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Productivity, nitrogen use efficiency and water use efficiency of maize for grain in long term field experiments

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Abstract. Maize, one of the most important cereals species grown in Poland, use large quantities of nitrogen, but water deficit through the vegetation period might lead to yield reduction and diminish nitrogen uptake. The aim of the study was to characterize the productivity of the crop, depending on its nitrogen and water use efficiency. In two locations, in Western and Eastern Poland, eleven-year field experiments with maize grown for grain were conducted. Maize was fertilized with increasing rates of nitrogen: 50, 100, 150, 200 i 250 kg N ha^{-1}. It was found, that grain yields of maize raised statistically significant up to 8.03 t ha^{-1} under 150 kg N ha^{-1}. Such a dose guaranteed: nitrogen uptake 182 kg N ha^{-1}, nitrogen use efficiency 121%, nitrogen surplus -32 kg N ha^{-1}, water use efficiency 14.5 kg ha^{-1} mm^{-1}, and nitrogen utilization efficiency 43 kg kg^{-1}. Increasing nitrogen doses over the years was not justified because maize productivity was limited by water availability under higher nitrogen rates.

Keywords: *Zea mays,* nitrogen rates, Nitrogen Use Efficiency (NUE), Water Use Efficiency (WUE), nitrogen surplus

INTRODUCTION

Maize grown for grain is the third largest cereal crop species in the world. In Poland, since 1990, the sowing area has increased 11 times, reaching 645.4 thous. ha in 2018, which accounts for 11% of the total area under cereal crops (GUS, 2019). It should be expected that due to climate changes, the share of this thermophilic plant in the cropping patterns will be steadily rising in Poland.

Maize originated from Mexico, and is mainly grown in warmer temperate regions and humid subtropics (Huang et al., 2006). It is a C_4 plant, which confers potentially more efficient use of CO_2, solar radiation, water and nitrogen in photosynthesis than C_3 crops. Even though maize is an efficient user of water, it is considered more susceptible to water stress than other crops because of its floral structure with separate male and female floral organs and the near--synchronous development of florets on a single ear borne on each stem (Huang at al., 2006).

Maize productivity is largely dependent on nitrogen fertilization at rates that satisfy its needs for nitrogen. The older species, yielding at the level 7.2 t ha^{-1} needed about 152 kg N ha^{-1}, while the new ones, with 9.0 t ha^{-1} of grain increased N uptake to 170 kg N ha^{-1} (Ciampitti, Vyn, 2012). According to Bender et al. (2013), at high yields – 14.4 t ha^{-1}, nitrogen uptake by the crop reached 280 kg N ha$^{-1.}$ In maize, 45–65% of the grain N is provided from preexisting N in the stover before silking, and the remaining 35–55% – from the post-silking nitrogen uptake (Quilleré et al., 2018).

It has been showed that maize productivity can be maintained under N-low input, nevertheless, high N fertilization rates have been, and still are, used in most high--yielding intensive agricultural maize production systems (Hossard et al., 2016), and in breeding strategies (Bänziger et al., 2000; Chen et al., 2016). Thus, the issue is of great importance, economic and environmental, in the improvement of nitrogen use efficiency (NUE) (Ciampitti, Vyn, 2012; Sharma, Bali, 2018). Due to the fact, that both nitrogen uptake and NUE are largely influenced by water availability, the efficiency of nitrogen utilization is considered together with the water use efficiency (WUE) (Ashraf et al., 2016; Kim et al., 2008; Li et al., 2019; Testa et al., 2016). There was found the "trade-off" relation between NUE and WUE; while NUE decreases together with nitrogen rates increase, WUE rises through nitrogen doses. Such dependences are characteristics for various crops, including maize (Sadras et al., 2012). Enhancement of water and nitrogen efficiency simultaneously will provide advantages in crop productivity (Li et al., 2019; Quemada, Gabriel, 2016). It could lead, on a global scale to 10% of water and

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18% of nitrogen savings in maize production (Li et al., 2019).

The purpose of this paper was to characterize the productivity of maize grown for grain, as well as water and nitrogen use efficiency of the crop in long – term field experiments.

