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Impact of Irrigation and Fertigation on the Yield and Quality of Sugar Beet (*Beta vulgaris* L.) in a Moderate Climate

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Abstract: In Poland, under conditions of the moderate climate and transition between maritime and continental climates, the average rainfall totals of the growing season are in the range of 350–400 mm; however, they are distinguished by great temporal and spatial variability. Climatological studies demonstrate that the drought frequency is approximately 30%. Therefore, under such conditions, irrigation has a supplementary and intervention nature and is applied only when dry periods occur. The aim of this study was to determine the impact of sprinkler irrigation and increased nitrogen fertilization on the yield and quality of sugar beet roots and yield of sugar. The average increase of the yield under irrigation was 18.1 t·ha^{-1} which constituted a 22.8% increase in the yield. Furthermore, there was a marked tendency of a higher sugar content in the roots of irrigated plants. The absolute, relative, and unit average sugar beet root yield increases obtained under the influence of sprinkler irrigation and the lack of a significant diversity in the sugar content in roots confirm that irrigation contributed to an appropriate pace of plant growth and development. The increased rate of nitrogen fertilization (N2) of 160 kg N·ha^{-1} plus an additional 40 kg N·ha^{-1} resulted in the significantly greater root yields compared to the control (N1) (160 kg N·ha^{-1}), i.e., an average of 7.6 t·ha^{-1} (9%). Based on the crop-water production function, the maximum root yields were obtained for the N1 rate at a total precipitation and irrigation amount of 382 mm, compared with 367 mm for the N2 rate.

Keywords: sugar beet; sugar yield; sprinkler irrigation; optimal precipitation; irrigation needs

1. Introduction

Sugar beet is a plant with increased water requirements due to its long growing season and high yield potential. Making full use of its yield potential as well as of the applied agrotechnical treatments including nitrogen fertilization depends on many factors e.g., genetic diversity of hybrids [1] (about 50% of the increase in yield and quality of sugar beet was achieved by breeding progress) [2] and adaptation abilities of cultivars to an individual environment [3], but it most heavily depends on the soil type or location and above all, on the availability of water during the period of high demand of the plants [4–6]. This water availability to plants is subject to the rainfall volume and distribution during a growing season, or in the case of rainfall shortages, it relies on the use of irrigation if possible.

In Poland, under conditions of the moderate climate transition between maritime and continental, the average rainfall totals in the growing season are in a range of 350–400 mm; however, they are distinguished by great temporal and spatial variability. Therefore, irrigation of sugar beet has a supplementary and intervention nature and is applied only when dry periods occur in the growing season [7,8], the frequency of which is approximately 30% [9–11]. There were relatively few national experiments until now, but they showed that sugar beet responds to sprinkling irrigation with a root yield increase but a decrease in the sugar content [12,13]. The increases in root yield depended on rainfall totals and distributions and soil properties [5,14–17]. The greatest yield increases were gained in multi-annual research conducted on very light soil near Bydgoszcz. They were on average 19.8 t·ha^{-1}, but in extremely dry years amounted to 37.7 t·ha^{-1} [8]. In recent years in Poland, no sugar beet irrigation experiments have been conducted. Due to the great breeding progress of sugar beet and agrotechnical development, yields of sugar beet roots have almost doubled compared to the 1980s and 1990s. This brings about the necessity to resume studies on the optimization of water use of new, more productive cultivars conducted under the conditions of upgraded and more effective practices in agriculture.

In the arid and semi-arid climate zones, sugar beet irrigation is basic agronomic management; therefore, considerable scientific research focuses on introducing new water and energy saving irrigation systems and obtaining more precise irrigation schedules and control methods [18–21]. Vamerali et al. [22] claimed that sugar beet is a field crop well suited for deficit irrigation applications. However, results of many studies report yield losses under water deficit conditions. Abyaneha et al. [23] showed that irrigation treatments were significant for all quantitative and qualitative characteristics of sugar beet. By increasing the amount of irrigation water, root and white sugar yields increased while the sugar content decreased. The highest root and white sugar yields were obtained through the full-irrigation treatment with a mean root and white sugar yields of 54.235 t·ha^{-1} and 7.803 t·ha^{-1}, respectively, compared to the treatment of 65% of the crop water requirements (30.588 t·ha^{-1} and 4.635 t·ha^{-1}, respectively). Mahmoodi et al. [24] showed that irrigation regimes had a significant effect on the sugar yield of sugar beet and its quality. The optimum soil water content for maximum root yield and quality was 70% of the field capacity. Kiziloglu et al. [25] indicated that deficit irrigation practices significantly decreased the root, leaf, and total sugar yields of sugar beet under semiarid and cool-season climatic conditions. Similarly, Topak et al. [18] found that root and white sugar yields of sugar beet significantly decreased by increasing the water deficit in a semiarid region. Okom et al. [26] indicated that the experimental implementation of a 16% water reduction applied to sugar beet plants grown in a greenhouse implies that reduced summer rainfall will have a significant impact on soil moisture (12% decrease; $p < 0.05$) and wet sugar beet yield (11% decrease; $p < 0.05$). The dry yield did not show a statistically significant result (7.4% decrease; $p = 0.11$), but there was far from conclusive acceptance of the null hypothesis put forward by the authors.

