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Water and Irrigation Requirements of *Glycine max* (L.) Merr. in 1981–2020 in Central Poland, Central Europe

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Abstract: Soya, one of the most economically important crops, is sensitive to periodic water deficits, which, because of climate change, are becoming more and more common in central Europe. The goal of this study was to estimate the water requirements of soybean from 1981 to 2020 in four provinces of central Poland and the rainfall deficits affecting soybean cultivation; the study also evaluates rainfall water use efficiency for soybean cultivated in production fields to investigate the future necessity of supplemental irrigation. Calculations were based on the values of monthly air temperature and the sum of precipitation. Soybean water requirements were calculated using the method of crop coefficients and reference evapotranspiration was estimated using the Blaney–Criddle approach. Crop water requirements were defined as potential evapotranspiration. Precipitation deficits for soybean were estimated using the Ostromęcki method. Water use efficiency was calculated based on rainfall totals and soybean yield in the rainfed fields. It was found that, on average in the central Poland provinces, from 1981 to 2020, the water requirements of soybean in the growing season amounted to 384 mm, and the highest water requirements occurred in June and July. In the studied forty-year period, a significant upward trend in soybean water requirements in central Poland was observed, both from 1 May to 31 August and from 1 June to 31 August. Rainfall deficits in soybean cultivation in central Poland were found from May to August and amounted to 123 mm in normal years ($N_{50\%}$). The rainfall water use efficiency from April to August for soybean cultivated in central Poland on average amounted to 6.6 kg ha^{-1} mm^{-1} and varied in individual years and regions. The results of the study indicate the need to develop supplemental irrigation systems for soybean crops cultivated in central Poland and other areas of the world with similar climate conditions to optimize yield and the sustainable use of water resources.

Keywords: evapotranspiration; global warming; rainfall deficit; soybean; supplemental irrigation; rainfall water use efficiency

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1. Introduction

Soybean (*Glycine max* (L.) Merr.), belonging to the Fabaceae family, is one of the most valuable legume species [1]. Soybean seeds, the consumable part of this species, contain a very high protein content, ranging from 40% to 45%, and also contain 18–24% fat and 26% carbohydrates. Mainly because of their high protein content, soybeans play a key role in both human and animal nutrition [2].

The origin of soybeans is related to the continental climate, so it is a species that is genetically adapted to the periodic water deficits that occur in these areas. The high resistance of soybean to drought is the result of a strong root system and the presence of hair on the stems, leaves, and pods, which significantly reduces plant transpiration. However, soybean resistance to drought is limited because, under prolonged periods of water deficit, plant growth is weaker and there is lower yield in terms of number of pods and number of seeds within pods. In addition, the seeds are smaller and ripen unevenly, and the seeds developed in the upper parts of the plant have non-viable embryos, causing the germination capacity of soybean seeds to drop as much as 40% [3,4]. The occurrence of water stress during the last three weeks of the soybean growing season can cause a decrease in the yield of seed of up to 65%. On the other hand, if a water deficit occurs at the beginning of seed formation and is prolonged until the end of the growing season, it can reduce the yield by up to 88% [5].

Because of the high thermal requirements of soybean, the cultivation area of this species in Poland is relatively small, averaging around 20,000 hectares and ranging from 12,000 to 24,000 hectares. Nevertheless, a gradual increase in areas of soybean cultivation is observable [1,4]. Soybean seeds should be sown in soil with a temperature of at least 12 °C, and the average temperature during the vegetation period of this species should be at least 15 °C [6]. It is believed that the optimal time for sowing soybean seeds in Poland is when the top layer of soil reaches a temperature of 10 °C; i.e., in the period from 21 April to 10 May [4,7,8]. According to research conducted by Niedbała et al. [9], the most important factors influencing the seed yield of soybean plants are the Seljaninov coefficient values calculated for the period between seed sowing and plant flowering, as well as the average daily air temperature in the second ten-day period of May. Nevertheless, the growing number of soybean cultivars which are better adapted to growing in Poland's climate is the main cause for the rise in cultivation area of this species in the country. The higher content of nutrients and lower soil requirements of soybean plants compared to other high-protein plants are increasingly appreciated [10,11]. Owing to its very high protein content, soybean cultivation in Poland is currently supported by government subsidies. As a result, the cultivation of this species is now more profitable than the cultivation of cereals and similar to the profitability of rapeseed. It should also be noted that soybean increases soil biodiversity [4,7].

The noticeable trend of climate warming, and thus, the earlier onset and extension of the plant vegetation periods, make soybean cultivation also possible in slightly colder regions of Poland, including central part of the country [12]. Nevertheless, research conducted by Prusiński et al. [13] in the years 2016–2019 in central Poland found a significant decrease in soybean yields due to a rainfall deficit. These studies confirm that soil moisture is an important factor in the effective use of nitrogen, determining the growth and yield of soybeans. Thus, the global warming observed for years [14–17] undoubtedly favors the growth of both area and yield of soybean in Poland. However, the key condition for the successful production of this species is undoubtedly the use of irrigation supplementing precipitation deficits. The use of irrigation in central Poland has improved the productivity of species such as asparagus [18,19], melon [20], potato [21], and watermelon [22].

The objective of the research presented in this paper was to calculate the water and irrigation requirements of soybean plants cultivated in four provinces located in central Poland, i.e., in central Europe, in the years 1981–2020 and to evaluate rainfall water use efficiency in soybean production fields during selected years. The region of central Poland is an area of the country that suffers rainfall shortages for crops and where, for many years during the growing season, the highest demand for irrigation has been recorded [23–29]. Special attention should be paid to supplemental irrigation applied at plants' critical growth stages to achieve high water use efficiency.

2. Materials and Methods

The water requirements of soybean (*Glycine max* (L.) Merr.) were assessed on the basis of measurements of air temperature and precipitation sums, carried out at four meteorological stations located in Bydgoszcz, Warsaw, Poznań, and Łódź (Table 1).

Table 1. Altitude above sea level and geographic coordinates for weather stations.

Province	Station	Altitude (m.a.m.s.l.)	Latitude	Longitude
Kuyavian–Pomeranian	Bydgoszcz	46	53°08′	18°01′
Masovian	Warszawa	106	52°09′	20°59′
Greater Poland	Poznań	86	52°25′	16°50′
Lodz	Łódź	184	51°44′	19°24′

It is assumed that the meteorological measurements made at these stations are representative of the four provinces located in central Poland (central Europe) which are the focus of this study, i.e., the Kuyavian–Pomeranian, Masovian, Greater Poland, and Lodz provinces, respectively (Figure 1).

