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The impact of drought stress on the production of spring barley in Poland

Beata Bartosiewicz, Jan Jadczyszyn

Department of Soil Science Erosion and Land Conservation
Institute of Soil Science and Plant Cultivation – State Research Institute
ul. Czartoryskich 8, 24-100 Puławy, POLAND

Abstract. Recently, the incidence of droughts in Poland has clearly increased. This is a result of the observed climate change, which, according to the most likely scenarios, will have a significantly perceptible influence on agricultural production. Amongst the observed changes, particularly noticeable is the conspicuous tendency towards an increase in air temperature, solar radiation and wind speed, along with the decrease in precipitation in the spring–summer period, i.e., in the period of peak water demand. The short growing season and the shallow root system make spring barley sensitive to drought stress. Both the quantity and quality of the yield of this crop depend on the volume and distribution of rainfall during the growing season. The water storage capacity of the soil and the plant genotype are equally important. Studies on the influence of drought on the spring barley yields carried out in various scientific centres have demonstrated that the best yields of this cereal are obtained on loamy and silty soils, while the size of the yield is largely limited by water shortage at the end of the vegetative development stage and the beginning of the formation of generative organs. The aim of this work was to summarize the current state of knowledge on the impact of drought stress on the production of spring barley in Poland and to indicate measures compensating for yield losses in drought conditions.

Keywords: spring barley, grain yield, soil retention, drought stress, climate change

INTRODUCTION

The water on Earth is in a continuous movement known as the hydrologic cycle. The inflow of solar energy results in the evaporation of water from: soil, plants and water bodies. After having condensed in the atmosphere, water particles drop to the surface of the Earth in the form of rain, snow or hail (Kuś, 2016). Part of rainwater flows down and feeds rivers, under the influence of gravity, part of it soaks into the soil and is accumulated therein, while the rest infiltrates the soil profile and replenishes groundwater resources (Kacperska, 2002).

It is estimated that agriculture in Poland consumes about 10% of water resources, with the seasonal variation in water demand being its specific feature. The peak (about 80%) water demand occurs in the summer, i.e., in the period when the amount of water is at its lowest (Kuś, 2016). Rainless periods or periods with less than average rainfall are increasingly frequent during the growing season (Doroszewski et al., 2012; Eitzinger et al., 2012; Mizak et al., 2011), and they are accompanied by high temperature values (Ceccarelli, Grando, 1996). Based on the records of meteorological stations, it is estimated that in recent decades the average annual air temperature in Poland has increased (depending on the region) from 0.5 °C to 1.0 °C (Graczyk et al., 2017), and according to the forecast for the years 2071–2100, it will further increase by 3.5–4.5 °C (Górski et al., 2008; Kundzewicz et al., 2018; Scenariusze...). A model of the impact of global warming on the development of crop plants has demonstrated that an increase in temperature by 1 °C per 100 years accelerates the development of cereals in Poland by 1 week (Górski et al., 2008), which, on the one hand, increases the production potential of agriculture (Nieróbca et al., 2013; Karaczun, Kozyra, 2020), at the same time posing a threat to crops (prolonged droughts, heat waves).

The measure for assessing soil moisture conditions is the climatic water balance (CWB) – an indicator defined as the difference between the inflow of water in the form of precipitation, and soil and plant evaporation losses (the so-called potential evapotranspiration) (Radzka, 2014). The increase in sunshine duration (the number of sunshine hours) observed in recent decades (Górski, 2002; Kożuchowski, 2005), combined with the increase in temperature, results in an intensified evaporation, thus reduc-

Corresponding author:
Beata Bartosiewicz
e-mail: bbartosiewicz@iung.pulawy.pl
phone +48 81 47 86 774