Besides water conditions, another factor plays an important role in shaping sugar beet yield quantity and properties. Appropriate nitrogen fertilization is essential for high root and sugar yields, but an excess of this nutrient influences juice purity and sugar extractability. In Poland, some investigators studied the effect of different levels of nitrogen fertilization on sugar beet grown in different types of soils. Michalska-Klimczak and Wyszyński [27] conducted an experiment on degraded phaeozems in the central-southern part of Poland. The authors stated that nitrogen fertilization at the rate of 120 kg N·ha^{-1} allowed an increase of beet root yield by 15.1 t·ha^{-1} (28.3%) and sugar yield increase by 2.4 t·ha^{-1} (27.2%). The mean root mass was the largest at a rate of 120 kg N·ha^{-1} despite that the final plant density was the highest at a nitrogen rate of 60 kg N·ha^{-1}. Bzowska-Bakalarz and Banach [28] estimated the effects of a modified system of fertilization of sugar beets on the content of saccharose and yield of sugar on luvisols in the south-eastern part of the country. The authors obtained better technological properties in the area under the modified system of fertilization (lower doses of nitrogen, 120 kg N·ha^{-1}; fertilization with microelements; fertilizer doses selection based on analyses of the soil). Rzekanowski et al. [13] examined the influence of N fertigation and sprinkler irrigation of sugar beet cultivated on haplic luvisols in the central–northern part of Poland. Between the two yield-forming factors studied, irrigation had a stronger impact on crops. Irrigation increased the yield from 15.1 to 18.4 t·ha^{-1} in comparison with the control, depending on the dose of fertilizers. The strongest differentiation of yields caused by irrigation was noted in dry years when the yield increment ranged from 24.4 t·ha^{-1} at a nitrogen rate of 90 kg N·ha^{-1} to 28.6 t·ha^{-1} at a nitrogen rate of 150 kg N·ha^{-1}. A higher nitrogen dose had no significant effect on the yield under the control conditions, but under irrigation, the rate of 150 kg N ha^{-1} caused an increase of yield of 2.5 t·ha^{-1} as compared with that at 90 kg N ha^{-1}. In the moderate climate conditions in Northwest Germany, sugar beet was grown from 1980 to 1988 on a luvisol. N-fertilizer levels ranged from 2 kg N·ha^{-1} to 211 kg N·ha^{-1}. Root yield, sugar yield, and white sugar yield increased with increasing N-supply and reached maximum values at 159, 136, and 129 kg N·ha^{-1}, respectively. Root yield showed no or only a slight decrease, whereas sugar yield and white sugar yield decreased with N levels beyond the optimum. Sugar concentration decreased with increasing nitrogen supply; it was highest at 32 kg N·ha^{-1} and decreased slightly with less N supply. White sugar yield had a broad optimum and decreased by only 2% of the maximum value within a range of approx. 100 kg N·ha^{-1} [29].

Poland is the third-largest producer of sugar beets in the European Union after France and Germany, with a sugar production of 2.3 Mt per year and 18 operating sugar manufacturers (the European Association of Sugar Statistics CEFS) [30]. In the years 2004–2018, sugar beets were cultivated in Poland within an area of about 223,327 ha, but this has fluctuated over time (Figure S1a). The multi-annual yield for the period 2004–2018 was on average 54.4 t·ha^{-1}, but this ranged from 41.6 t·ha^{-1} in 2004 to 68.3 t·ha^{-1} in 2014 (Figure S1b) [31], which may be due to the effect of the breeding progress [32], cultivar adaptation to environmental conditions [3], or irrigation used in agricultural production [33,34]. The average annual yield of sugar beet roots in Poland varies by year; e.g., in the 2018 dry growing season, the average yield of sugar beet amounted to 59.9 t·ha^{-1}, which constituted 88.2% of the yield in 2017 (Figure S1b), but it was higher by 5.46 t·ha^{-1} (9, 1%) compared to the average yield for 2004–2018 (54.4 t·ha^{-1}) [31]. The second-largest producer of sugar beets in the country is the Kujawsko–Pomorskie region located in the northern part of central Poland (Figure 1). In the years 2011–2017, sugar beets were cultivated here within an area of about 40 thousand hectares, representing 19.5% of the total domestic acreage [31].

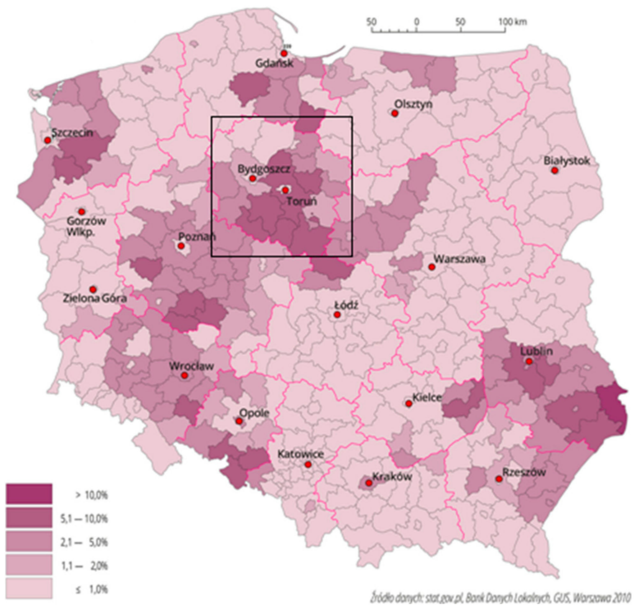

Figure 1. Share of sugar beet in the total cultivated area by district in 2010; the second-largest producer of sugar beets is Kujawsko–Pomorskie, marked on the map with the square shape [31].