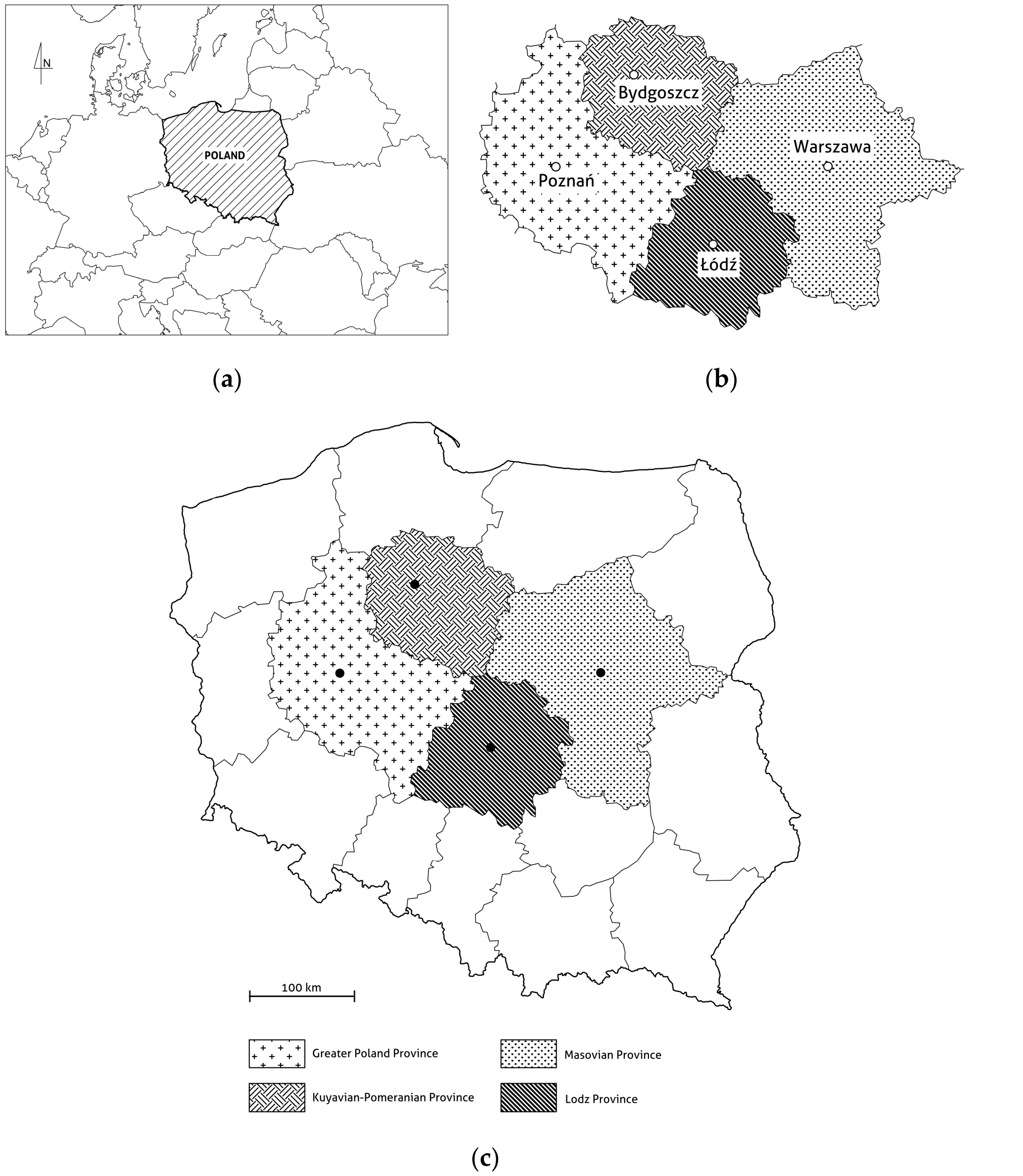

Figure 1. Geographical position of Poland (**a**), meteorological stations (**b**), and the studied provinces of central Poland (**c**).

The overview of long term (1991–2020) average air temperature and precipitation totals in central Poland is shown in Figure 2, developed using data from the three meteorological stations of the Institute of Meteorology and Water Management (Warsaw, Poznań, and

Łódź) and one station (Bydgoszcz) operated by the Institute of Technology and Life Sciences. The included areas, like all of Poland, are located in temperate climates (characteristic of the mid latitudes) and transitional climates (between Atlantic Ocean air masses from the west and continental air masses from the east). The average (1991–2020) yearly temperature was 9.1 °C, whereas in the growing season (April–September) it was 15.6 °C. The lowest temperatures were recorded in Łódź during the October–March period. In the growing season, the differences with three other sites did not exceed 0.3 °C. The average precipitation totals in the year equaled 547 mm, whereas in the April–September period it was only 333 mm, constituting 60–63% of total precipitation in the year. The average differences (from 1991 to 2020) between these four stations reached 31 mm in the growing season and 58 mm for the whole year. The lowest sums occurred in Bydgoszcz, the highest in Łódź. Great differences in meteorological conditions were observed during these times, i.e., between individual years or in shorter periods. For example, in Bydgoszcz during April–September in 2015, total rainfall amounted only to 186 mm, whereas in the same period in 2020 it amounted to as much as 454 mm.

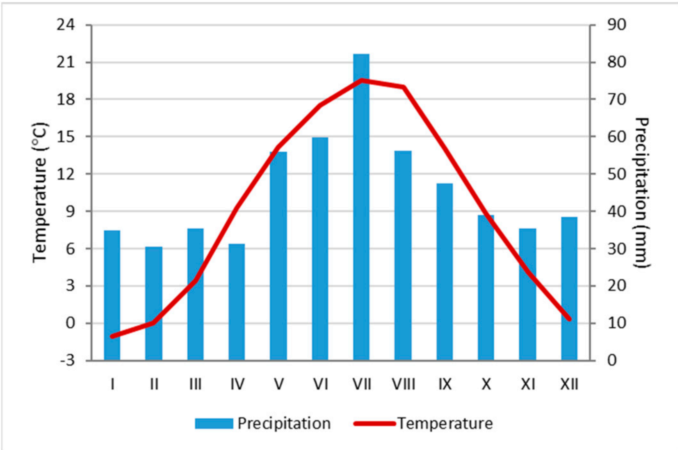

Figure 2. Long term average (1991–2020) monthly mean air temperature and precipitation totals in central Poland.

The assessment of soybean water requirements presented in this paper was carried out for the growing season of this species. It is assumed that the growing season of soybean grown in Poland begins on 21 April and ends on 10 September. In the calculation, meteorological datasets (air temperature and precipitation sums) collected over a forty-year period from 1981 to 2020 were used. Our work was based on soybean cultivars adapted to the Polish climatic zone. Because the analysis was performed using forty years of data, we did not specify the cultivars.

In this study, the soybean water requirements were calculated using a method based on crop coefficients. This method is created using reference evapotranspiration [30]. According to method of crop coefficients, the water requirements of soybean were defined as potential evapotranspiration of these species. Therefore, the potential evapotranspiration of soybean was calculated according to Formula (1):

$$\mathrm{ETp} = \mathrm{ETo} \times \mathrm{kc}, \tag{1}$$

where:

ETp = potential evapotranspiration, i.e., crop evapotranspiration in conditions without water deficits in soil (mm);
ETo = reference evapotranspiration (mm);
kc = crop coefficient, the quotient of evapotranspiration measured in conditions of sufficient humidity and reference evapotranspiration [31].

The values of crop coefficients, determined for central Poland during the months comprising the growing season of soybean, are listed in Table 2.

Table 2. Crop coefficients values for soybean plants cultivated under the growing conditions of central Poland [31–34].

Months of Soybean Growing Season					
21–30 April	**1–31 May**	**1–30 June**	**1–31 July**	**1–31 August**	**1–10 September**
0.13	0.62	0.84	0.94	0.73	0.12

In this study, the Blaney–Criddle Formula (2) adapted by Żakowicz [35] was used to calculate reference evapotranspiration:

$$\mathrm{ETo} = \mathrm{n} \times [\mathrm{p} \times (0.437 \times \mathrm{t} + 7.6) - 1.5], \quad (2)$$

where:

ETo = reference evapotranspiration (mm);
n = number of days in the month;
p = evaporation coefficients for months and latitude according to Doorenbos and Pruitt [32];
t = average monthly air temperature (°C).

The advantage of the Blaney–Criddle Formula (2) modified by Żakowicz [35] is that it can be used for general agro–climatological analysis and is based only on mean air temperature and the geographical latitude of the area, which affects the astronomical length of the day. Whereas the Penman–Monteith formula, recommended by FAO, is based on more parameters that often are either difficult to measure or not measured. Table 3 presents evaporation coefficients according to Doorenbos and Pruitt [32] for months and latitudes in Poland.

Table 3. Average value of evaporation coefficients (p) for chosen months and latitude according to [32,35].

Latitude N (°)	Months						
	IV	**V**	**VI**	**VII**	**VIII**	**IX**	**X**
50	0.31	0.34	0.36	0.35	0.32	0.28	0.24
52	0.31	0.35	0.37	0.36	0.33	0.28	0.24
54	0.31	0.36	0.38	0.37	0.33	0.28	0.23

Precipitation deficits (N) for soybean plants in normal ($N_{50\%}$), medium dry ($N_{25\%}$), and very dry ($N_{10\%}$) years were calculated using the Ostromęcki method [35–38] based on Formula (3):

$$\mathrm{Np\%} = \mathrm{Ap\%} \times \mathrm{ETp} - \mathrm{Bp\%} \times \mathrm{P}, \quad (3)$$

where:

Np% = rainfall deficit with the probability occurrence of p% (mm period^{-1});
ETp = multi-year average of potential evapotranspiration in the studied period (mm period^{-1});
P = multi-year average of rainfall in the studied period (mm period^{-1});
Ap% and Bp% = numerical coefficients describing the variability of evapotranspiration and rainfall for the meteorological station.

The results of this research were subjected to statistical analysis in which the following values were determined: minimum, maximum, median, and mean, as well as standard deviation and variability coefficient. Trends in soybean water requirement changes in the four studied provinces of central Poland were also determined. For this purpose, linear regression analysis was used, calculating the correlation and variability coefficients.

Then, for $p = 0.1$, $p = 0.05$, and $p = 0.01$, the significance of the correlation coefficients was determined with a sample size of $n = 40$ [39].

We also estimated the rainfall water use efficiency (RWUE), the ratio between crop yield and total precipitation in the given plants' period of growth and expressed in kg $ha^{-1} \cdot mm^{-1}$ units.

$$\mathrm{RWUE} = \frac{\mathrm{Y}}{\mathrm{P}}$$

where:

Y = crop yield (kg ha^{-1});
P = cumulative precipitation in the crop growth period (mm).