MATERIALS AND METHODS

Field experiments were carried out at two experimental stations of the Institute of Soil Science and Plant Cultivation in Poland between 2003–2013. Experiments were located at Baborówko in Western Poland (16°37' E, 52°37' N) and in Grabów (21°39' E, 51°21' N) in Eastern Poland on a sandy loam soil. Maize for grain was grown in the rotation: winter oilseed rape – winter wheat – maize – spring barley, and was fertilized with five rates of ammonium nitrate: 50, 100, 150, 200 i 250 kg N ha^{-1}. In N150–N250 treatments the first rate of 100 kg N ha^{-1} was applied after maize emergence, and the subsequent doses of 50 kg N ha^{-1} were applied in 14 days intervals. In N50–N100 treatments the whole dose of fertilizer was applied after emergence.

According to fertilization recommendation ISSPC, P, K and Mg were applied in the experiments. At both sites soil shows slightly acid to neutral reaction, low to high content of potassium, and high to very high content of phosphorus and magnesium. No manure and other organic residues were added during the experimental years. In the period of the investigations, the average annual rainfall in Baborówko at the vegetation of maize was 320 (189–539) mm and 371 (248–505) mm in Grabów.

After maize harvest at full maturity, its grain (at 15% moisture) and straw yields were assessed. The concentration of nitrogen in the principal and in the by-product crop by Kjeldahl method was determined, and then nitrogen uptake by the crop was calculated.

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

Nitrogen use efficiency:

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

Nitrogen surplus:

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

Water use efficiency (Sinclair et al. 1984):

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

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

Nitrogen utilization efficiency (Moll et al. 1982):

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

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: location of the experiment, 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

The yields of maize in the experimental stations oscillated within 1.22–15.8 t ha^{-1}, with the mean of 7.59 t ha^{-1}. There were significant statistical differences among yields and among the other analyzed parameters (Table 1).

The average yields achieved in the experiments were lower than grain yields of maize obtained globally, which amounted to 8.3 t ha^{-1}, but were within the range of 8.3±3.7 t ha^{-1} (Li et al., 2019). The nitrogen uptake (Yn) was high in relation to the yield, and comparable to that of the new varieties of maize which gave 9.0 t ha^{-1} grain yield. NUE was over the desired value 50–90% which means an excessive depletion of nitrogen from soil by the crop (EU Nitrogen Expert Panel, 2015; Quemada et al., 2018). The negative value of nitrogen surplus (Ns) indicates that maize derived from soil reserves from 13 to 28 kg N ha^{-1}. Nitrogen soil mining in the long term may lead to the deterioration of soil fertility. In Baborówko, WUE achieved 14.7 kg mm^{-1}, close to the value recorded for maize cultivated without irrigation under fertilization of 120 kg N ha^{-1}. The lowered WUE, and, consequently, Yd and NutEY, in Grabów, may be the result of potassium deficiency in the soils of this experimental station (Rutkowska et al., 2014).

There was a variability and statistical differences for the tested characteristics across the years of the experiments (Table 2).

Experimental yields (Yd) ranged from 1.84 to 11.61 t ha^{-1}. In 2011, when the optimal conditions for growth of maize occurred, maximal yield 11.6 t ha^{-1} of grain was obtained, assured by nitrogen uptake of 227 kg N ha^{-1} (EU Nitrogen Expert Panel, 2015). NUE was excessively high, which resulted from the uptake of 77 kg N ha^{-1} from N stocks by maize. Similarly, this year, the highest value of WUE was recorded, amounting to 21 kg ha^{-1} mm^{-1} and, NutEY reached 51.9 kg kg^{-1}.

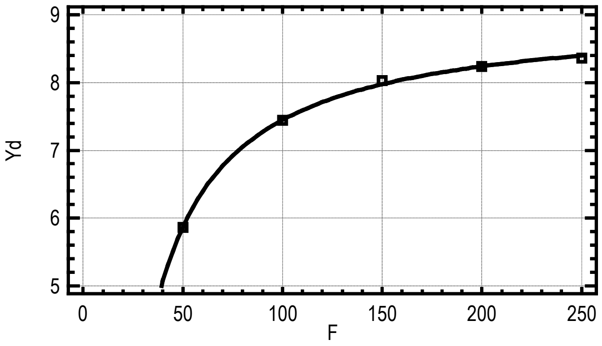
Analysis of the variance of the third factor (N doses), showed that all of the variables depended significantly on the nitrogen fertilization. Grain yields increased through the nitrogen rates (Fig. 1), however the statistically significant increase was proven up to 150 kg N ha^{-1}, which provided the grain yield of 8.03 t ha^{-1}.