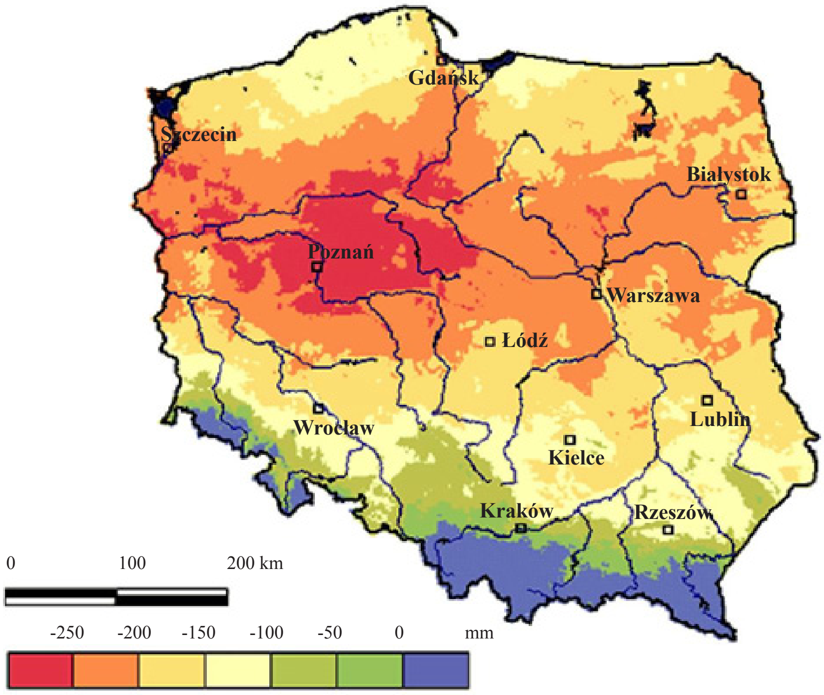

Figure 1. Climatic water balance in Poland from April to September (source: Górski, Zaliwski, 2002); map development: Jerzy Kozyra.

ing the soil water content (Kozyra et al., 2009; Kuczyńska et al., 2019). According to Kozyra and Górski (2008), as well as Doroszewski et al. (2012; 2014), in recent years, especially in the spring and early summer, the CWB index shows a downward trend, while in the April–September period positive CWB values may only be found in mountain and foothill regions (Fig. 1). The conditions in which CWB reaches slightly negative values are considered to be the most advantageous for crop plants, such as those in the southern belt of Poland (Fig. 1) (Kozyra, Górski, 2008); lower values, observed in the rest of the country, have a negative impact on plant development (Doroszewski et al., 2012; 2014). This was the case in the years: 1963, 1964, 1975, 1976, 1979, 1983, 1989, 1992–1994, 2000, 2003, 2005, 2006, 2008 (Doroszewski et al., 2014) and 2015 (Kundzewicz, Kozyra, 2017), when the shortage of rainfall combined with high temperatures caused significant yield losses in spring-sown cereals.

Drought, despite being an extreme weather phenomenon, possessing the character of an atmospheric anomaly (Paulo, Pereira, 2006), is a natural feature of climate, capable of occurring in all its zones. From the point of view of agriculture, drought is a long-term shortage of soil water in a given site, which lasts over a certain period of time and results in the deterioration of growth and development conditions, and the reduction in crop plant yields (Łabędzki, 2006). On account of a short growing season of about 100 days and the shallow root system, spring barley is sensitive to drought stresses, even the temporary ones (Pecio, Wach, 2015). This is confirmed by studies carried out in independent scientific centres, which showed the negative impact of drought stress on the components of this cereal yield (number of grain-bearing ears, number of seeds per ear, weight of 1000 seeds). The conducted research also shows that the quantity and quality of spring barley yield obtained under drought stress conditions are mostly influenced by the development stage in which the drought stress occurred, the genotype and the type of soil on which the barley was grown. (Albrizio et al., 2010; Ajalli, Salehi, 2012; Cossani et al., 2009; Ferrante et al., 2008; Gol et al., 2021; Haddadin, 2015; Hossain et al., 2012, Jamieson et al., 1995; Noworolnik, 2003, 2015; Pecio, Wach, 2015; Zare et al., 2011).

