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Analysis of water and nitrogen use efficiency in winter wheat grown under mildly dry conditions

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Abstract. Improving Nitrogen Use Efficiency (NUE) in crops of winter wheat is of interest in Poland, due to their significant share in the sown area. The aim of this study was, therefore, to determine the relationships between grain (Yd) and N yields (Yn), NUE, Water Use Efficiency (WUE) depending on N rates (F) and actual potential evapotranspiration (APET). The study used the results of field experiments, conducted in the years 2003–2013 in two locations in Poland. In the experiments, wheat was fertilized with doses of 40, 80, 120, 160 and 200 kg N/ha under the fertilization with P, K, Mg and Ca. It was found that the dose range of 80 ± 40 kg N/ha allowed to obtain Yd of 5.34 ± 1.43 t/ha and NUE values of 116 ± 17%, which brought the risk of soil N mining. Increasing N doses (160 ± 40 kg/ha) increased Yd (6.08 ± 0.71 t/ha) and allowed for obtaining the desired values of NUE (73 ± 5%), Yn (119 ± 18 kg/ha) and N surplus (43 ± 13 kg/ha). The performed statistical analysis showed that Yd, Yn and WUE had grown with increasing doses of N under the influence of water shortages in the range of APET less than 398 mm. Under these conditions positive interaction between Yd, Yn, WUE depending on F and APET has been demonstrated. Only for a dose of 200 kg N/ha were found negative interactions between Yd, WUE on F and APET. NUE decreased with increasing N doses. The relationship between NUE and WUE was positive but specific for N doses due to the statistically significant interaction of F×WUE. The maximum value of WUE obtained in the experiments was 26 kg grain/ha/mm. In the absence of limiting factors WUE increased linearly together with growing NUE up to the value of 93.9% and then linearly decreased. In the range of the desired NUE values (50–90%), WUE values were between 16,4–23,5 kg grain/ha/mm.

Keywords: winter wheat, Nitrogen Use Efficiency (NUE), Water Use Efficiency (WUE), field experiments

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INTRODUCTION

In Poland, the value of NUE for basic cereals, estimated on the basis of data from public statistics, ranged from 50 to 70% (Faber et al., 2016a). These values fall within the range of 50–90%, recently assumed as desirable (Oenema, 2015; EUNEP, 2015). Since winter wheat accounts for the largest amount (13.7%) of Poland's total cropland, the possibilities for improving the NUE of individual winter wheat crops, which, according to statistical data, amount to 65% (Faber et al., 2016a), are a subject of interest. However, other research shows that in 50% of farms growing winter wheat in Poland NUE was higher than 90%, which means the risk of N soil mining (Faber et al., 2016b). Reducing this risk was possible by increasing N doses. It was achieved in 37% of the total farms where nitrogen was applied at the rates of 144 ± 18 kg N/ha, which allowed for obtaining the desired NUE value (50–90%), nitrogen yields (>80 kg N/ha) and nitrogen surplus (<80 kg N/ha) (Faber et al., 2016b). This improvement was accompanied by grain yields of 5.5 t/ha both under extensive and intensive fertilization, which indicated that they were limited by factors other than nitrogen (Faber et al., 2016b). These factors could be numerous but the work has focused on the influence of water shortage, which is increasingly present in Poland (Doroszewski et al., 2014).

A number of interactions between NUE and WUE have been identified, ranging in scale from the leaf to the field crop (Garnett, Rebetzke, 2013). WUE and NUE of crops vary greatly among crop production systems, region and management (Qin, 2015). The modelling analyses show the high degree of seasonal variability in yield, WUE and NUE of wheat, depending on soil type, N fertilizer input, rainfall amount and rainfall distribution (Asseng et al., 2001). However, WUE for grain production can be an important parameter defining the productivity of crops in water-limited environments (Asseng et al., 2001; Angus et al., 2001). So far, WUE and NUE and their relationships have been quantified in a limited number of studies (Asseng et al., 2001; Sadras, Angus, 2006; Sadras, Rodriguez, 2010, Cossani et al., 2012; Qin, 2015).

