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Productivity of winter oilseed rape depending on its nitrogen and water use efficiency

Agnieszka Rutkowska

Department of Plant Nutrition and Fertilization
Institute of Soil Science and Plant Cultivation – State Research Institute
Czartoryskich 8, 24-100 Puławy, POLAND

Abstract. This paper presents the results of 11 years of field experiment concerning winter oilseed rape in Eastern Poland. The aim of the study was to characterise rape production depending on the nitrogen and water use efficiency. Oilseed rape was fertilised with increasing doses of nitrogen, i.e. 50, 100, 150, 200 and 250 kg N ha^{-1}. It was found that rapeseed yields increased statistically significantly to 3.33 t ha^{-1} at a rate of 200 kg N ha^{-1}. This dose guaranteed: nitrogen uptake of 155 kg N ha^{-1}, nitrogen use efficiency of 78%, nitrogen surplus of 45 kg N ha^{-1}, water use efficiency of 8.4 kg ha^{-1} mm^{-1} and nitrogen utilisation efficiency of 22 kg kg^{-1}. Increasing the nitrogen rate in the long term to 250 kg N ha^{-1} proved to be unjustified because it did not cause a significant increase in the yield or water use efficiency, while it significantly increased the nitrogen uptake, its surplus in the soil and reduced the efficiency of nitrogen from fertilisers utilisation.

Keywords: *Brassica napus* L., nitrogen rates, Nitrogen Use Efficiency (NUE), Water Use Efficiency (WUE), nitrogen surplus

INTRODUCTION

Winter rapeseed is the main oilseed crop cultivated in Poland for consumption and fuel substitution purposes. In recent years, the area of rapeseed cultivation has fluctuated around 0.8 million ha, which placed Poland in the third position among the producers of the crop in the EU (EUROSTAT, 2015). In 2018, rapeseed covered the area of 812 712 ha, which corresponded to 7.5% share of the crop structure (Central Statistical Office of Poland – GUS, 2019a). The average yield of rapeseed and agrimony achieved this year was 2.63 t ha^{-1}, while the harvest of these plants accounted for a total of 2 140 310 Mg (GUS, 2019b). In the 2005–2014 period, rape and agrimony yields ranged within 2.63–3.44 t ha^{-1}, which means a decrease in the yield by 24% (GUS, 2015) in year 2018 compared to the highest yields achieved up to the year 2014.

The production of winter rapeseed requires a relatively high level of nitrogen fertilisation in comparison to other crops. In Poland, in accordance with the recommendations of IUNG-PIB (Institute of Soil Science and Plant Cultivation), nitrogen doses should be determined depending on the quality of the soil, including mineral nitrogen content, the amount of expected yield and fertilising needs of plants in relation to nitrogen. For yields of 3.6 t ha^{-1} and high fertilisation needs, doses in the range of 160–220 kg N ha^{-1} are recommended, while for low fertilising needs 125–190 kg N ha^{-1}. In Germany, for yields in the range of 3–5 t ha^{-1}, the recommended rates are 160–225 kg ha^{-1}, while the Joint Research Center (JRC EC) recommends a nitrogen dose of 137 kg ha^{-1} for crops of 3.11 t ha^{-1} (Osterburg, 2015). Considering the above, for every 100 kg of rapeseed, it is recommended to use nitrogen fertilisers at the following rates (kg N ha^{-1}): in Poland 3.5–6.1, in Germany 4.5–5.3, and according to JRC EC 4.4.

At high fertilisation levels, nitrogen use efficiency (NUE) by winter rapeseed, expressed as the ratio of N content in total biomass to the amount of N available to plants, ranges from 50 to 60% (Malagoli et al., 2005). A significant problem in the production of rapeseed, therefore, is the considerable nitrogen surplus in the full maturity phase (Bouchet et al., 2016; Weiser et al., 2017; Stahl et al., 2019), which is unfavourable for the economics of husbandry and can increase the N losses to the environment (nitrate leaching, gas loss of nitrous oxide and ammonia). Hence, improving the efficiency of the use of nitrogen from fertilisers is a key issue for ensuring the competitiveness of its production as well as sustainability of this production in the environmental and economic aspects.