Table 1. Table of means with confidence intervals for the first factor (locations of the experiments; n = 110 for each location).

Location	Yd t ha^{-1}	Yn kg ha^{-1}	NUE %	Ns kg ha^{-1}	WUE kg ha^{-1} mm^{-1}	NutEY kg kg^{-1}
Grabów	7.07	163	135	-28	12.7	42.7
Baborówko	8.11	178	141	-13	14.7	45.3
HSD (0.05)	0.21	5.25	5.19	5.25	0.380	1.05

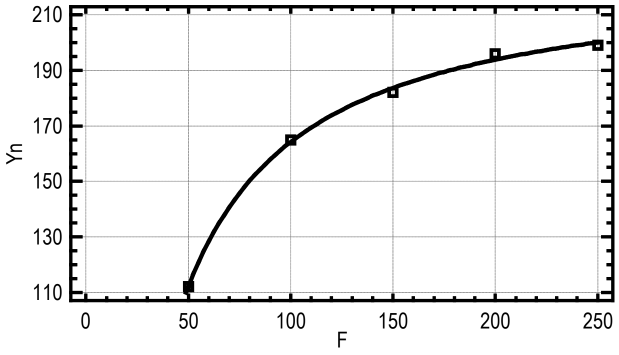
Table 2. Table of means with confidence intervals for the second factor (nitrogen rates; n = 20 for each year).

Year	Yd t ha^{-1}	Yn kg ha^{-1}	NUE %	Ns kg ha^{-1}	WUE kg ha^{-1} mm^{-1}	NutEY kg kg^{-1}
2006	1.84	105	85	45	3.6	22.6
2003	4.51	128	107	22	7.9	33.5
2005	6.89	157	129	-7	12.3	45.5
2004	7.28	159	135	-9	13.4	46.0
2010	7.46	192	159	-42	13.4	39.5
2013	7.53	172	134	-22	13.5	44.2
2008	7.54	159	128	-9	13.6	48.9
2007	8.76	201	160	-51	15.5	44.6
2012	8.81	188	147	-38	15.8	47.9
2009	11.24	192	148	-42	20.4	59.6
2011	11.61	227	184	-77	21.0	51.9
HSD (0.05)	0.824	20.4	20.2	20.4	1.47	4.07



$Yd = 9.03 - 158.32/F$; $R^2 = 99.9\%$, n = 5

Figure 1. Relationship between grain yields (Yd, t ha^{-1}) and nitrogen rates (F, kg ha^{-1}).



$Yn = (15{,}03 - 222{,}2/F)^\wedge 2$; $R^2 = 99{,}8\%$, n = 5

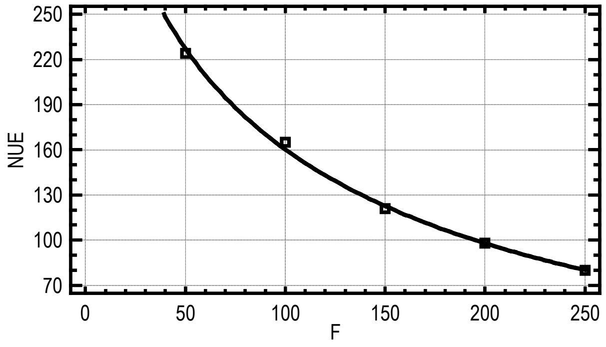
Figure 2. Relationship between nitrogen uptake (Yn, kg ha^{-1}) and nitrogen rates (F, kg ha^{-1}).

Nitrogen uptake (Yn) by maize grew together with N doses (Fig. 2). The increase was statistically significant up to the dose of 200 kg N ha^{-1}, which corresponded with Yn equal to 196 kg N ha^{-1}.