This is the indicator for assessing the response of cultivated plants to environmental conditions and changes in these. The RWUE for soybean in the analyzed four provinces was estimated using soybean yield data from the Central Statistical Office [40] and rainfall data from analyzed meteorological stations in the period from 1 April until 31 August, assuming that rainfall before sowing complements post-winter water resources in the soil and impacts seed germination and emergence. In similar way, the RWUE for several cultivars of soybean cultivated in five productive fields in Greater Poland and Kuyavian–Pomeranian provinces in the years 2018–2019 was calculated based on results of the cooperative project realized between researchers, agriculture advisors, and farmers within operational groups of the agricultural European Innovation Partnership (EIP-AGRI) [41].

3. Results

The statistical characteristics of soybean water requirements are showed in Table 4. In the multi-year period, 1981–2020, among the four provinces located in central Poland, the highest standard deviations, in this case measuring the diversity of monthly totals of soybean water requirements in the period of increased water requirements (i.e., from June to August) was found in the Greater Poland province. The values of this parameter amounted to 7.0 mm in June, 8.2 mm in July, and 5.0 mm in August, respectively.

Table 4. Statistical characteristics of soybean water requirements from 1981 to 2020 in provinces of central Poland.

Statistical Characteristic	Province [a]	Months of Soybean Growing Season					
		21–30 IV	1–31 V	1–30 VI	1–31 VII	1–31 VIII	1–10 IX
Minimum (mm)	K–P	2	54	97	113	74	2
	M	2	57	96	111	74	2
	GP	2	52	92	108	72	2
	L	2	52	90	106	71	2
Maximum (mm)	K–P	3	79	131	146	96	3
	M	4	76	128	145	97	3
	GP	3	75	128	146	97	4
	L	3	73	124	140	95	3
Median (mm)	K–P	3	67	107	128	84	3
	M	3	66	106	127	84	3
	GP	3	65	102	125	83	3
	L	3	63	102	121	83	3
Standard Deviation (mm)	K–P	0.2	4.9	6.4	7.6	4.5	0.2
	M	0.3	4.3	6.3	7.0	4.4	0.2
	GP	0.3	4.8	7.0	8.2	5.0	0.3
	L	0.3	4.4	6.3	7.7	4.4	0.2
Variability Coefficient (%)	K–P	8.9	7.4	6.0	6.0	5.4	7.4
	M	10.6	6.5	5.9	5.6	5.1	7.3
	GP	10.1	7.4	6.8	6.7	6.0	10.3
	L	11.0	7.0	6.2	6.3	5.3	7.8

[a] K–P = Kuyavian–Pomeranian province; M = Masovian province; GP = Greater Poland province; L = Lodz province.

Taking into account the period of increased water requirements (June, July, and August), the highest variability coefficients, informing about the relative differentiation of soybean water requirements, were also recorded in the Greater Poland province. The values of this parameter in this province for June, July, and August amounted to 6.8%, 6.7%, and 6.0%, respectively.

Figure 3 shows the water requirements of soybean—daily and throughout the growing season. The daily water requirements of soybean on average, for the four analyzed provinces of central Poland, was the highest in July, reaching 4.0 mm (Figure 3a). Lower values of soybean daily water requirements were found in June (3.5 mm), August (2.7 mm), and May (2.1 mm). Soybean plants needed the lowest water amounts at the beginning and end of their growth, respectively, third ten-day period of April and first ten-day period of Septeber (about 0.3 mm). On average, in the years 1981–2020, in four provinces of central Poland, the water requirements of soybean in the entire growing season, i.e., from 21 April to 10 September, amounted to 384 mm (Figure 3b).

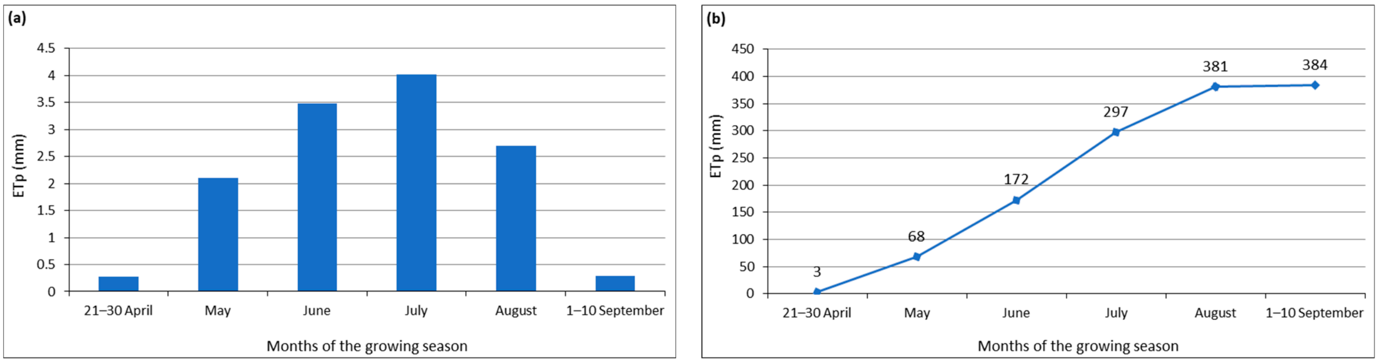

Figure 3. Potential evapotranspiration (ETp) of soybean in central Poland in the growing period during 1981–2020 showed as mean daily values for the individual months (**a**) and the cumulated sum curve (**b**).

The calculations show that the greatest water requirements of soybean grown in central Poland, on average during 1981–2020, both in the entire soybean growing season, i.e., from 21 April to 10 September (Figure 4a), and in the period of increased water requirements, i.e., from 1 June to 31 August (Figure 4b), as well as in July (Figure 4c), the month characterized by the greatest water requirements, occurred in the Kuyavian–Pomeranian and Greater Poland provinces (Figure 4a–c). The totals of soybean potential evapotranspiration for these three periods were 391 mm, 319 mm, and 127 mm in the Kuyavian–Pomeranian province, and 390 mm, 318 mm, and 127 mm in the Greater Poland province, respectively. The lowest water requirements of soybean, amounting to 373 mm, 305 mm, and 121 mm, respectively, were found in the Lodz province. The lowest precipitation totals in the entire soybean growing season and in the period of increased water requirements, amounting to 266 mm and 192 mm, respectively, were found in the Kuyavian–Pomeranian province, and the highest, 306 mm and 216 mm, respectively, in the Masovian province. The total precipitation in July in the four analyzed provinces was very similar and ranged from 78 mm (Kuyavian–Pomeranian province) to 81 mm (Greater Poland province).

A comparison of successive ten-year periods, i.e., the decades of the studied forty years spanning 1981–2020, showed that during the entire growing season the water requirements of soybean increased in each subsequent decade in each of the four considered provinces of central Poland, ranging from 15 mm (i.e., an increase of 4%) in the Kuyavian–Pomeranian province to 28 mm (8%) in the Greater Poland province (Figure 5a). The soybean water requirements between 1 June and 31 August also increased in each subsequent decade in each of the four provinces of central Poland (Figure 5e). On average, in central Poland, the increase in soybean water requirements was from 302 mm to 323 mm (i.e., by 21 mm, and increase of 7%). Water requirements increased the least in the Kuyavian–Pomeranian province (15 mm or 5%), and the most in the Greater Poland province (increasing by 27 mm or 9%). Nevertheless, it should be noted that in June (Figure 5b) and August (Figure 5d), the water requirements of soybean increased in each decade of the forty-year period. However, in July (Figure 5c), in all the analyzed provinces of central Poland, the water requirements of soybean increased only in the first three decades (1981–2010), and in the last decade (2011–2020) they were lower than in the previous decade (2001–2010).