ECONOMIC IMPORTANCE OF SPRING BARLEY

In terms of cultivation area, spring barley is the fourth, after winter wheat, winter triticale and winter rye, cereal plant in Poland, and although the area of its cultivation has decreased by 20% in the last 20 years, it is still the cereal with the largest economic importance among spring cereals. In 2019, the area of its cultivation was 750,000 ha, which accounted for 80% of the total barley cultivation and 9.5% of the grain plantation structure (Statistics Poland, 2020). Spring barley has the largest share in the structure of crops cultivation in the following voivodeships:

Świętokrzyskie, Kujawsko-Pomorskie and Opolskie; with the smallest in the following voivodeships: Podlaskie, Mazowieckie and Lubuskie (Szarzyńska, 2020). Due to good quality parameters (protein content of about 11% and low content of non-nutritional substances), barley grain is an excellent feed for all farm animals (Leszczyńska, Noworolnik, 2012; Liszewski, 2008; Noworolnik, 2014). All varieties of spring barley can be grown for fodder purposes, including malting varieties (Chojnacka et al., 2018). Also, the straw, due to its higher protein content, has a better fodder value than other cereals (except oats) (Noworolnik, 2014). In addition, due to the relatively high content of palmitic and stearic acid, barley grain has a positive effect on the palatability and durability of animal products: milk, butter, meat, lard (Leszczyńska, Noworolnik, 2012; Liszewski, 2008; Noworolnik, 2014). Climate change and the resulting droughts, which occur more and more often, have caused visible progress in the cultivation of fodder barley. Cultivars with higher yield and greater resistance to unfavourable habitat and climatic conditions are being developed (Chojnacka et al., 2018; Friedt, 2011).

INFLUENCE OF WATER SHORTAGE ON THE DEVELOPMENT AND YIELD OF BARLEY

In Poland, agriculture is based mainly on rainwater, which is why the lack of rainfall is a real threat to agricultural production (Staniak, Fariaszewska, 2014). On the basis of the available information, it has been estimated that over the last 600 years droughts have occurred in Poland with a frequency of 19 to 25 times per century (Kuś, 2016), but recently this phenomenon has intensified and over the years 2001–2012 droughts occurred 5 times (Doroszewski et al., 2012; Kuś, 2016). This is also confirmed by the 2006 Report of the Institute of Meteorology and Water Management, according to which droughts occurred on average every 5 years over the period 1951–1981, while in the period 1982–2006, on average every 2 years. The observed tendency of an increase in air temperature and the changing evaporation conditions caused a situation in which the area of the moderately dry region of Poland increased from 13% to 20% over the years 1971–2000, while the area of the humid region decreased from 32% to 10% (Ziernicka-Wojtaszek, 2009).

Water shortages occurring with increasing frequency (often covering large parts of the country) (Lipiec et al., 2013), constitute one of the most common environmental stresses for cultivated plants (Al-Ajloun et al., 2016; Anjum et al., 2011; Alqudah et al., 2011; Carter et al., 2019; Ceccarelli et al., 2010; Datta et al., 2011; Fathi, Tari, 2016; Forster, 2004; Hossain, Uddin, 2011; Khalili et al., 2013). The effect of drought stress is initially manifested at the cellular level, and consequently affects the functioning of the entire plant (Farooq et al., 2009; Grzebisz et al., 2013). Under conditions of drought stress, the uptake of water and minerals from the soil decreases, which hinders the process of photosynthesis, stomatal conductance and transpiration (Farooq et al., 2009; Grzebisz et al., 2013). In order to reduce water loss in the transpiration process, the stomata close, which causes the water potential to be reduced and brings about leaf turgor (Sayar et al., 2008) and results in a reduction of carbon dioxide uptake from the environment (Anjum et al., 2011; ul-Haq et al., 2010). Lowering carbon assimilation inhibits the growth of plant biomass (ul-Haq et al., 2010). Under drought conditions, a higher carbon allocation is observed in the root system (Sanaullah et al., 2012), therefore the reduction in growth affects the aboveground parts more than the roots (Mostafavi, 2011).