The general feature of the precipitation regime in Poland is the predomination of warm-half-year precipitation over the cold-half-year [35]. The Kujawsko–Pomorskie region has the lowest precipitation in Poland, i.e., a multi-annual yearly average of about 500 mm and 350 mm in the growing season from April to September. Another feature of this region is frequent and long-lasting periods without rainfall, on average 22 days, but maximal at even 38 days [36].

Even during the growing seasons, when the weather conditions are favourable for sugar beet production, water deficits may occur due to high values of air temperature, saturation deficits, and as a consequence of intensive evapotranspiration in the summer months. Consequently, the reduction of the sugar beet yield occurs due to water scarcity, especially on light soils [37]. Predicted climate change may be expected to reinforce this effect in the future [26]. According to the climate forecasts, the frequency of extreme weather conditions and hence the occurrence of rainfall shortages are expected to increase [38]. In recent years in Poland, changes in the course of droughts have been observed more frequently, which especially applies to the increase in air temperature [39]. Although the annual precipitation totals in Poland change slightly (a gentle, but not significant increase has been noted), substantial changes have been observed in seasonal and monthly precipitation patterns [40]. Without adequate irrigation, yields can fluctuate each season, resulting in difficulties for sugar manufacturers to plan, as well as financial pressure for farmers. Irrigation guarantees stability and mitigates problems of drought occurrence caused by climate change, as one can maximize yield quantity and the sugar content as well as achieve better uniformity of yield year after year. Therefore, the aim of the study was to determine the impact of sprinkler irrigation and increased nitrogen fertilization on the yield and quality of sugar beet roots and yield of white sugar. The research hypothesis assumed an increase in efficiency and quality improvement of sugar beet root yield under the conditions of irrigation and an increased rate of nitrogen fertilizer. The expected audience is not limited to regional or state levels, but also includes international communities interested in agriculture in this part of Europe. In addition, the development of irrigation in this area will affect the greater demand for water and thus water resources and their management in this region. In our view, the results of this study may encourage farmers to control irrigation more efficiently and officials and policymakers to rationally plan agricultural policy and the food market in the face of anticipated climate change.

2. Materials and Methods

2.1. Experimental Design

A field experiment was carried out in the 2016–2018 period at the Research Centre of the University of Technology and Life Sciences in the city of Bydgoszcz. It is located in the town of Mochełek at a distance of 20 km from the city centre, on the south-eastern edge of the Krajeńska Upland (latitude 53°13′ N, longitude 17°51′1 E).

The experiment was carried out on a Luvisol, created by fluvioglacial sand, which belongs to the IVa quality class and is a very good rye agricultural complex. It is a light soil on compacted subsoil (weak loamy sand on sandy clay loam). The content of the mechanical particles of diameter <0.02 mm in the 0–50 cm depth layer is 18% and at 51–100 cm, 46%. The soil water storage from one metre to the depth of the soil profile is 215 mm at field water capacity [41].

The experimental design was a randomized complete block design (RCBD) with treatments arranged in a split-plot. The main plots were W0 and W1, and the subplots were N1 and N2. The number of replications of each treatment was 4. The size of the harvesting plot was 10.8 m^2. Two factors were considered, and two levels of each factor were applied. The first factor (W) was water supply; the first, control level (W0) was the rainfed option without irrigation, and the second level (W1) was optimal sprinkler irrigation that assured 100% coverage of the sugar beet's water needs during the period of high demand. The second factor was the nitrogen fertilizer (N); the first level (N1) was a pre-sowing fertilization rate of 160 kg $N{\cdot}ha^{-1}$, and the second level (N2) was a pre-sowing fertilization rate 160 kg $N{\cdot}ha^{-1}$ plus an additional 40 kg $N{\cdot}ha^{-1}$ at the stage when the rosette covered the inter-rows, which is 8 weeks after the sowing date, approximately in the second 10-day period of June). Nitrogen fertilization was applied before sowing in the form of urea (46%), while the second rate for the N2 treatment was 36% ammonium nitrate.

Sugar beet cultivar ‘Igloo’ was chosen for the experiment. This cultivar predominated in the Polish register of varieties in 2014. The cultivar ‘Igloo’ is characterized by a high sugar yield per hectare and high polarization at the early harvest date. The crop previous to sugar beet was soybean.

In each year of the experiment, agronomic management recommended to this crop was applied, including diligent tilling of the soil; phosphorus and potassium fertilization at a rate corresponding to the soil’s nutrient abundance (phosphorus was used in the form of superphosphate 5%, and potassium in the form of potassium salt, 60%); early sowing date; and plant protection treatments, which included weed (Betanal Max spraying—two treatments) and pest (Proteus 0.6 L) prevention.

The sowing dates were 5 April in 2016 and 2017 and 13 April in 2018. The harvest dates were 3 and 7 November and 20 October, respectively.

The plots were irrigated using a sprinkler system consisting of 10 micro-sprinklers with a unit capacity of 0.1 $m^3 \cdot h^{-1}$. The source of water was the public water supply system. Decisions on irrigation were taken on the basis of a method which employed precipitation measurements [9]. Agrometeorological monitoring has been conducted in the neighbourhood of the experimental field.

2.2. Actual and Optimal Precipitation Conditions

In the growing season of 2016, but especially that of 2017, monthly totals of rainfall were higher than long-term average totals (Table 1); therefore, sugar beet was irrigated occasionally: twice in 2016 on 25 and 31 August, with doses of 25 and 25 mm of water, respectively, and once in 2017 on 28 June, i.e., 20 mm of water.