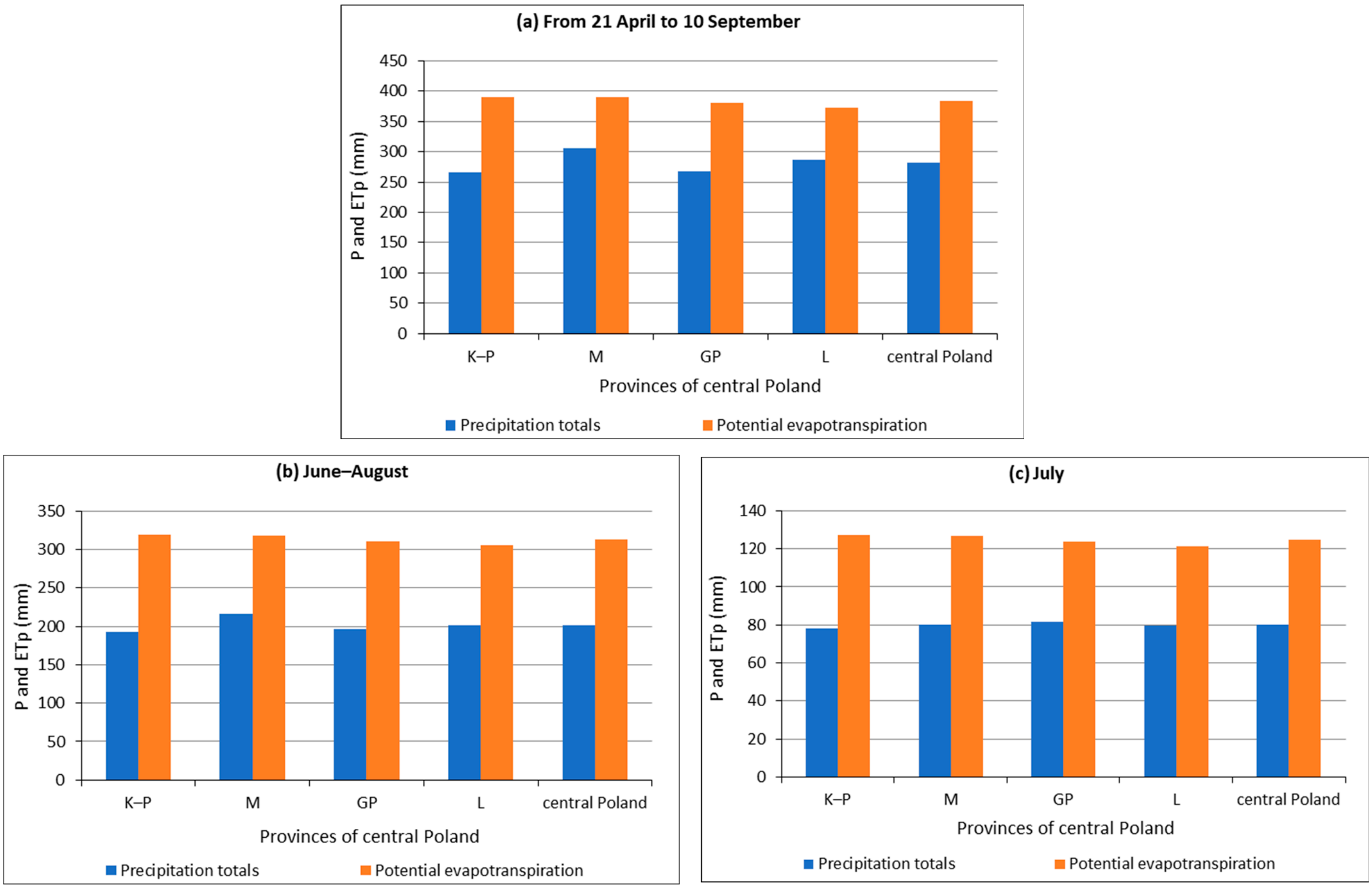

Figure 4. Potential evapotranspiration (ETp) of soybean and the precipitation totals (P) throughout the growing season (**a**) and during the period of increasing water requirements by plants (**b**), and in the month with the highest water requirements (**c**) in the provinces of central Poland (K–P = Kuyavian–Pomeranian, M = Masovian, GP = Greater Poland and L = Lodz).

In the analyzed forty-year period, in all four provinces of central Poland, there was a significant trend in terms of the increased water requirements of soybean during vegetation periods (Table 5, Figures 6–8). Based on the trend equations of soybean water requirements, it was found that in the period from May to August in 1981–2020, the water requirements of this species increased in each decade from 4.8 mm (Kuyavian–Pomeranian province) to 9.2 mm (Greater Poland province). During the three summer months (June–August), soybean water requirements in both these provinces increased by 4.8 mm and 8.8 mm, respectively. It should be noted that in July, typically characterized by the greatest water requirements, the upward trend in soybean potential evapotranspiration was statistically insignificant in the Kuyavian–Pomeranian province.

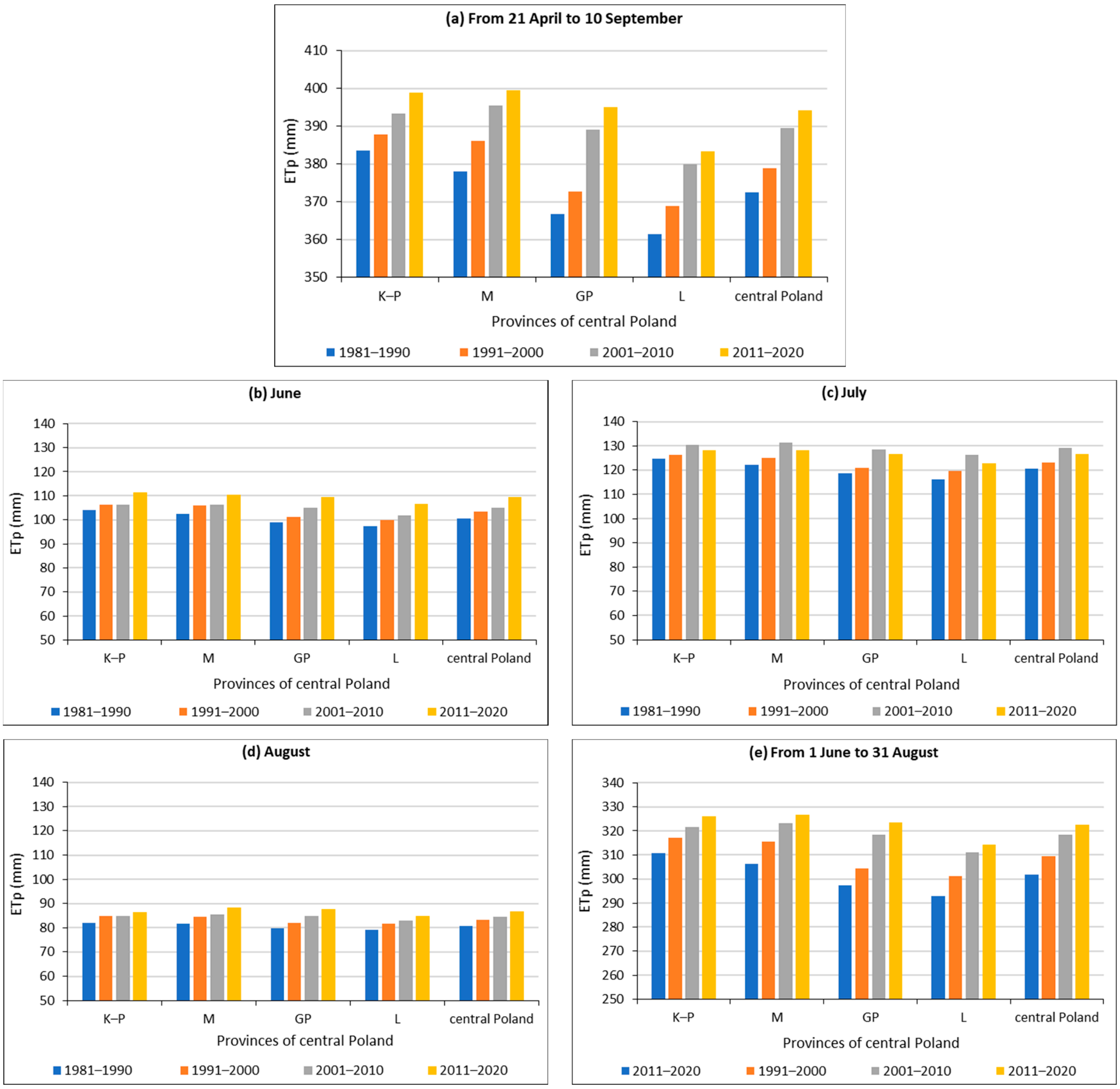

Figure 5. Potential evapotranspiration (ETp) of soybean in the growing season (**a**), in June (**b**), July (**c**), August (**d**), and in the period from 1 June to 31 August (**e**) presented for subsequent decades from 1981–2020 in the provinces of central Poland (K–P = Kuyavian–Pomeranian, M = Masovian, GP = Greater Poland and L = Lodz).

Table 5. Correlation coefficients and tendencies of soybean water requirements, 1981–2020.

Period	**Provinces of Central Poland**			
	Kuyavian–Pomeranian	**Masovian**	**Greater Poland**	**Lodz**
	Linear Correlation Coefficient (r)			
May–August	0.400 **	0.579 ***	0.646 ***	0.581 ***
June–August	0.432 ***	0.611 ***	0.659 ***	0.606 ***
July	0.184 n.s.	0.357 **	0.389 **	0.335 **
	Tendency of Water Requirements (mm decade^{-1})			
May–August	4.8	7.0	9.2	6.9
June–August	4.8	6.8	8.8	6.8
July	1.2	2.2	2.8	2.2

—significant at $p = 0.05$; *—significant at $p = 0.01$; n.s.—not significant.