Various plant species exhibit varying water requirements in the subsequent development stages. Despite the fact that spring barley is characterized by a relatively low transpiration coefficient (500–600 dm^3 H_2O kg^{-1} of dry matter) (Grzebisz, 2012; Zscheischler et al., 1990) and a fairly high root suction power (Noworolnik, 2008; Noworolnik, Terelak, 2006), it is a short vegetation season and a relatively shallow root system (in the soil layer up to 30 cm deep, 70% to 95% of the root mass (Pasela, 1975)) that makes it a crop sensitive to drought stress (Pecio, Wach, 2015). The water requirements of spring barley rise as the mass and transpiration increase (Dmowski, Dzieżyc, 2009), therefore its yield is influenced by both the amount and distribution of rainfall during the growing season (Chmura et al., 2009). In Poland drought usually coincides with periods of the highest demand for water in plants (Demidowicz et al., 1996; Doroszewski et al., 2014), therefore the consequences of water deficit in barley cultivation depend on the degree of its development (Ahmad et al., 2009; Brisson et al., 2002; Chmura et al., 2009; Dmowski, Dzieżyc, 2009; Liszewski, 2008; Pecio, 2002; Rajala et al., 2011). Water deficiency during the stage of spring barley germination results in the reduction of seedling appearance (Chmura et al., 2009; Budzyński, Szempliński, 1999; Křen et al., 2014). Trnka et al. (2004) emphasize that one of the key elements is the soil water content available for plants on the day of sowing. This team of researchers demonstrated that an increase in available water content by 1% leads to an increase in yields ranging from 0.54 to 1.01 dt ha^{-1}. Water deficit at the tillering stage inhibits the development of the aerial parts and roots, reducing the number of tillers, ears and the number of seeds per ear (Chmura et al., 2009; Budzyński, Szempliński, 1999; Křen et al., 2014), a lack of water during the shooting stage impairs the growth of vegetative organs, which in turn results in reduced grain and straw yields. The drought stress during the earing and flowering stage causes poor ear formation, reduction in the number of seeds per ear and the formation of underdeveloped ears. Grain filling is a period when water is indispensable for appropriate grain filling, therefore its lack during the milky stage results in poor seed formation with a higher content of chaff (Chmura et al., 2009; Budzyński, Szempliński, 1999). Research on the influence of the water factor on the yield has shown that the development stages: shooting – earing as well as grain filling and ripening are critical for the development of crop plants, therefore, in these periods, barley plants are extremely sensitive to water shortage (Chmura et al., 2009).

Moreover, the studies carried out in research centres point to a varying (depending on the development stage) spring barley tolerance to drought stress. A series of experiments carried out at IUNG-PIB (Institute of Soil Science and Plant Cultivation – State Research Institute) over the years 2011–2013 demonstrated a higher tolerance of this cereal to drought stress at the tillering stage than at the flag leaf stage. This tolerance results from the ability (after the restoration of optimal hydration conditions) to produce additional fertile shoots, which significantly influenced the final yield. Temporary stress at the flag leaf stage significantly reduces the number of seeds per ear (Pecio, Wach, 2015).

Manschadi et al. (2006) demonstrated that in spring barley cultivation the key factor in the reduction of losses caused by water deficit is a well-developed root system. This is confirmed by the research results obtained by Kuczyńska et al. (2019), which showed a positive correlation between the size of the root system and the plant height, ear length, number and weight of seeds per ear, weight of seeds per plant and the mass of 1000 seeds.