In this work, data from field experiments with winter wheat was tested. On its basis, grain yield (Yd), N yield (Yn), NUE, N surplus (Nb), the actual potential evapotranspiration (APET) and water use efficiency (WUE) were assessed. The listed assessments were used for estimating the effects of nitrogen fertilization (F) for the entire data set and the subsets with different ranges of NUE values. Also, the relationships between Yd, Yn, NUE, WUE and APET for N doses were determined.

MATERIALS AND METHODS

Experiments

Field experiments were carried out at two experimental stations of the Institute of Soil Science and Plant Cultivation (ISSPC) in Poland between 2003 and 2013. Experiments were located at Baborowko in West Poland (19°12' E, 52°01' N) on the sandy loam and at Grabow in Eastern Poland (19°37' E, 52°37' N) on a heterogeneous sandy loam. In two factorial experiments, four crops were grown each year in the rotation of winter oilseed rape–winter wheat–maize–spring barley. The first factor was P, K, Mg, Ca fertilization in plus or minus variants, and the second one were six levels of N fertilizers applied in split doses. For almost 30 years, no manure was applied to the experimental field. The data included treatments with the P, K, Ca, Mg fertilization and rates of nitrogen at 40, 80, 120, 160 and 200 kg N/ha (11 years x 5 N rates x 2 replications x 2 locations = 220). In total, 220 results of yield and N contents were taken into consideration.

Rainfall

Both experimental stations are located in the cold temperate dry climate zone (IPCC, 2006). Average annual rainfall at Baborowko was 483 mm (313–621 mm) and at Grabow 559 mm (387–722 mm) in the period of investigations. Seasonal rainfalls (March – July) in both locations were 245 mm (165–393 mm) and 277 mm (159–387 mm), respectively. The rarity of drought has been characterized for a period of thirty years using the Standardized Precipitation Index (SPI) (WMO, 2012). The index was calculated for the period of 12 months of the year with the program SPI_SL_6 (NDMC). SPI indices for annual rainfall for over three decades are shown in Figure 1. The SPI are standardized so they have a normal statistical distribution. Using this distribution and the data presented in Figure 1 it was found that in both locations SPI indicated mild dryness (-0.44) in 33%, moderate dryness (-1.30) in 10%, severe dryness (-1.67) in 5% and extreme dryness (<-2.00) in 2.5% of the time. Categories of droughts were adopted from the publication by McKee et al. (1993). Figure 1 showed that the drought in the period 2003–2013 was the deepest during the three decades. In this period, SPI were -0.65 for Baborowko and -0.88 for Grabow in 33% of the time. This means that the rainfall during this period can be considered as causing mild dryness (0 to -0.99) according to McKee et al. (1993) dryness categories.

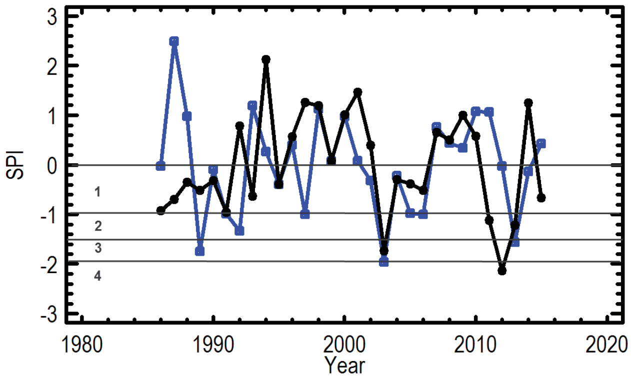

Fig. 1. The Standarized Precipitation Index for 12 month rainfall totals in 1986-2015 (Baborowko – blue, Grabow – black; Dryness categories acc. McKee et al. (1993).: 1 – mild dryness (0 to -0.99), 2 – moderate dryness (-1 to -1.49), 3 – severe dryness (-1.5 to -1.99) and extreme dryness (<-2.0)

Statistical analysis

On the basis of grain yields (t/ha, moisture 15%) and the applied nitrogen rates (F, kg N/ha), the characteristics useful for the evaluation of the efficiency of N fertilization were assessed according to the methodology proposed by EU Nitrogen Expert Panel (Oenema, 2015, EUNEP, 2015) NUE (%) was assessed by the formula:

$$NUE = (Yn/F) \cdot 100 \qquad [1]$$

where: Yn (kg N/ha) – nitrogen yield (= N uptaken by grains = N output), F (kg N/ha) – a dose of N. Thus defined NUE is usually interpreted as the efficiency of N uptake by a plant.