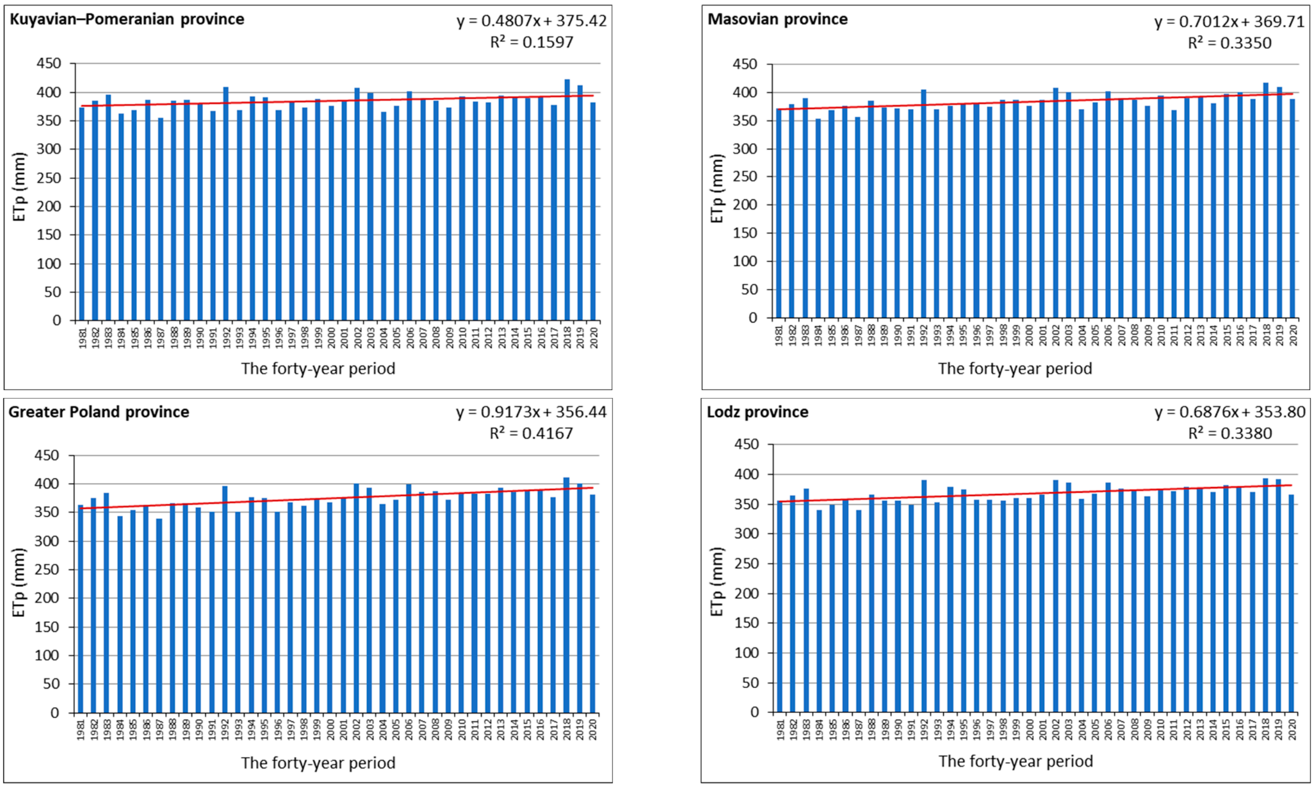

Figure 6. Time trend of soybean potential evapotranspiration (ETp) in the period from 1 May to 31 August in the provinces of central Poland. The red line is the trend line.

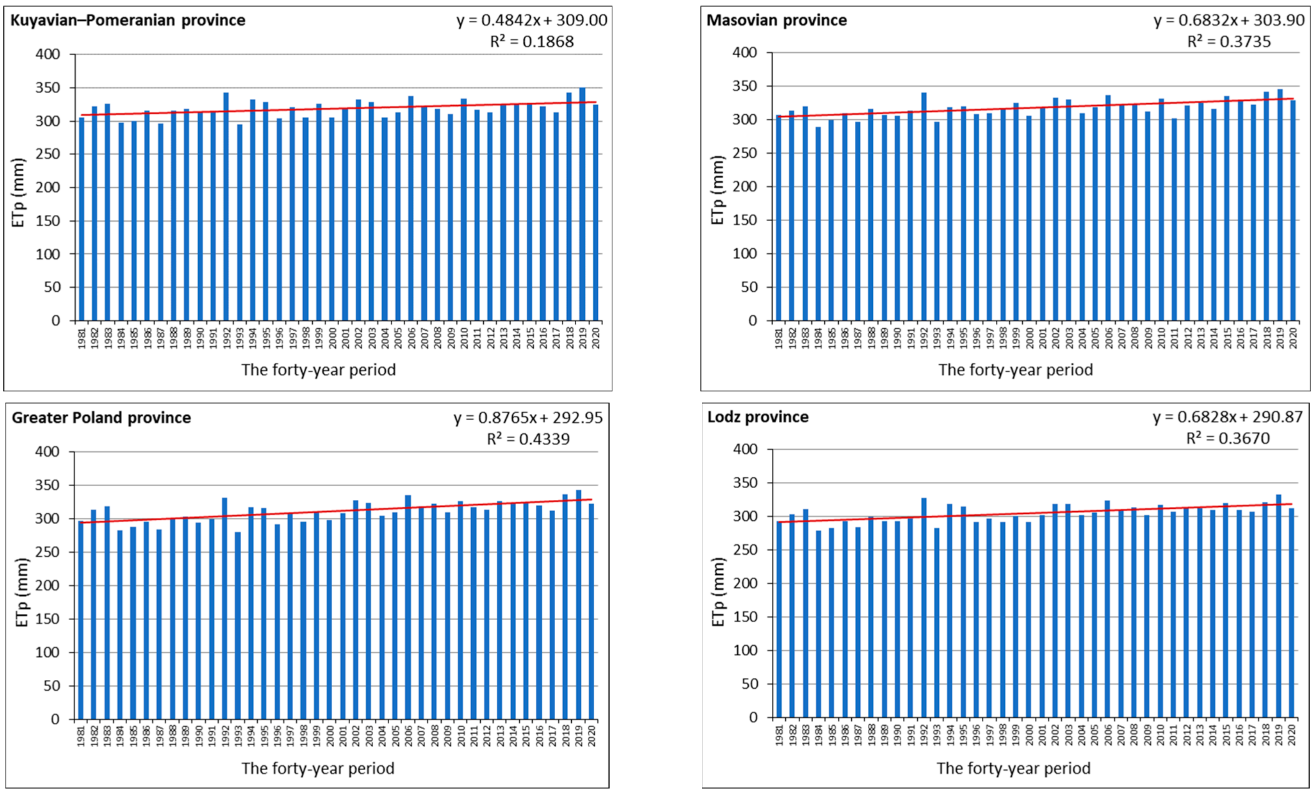

Figure 7. Time trend of soybean potential evapotranspiration (ETp) in the period from 1 June to 31 August in the provinces of central Poland. The red line is the trend line.