Research conducted in recent years indicates the possibility of improving NUE in rapeseed cultivation, by simultaneously taking into account: improved crop management (Hegewald et al., 2016, 2017; Kirkegaard et al. 2016), bet-

Corresponding author:
Agnieszka Rutkowska
e-mail: agrut@iung.pulawy.pl
phone: +48 81 4786 840

ter forecasting of nitrogen fertilisation needs (Barlog and Grzebisz, 2004 a,b; Henke et al., 2007), using nitrogen at an appropriate time (Berry and Spink, 2009; Gombert et al., 2010; Sieling and Kage, 2010) and precise application of fertilisers (Berry and Spink, 2009; Spackman, 2018). The latest studies also suggest that the proper use of genetic variation (genetic progress) can be an important step towards improving rapeseed yields and increasing the nitrogen use efficiency (Berry et al., 2010; Bouchet et al., 2016; He et al., 2017; Stahl et al., 2017; Stahl et al., 2019), even in conditions of poor supply of this macronutrient to plants (Bouchet et al., 2016). This was confirmed by the results of the study by Miersch (2014), which indicate higher nitrogen uptake efficiency, nitrogen utilisation efficiency, and seed yields in the semidwarf hybrids under low N and similar seed yields at high N. According to other studies, despite the significant impact of nitrogen fertilisation on the yield of 30 winter rapeseed varieties grown from foundation seed in Germany, a surprisingly low average seed yield gap of 180 kg N ha^{-1} was noted between high and low nitrogen fertilisation (Stahl et al., 2017). These data reveal that genetic improvement through modern breeding techniques in conjunction with reduced N fertiliser inputs has a tremendous potential to increase NUE of oilseed rape.

There is a lack of data in Europe on the water use efficiency (WUE) in rapeseed crops. Hess (2011) reports that WUE for rape seeds cultivated outside Europe range broadly between 0.14–1.0 g m^{-2} mm^{-1} and are smaller than in the case of wheat (0.6–1.7 g m^{-2} mm^{-1}) or maize (1.1–2.7 g m^{-2} mm^{-1}). Generally, WUE values increase with lower water availability for plants; however, this tendency was not found for rapeseed (Hess, 2011). Rapeseed, with roots reaching 1.5 m, is less exposed to water deficits than shallow rooted wheat.

The purpose of the present work was to characterise the productivity of rapeseed and the nitrogen and water use efficiency in experimental crops fertilised with various rates of nitrogen under the conditions of the currently recommended agrotechnics.

MATERIALS AND METHODS

Field experiment was carried out at Experimental Station in Grabów of the Institute of Soil Science and Plant Cultivation in Poland between 2003–2013 in Eastern Poland (21°39’ E, 51°21’ N), on a sandy loam soil (WRB, 2015: Stagnic Luvisols). Winter oilseed rape was grown in the rotation: oilseed rape – winter wheat – maize – spring barley, and was fertilized with five rates of ammonium nitrate: 50, 100, 150, 200 and 250 kg N ha^{-1}. The experiment was set up in two replications. In N150–N250 treatments the first rate of 100 kg N ha^{-1} was at the beginning of the spring vegetation, and the subsequent doses of 50 kg N ha^{-1} were applied in 14 days intervals. In N50 and N100 treatments the whole dose of fertilizer was applied in the beginning of the spring vegetation. Nitrogen fertilisation was applied based on uniform P, K, Mg and Ca fertilisation determined in accordance with the IUNG-PIB fertiliser recommendations. Other crop management operations were carried out in accordance with current recommendations for this crop.

Oilseed rape was harvested at full maturity and the seed yield at 12% humidity as well as straw yield were determined. Nitrogen content in the main and side crop was determined by the Kjeldahl method.

During the 11 years of the study, rainfall after the resumption of rapeseed vegetation was on average 277 (159–387) mm.

The following data were used in the paper: grain yield (Yd), nitrogen rates (F), nitrogen uptake by grain and straw (Yn), nitrogen use efficiency (NUE), nitrogen surplus (Ns), water use efficiency (WUE), and efficiency of nitrogen utilization (NutEY).