NUE dropped systematically with N doses and at 250 kg N ha^{-1} reached the value 80% (Fig. 3). It was the only value which fell within the desired range of 50–90%, resulting in the acceptable nitrogen surplus Ns = 51 kg N ha^{-1} (Ns < 80 kg N ha^{-1}) (EU Nitrogen Expert Panel, 2015).

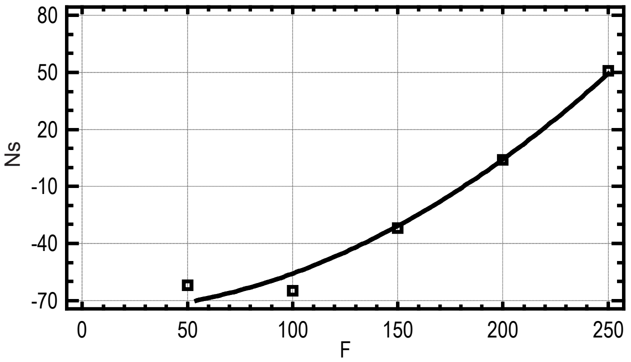
The negative nitrogen surplus (Ns) found up to the rate 150 kg N ha^{-1}, indicates the necessity of soil nitrogen utilization by maize at N fertilization below this level. In the experiment, the fertilizer requirements for nitrogen was satisfied with 200 and 250 N ha^{-1} doses exclusively (Fig. 4).

WUE grew statistically significant to the rate of 150 kg N ha^{-1} when reached the value of 14.1 kg mm^{-1}. Further increasing of nitrogen doses resulted in negligible growth of the parameter (Fig. 5). It suggests that water use



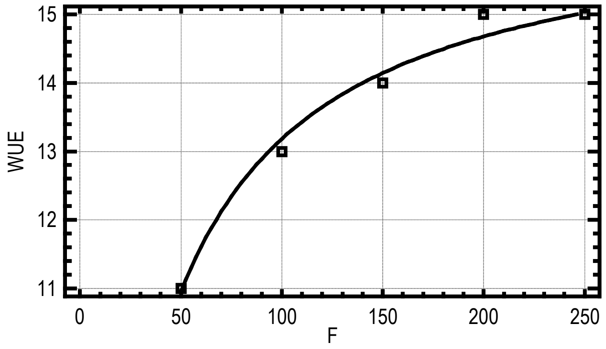
NUE = exp (6.26778 - 0.119087 sqrt (F)); $R^2 = 99.8\%$, n = 5

Figure 3. Relationships between nitrogen use efficiency and (NUE, %) and nitrogen rates (F, kg ha^{-1}).



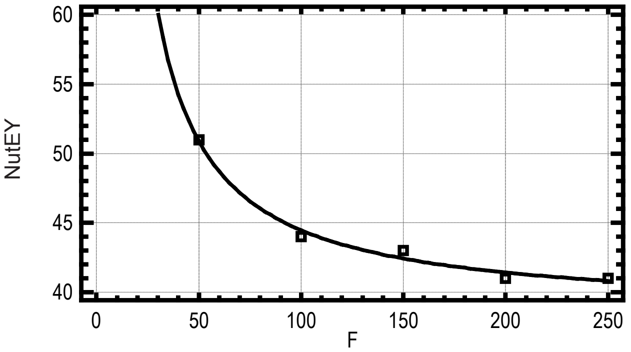
Ns = -75.89 + 0.002000*F^2; $R^2 = 98.2\%$, n = 5

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



WUE = 1/(0.0604 + 1.54778/F); $R^2 = 99.0\%$, n = 5

Figure 5. Relationship between WUE (kg ha^{-1}mm^{-1}) and nitrogen rates (kg ha^{-1}).