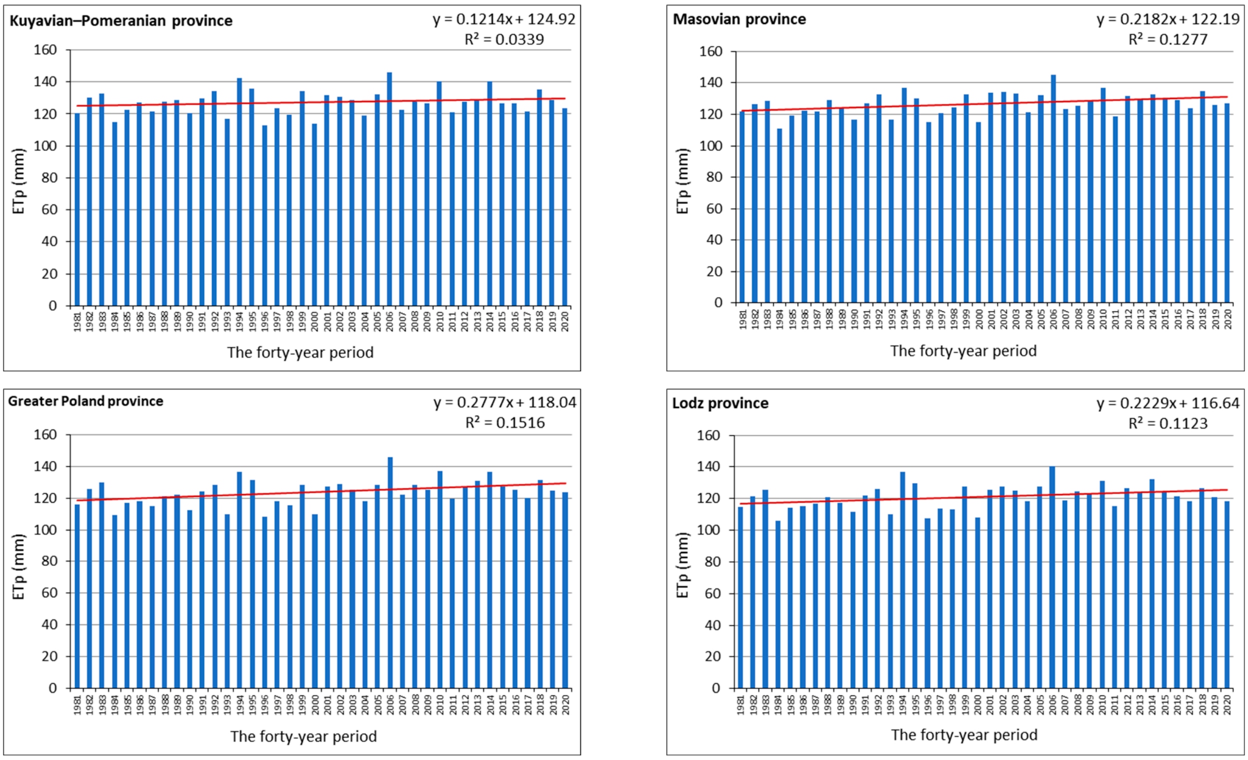

Figure 8. Time trend of soybean potential evapotranspiration (ETp) in July in the provinces of central Poland. The red line is the trend line.

The analysis of the precipitation deficits showed that both at the beginning of the soybean growing period, i.e., from 21 to 30 April, and at its end, i.e., from 1 to 10 September, in normal years ($N_{50\%}$, i.e., once in two years), medium dry years ($N_{25\%}$, i.e., once in four years), and very dry years ($N_{10\%}$, i.e., once every ten years), no rainfall deficits were found (Table 6). The highest deficits in terms of rainfall in the period of May to August, in the normal, medium dry, and very dry years, were found in the Kuyavian–Pomeranian province and were 143 mm, 230 mm, and 293 mm, respectively. Slightly lower rainfall deficits of 131 mm, 217 mm, and 279 mm, respectively, were found in the Greater Poland province. On the other hand, the lowest precipitation deficits (except for the medium dry years) were found in the Lodz province. In the period from 1 June to 31 August, high rainfall deficits in the analyzed forty-year period also occurred in the Kuyavian–Pomeranian province, and slightly smaller deficits were observed in the Greater Poland province. The deficits of the Kuyavian–Pomeranian province amounted to 127 mm, 197 mm, and 248 mm, respectively, and for the Greater Poland province they totaled 115 mm, 185 mm, and 236 mm, respectively.

The values of rainfall deficits in medium dry ($N_{25\%}$) and very dry ($N_{10\%}$) years cover soybean water needs at the level of 75% and 90%, respectively. This approach is essential when estimating water needs and planning the amount of water for irrigation.

In the last five years (2018–2022), a tendency to increase soybean yields in Poland was found (Figure 9a), including in the provinces situated in central Poland—Kuyavian–Pomeranian, Masovian, Lodz, and Greater Poland (Figure 9b). Based on linear regression equations for this relationship, it can be stated that the increase in soybean seeds yield in each year of this five-year period was 1.29 dt ha^{-1} and 1.79 dt ha^{-1}, respectively. However, it should be noted that in conditions without irrigation, the main factor determining yield are agro–meteorological conditions, in particular precipitation and distribution during subsequent phases of plant development.

Figure 10 shows the dependence of soybean yield on the sum of natural precipitation in July in the Masovian province (Figure 10a) and in July–August in the Lodz province (Figure 10b) in 2016–2022. The linear regression equations analyzing these relationships indicate that each 1 mm of natural precipitation increased the soybean yield by 2.7 kg ha^{-1} and 6 kg ha^{-1}, respectively. The linear regression equation presented in Figure 11 shows that in the period from June 1 to August 31—in the years 2016–2022 in the Lodz province—every 1 mm of natural precipitation increased the yield of soybean seeds by over 4.9 kg ha^{-1}.

Table 6. Rainfall deficit (mm) in soybean cultivation in central Poland, 1981–2020.

Years	Provinces of Central Poland				Mean for Provinces of Central Poland
	Kuyavian–Pomeranian	**Masovian**	**Greater Poland**	**Lodz**	
	April–September (May–August) [a]				
Normal ($N_{50\%}$)	143	107	131	110	123
Medium dry ($N_{25\%}$)	230	201	217	198	212
Very dry ($N_{10\%}$)	293	267	279	261	275
	June–August				
Normal ($N_{50\%}$)	127	102	115	104	112
Medium dry ($N_{25\%}$)	197	177	185	175	184
Very dry ($N_{10\%}$)	248	230	236	225	235
	July				
Normal ($N_{50\%}$)	49	46	42	41	45
Medium dry ($N_{25\%}$)	78	75	71	70	73
Very dry ($N_{10\%}$)	98	96	92	90	94

[a] During the periods of 21–30 April and 1–10 September, no rainfall deficits were recorded.

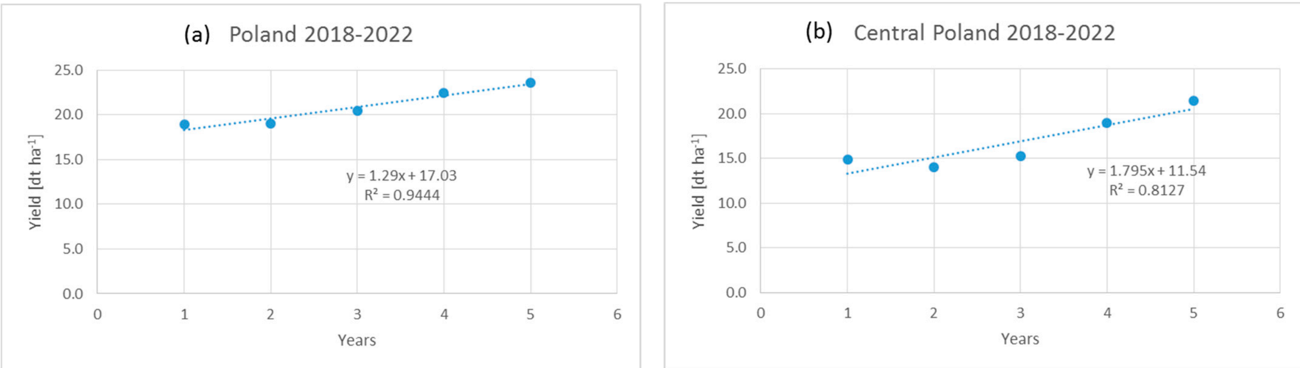

Figure 9. Tendency to increase soybean yields in Poland (**a**) and Central Poland (**b**); Central Poland includes the provinces: Kuyavian–Pomeranian, Masovian, Lodz, and Greater Poland.

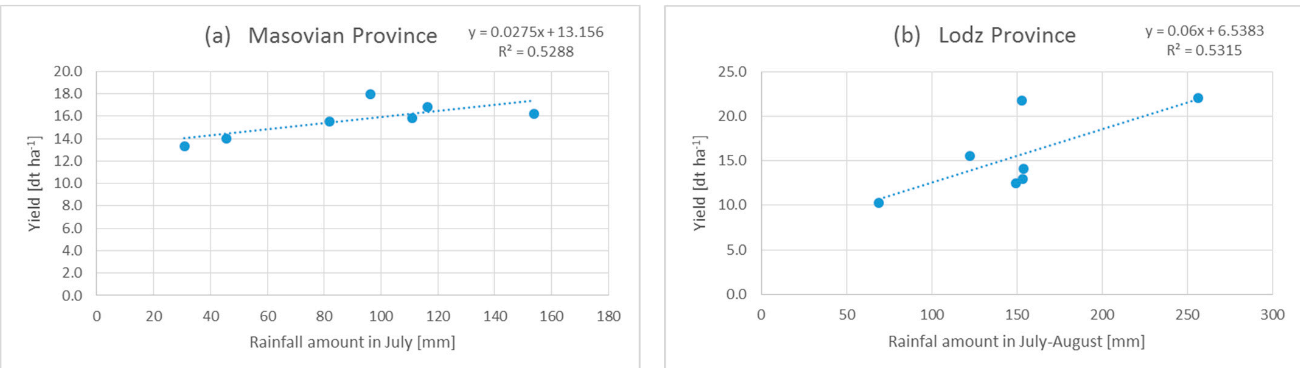

Figure 10. The dependence of soybean seed yield on total precipitation in July in the Masovian province (**a**) and total precipitation in July-August in the Lodz province (**b**) in 2016–2022.