According to the methodology proposed by EU Nitrogen Expert Panel (EU Nitrogen Expert Panel, 2015; Brentrup, Palliere, 2010; Quemada et al., 2018), the indices were calculated according to the formulas:

Nitrogen use efficiency:

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

Nitrogen surplus:

$$Ns = F - Yn \quad [2]$$

Water use efficiency (Sinclair et al., 1984):

$$WUE = Yd/PET \quad [3]$$

where: PET – potential evapotranspiration calculated by Thornthwaite and Mather method (1955).

Nitrogen utilization efficiency (Moll et al., 1982):

$$NutEY = Yd/Yn \quad [4]$$

The literature assumes, that NUE characterizes N uptake in its high availability, while NutEY is more important at low nitrogen availability for crops (Moll et al., 1982).

The material was processed using multivariate analysis of variance, where the following factors were included: years of the experiments, and nitrogen rates. The relationship between the mean values Yd, Yn, NUE, Ns, WUE and NutEY obtained from the analysis of variance and nitrogen rates were assessed using analysis of regression. These statistics were estimated using Statgraphics 5.0 package.

RESULTS AND DISCUSSION

Both rapeseed yields as well as other examined variables differed statistically significantly during the years of the study (Table 1).

The rapeseed yields (Yd) achieved in the experiment fluctuated in the range of 1.21–4.02 t ha^{-1}, with an average of 2.92 t ha^{-1}. The values were larger, on average by 0.3 t ha^{-1}, compared to the statistical yields obtained in Poland in the period close to the duration of the experiments (Faber et al., 2016). Nitrogen uptake (Yn) was variable

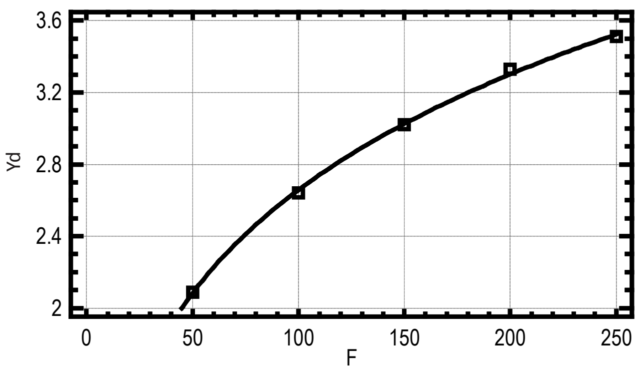
Table 1. The table of means with confidence intervals for the first factor (years, n = 10 for each year) (n = 110).

Year	Yd t ha^{-1}	Yn kg ha^{-1}	NUE %	Ns kg ha^{-1}	WUE kg ha^{-1} mm^{-1}	NutEY kg kg^{-1}
2012	1.21	70	54	80	2.9	17.5
2004	2.24	106	75	44	6.1	22.4
2003	2.36	117	89	33	5.7	20.7
2011	2.64	107	89	43	6.6	25.1
2007	2.77	119	84	31	6.5	25.0
2008	3.18	124	96	26	8.1	26.9
2013	3.25	144	122	6	8.2	22.7
2009	3.31	127	92	23	8.2	27.2
2010	3.36	183	132	-33	8.1	20.2
2006	3.76	151	106	-1	9.6	27.2
2005	4.02	146	115	4	10.5	28.3
HSD (0.05)	0.519	21.2	24.9	21.2	1.33	0.527

over the years (70–183 kg ha^{-1}); however, with the exception of 2012, greater than 80 kg N ha^{-1}, which is suggested as very low (EU Nitrogen Expert Panel, 2015). It can therefore be concluded that, with the exception of 2012, no extreme factors limiting nitrogen uptake occurred during the experiment. NUE fluctuated during the analysed period in the range of 54–132%, with an average of 96%. Thus, the average nitrogen use efficiency was greater than 90%, which indicates that, at an average rate of 150 kg N/ha, the plants depleted nitrogen from the soil resources (EU Nitrogen Expert Panel, 2015). In the long run, this situation should be counteracted in practice by increasing the level of nitrogen fertilisation. Nitrogen surplus (Ns) ranged from -33 to 80 kg ha^{-1}, with an average of 23 kg ha^{-1}. In 2012 exclusively, the values reached 80 kg ha^{-1}, considered as very high (EU Nitrogen Expert Panel, 2015). WUE reached values of 2.9–10.5 kg ha^{-1} mm^{-1} (on average 7.3 kg ha^{-1} mm^{-1}) and were in the range (1.4–10.0 kg ha^{-1} mm^{-1}) reported in the literature (Hess, 2011). The variability in the nitrogen use efficiency during the years (NutEY) oscillated around 17.5–28.3 kg kg^{-1} with an average of 23.9 kg kg^{-1}.