Nitrogen yield Yn (kg N/ha) was assessed according to the formula:

$$Yn = \text{grain yield} \cdot \text{N content in grains} \qquad [2]$$

N balance (Nb; = N surplus, kg N/ha) was assessed according to the formula:

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

Nb remains in the direct relationship with NUE and Yn according to the formula:

$$Nb = Yn \cdot (1/NUE - 1) \qquad [4]$$

Nb is usually interpreted as a partial N balance. In the crops located on arable lands, 80–100% of Nb may leach into waters (Billen et al., 2014).

Monthly potential evapotranspiration (PET) adjusted for temperatures was estimated according to Thornthwaite and Mather method (1955). Monthly APET was estimated from annual soil-water budget (Thornthwaite, Mather, 1957) assumes decreasing availability of soil moisture (Mather, 1974, curve C, WATBUG default). Practically, APET

= PET when precipitation (P) minus run-off (Ro) > PET. In dry months, when P – Ro < PET, the precipitation is no longer able to meet the evapotranspiration demand. Therefore, the unmet amount of water required by the evapotranspiration demand is progressively taken from the soil moisture storage until it is completely depleted. Hence, even if there is not enough precipitation, the APET can still approach the PET when there is still enough water within the soil moisture storage.

WUE was defined as:

WUE = Yd/APET

where: Yd – grain yield (kg/ha), APET – actual evapotranspiration (mm).

Variability of Yd, F, Yn, NUE, Nb, APET and WUE in the entire set of data was characterized by medians (Me), median absolute deviation (MAD) as well as by minimal and maximal values.

The evaluation of F impact on NUE value was analyzed in 4 subsets of data (Oenema, 2015, EUNEP, 2015):

– NUE > 90% (risk of soil mining) (E1),
– NUE 50–90%, Yn < 80 kg N/ha/yr (risk of Yn limitation) (E2),
– NUE 50–90%, Yn > 80 kg N/ha/yr, Nb <80 kg N/ha/yr (desirable range for NUE, Yn and Nb) (E3),
– NUE < 50% (risk of inefficient N use) (E4).

Variability of Yd, F, Yn, NUE, Nb, APET and WUE in these data subsets was characterized in the manner previously described using Statgraphics statistical package. The relationships between Yd, Yn, NUE, WUE and APET on N doses were fitted to a linear-plateau functions using SegReg software. These function were used to derive three parameters: the maximum value of parameter, the APET break point (APET BPx) when the parameter reaches its maximum and the rate of the parameter response in the linear phase (i.e. ΔYd/ΔAPET). The piecewise linear regression between WUE and NUE was calculated by SegReg software.

RESULTS

The tested variables were characterized by skewed statistical distributions, hence their values and variability were characterized with medians (Me), MAD and the minimal and maximal values.

Experimental yields oscillated within 1.34–9.66 t/ha with the median of 4.70 t/ha and MAD of 1.45 t/ha (4,70 ± 1.45 t/ha) (Table 1). The estimated values of Yn, NUE, Nb, APET and WUE fell into fairly wide ranges (Table 1). NUE ranged within 31–243% (77 ± 23%). The Yn median (82 ± 24 kg N/ha) was close to the value indicating the risk of Yn limitation. It suggests the activity of factors limiting N uptake during the experiments.

The assessment of the effects of fertilization on NUE, Yd and Nb allowed for designating four subsets (E1-E4) from the entire set of data.

Subset E1 included fertilization combinations 80 ±40 kg N/ha, for which NUE was higher than 90% (Table 2). These fertilization rates assured Yn (81 ± 27 kg N/ha), as to the value close to the proposed value causing risk of Yn limitation. The values of NUE> 90% due to too low N rates could result in excessive depletion of nitrogen from the soils (the risk of N mining).

The NUE of subset E2 fell within the desired range (50–90%), but its Yn was too low (<80 kg N/ha) (Table 3).