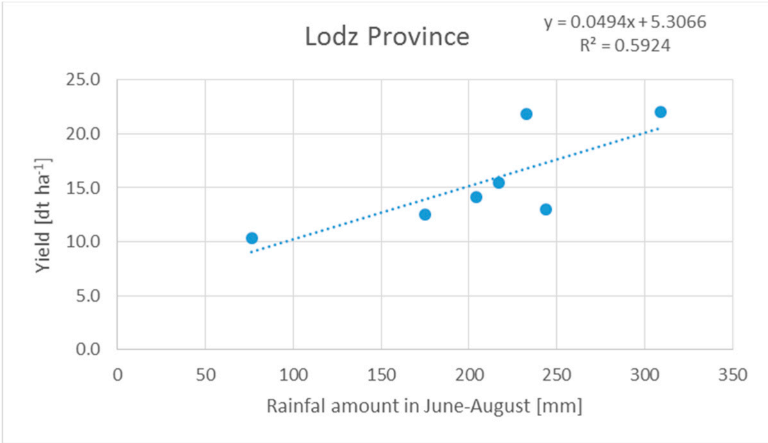

Figure 11. The dependence of soybean seed yield on total precipitation in June–August in the Lodz province in the years 2016–2022.

The results in Table 7 shows that the highest rainfall water use efficiency in the period from 1 April to 31 August in the years 2016–2022 was found in the Greater Poland province (8.7 kg ha^{-1} mm^{-1}) and in the Kuyavian–Pomeranian province (7.3 kg ha^{-1} mm^{-1}). In the Masovian and Lodz provinces, the RWUE was lower (5.0 and 5.4 kg ha^{-1} mm^{-1}, respectively). The analysis of the RWUE in individual years of the 2016–2022 period shows that the highest values of this indicator were in 2019 and slightly lower in 2022 (Table 7). In this last year, according to the Central Statistical Office [40], the highest soybean yields have been recorded in whole the country and all examined provinces. This was the result of better distribution of precipitation, especially at the critical growth stages of soybean.

Table 7. Rainfall water use efficiency (RWUE kg ha^{-1} mm^{-1}) between 1 April and 31 August for soybean cultivation (2016–2022) in the provinces of Central Poland.

Year	Provinces of Central Poland				Central Poland
	Kuyavian–Pomeranian	**Masovian**	**Greater Poland**	**Lodz**	
2016	6.2	5.6	5.7	4.5	5.5
2017	5.3	3.8	6.6	4.7	5.1
2018	7.5	5.6	9.5	4.6	6.8
2019	11.4	6.2	12.1	7.7	9.3
2020	4.5	3.5	7.4	4.1	4.9
2021	6.7	3.2	6.8	5.1	5.5
2022	9.7	7.3	12.9	7.4	9.3
Mean	7.3	5.0	8.7	5.4	6.6 *
Maximum	11.4	7.3	12.9	7.7	12.9 *
Minimum	4.5	3.2	5.7	4.1	3.2 *
Standard Deviation	2.4	1.5	2.9	1.5	2.5 *

* n = 28.

Figure 12 presents the rainfall water use efficiency calculated for some production fields in the Greater Poland and Kuyavian–Pomeranian provinces in 2018–2019. The RWUE varied widely and depended mainly on rainfall distribution within the year, location of the field, soil type, and cultivar. It ranged from 5.5 to 14.3 kg ha^{-1} mm^{-1} in the Greater Poland province and from 3.1 to 15.1 kg ha^{-1} mm^{-1} in the Kuyavian–Pomeranian province. There were also clear differences in the RWUE in individual cultivars. The highest rainfall water use efficiency was found in the cultivars 'Abelina' and 'Bohemians'. In 2018, the values of RWUE for these cultivars were 14.3 and 13.4 kg ha^{-1} mm^{-1} in the Greater Poland province as well as 15.1 and 13.2 ha^{-1} mm^{-1} in the Kuyavian–Pomeranian province.

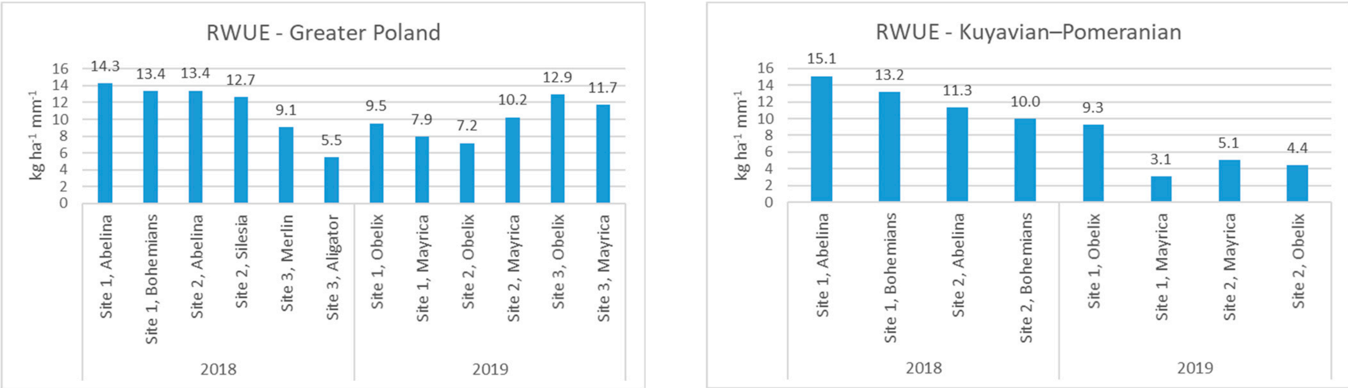

Figure 12. Rainfall water use efficiency (RWUE, kg ha^{-1}·mm^{-1}) for different soybean cultivars cultivated in the production fields located in three sites in the Greater Poland province and two sites in the Kuyavian–Pomeranian province, 2018–2019.

4. Discussion

The current study is one of the first examining soybean water requirements and rainfall deficits in normal, medium, and very dry years for soybeans grown in Poland and Central Europe. This research is essential to estimate water needs and plan the amount of water needed for irrigation.

Considering the four studied provinces of central Poland in the last forty years, 1981–2020, the highest water requirements of soybean, assessed using the potential evapotranspiration, were found in the Kuyavian–Pomeranian province (391 mm) and Masovian province (390 mm). In the study published by Kasperska-Wołowicz et al. [42], it was found that in the period of thirty years (1981–2010), the average water needs of soybean grown in the Kuyavia region situated in central Poland also amounted to around 390 mm. It was also predicted that in the years 2021–2050, soybean water requirements will rise by 21 mm.

In the 5-year studies of the early 21st century, reported by Suyker and Verma [43], where soybean cultivation was carried out in eastern Nebraska, in the slightly warmer and wetter climatic conditions than Poland, the average water needs of soybeans, measured by potential evapotranspiration, were 452 mm under irrigation conditions and 431 mm under rainfed conditions. Specht et al. [44] found that, in 1995, lack of rainfall and very high temperatures during the growing season caused severe drought and 100% of soybean evapotranspiration (measured at 410 mm), and was supplemented using irrigation treatment. In the years 1993–2004, in the climate of Serbia (Vojvodina region, Novi Sad) under irrigation conditions, the rate of evapotranspiration ranged from 432 mm to 501 mm, and under rainfed conditions ranged from 170 mm to 450 mm [45]. In the studies conducted by Vučić and Bošnjak [46], also in the region of Vojvodina, the ETc of soybean ranged from 450 mm to 480 mm.

On average, for four provinces of central Poland, the daily water requirements of soybean were the highest in July (4.0 mm), and slightly lower in June (3.5 mm), August (2.7 mm), and May (2.1 mm). Soybean plants needed the least water during the day at the beginning and end of the growing season, i.e., from 21 to 30 April and from 1 to 10 September (about 0.3 mm). The daily water consumption of soybean, expressed by ETm, reported by Pejić et al. [45], was in the 2.0–3.5 mm interval. In the period from emergence to flowering of soybean plants (i.e., at the beginning of the growing season) the lowest daily water requirements were recorded, while in the development stage of pods and seeds, daily water requirements were the highest.

This study shows that the water requirements of soybean grown in central Poland are relatively high, and precipitation alone is not able to meet them. A number of earlier studies show that central Poland has a very high need for the development of irrigation treatments, as evidenced by the negative values of climatic water balance in this region [25–27,47–49].