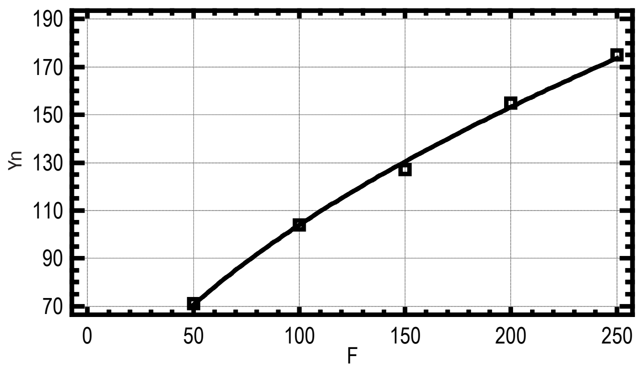
Analysis of the variance of the second factor – N doses, demonstrated that all studied variables depended statistically significantly on the level of nitrogen fertilisation. Grain yields grew significantly to the dose of 200 kg ha^{-1} according to the curvilinear dependence (Fig. 1). The statistically optimal dose determined in the experiment is close to the dose of 180 kg N ha^{-1}, at which the smallest yield gap between high and low nitrogen fertilisation was found for foundation seed of 30 cultivars grown in Germany (Stahl et al., 2017).

The nitrogen uptake increased and was statistically significant over the entire range of the tested doses (Fig. 2). At a dose of 150 kg N ha^{-1}, the uptake reached 127 kg ha^{-1} and was higher than in agricultural practice (88 kg ha^{-1}) with an average dose of 169 kg N ha^{-1} (Faber et al., 2016). The dose of 150 kg N ha^{-1} allowed to obtain NUE at the level of 85% and Ns of 23 kg ha^{-1} in the experiment. NUE in production



Yd = (0.389038 + 0.26949*ln (F))^2; R^2 = 99.9%, n = 5

Figure 1. The relation between the average seed yields (Yd, t ha^{-1}) and nitrogen rates (F, kg ha^{-1}).



Yn = exp (2.06684 + 0.559615*ln (F); R^2 = 99.8%, n = 5

Figure 2. The relation between the average nitrogen uptake (Yn, kg ha^{-1}) and nitrogen rates (F, kg ha^{-1}).

at a similar dose was 54%, while Ns was 73 kg ha^{-1} (Faber et al., 2016).

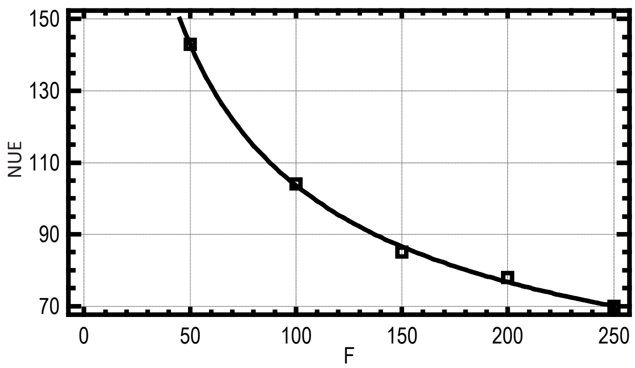
Comparison of the data from the strict experiment and production may indicate that the limitations in the uptake and nitrogen use efficiency in production conditions result from inadequate crop management practices. It is emphasised in the literature that improving NUE requires ensuring good conditions for plant growth, eliminating plant abiotic and biotic stress (Good et al., 2004). In the experiment, oilseed rape yields increased statistically significant to the rate of 200 kg N ha^{-1} (3.33 t ha^{-1}), which ensured the nitrogen uptake at the level of 155 kg ha^{-1}.