Table 1. Grain yields (Yd), nitrogen yields (Yn), nitrogen rates (F), nitrogen use efficiency (NUE), nitrogen balance (Nb), actual potential evapotranspiration (APET) and water use efficiency (WUE) in the experimental crops of winter wheat (n=220).

Statistics	Yd t/ha	F kg/ha	Yn kg/ha	NUE %	Nb kg/ha	APET mm	WUE kg/ha/mm
Median	4.70	120	82	77	29	357	13
MAD	1.45	40	24	23	33	32	3
Minimum	1.34	40	20	31	-57	265	5
Maximum	9.66	200	196	243	138	515	26

n – number of data

Table 2. Grain yields (Yd), nitrogen yields (Yn), nitrogen rates (F), nitrogen use efficiency (NUE), nitrogen balance (Nb), actual potential evapotranspiration (APET) and water use efficiency (WUE) in the data set with NUE > 90% (E1; n=82)

Statistics	Yd t/ha	F kg/ha	Yn kg/ha	NUE %	Nb kg/ha	APET mm	WUE kg/ha/mm
Median	5.34	80	81	116	-11	363	13
MAD	1.43	40	27	17	12	20	3
Minimum	1.74	40	36	91	-57	269	6
Maximum	9.66	200	196	243	15	515	26

Table 3. Grain yields (Yd), nitrogen yields (Yn), nitrogen rates (F), nitrogen use efficiency (NUE), nitrogen balance (Nb), actual potential evapotranspiration (APET) and water use efficiency (WUE) in the data set with the desired NUE (50–90%) but Yn < 80 kg N/ha (E2; n=32)

Statistics	Yd t/ha	F kg/ha	Yn kg/ha	NUE %	Nb kg/ha	APET mm	WUE kg/ha/mm
Median	3.04	80	61	65	24	293	10
MAD	0.52	20	12	10	12	18	2
Minimum	1.34	40	20	50	8	269	5
Maximum	5.31	120	79	90	59	382	15

Table 4. Grain yields (Yd), nitrogen yields (Yn), nitrogen rates (F), nitrogen use efficiency (NUE), nitrogen balance (Nb), actual potential evapotranspiration (APET) and water use efficiency (WUE) in the data set with the desired NUE (50-90%), Yn > 80 kg N/ha, and Nb < 80 kg N/ha (E3; n=63)

Statistics	Yd t/ha	F kg/ha	Yn kg/ha	NUE %	Nb kg/ha	APET mm	WUE kg/ha/mm
Median	6.08	160	119	73	43	363	16
MAD	0.71	40	18	5	13	14	2
Minimum	3.48	120	81	52	15	269	9
Maximum	8.12	200	161	87	77	515	24

Table 5. Grain yields (Yd), nitrogen yields (Yn), nitrogen rates (F), nitrogen use efficiency (NUE), nitrogen balance (Nb), actual potential evapotranspiration (APET) and water use efficiency (WUE) in the data set with NUE < 50% (E4; n=38)

Statistics	Yd t/ha	F kg/ha	Yn kg/ha	NUE %	Nb kg/ha	APET mm	WUE kg/ha/mm
Median	3.21	160	66	40	100	293	11
MAD	0.45	40	8	4	23	17	1
Minimum	1.99	80	33	31	44	269	7
Maximum	5.21	200	97	48	138	363	16

A comparison of the data provided in Tables 2 and 3 indicates that decrease of Yn and Yd in E2 subset may be attributed to drought, as evidenced by lower values of APET and WUE. They limited Yd (by 43%) to a greater extent than Yn (by 25%) compared with E1 subset.

E3 subset included fertilizer combinations of N doses two-fold higher (160±40 kg N/ha) than E1 subset (Table 4). Such an increase of doses ensured the desired values of NUE (50–90%), Yn (>80 kg N/ha) and Nb (<80 kg N/ha). They were achieved under similar characteristics of APET and higher WUE in comparison with E1 subset (Table 4 and 2).

The deterioration in the water availability in E4 subset (APET 293±17 mm), caused that under the same fertilization rate (160 ± 40 kg N/ha), Yd decreased by 47%, Yn – by 45%, NUE – by 45%, WUE – by 31%, while Nb increased by 2.3 times (Table 5), as compared to E3 (APET 363 ± 14 mm).

