensive crops, especially of wheat, triticale and barley. They are characterized by higher yields, Yn, Ymax, Yn gap, and a larger share in the sowing structure compared to the extensive crops. Increasing their NUE would require increasing Yn without changing F, which would further reduce the non-productive excess of Nb, contributing to overburdening of the environment with reactive nitrogen.

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