NUE decreased considerably with the increase in nitrogen fertilisation. Doses in the range of 150–250 kg N ha^{-1} meant that NUE was in the range of 70–85%, i.e. in the range of desirable values of 50–90% (Nitrogen Expert Panel, 2015). At a dose of 200 kg N ha^{-1}, the nitrogen use efficiency reached 78% and was higher than the value reported in the literature (50–60%) (Malagoli et al., 2005) (Fig. 3).

Nitrogen surplus (Ns) values at doses of 50 and 100 kg N ha^{-1} were negative. Starting from a dose of 150 kg N ha^{-1}, they reached positive values, and their increase was linear (Fig. 4). Moreover, at a statistic optimum, due to yield reasons, dose of 200 kg N ha^{-1}, the nitrogen surplus reached 45 kg N ha^{-1}; however, this value was lower than the accepted value considering the risk of excessive depletion of nitrogen resources from the soil, estimated at 80 kg N ha^{-1} (Nitrogen Expert Panel, 2015) as well as lower than surpluses (60–80 kg N ha^{-1}) usually found in the rapeseed production (Quemada et al., 2018).

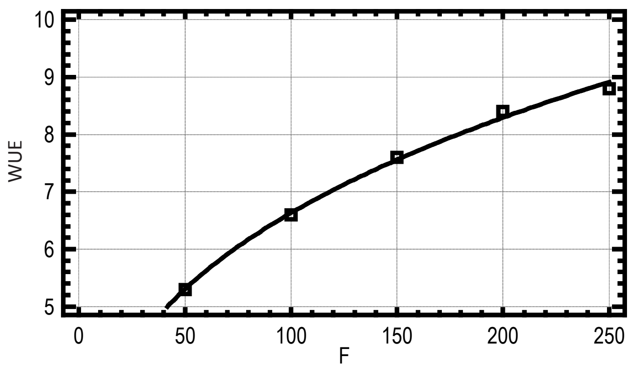
The water use efficiency increased significantly to the value of 8.4 kg ha^{-1} mm^{-1} achieved at a dose of 200 kg N ha^{-1} (Fig. 5). Further increase in the fertilisation level caused a negligible increase in WUE. This correlation suggests that increasing the doses above 200 kg N ha^{-1} may face a barrier of water availability limits.

The efficiency of nitrogen utilization (NutEY) decreased significantly across the entire range of doses (Fig.



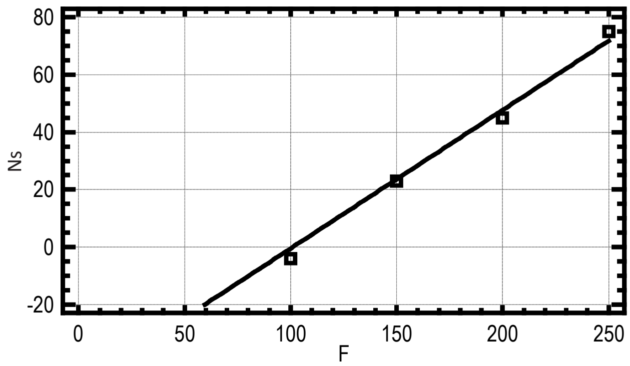
NUE = sqrt (1026.83 + 970946/F); R^2 = 99.9%, n = 5

Figure 3. The relation between the average nitrogen use efficiency (NUE, %) by rape and nitrogen rates (F, kg ha^{-1}).



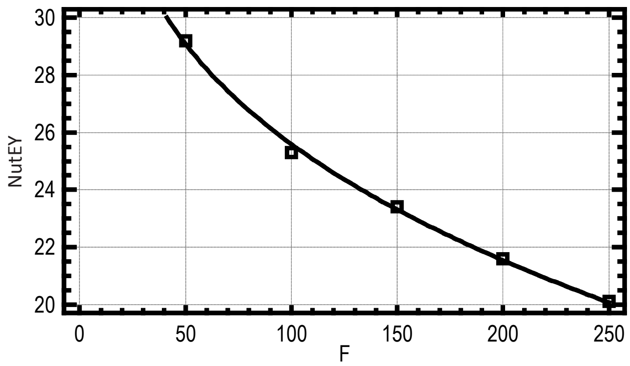
WUE = exp (0.407023 + 0.322446*ln (F)); R^2 = 99.8%, n = 5

Figure 5. The relation between the average water use efficiency (WUE, kg ha^{-1} mm^{-1}) and nitrogen rates (F, kg ha^{-1}).