The linear-plateau models showing relationships between Yd, Yn, NUE, WUE and APET depending on N doses were statistically significant. These relationships were estimated separately for each N dose using all data (n = 44).

Across nitrogen supplies, maximum Yd's ranged from 4.20 to 7.03 t/ha at APET BPx ranging from 362 to 397 mm (Table 6). The values ΔYd/ΔAPET reached a maximum 43.4 kg grain/ha/mm at a dose of N 160 kg N/ha and then decreased to 31.7 kg grain/ha/mm for rate 200 kg N/ha. Increments of ΔYd/ΔAPET in doses ranging from 40 to 160 kg N/ha indicate positive interaction between these doses and APET. The decrease in the value of the slope parameter for a dose of 200 kg N/ha indicates negative interaction between F and APET compared to doses in the range of 80–160 kg N/ha.

The maximum Yn's varied in range of 63 to 146 kg N/ha at APET BPx of 390–396 mm and systematic increase of ΔYn/ΔAPET in the range of 0.266–0.691 kg N/ha/mm (Table 7). Interactions between Yn depending on F and APET were positive in the range of 40 to 200 kg N/ha.

NUE reaches the maximum value from 73 to 158% at 390–398 APET and drops systematically ΔNUE/ΔAPET with the N doses in the range of 0.665 to 0.345%/ha/mm (Table 8).

Table 6. Parameters of the linear-plateau model relating grain yield (Yd) and actual evapotranspiration (APET) as affected by nitrogen supply. APET BPx is the threshold actual evapotranspiration after which yield does not respond to APET, ΔYd/ΔAPET is the slope of the linear phase of the model, and Yd max is maximum grain yield (n=44 for each dose; r^2 = 42.6–66.3)

F (kg N/ha)	APET BPx (mm)	ΔYd/ΔAPET (kg grain/ha/mm)	Yd max (t/ha)
40	362	27.7	4.20
80	360	37.5	5.47
120	360	39.6	5.98
160	357	43.4	6.35
200	397	31.7	7.03

Table 7. Parameters of the linear-plateau model relating nitrogen yield (Yn) and actual evapotranspiration (APET) as affected by nitrogen supply. APET BPx is the threshold actual evapotranspiration after which N yield does not respond to APET, ΔYn/ΔAPET is the slope of the linear phase of the model, and Yn max is maximum nitrogen yield (n=44 for each dose; r^2 = 44.7–51.0)

F (kg N/ha)	APET BPx (mm)	ΔYn/ΔAPET (kg N/ha/mm)	Yn max (kg N/ha)
40	392	0.266	63
80	394	0.387	94
120	396	0.515	118
160	390	0.590	131
200	390	0.691	146

Table 8. Parameters of the linear-plateau model relating NUE and actual evapotranspiration (APET) as affected by nitrogen supply. APET BPx is the threshold actual evapotranspiration after which NUE does not respond to APET, ΔNUE/ΔAPET is the slope of the linear phase of the model, and NUE max is maximum Nitrogen Use Efficiency (n=44 for each dose; r^2 = 45.1–51.1)

F (kg N/ha)	APET BPx (mm)	ΔNUE/ΔAPET (%/ha/mm)	NUE max (%)
40	398	0.665	158
80	394	0.480	118
120	397	0.429	98
160	390	0.367	83
200	390	0.345	73

Estimates obtained for WUE indicate that the maximum value of the parameter to rise to a value of 16.3 kg grain/ha/mm is 160 kg N/ha (Table. 9). Increasing the N dose to 200 kg N/ha did not result in a further increase in WUE. Similarly, up to dose of 160 kg N/ha was observed a growth in ΔWUE/ΔAPET up to a value of 0.0797 kg grain/ha/ mm. Increasing the dose to 200 kg N/ha reduced the ΔWUE/ΔAPET. Thus, in the range of 40 to

Table 9. Parameters of the linear-plateau model relating WUE and actual evapotranspiration (APET) as affected by nitrogen supply. APET BPx is the threshold actual evapotranspiration after which WUE does not respond to APET, ΔWUE/ΔAPET is the slope of the linear phase of the model, and WUE max is maximum Water Use Efficiency (n=44 for each dose; r^2 = 25.7–35.4)

F (kg N/ha)	APET BPx (mm)	ΔWUE/ΔAPET (kg grain/ha/mm)	WUE max (kg grain/ha/mm)
40	360	0.0390	10.7
80	355	0.0641	14.2
120	345	0.0781	15.5
160	345	0.0797	16.3
200	345	0.0614	16.3

160 kg N/ha positive interaction was found between WUE depending on F and APET. The interaction was negative at a dose of 200 kg N/ha relative to doses between 80 and 160 kg N/ha.