Table 1. Monthly precipitation totals in the field experiment in the years 2016–2018 in the background of long-term average totals 1981–2010 (mm).

Year	Months						April–September
	April	May	June	July	August	September	
1981–2010	27.0	49.3	52.8	69.8	62.6	46.0	307.6
2016	28.7	51.4	98.1	133.8	55.3	19.4	386.7
2017	40.8	56.3	54.3	118.9	126.1	78.4	474.8
2018	40.4	14.2	26.4	86.0	23.7	17.0	207.7

The difference between actual and optimal precipitation was applied to calculate precipitation deficits for the respective months of the plant cultivation and total deficit for the growing periods. Optimal precipitation for sugar beet was determined for medium soil in the successive months of the growing season based on the method proposed by Klatt (Table S1) after Kuśmierek-Tomaszewska et al. [10]. According to the method, optimal precipitation amounted to 50 mm in April (at an average air temperature of 8 °C), 50 mm in May (13 °C), 60 mm in June (16 °C), 90 mm in July and August (18 °C and 17 °C, respectively), and 60 mm in September (14 °C). For each 1 °C above or below mean monthly air temperature determined by Klatt, 5 mm of precipitation was added or subtracted, respectively. A comparison of actual precipitation and calculated optimal precipitation for sugar beet production showed that the multi-annual precipitation deficiency during the period of high water needs was on average 43 mm [42]. Figure 2 shows that in the consecutive growing seasons of 2016 and 2017, precipitation was excessive for sugar beet requirements and amounted to 24 and 76 mm, respectively. However, in 2018, during the period of high water needs of sugar beet, precipitation shortages of −89 mm occurred, i.e., much greater than the average deficit in the 1981–2010 period.

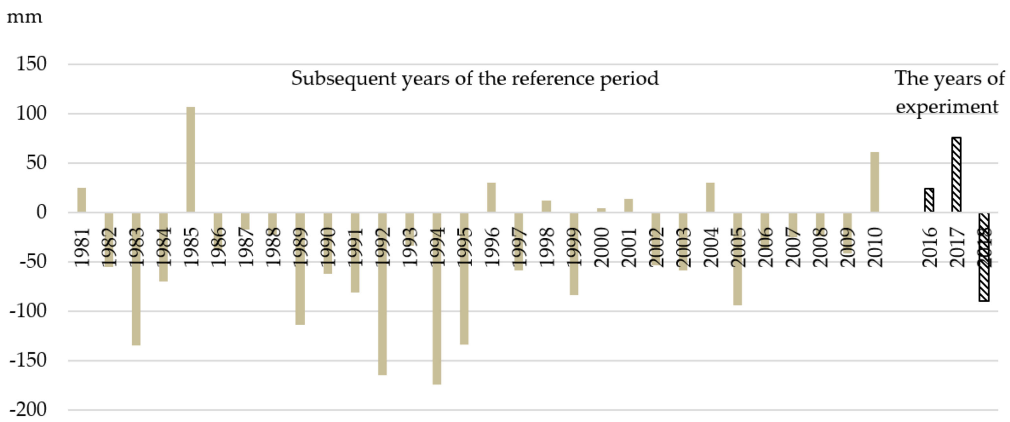

Figure 2. Precipitation deficiencies (−) and excesses (+) in the period of high water needs of sugar beet (July–August) in the years of the experiment, 2016–2018, in the background of the variability in the reference period, i.e., 1981–2010 (mm).

2.3. Sample Collection and Analysis

During the harvest in each year of the experiment, root yield was determined for each of the 16 plots. Determination of the sugar content was performed on aggregate samples in the Raw Material Assessment Laboratory—'Kruszwica' Sugar Plant. One way of measuring the concentration of sugar in a solution is to observe how it affects the polarization of light. This is actually one of the ways sugar concentrations are measured in industry. The polarization of the aggregate samples for the individual treatments of the experiment amounted to 17.65%—W0N1, 17.96%—W0N2, 17.95%—W1N1, and 18.25%—W1N2. In the sugar plant, the sugar content in the beet sample is assessed automatically in accordance with the pickup instructions. The pulp is obtained from a given sample using a disc cutter where the pulp is cut from the roots for evaluation. In the laboratory, the pulp is subjected to homogenization. From homogeneous pulp, a sample of 22 to 32 g is taken and placed in a mixing vessel located on the dosing scale. The extraction of sugar from the pulp takes place automatically on a mixing line by the so-called 'cold' extraction for which aluminium sulphate is used. The dosing of the aluminium sulphate solution into the previously prepared pulp from the beet sample is based on an electric dosing system: 178.2 mL of solution is used for 26 g of pulp. The solution temperature is 20 °C (with a tolerance of 2 °C), and the concentration of aluminium sulphate is 3 g·1000 mL^{-1}. The sugar content is read using a polarimeter SACCHAROMAT V Schmidt & Haensch GmbH & Co. Waldstraße 80-81, 13403 Berlin, Germany.

2.4. Soil Moisture Content

The monitoring of soil moisture during the high water needs of sugar beet covered the effective root zone of the plant which is 0–60 cm. The balance of readily available water was determined using an indirect method developed by Drupka [43]. To date, it is recommended for drainage and agricultural practice as per the guideline of the Ministry of Agriculture [44]. The method is based on the balance maintenance between water consumption due to potential evapotranspiration (conditioned by meteorological and soil terms) and the total water supply (precipitation and irrigation). The total of readily available water (RAW) was maintained in the root zone in a range of 0–40 mm of water depth. The balance was conducted day after day from June 16 to September 10.