THE IMPORTANCE OF SOIL FOR THE CONSEQUENCES OF DROUGHT STRESS

Water deficiency in soil has a negative effect on the size and structure of spring barley grain yield. This has been confirmed by multiple field experiments (Noworolnik, 2003, 2015), therefore, during drought, the ability of the soil to retain water is of key importance for reducing unfavourable changes in plant metabolism and growth (Akram, 2011; Datta et al., 2011; Promkhambut et al., 2010; Seghatoleslami et al., 2008). The retention properties of soil are mostly influenced by: the share of floatable fraction, especially clay fraction, in the organic matter content and grain size composition. The thickness and the deposition of individual genetic layers with different grain sizes has a significant impact too (Hewelke et al., 2013). The water-holding capacity of soil is closely correlated with the size of the surface of soil particles, therefore the soil texture holds a special importance amongst the above-mentioned properties (Thompson, Troeh, 1978). The smaller the soil particles, the larger the specific surface area for holding water, and the larger the total volume of small pore spaces (Thompson, Troeh, 1978), therefore compacted soils made of clay and loam have up to 2.5 times greater water-holding capacity than light soils created from sandy formations.

Table 1. Differentiation of soil cover in Poland according to categories of soil susceptibility to drought (Dz.U. nr 75, poz. 480, 2010).

Category of soil	Sensivity to drought	Soil type
I	very sensitive	loose sand loose silty sand slightly loamy sand slightly silty loamy sand
II	sensitive	loamy light sand loamy silty light sand loamy heavy sand loamy silty heavy sand
III	medium sensitive	sandy silt silt-loam loamy silt light loam light silty loam
IV	slightly sensitive	medium loam medium silty loam heavy loam heavy silty loam clayey silt clay silty clay

The information on the grain size composition of the soil profile on the agricultural soil map allowed for dividing Polish soils into four categories as regards the sensitivity to drought, namely: soils of category I — very sensitive (very light), II — sensitive (light), III — medium sensitive (medium), IV — slightly sensitive soils (heavy) (Table 1) (Dz.U. nr 75, poz. 480, 2010; Jadczyszyn, Bartosiewicz, 2020). Since light and very light soils constitute 60% of Polish arable land (Igras, Lipiński, 2006; Karaczun, Kozyra, 2020), characterised by low and very low capacity to retain water in the soil profile, as well as the tendency to dry out faster in the Polish agroclimatic conditions, drought begins on these soils usually 10–15 days earlier than on heavy soils (Wójcik et al., 2018). Low retention also significantly increases the frequency of agricultural drought, which was confirmed by the analyses carried out by Doroszewski et al. (2014). These analyses indicate that in the studied period (1961–2010), drought was most frequently recorded on the soils of category I and II in the cultivation of spring crops (Table 2 and 3).

Spring barley has higher soil requirements than oats, triticale or rye. The research carried out by Noworolnik (2008) demonstrated that the best harvests of this grain are obtained on soils classified as agronomic categories II and III (Table 1), i.e., silt-loams and light loams and on loamy heavy sands lying on light loams. Average harvests can be obtained on full loamy heavy sands and on loamy light

Table 2. The frequency of agricultural drought in the years of 1961–2010 for spring cereals on soils I–IV category (source: Doroszewski et al., 2014).

Period	Soil category			
	I	II	III	IV
1961–1970	8	4	1	0
1971–1980	7	7	2	0
1981–1990	6	5	2	1
1991–2000	9	5	3	2
2001–2010	10	8	5	1

Table 3. The frequency of agricultural drought in the years of 1961–2010 on soils I–IV category (source: Doroszewski et al., 2014).

Soil category	Average frequency (in years)
I	1.1
II	1.4
III	2.6
IV	4.5

sands underlain by light loams, with lower harvests on full loamy light sands and on slightly loamy sands underlain by light loams.

The decline in barley yield in the cultivation on slightly loamy sands compared to the cultivation on silt-loams or light loams was as high as 24%. Also, long-term experiments carried out by Noworolnik (2015), and Noworolnik and Terelak (2005) confirm that a more compact substrate contributes to obtaining a higher yield of barley grain. The researchers also point out that despite the higher harvests of spring barley obtained on loamy and silty soils, satisfactory yields can also be obtained on lighter soils, but these soils must be in good condition. Noworolnik (2014) also emphasizes that the increase in the protein content of the barley grain is a partial compensation for the lower yields obtained in poorer soil conditions.