NutEY = (6.2023 + 46.5782/F)^2; $R^2 = 98.8\%$, n = 5

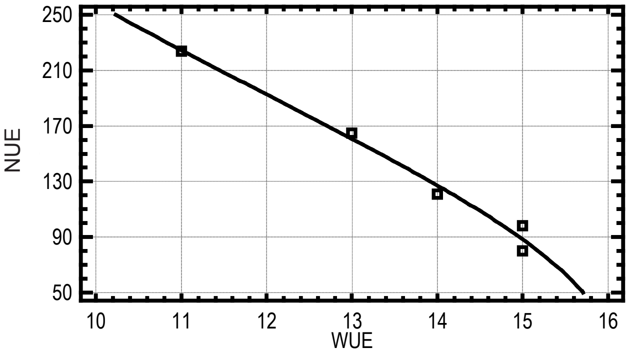
Figure 6. Relationship between nitrogen utilization efficiency (NutEY, kg kg^{-1}) and nitrogen rates (F, kg ha^{-1}).

efficiency for maize might be limited by a shortage of water in the range of 200–250 kg N ha^{-1}.

Nitrogen utilization efficiency dropped systematically through nitrogen rates up to 200 kg N ha^{-1}, reaching the value of 40.7 kg kg^{-1} (Fig. 6).

A trade-off relationship was found between NUE and WUE in the experiments – NUE decreases, while WUE grows with increasing nitrogen rates. The relationship allowed to state, that in the desirable range of NUE 50–90% (EU Nitrogen Expert Panel, 2015), WUE values will be within in the narrow range of 14.9–15.7 kg ha^{-1} mm^{-1} (Fig. 7).

Analysis of the results obtained leads to the conclusion that, based on the values of the NUE and WUE for the long term period, the optimal nitrogen rate should amount to 150 kg N ha^{-1}. Such a rate ensured the highest significant yields, N uptake and N efficiency in another analyzed experimental series with maize (Rutkowska et al., 2014). In favorable conditions (precipitation 479 mm during the growing season) the rate of 150 kg N ha^{-1} ensured obtaining the maximum grain yield of 15.2 t ha^{-1} under Yn 246 kg ha^{-1}, NUE 164%, Ns -96 kg N ha^{-1}, WUE 27 kg ha^{-1} mm^{-1}, NutEY 61.8 kg kg^{-1} and. The obtained yield was higher than the yield of 14.4 t ha^{-1} obtained at 280 kg N ha^{-1} (Bender et al., 2013).



NUE = sqrt (-109567 + 1,76031E6/WUE); $R^2 = 99{,}2\%$, n = 5

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

CONCLUSIONS

Over the recent years, in Poland, drought has been occurring with increasing frequency and field crops have been exposed to long rainless periods during their vegetation. The prolonged period of water shortage result in yield reduction and insufficient uptake of nitrogen from mineral fertilizers causing losses of the nutrient to the environment. The results of long-term field experiments with maize, grown in Eastern and Western Poland showed that the yields of grain raised statistically significant up to 8.03 t ha^{-1} a nitrogen rate of 150 kg N ha^{-1}. Such a dose guaranteed: nitrogen uptake of 182 kg N ha^{-1}, NUE 121%, surplus N -32 kg N ha^{-1}, WUE 14.5 kg ha^{-1} mm^{-1}, and efficiency of nitrogen utilization of 43 kg kg^{-1}. Fertilization rate increases were not required over the long term period as water efficiency increased insignificantly, indicating that water availability limits maize productivity.

REFERENCES

Ashraf U., Salim M.N., Sher A., Sabir S., Khan A., Pan S., Tang X., 2016. Maize growth, yield formation and water-nitrogen usage in response to varied irrigation and nitrogen supply under semi-arid climate. Turkish Journal of Field Crops, 21(1): 88-96, doi: 10.17557/tjfc.93898.

Bänziger M., Edmeades G.O., Beck, D., Bellon M., 2000. Breeding for Drought and Nitrogen Stress Tolerance in Maize: From Theory to Practice; CIMMYT: Mexico City, Mexico, 2000.

Bender R.R., Haegele J.W., Ruffo M.L., Below F.E., 2013. Nutrient uptake, partitioning, and remobilization in modern, transgenic insect-protected maize hybrids. Agronomy Journal, 105: 161-170, doi:10.2134/agronj2012.0352.

Brentrup F., Palliere Ch., 2010. Nitrogen Use Efficiency as an Agro-Environmental Indicator. OECD Workshop on Agri-Environmental Indicators, Leysin, Switzerland, 23-26 March 2010.