2.5. Statistical Methods

The results of root yield and sugar yield were subjected to analysis of variance (ANOVA) and Tukey's tests at the 5% significance level. The test enabled the detailed comparative analysis of means, by separation of statistically homogenous groups of means, and determination of the least significant differences of means. The calculations were made using ANALWAR_5.1_FR software. Furthermore, a regression and trends analysis were carried out as a result of which the crop-water production function was derived. The analysis was based on the relationship between the yields obtained for the N1 and N2 treatments and the total water (precipitation plus irrigation) used in subsequent growing seasons in the course of the experiment. Data analysis was performed with the Analysis ToolPak of Microsoft Excel 2010 add-in program data analysis tools.

3. Results

3.1. Soil Water Conditions in the Period of Sugar Beet High Water Needs

Figure 3 shows that irrigation prevented the depletion of readily available water for plants in the root zone during the period of high water needs (from June 16 to September 10) in each growing season. The amount of water in the sugar beet root zone in irrigated plots was held throughout the period of plant growth in the range of easily accessible to plants, between 0–40 mm. The exceptions were single days at the beginning of August 2018, as this growing season proved to be very dry (Figure 3c).

During the growing season of 2016 (Figure 3a), there were no periods with RAW depletion in non-irrigated sugar beet plots. In 2017 (Figure 3b), a period with RAW depletion occurred between 6 and 10 July, while in the growing season of 2018, long periods without rainfall occurred, resulting in an agricultural drought phenomenon, a consequence of which the plants on rainfed plots (W0) were grown under conditions of deficits of readily available water (water stress). These deficits emerged from 16 to 23 June and from 30 June to 10 July, with very short intervals from 6 August to the end of the period of high water needs.