THE IMPORTANCE OF GENOTYPE

Spring barley is sensitive to both unfavourable weather and soil conditions. Climate change and increasingly frequent droughts have contributed to the visible progress in the cultivation of this grain. Breeders create new cultivars with stable genotypes, characterized by greater resistance to unfavourable habitat conditions and ensuring high quality of grain in various soil and climatic conditions (Chojnacka et al., 2018; Friedt, 2011). Currently, there are 92 varieties of spring barley on the list of the national register, 67 of which are fodder varieties (http://www.coboru.gov.pl/Polska/Rejestr/odm_w_rej.aspx?kodgatunku=JEZJ). The varieties included in the Common catalogue of varieties of agricultural plants species (CCA) are also allowed to be marketed.

The studies of Cai et al. (2020) indicate significant variability of the barley genotype in terms of drought tolerance. In conditions of water scarcity, the sensitive genotypes were characterized by a greater reduction of biomass, compared to the resistant genotypes. Also, the studies by IUNG-PIB, which were carried out on 206 genotypes of spring barley, confirm its significant influence on the yield under conditions of drought stress. Cluster analysis carried out for the results obtained in the conditions of drought stress introduced at the tillering stage and drought stress introduced at the flag leaf stage allowed for isolating a group of drought-sensitive and drought-tolerant genotypes (Pecio, Wach, 2015). In drought conditions, the sensitive genotypes decreased the grain yield, while the tolerant genotypes showed similar yield capability as in the conditions of optimal humidity. The tolerance of barley genotypes to drought stress at the tillering stage results from the ability to create additional fertile shoots after restoring optimal hydration conditions, while at the flag leaf stage it results from the ability to compensate for the reduced number of grains in ears by increasing the weight of 1000 grains (Pecio, Wach, 2015). Both Gołębiowski et al. (2013) and Noworolnik (2014) also point out a significant influence of the genotype on the protein content in grain.

In the course of the research, it was established that native varieties are better adapted to the climatic and soil conditions in Poland than foreign varieties (Noworolnik et al., 2007). The results of experiments carried out as part of the Post-Registration Cultivar Testing (PDO) are helpful in making the decision on the choice of agricultural seed, and their purpose is to check the suitability of varieties for cultivation in various climatic and soil conditions in Poland and the potential risk of drought, verify their characteristics, as well as recommend varieties for cultivation in individual voivodeships. To this end lists of recommended varieties (LZO) for a given voivodship are created (Szczepańska, 2018).

SUMMARY

In recent years, Poland has seen an increased frequency of periodic water shortages in agriculture covering large areas of the country. Due to the intensified incidence of the phenomenon of drought, it has become a significant economic and environmental problem. According to the most probable forecasts of climate change, over the next several dozen years we will observe a further reduction of the number of rainy days and the total amount of precipitation in the spring and summer period. On the other hand, the average annual air temperature will continue increasing, which may aggravate the problems with satisfying the water needs of agriculture. The increase in temperature will also contribute to the extension of the growing sea-

son of crops, providing opportunities for the cultivation of new plant species on the one hand, and, on the other hand, creating threats to crops (prolonged droughts, heat waves, increased pressure from pests and diseases). Since climate change significantly impacts the reduction in agricultural production, in order to ensure stable crops with appropriate quality characteristics, plant breeders, biotechnologists, physiologists and biochemists face new challenges related to the search for plant varieties with increased resistance to drought, efficient management of water and nutrients and with increased resistance to pests and diseases. On the other hand, farmers must create the right conditions for plants to grow and develop. It is possible owing to a properly selected and prepared cultivation area, selection of the right variety, characterized by high fertility and health, adhering to the sowing date, which extends the vegetation period and increases the productivity of the ears. An important role is also played by the timely application of agrotechnical treatments related to the protection and fertilization of plants.

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Author	ORCID
Beata Bartosiewicz	0000-0003-0148-2999
Jan Jadczyszyn	0000-0003-4921-7609

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