Ns = -48.7 + 0.482*F; R^2 = 99.0%, n = 5

Figure 4. The relation between the average nitrogen surplus (Ns, kg ha^{-1}) and nitrogen rates (F, kg ha^{-1}).

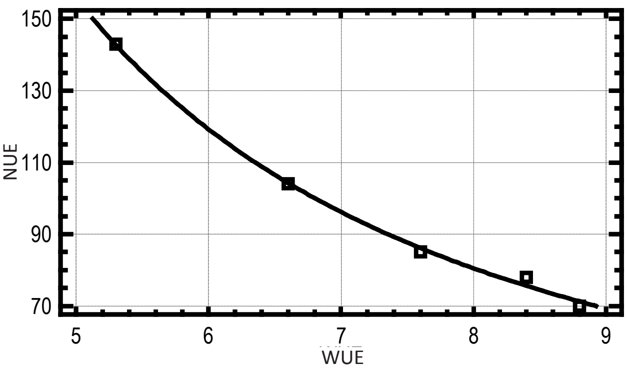


NutEY = sqrt (1923.2 - 275.392*ln (F)); R^2 = 99.7%, n = 5

Figure 6. The relation between the average efficiency of nitrogen utilization (NutEY, kg kg^{-1}) and nitrogen rates (F, kg ha^{-1}).

6), confirming the previous findings that rapeseed is characterised by relatively high uptake efficiency and low nitrogen use efficiency (He et al., 2017). The results are consistent with the literature data, according to which the nitrogen use efficiency is significant at lower doses of N (Moll et al., 1982; Stahl et al., 2017).

The dependence between the nitrogen use efficiency and the water use efficiency indicated that NUE was decreasing with the increase in WUE (Fig. 7), which is a typical trade-off relation.



NUE= (3.13337+ 46.713/WUE)^2; R^2 = 99.5%, n = 5

Figure 7. The relation between the average nitrogen use efficiency (NUE, %) and water use efficiency (WUE, kg ha^{-1} mm^{-1}).

This provided the grounds to conclude that in the range of desirable NUE values (50–90%) (Nitrogen Expert Panel, 2015), theoretically, WUE will be in the range of 12.0 – 7.5 kg ha^{-1} mm^{-1} in the period of many years. However, as the rapeseed WUE does not increase at low water availability (Hess, 2011), it is safer to assume that, according to the estimation, at a dose of 200 kg N ha^{-1} and NUE of 78%, the maximum WUE value will be 8 kg ha^{-1} mm^{-1}, i.e. it will be less than the maximum efficiency (10 kg ha^{-1} mm^{-1}) reported in the literature (Hess, 2011).

The analysis of the results from this study leads to the conclusion that over a long-term period, the nitrogen fertilization rate for rapeseed warranted by NUE and WUE values amounts to 200 kg N ha^{-1}. That application rate ensured seed yields of 3.33 t ha^{-1} and water use efficiency at NUE = 78%, with an environmentally acceptable nitrogen surplus of 45 kg ha^{-1}.

CONCLUSIONS

In the conditions of the long-term field experiment, winter oilseed rape yields increased statistically significantly to 3.33 t ha^{-1} at a nitrogen rate of 200 kg N ha^{-1}. It was also the rate, at which all nitrogen efficiency indicators were within the range reported by EU Nitrogen Expert Panel as being safe for environmental reasons. Such a dose guaranteed: nitrogen uptake in the amount of 155 kg N ha^{-1}, nitrogen use efficiency (NUE) of 78%, nitrogen surplus (Ns) of 45 kg N ha^{-1}, water use efficiency (WUE) of 8.4 kg ha^{-1} mm^{-1} and nitrogen utilisation efficiency (NutEY) of 21.6 kg kg^{-1}. As indicated by the results for the period of 11 years, increasing the level of fertilisation above this dose is not justified, because it leads to a negligible increase in the water use efficiency by rapeseed, which demonstrates that its availability limited the rapeseed productivity at a dose of 250 kg N ha^{-1}.

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Author	ORCID
Agnieszka Rutkowska	0000-0001-9799-0327

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