The data presented indicate that in the period of the experiments, water availability (APET <360 mm) limited ΔWUE/ΔAPET and maximum WUE at doses greater than 160 kg N/ha. It is commonly known that there is a trade-off relationship between NUE and WUE and F. NUE decreases, while WUE grows with increasing N doses (Fig. 2). The figure showing the maximum values of NUE and WUE (Table 8 and 9) suggests that under F = 75 kg N/ha, the curves of NUE and WUE intersected in a point with the lowest trade-off with NUE value = 118% and WUE = 13.5 kg/ha/mm. It was the point of the most efficient, simultaneous use of water and nitrogen. Increasing F to 160 kg N/ha in order to reduce the risk of N soil mining allowed for obtaining maximum NUE = 81% with maximum WUE rising to the value of 16.3 kg/ha/mm. Further increasing the N dosedid not affect the maximum WUE.

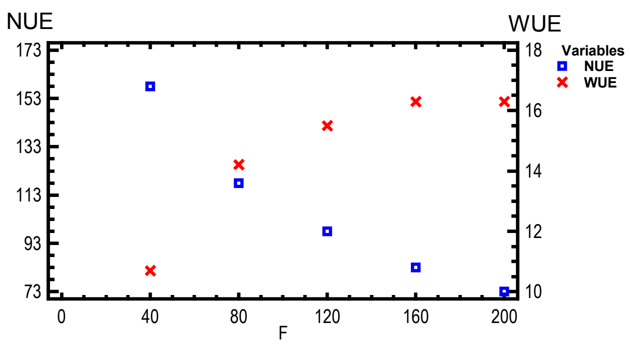

Fig. 2. The maximum values of NUE (%) and WUE (kg/ha/mm) depending on N doses (F, kg N/ha) from the linear phase of the linear-plateau model relating these parameters and actual evapotranspiration (APET).

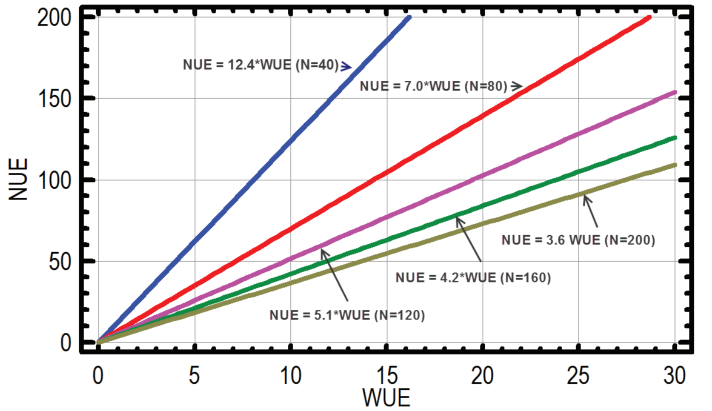

Fig. 3. Nitrogen use efficiency (NUE, %) versus water use efficiency (WUE, kg grain/ha/mm) on nitrogen dose levels (kg N/ha) (r^2 = 97.2 – 98.0)

In considering the possibility of simultaneous optimization of NUE and WUE it is necessary to know the interaction between these variables. Positive relationships between NUE and WUE were found for the data set with APET range smaller than 400 mm (Fig. 3). As previously stated, in this range water shortages affect the value of Yd, Yn, NUE and WUE (Tables 6 to 9). Regressions were estimated separately for each N dose, because there was a statistically significant interaction between WUE and F. The presented data show that the dose of 160 kg N/ha can provide for NUE 50% and 90% achievement of WUE, which is 12 and 21 kg grain/ha/mm, respectively. Estimation is given for the highest F dose that provides a positive interaction between the N and APET (Tables 6 and 9).