Chen K., Camberato J.J., Tuinstra M.R., Kumudini S., Tollenaar M., Vyn T.J., 2016. Genetic improvement in density and nitrogen stress tolerance traits over 38 years of commercial maize hybrid release. Field Crops Research, 196: 438-451, doi: 10.1016/j.fcr.2016.07.025.

Ciampitti I.A., Vyn T. J., 2012. Physiological perspectives of changes over time in maize yield dependency on nitrogen uptake and associated nitrogen efficiencies: A review. Field Crops Research, 133: 48-67, doi: 10.1016/j.fcr.2012.03.008.

EU Nitrogen Expert Panel, 2015. Nitrogen Use Efficiency (NUE) an indicator for the utilization of nitrogen in food systems. Wageningen University, Alterra, Wageningen, Netherlands.

GUS, 2019. Użytkowanie gruntów i powierzchnia zasiewów. Informacje Statystyczne, Warszawa.

Hossard L., Archer D.W., Bertrand M., Colnenne-David C., Debraeke P., Ernfors M., Jeuffroy M.H., Munier-Jolain N., Nilsson C., Sanford G.R., et al., 2016. A meta-analysis of maize and wheat yields under low-input vs. conventional and organic systems. Agronomy Journal, 108: 1155-1167, doi: 10.2134/agronj2015.0512.

Huang R., Birch C.J., George D. L., 2006. Water use efficiency in maize production – the challenge and improvement strategies. Maize Association of Australia, 6th Triennial Conference 2006.

Kim K.-I., Clay D.E., Carlson C.G., Clay S.A., Trooien T., 2008. Do synergistic relationships between nitrogen and water influence the ability of corn to use nitrogen derived from fertilizer and soil? Agronomy Journal, 100(3): 551-556, doi: 10.2134/agronj2007.0064.

Li Y., Li Z., Cui S., Chang S. X., Jia Ch, Zhang Q., 2019. A global synthesis of the effect of water and nitrogen input on maize (*Zea mays*) yield, water productivity and nitrogen use efficiency. Agricultural and Forest Meteorology, 268: 136-145, doi: 10.1016/j.agrformet.2019.01.018.

Moll R.H., Kamprath E.J., Jackson W.A., 1982. Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization. Agronomy Journal. 74: 562-564.

Quemada M., Gabriel J.L., 2016. Approaches for increasing nitrogen and water use efficiency simultaneously. Global Food Security, 9: 29-35.

Quemada M., Brentrup F., Jensen L.S., Oenema J., Buckcley C., Lassaletta L., Oenema O., 2018. Nitrogen Use Efficiency as an indicator of farm performance. 20th N Workshop, Rennes, France, 25th to 27th June 2018.

Quilleré I., Dargel-Graffin C., Lea P.J., Hirel B., 2018. Variability for nitrogen management in genetically-distant maize (*Zea mays* L.) lines: impact of post-silking nitrogen limiting conditions. Agronomy, 8, 309: 1-12, doi: 10.3390/agronomy8120309.

Rutkowska A., Pikuła D., Stępień W., 2014. Nitrogen use efficiency of maize and spring barley under potassium fertilization in long-term field experiment. Plant Soil and Environment, 60(12): 550-554, doi: 10.17221/434/2014-PSE.

Sadras V.O., Grassini P., Steduto P., 2012. Status of water use efficiency of main crops. FAO, SOLAW Background Thematic Report - TR07.

Sharma L.K., Bali S.K., 2018. A review of methods to improve nitrogen use efficiency in agriculture. Sustainability, 10(51): 1-23, doi: 10.3390/su10010051.

Sinclair T.R., Tanner C.B., Bennett J.M., 1984. Water-Use Efficiency in Crop Production. BioScience, 34(1): 36-40, doi: 10.2307/1309424.

Testa G., Reyneri A., Blandino M., 2016. Maize grain yield enhancement through high plant density cultivation with different inter-row and intra-row spacings. European Journal of Agronomy, 72: 28-37, doi: 10.1016/j.eja.2015.09.006.

Thornthwaite C.W., Mather J. R., 1955. The water balance. Laboratory of Climatology Publ. 8, 1 Centerton, NJ.

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