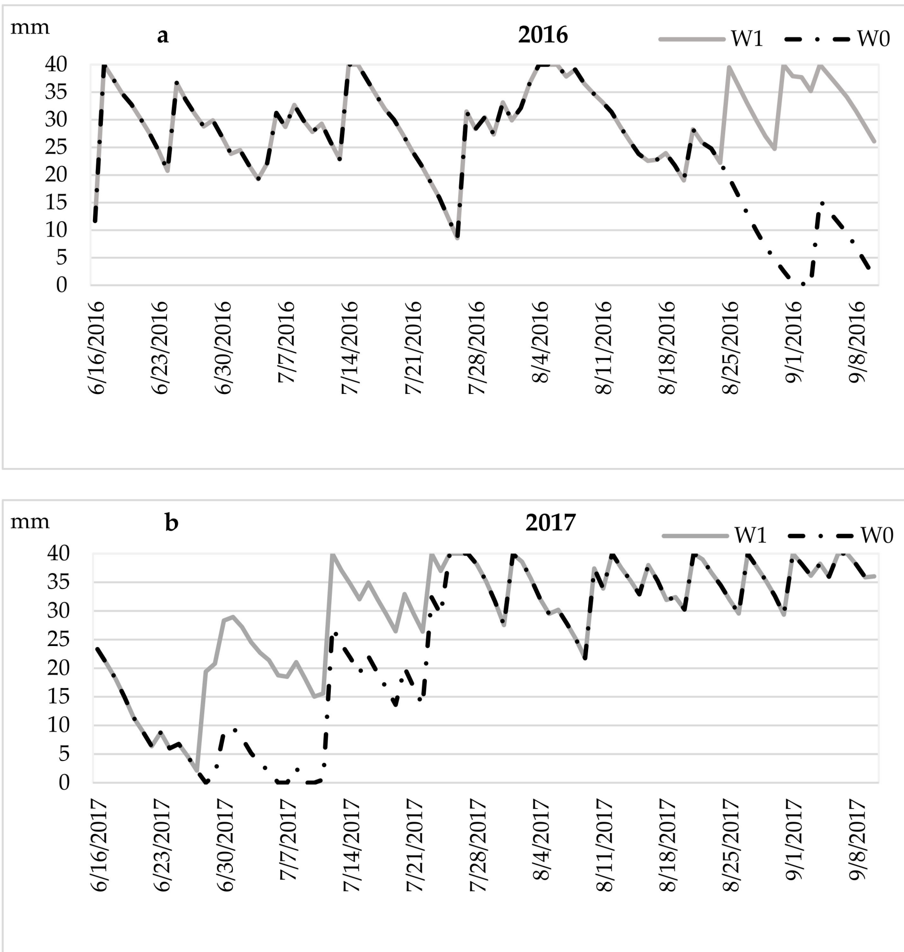

Figure 3. *Cont.*

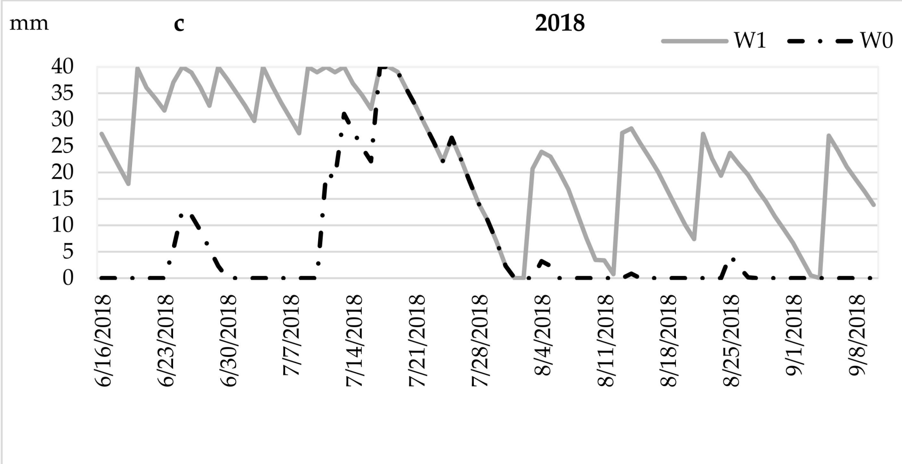

Figure 3. The balance of readily available water in the sugar beet cv. 'Igloo' root zone in consecutive growing seasons: (**a**) 2016, (**b**) 2017, and (**c**) 2018; W0—rainfed, W1—irrigation.

3.2. Sugar Beet Root Yield under the Influence of Sprinkler Irrigation

As a result of the experiment, the average yield of beet roots amounted to 88.3 t·ha^{-1}, ranging from 48.5 t·ha^{-1} in non-irrigated and fertilized plots with a lower rate of nitrogen (W0N1) in the dry year, up to 120.8 t·ha^{-1} in irrigated plots with a higher nitrogen rate (W1N2) in the year with precipitation totals that fully covered the plant water needs (Table 2). The greatest yields were obtained in 2016 when the precipitation excess during the growing season amounted to 24 mm. In the growing season of 2017, characterized by excessive rainfall during the period of increased beet water needs at the level of +76 mm, some yield losses were recorded. However, the lowest root yield was obtained in the dry season of 2018 when precipitation shortages amounted to −79 mm.

Table 2. Yields of sugar beet root cv. 'Igloo' under the influence of experimental factors: water regime (W) and nitrogen fertilization (N) (t·ha^{-1}); W0—rainfed, W1—optimal sprinkler irrigation, N1—a pre-sowing rate of 160 kg N·ha^{-1}, N2—a pre-sowing rate of 160 kg N·ha^{-1} plus an after sowing rate of 40 kg N·ha^{-1}, I—the interaction between the factors, N.S.—non significant.

Treatments		2016	2017	2018	Mean
W0	N1	99.5	80.0	48.5	76.0
	N2	112.2	77.1	58.3	82.5
	Mean	105.9	78.5	53.4	79.3
W1	N1	106.3	82.6	90.2	93.1
	N2	120.8	90.6	93.5	101.6
	Mean	113.6	86.6	91.9	97.3
N	N1	102.9	81.3	69.4	84.5
	N2	116.5	83.8	75.9	92.1
	Mean	109.7	82.6	72.6	88.3
W1-W0	t·ha^{-1}	7.7	N.S.	38.5	18.1
	%	7.3	N.S.	72.1	22.8
$LSD_{0.05}$	W	4.5	N.S.	8.4	3.4
	N	8.4	N.S.	N.S.	6.6
	I (N × W)	N.S.	N.S.	N.S.	N.S.

Irrigation caused significant differences in the beet root yield. The average increase of the yield under this treatment was 18.1 t·ha^{-1}, which constituted a 22.8% rise in the yield. Water use efficiency (WUE) was 175 kg·ha^{-1}·mm^{-1}. The efficiency of irrigation depended on the water conditions within the span of the sugar beet high water needs. In 2018 when high rainfall shortages occurred, the increase in the yield of irrigated plants was definitely the greatest; it amounted to 72.1% as compared to rainfed plants. In 2016, when a minor excess of precipitation occurred compared to the sugar beet precipitation needs, the rise in yield under the irrigation treatment amounted to 7.3%, whereas in the year 2017 with a high precipitation total, when the water needs of the plant were high, the increase in the yield of irrigated plants in relation to the yield of non-irrigated plants was not significant. Irrigation efficiency under different rates of nitrogen fertilization did not differ significantly.

3.3. Sugar Beet Root Yield under the Influence of Increased Nitrogen Fertilization

Under the conditions of the higher rate of nitrogen fertilization (N2), the root yields were significantly greater compared to the control (N1), by an average by 7.6 t·ha^{-1} (9%) (Table 3). The sugar beet response to the higher rate of nitrogen fertilization expressed in root yields did not differ significantly from the average, either in the rainfed or irrigated treatment.

Table 3. Sugar content in sugar beet roots of cv. 'Igloo' under the influence of experimental factors (%); W0—rainfed, W1—optimal sprinkler irrigation, N1—a pre-sowing rate of 160 kg N·ha^{-1}, N2—a pre-sowing rate of 160 kg N·ha^{-1} plus an additional after sowing rate of 40 kg N·ha^{-1}, I—the interaction between the factors, N.S.—non significant.

Treatments		2016	2017	2018	Mean
W0	N1	16.8	16.4	17.5	16.9
	N2	16.0	15.9	18.1	16.7
	Mean	16.4	16.2	17.8	16.8
W1	N1	17.2	17.1	19.3	17.9
	N2	16.5	16.9	18.7	17.4
	Mean	16.8	17.0	19.0	17.6
N	N1	17.0	16.7	18.4	17.4
	N2	16.2	16.4	18.4	17.0
	Mean	16.6	16.6	18.4	17.2
$LSD_{0.05}$	W	N.S.			
	N	N.S.			
	I (N × W)	N.S.			