In the analyzed experiments NUE and WUE depend not only on APET and F, but also on the effects of other factors. In order to eliminate their limiting effects, the data lying in the vicinity of upper boundary line were selected on the basis of WUE= f (NUE) relationship. The piecewise linear regression with the optimal breakpoint was assessed for these data (Fig. 3).

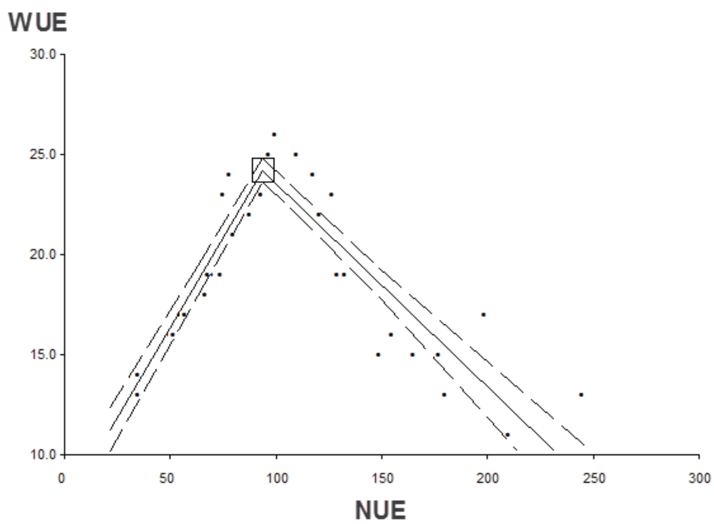

Fig. 4. The relationship between WUE (kg/ha/mm) and NUE (%) for upper boundary line data (n=31, r=84,1%)

The breakpoint (BPx) had NUE value amounting to 93,9%. The linear regression for NUE < 93,9% showed that for NUE of 50 and 90%, WUE will amount to 16,4 and 23,5 kg grain/ha/mm, respectively. The increase of NUE above the value of NUE=93,9 will cause the decrease of WUE.

DISCUSSION

Water and nitrogen availability remain, globally, the most limiting crop growth factors. Improvements of WUE and NUE in crop production are crucial for maintaining food security (Mueller et al., 2012), mitigation of environmental degradation (Sutton, Bleeker, 2013) and climate change (Brouder, Volenec, 2008). Mueller et al. (2012) estimated that global wheat production may be increased by 71% following improvements in water and N management.

WUE of wheat has been reported to be variable (Zwart et al., 2010). The average value was 10 kg grain/ha/mm for main wheat producers. The highest country average values of 14.2 and 13.5 kg grain/ha/mm were assessed for France and Germany. WUE identified in our study were in the range of 5 to 26 kg grain/ha/mm with a median of 13 kg grain/ha/mm (Table 1). The estimated median was therefore lower than the average WUE found in Germany.

NUE in Europe had a slightly upward trend in recent years (Lassaletta et al., 2014), which was an effect of environmental regulations and improved N management. According to the authors cited, the average NUE for crop production in Poland amounted to 43.2% (1960–1980) and increased to 52.7% (1990–2009). Recent studies have shown that winter wheat grown in farms in Poland was characterized by a median NUE of 89% (Faber et al., 2016b). The median NUE found in this study was 77% (31–243%) (Table 1). A large variability in NUE was an effect a large seasonal variation in yield response (1.34 to 9.66 t/ha) to water and N supply.

The relationships between Yd, Yn, NUE, WUE and APET, fitted to a linear-plateau function, showed that the analyzed parameters were limited by APET up to 345–398 mm depending on a parameter and N doses (Tables 6-9). This indicated that during the study water shortages have occurred, that affected the magnitude of the analyzed parameters and the interaction between APET and F. Limitation of maximum yield of wheat for evapotranspiration of

214 to 483 mm, depending on the dose range of 50–250 N in kg/ha, also has been found in other studies (Sadras, Rodriguez, 2010).

The maximum water-limited grain yield in studies was 7.03 t/ha at a dose of 200 kg N/ha (Table 6). It was greater than the yield of 6.5 t/ha, which was established as the water-limited yield for Central Europe (Rabbinge, van Diepen, 2000). Values ΔYd/ΔAPET indicated that the interaction between the grain yield and APET was positive at doses ranging from 40 to 160 kg N/ha (Table 6). Positive interactions suggest that increasing both water and N availability increases yield more than increasing water input or N input alone (Sadras, 2005; Cossani et al., 2010). Negative interaction was observed for the dose of 200 kg N/ha compared to the doses between 80 and 160 kg N/ha. This N dose probably caused excessive growth of dry mass, causing water shortages during the generative development of wheat.

Yields of nitrogen (Yn) increased with N doses and reached a maximum value of 146 kg N/ha at a dose of 200 kg N/ha (Table 7). Between Yd, APET and F were found positive interaction over the range of doses studied.

NUE decreased with increasing N application, as shown many experimental and simulation data (i.e. Asseng et al., 2001). The desired value of NUE from 83 to 73% provide doses of 160 and 200 kg N/ha, respectively (Table 8). However, because of the negative interaction between grain yield, APET and F at a rate of 200 kg N/ha only NUE 83% and the dose of N 160 kg N/ha may be regarded as the near optimum in conditions of these experiments.

As might be expected on the basis of the yield interactions (Table 6), WUE grew at a dose range of 40–160 kg N /ha (Table 9). In this range, the interaction between WUE, APET and F were positive. Negative interaction, as for grain yield, was found at a dose of 200 kg N/ha compared to the doses of 80–160 kg N/ha. These data indicate that the value Yd and WUE has been limited by a shortage of water and nitrogen in the range of APET less than 400 mm and N doses in the range of 40–160 kg N/ha. The data obtained seem to confirm previous results indicating that nitrogen fertilization modified grain yield mainly through changes in water use efficiency (Cossani et al., 2012).

Relationships between NUE and WUE at N doses were in the form of growing linear regression of 1:1 (Fig. 3). These relationships have shown that it was possible to obtain NUE in the range 80 to 68% for maximum WUE of 15.5 to 16.3 kg grain/ha/mm, respectively. Larger values of WUE would be possible to obtain for NUE greater than 100% (N soil mining). A similar result was obtained for wheat fertilization trials carry out in Spain (Quemada, Gabriel, 2016).

Simultaneous increase NUE and WUE on the occurrence of water and N shortages is limited to some extent because of the trade-off between NUE and WUE (Fig. 2). A trade-off relationship between these parameters also been found in other studies (Sadras, Angus, 2006; Sadras, Rodriguez, 2010). However, in the absence of limiting factors WUE increased linearly together with increasing NUE up to the value of 93.9% and then linearly decreased. In the range of the desired NUE values (50–90%), WUE values were between 16.4–23.5 kg grain/ha/mm. The upper value NUE found in this study was close to the maximum value of 24 kg grain/ha/mm obtained for the current varieties of wheat in Australia (Sadras, Lawson, 2013). The maximal water-unit productivity from 20 to 30 kg grain/ha/mm was obtained for wheat (French, Schultz, 1984; Angus, van Herwaarden, 2001). This level of productivity can be achieved only under optimum growth conditions without disturbances from low soil fertility or weeds and pests (Turner, 2004; Passioura, 2006). Therefore, there are reasons to believe that it is possible to obtain maximal WUE when NUE amounts to 90% rounded. This indicates that the upper value of the desirable range for NUE (50–90%) was determined properly (Oenema, 2015).

CONCLUSIONS

This study has indicated that grain and nitrogen yields, WUE and NUE of winter wheat in the cold temperate dry climate of Poland all vary markedly depending on actual evapotranspiration and N management. The results suggest that grain yields and WUE interact positively with actual evapotranspiration up to 400 mm and with N doses up to 160 kg N/ha. In these ranges of parameters it was possible to achieve the maximum value: grain yield 6.35 t/ha, WUE 16.3 kg grain/ha/mm and NUE of 83%. Under near optimal supply of the water and nitrogen maximum values of grain yield, NUE and WUE amounted to 9.66 t/ha, 94% and 23.5 kg grain/ha/mm, respectively.

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