3.4. Crop-Water Production Function

The significant dependence of sugar beet root crops on water conditions in the consecutive growing seasons (April–September) is presented in Figure 4. This relationship is a second-degree polynomial function. According to the formulas presented in Figure 5, one can state that the maximum root yields at the N1 level of nitrogen fertilization were recorded at the total of precipitation and irrigation dose of 382 mm, compared with 367 mm for the N2 treatment. These values can be considered as the approximate precipitation requirements of sugar beet cultivated on light soil in the growing season within the moderate climate of Poland.

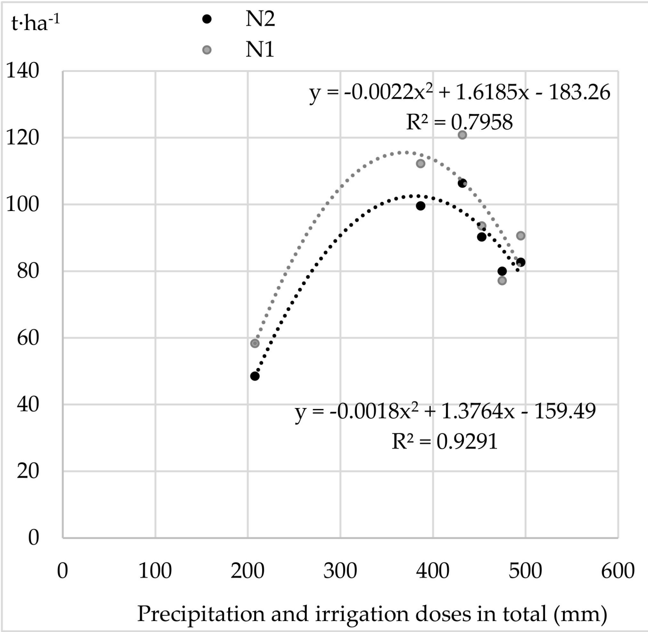

Figure 4. Dependence of the yield of sugar beet roots of cv. 'Igloo' on water supply during the growing season (April–September).

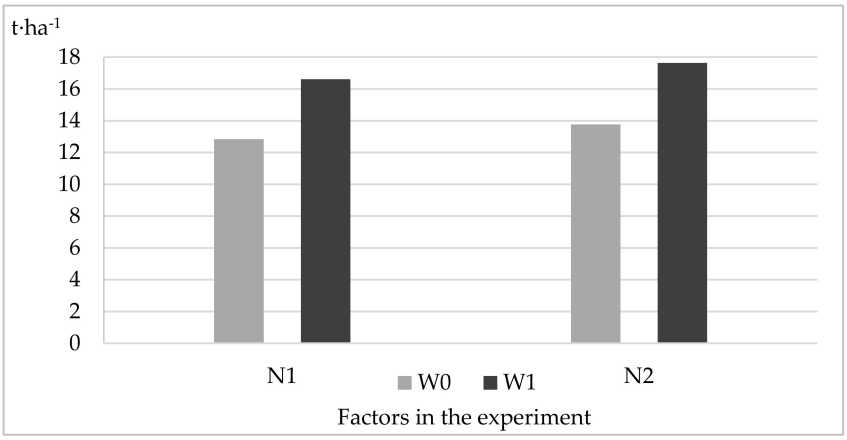

Figure 5. Impact of irrigation and diverse nitrogen fertilization on the sugar yield of sugar beet cv. 'Igloo' (t·ha^{-1}) (mean of 2016–2018).

3.5. Sugar Yield under the Influence of the Experimental Factors

According to the data presented in Table 3, irrigation did not significantly reduce the sugar content in sugar beet roots; quite the opposite, there was a marked tendency of a higher sugar content in the roots of irrigated plants. Furthermore, the sugar content did not significantly depend on the level of nitrogen fertilization in any of the water treatment. However, a tendency of a lower sugar content in roots of plants fertilized with the higher nitrogen rate (N2) was observed. The sugar content varied in the consecutive years of the experiment. A significantly higher sugar content was found in roots harvested after the dry growing season of 2018 (the sugar content contributed to 18.4% on average) in comparison with the 2016 and 2017 season (the average content amounted to 16.6%) when precipitation totals exceeded sugar beet water needs.

Sugar yield analysis is a derivative of the root yield analysis. Therefore, as in the root analysis, there was no significant interaction between the factors of the experiment W and N (Figure 5). The differences in the yield increments under irrigation at the nitrogen fertilizer levels N1 and N2 were similar; they amounted to 3.77 t·ha^{-1} and 3.87 t·ha^{-1}, respectively. The application of nitrogen at the rate of

N2 compared to N1 caused an increase in sugar yield of 0.98 t·ha^{-1} (6.7%) for both the rainfed and irrigated treatments.

4. Discussion

According to numerous national studies concerning the irrigation of crop plants, including sugar beet, this treatment contributes to the proper pace of plant growth and development as well as the intensification of physiological processes. As a result, it brings about an increase in yields and their stabilization over and also has a positive effect on the quality of the crop [5,12,13,41]. The absolute, relative, and unit average sugar beet root yield increases obtained under the influence of sprinkler irrigation and the absence of significant diversity in the sugar content in roots confirm the above thesis.

4.1. Sugar Beet Root Yield and Sugar Content under the Influence of Sprinkler Irrigation

In the moderate climate in the region of the city of Bydgoszcz, sugar beet irrigation caused significant differences in the root yield. The average increase of the yield under irrigation was 18.1 t·ha^{-1}, which constituted a 22.8% rise in the yield. Furthermore, there was a marked tendency for a higher sugar content in the roots of irrigated plants. On the other hand, in an arid area, Isoda et al. [45] found that irrigation resulted in an increase in the net sugar yield due to a root yield increase. However, a slight reduction in the sugar content in roots occurred. Brar et al. [46] emphasized that either deficit or excess irrigation affects crop growth negatively. The authors pointed out that irrigation should be conducted in such a way to supply the optimum amount of water throughout the growing season depending on the type of soil and climate. Topak et al. [18] reported an increase in the sugar content in response to deficit irrigation treatments. The authors reported a sugar content ranging from 18.81% to 21.42%. Sahin et al. [47] observed a sugar content range from 16.16% to 17.51% in irrigation treatments. Ghamarnia et al. [48] obtained a sugar content ranging from 12.62% to 23.53% and proclaimed that with increasing water deficit, the sugar content increased. The results reported by Abyaneha et al. [8] showed that with an increase in water stress, sugar beet crops, when faced with a water shortage, increase their sugar content.

4.2. Sugar Beet Root Yield and Sugar Content under the Influence of Increased Nitrogen Fertilization

The results revealed that increased N rates had a significant effect on root yield. This increasing in root weight was mainly due to the role of nitrogen stimulating the meristematic growth activity which contributes to the increase in the number of cells in addition to cell enlargement. Similar findings were reported by Masri et al. [49], El-Hennawy et al. [50], and Mahmoud et al. [51]. In Spain, Lopez et al. [52] determined that the response of sugar yield to nitrogen fertilizer rates depended on the nitrogen available in the soil. They also found that optimum yield from soil with a low available N content was obtained with the application of 160 kg N·ha^{-1}. Norton [53] recorded that application of diverse rates of nitrogen (26, 134, and 220 lbs·acre^{-1}) resulted in non-significant differences in the sugar content (%) and sugar yield in the USA on Garland series soils (fine loamy over sandy or sandy-skeletal, mixed, super active, mesic Typic Haplargids). Barik [54] worked in Calicutta (India) on medium organic carbon soils and reported that applying nitrogen fertilizer at the rate of 150 kg N·ha^{-1} resulted in the greatest root yield and sugar yield per hectare, while the highest values of sugar concentration were recorded when 120 kg N·ha^{-1} was applied. Weeden [55] stated that a decrease in the sugar content occurs with a decrease in nitrogen fertilizer use due to greater water accumulation in the root. Kaffka and Grantz [56] explained that when nitrogen becomes deficient before harvesting, leaf initiation and expansion slow in comparison to photosynthesis, and photosynthesis produces sucrose which accumulates in roots as storage rather than as new vegetative growth.

4.3. Crop-Water Production Function

The maximum root yields at the N1 level of nitrogen fertilization were recorded at the total precipitation and irrigation doses of 382 mm, compared with 367 mm for the N2 treatment. The results show great potential for a sugar beet production increase, provided that the water factor is optimized. Average increases in root yield of 18.1 t·ha^{-1} (22.8%) and sugar of 3.82 t·ha^{-1} (28.7%) were obtained in the three-year experiment (2016–2018) when precipitation conditions were more favourable in comparison to the reference period of 1981–2010. Therefore, based on the analysis of the crop-water production function [41], it can be assumed that the average production effects of sugar beet irrigation in the region of Bydgoszcz will be greater than those obtained in our own research. Tarkalson et al. [33] presented the results of research of ten site-years of sugar beet cultivation on a common silt loam soil. The authors confirmed a strong quadratic relationship between root yield and water input. Reductions in roots and estimated recoverable sucrose yields levelled off after water input amounted to 598 mm and 605 mm, respectively. These results were based on an experiment carried out in deep silty loam soil. The authors suggest that the results could be different in sandy soils and shallow soils. The quantitative relationships developed from this study can be used to develop tools to evaluate and guide sugar beet irrigation management from full to deficit conditions. According to Pereira et al. [57] and Liu et al. [58], such models allow a combined assessment of different factors affecting yield in order to derive optimal irrigation quantities for different scenarios.

5. Conclusions

Irrigation prevented the depletion of readily available water for plants in the zone of controlled soil moisture. Under the condition of irrigation, this water supply persisted within the range of readily available throughout the entire period.

Sprinkler irrigation contributed to a significant increase in root and sugar beet yields. The production effect can be considered lower than the average for a given soil and climatic conditions because the experiment was carried out in years with higher atmospheric precipitation totals compared to the climate norm for this region. The sugar content in irrigated and non-irrigated roots did not differ significantly.

The effect of nitrogen fertilization on the quantity and quality of sugar beet root yield was similar to previous findings of the authors. A greater yield of roots and sugar was found in the plants fertilized with an increased nitrogen rate; the difference in the sugar content in the roots was significant. Interaction between the supplied water and nitrogen fertilization did not significantly influence sugar beet yield.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/10/2/166/s1, Figure S1: Temporal changes in sugar beet cultivation area (a) and yield of sugar beet roots per hectare (b) in Poland in the period 2004–2018 [26], Table S1: Precipitation requirements of sugar beet in the growing season according to Klatt's (after Kuśmierek-Tomaszewska et al. [20]).

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