In the analyzed forty-year period (1981–2020), there was a clear statistically significant upward trend in the water requirements of soybean in central Poland. This trend was noticeable in the May–August period, as well as in the period from June to August. The largest increase in the water requirements of soybean in these two periods, by 9.2 mm and 8.8 mm, respectively, was found in the Greater Poland province. The explanation for this situation is the rise in temperature in the area of central Poland (Table 8). An increase in air temperature causes an increase in the water requirements of plants. The analysis of air temperature trends carried out for the four provinces of central Poland shows that the strongest increase in the average monthly temperature value occurred in the Greater Poland province. In the analyzed forty-year period, the average temperature value for the period of increased water requirements (1 June to 31 August) climbed in this province by 0.7 °C decade^{-1}, while in the month characterized by the highest water requirements (July) the temperature increase was by 0.6 °C decade^{-1}. This is also confirmed by the research published by Kasperska-Wołowicz and Bolewski [50], in which the average annual temperature in the Kuyavian–Pomeranian province increased by 0.19 °C per 10 years, i.e., 1.9 °C per 100 years, a finding based on of 80 years of research conducted in the meteorological station located in Bydgoszcz.

Table 8. Equations of mean air temperature trends in the period of June–August in 1981–2020, in central Poland.

Period	**Trend Equation**	**R^2**	**Tendency (°C decade^{-1})**
Kuyavian–Pomeranian Province			
June–August	y = 0.0406x + 17.874	R^2 = 0.1952 ***	0.4
July	y = 0.0262x + 19.006	R^2 = 0.0339 n.s.	0.3
Masovian Province			
June–August	y = 0.0577x + 17.720	R^2 = 0.3848 ***	0.6
July	y = 0.0477x + 18.813	R^2 = 0.1277 **	0.5
Greater Poland Province			
June–August	y = 0.0739x + 16.813	R^2 = 0.4480 ***	0.7
July	y = 0.0607x + 17.906	R^2 = 0.1516 **	0.6
Lodz Province			
June–August	y = 0.0572x + 16.821	R^2 = 0.3726 ***	0.6
July	y = 0.049x + 17.794	R^2 = 0.1123 **	0.5

—significant at p = 0.05; *—significant at p = 0.01; n.s.—not significant.

During the period from 1 June to 31 August, in the analyzed forty years, there was a slight increase in the sum of precipitation (Table 9). However, because of the high variability of precipitation occurring in subsequent years, this trend was not significant. A slight downward trend, but also insignificant, was recorded in the Lodz province.

According to the current study, there were no rainfall deficits at the beginning of the soybean growing season, i.e., from 21 to 30 April, and at its end, i.e., from 1 to 10 September. This situation occurred in normal, medium dry, and very dry years. In the study published by Prusiński et al. [13], which was carried out in the Kuyavian–Pomeranian province from 2016 to 2019, rainfall recorded in May and September had no effect on soybean yield, although the results obtained there were not statistically significant (r Pearson values were −0.08 in May and −0.26 in September).

In the current study, rainfall deficits in soybean cultivation in the Kuyavian–Pomeranian province in the June–August period amounted to 127 mm in normal years and 197 mm in medium–dry years. Correlation analysis performed by Prusiński et al. [13] showed a significant dependence between the yield of soybean seeds and the total rainfall recorded in the months from June to August. The increase in yield was 0.012 t ha^{-1} with an increase in rainfall by 0.36 mm, so the correlation was very high (r = 0.99). The coefficient of determination (R^2) in this study was 0.98, meaning that the described model explains 98% of the studied parameter. In this study, high and proportionally distributed sums of precipitation occurring in July and August were only observed in 2016 and 2017, which affected the high yield of soybean plants. However, in 2018 and 2019, in July and August, soil drought occurred, which reduced the yield of plants.

Table 9. Time tendency of the rainfall in the period of June–August in 1981–2020, in central Poland.

Period	Provinces of Central Poland			
	Kuyavian–Pomeranian	Masovian	Greater Poland	Lodz
Linear correlation coefficient (r)				
June–August	0.080 n.s.	0.261 n.s.	0.028 n.s.	0.068 n.s.
July	0.117 n.s.	0.185 n.s.	0.127 n.s.	0.030 n.s.
Tendency of rainfall (mm decade^{-1})				
June–August	5.1	16.5	1.7	–3.9
July	4.1	8.7	5.5	–1.2

n.s.—not significant.

Soybean plants react very badly to prolonged drought and are usually unable to survive it [51]. According to Janeczko et al. [3], periodic droughts have a very negative effect on the flowering and formation of soybean seeds. As a result of drought stress, soybean plants drop flowers and young pods, and seeds are not sufficiently developed. In the research conducted from 2013 to 2014 in the Kuyavian–Pomeranian province, Dudek et al. [52] reported on the beneficial effect of irrigation treatments carried out in the above-mentioned development stages of soybean plants on the seed yield. In these studies, soybean plants were irrigated five times with a total water dose of 115 mm in 2013 and 140 mm in 2014. The average seasonal water dose in the current study was 127.5 mm, and the precipitation deficit in a normal year for the period 1981–2020 was 127 mm. Applied by Dudek et al. [52], irrigation of soybean plants during the period of increased water needs, i.e., during flowering, pod formation, and pod filling, resulted in an average seed yield increase from 2.04 t ha^{-1} to 3.03 t ha^{-1} for two years and for two tested cultivars, 'Aldana' and 'Merlin' (by 0.99 t ha^{-1}, i.e., an increase of 49%). During these studies, the monthly precipitation totals were close to the long-term average, but there were numerous periods without precipitation. In an experiment conducted in Serbia from 1993 to 2004, the average soybean yield due to irrigation was significantly higher than in rainfed conditions [45]. Irrigation resulted in an increase in the yield of soybean seeds by 0.82 t ha^{-1}, i.e., by as much as 22%. The average increase in soybean yield obtained through the application of irrigation treatments ranged from 2.465 t ha^{-1} in years with limited rainfall and warmer than usual seasons (2000) to 0 t ha^{-1} in rainy years (1996, 1997, and 1999). The total amount of water that was used by irrigated soybean plants was 460 mm, of which 28.2%, 21.1%, and 50.7% were used in the vegetative, flowering, and yield formation phases, respectively. For comparison, in the years 1987–1994, Bošnjak and Pejić [53], after using irrigation, recorded an increase in the yield of soybean seeds by an average of 1.5 t ha^{-1}, which is 55%.

The effects of the present research are consistent with the results of research carried out in 2015–2017 in two locations (Grocholin and Mochełek) in the Kuyavian–Pomeranian province, where the yield and quality of soybean seeds depended mainly on weather conditions [54]. In these studies, the highest yield was obtained in 2016, when the sum of rainfall was 503 mm in Mochełek and 652 mm in Grocholin, and the lowest yield was in 2015, when the sum of precipitation in Mochełek amounted to 214.2 mm, and in Grocholin 293 mm. As a result of this study, it was found that with prolonged water deficits in the soil, there is a need to irrigate soybean crops. The unfavorable distribution of precipitation and the occurrence of frequent and long-lasting periods of drought in central Poland (specifically, the Kuyavian–Pomeranian province) was also reported by Kasperska-Wołowicz et al. [55]. These studies found that periods of drought, which can last even longer than 21 days, also occur during wet years. Du et al. [56] and Stojmenowa and Alexieva [57] found that long-term water deficits, specifically during the phase of flowering and seed filling, reduces the allocation of nutrients in soybean seeds, which causes a decrease in the weight of seeds in the pod, and thus protein and nitrogen content of seeds. The sensitivity of soybean to drought stress was confirmed, both in the phase of vegetative development, as well as at the stage of flowering and seed development [58]. The most critical step during the soybean growing season was the seed enlargement step [51,59,60]. Many studies indicate a positive effect of irrigation of soybean plants, performed only at the stage of pod elongation and/or seed enlargement on the yield [61–63].

In the provinces of central Poland, there are very limited water resources [27,49,64]; therefore, irrigation plays a very important role in the process of optimal use of water resources in agriculture [60]. Crop irrigation has been proven to be a valuable and sustainable approach to production in water stressed areas [65]. It was found that with increased water doses used for soybean irrigation, there was an increase in seed yield, dry matter content, and percentage of protein and oil content in the seeds of the tested cultivars [66]. Crabtree et al. [67] found that the soybean yield after every alternate furrow irrigation was significantly lower compared to the soybean yield cultivated under the conditions of every time furrow irrigation, but it was still satisfactory. The every alternate furrow irrigation scheme used in this experiment allowed for 40–50% less water used in irrigation, an acceptable compromise between yield and water savings. In the mid-south USA, an experiment was carried out that confirmed the usefulness of supplemental irrigation as an alternative to no-irrigation and all-season irrigation in terms of obtaining high quality and yield of soybean seeds [68]. In the study by Eck et al. [5] the usefulness of the method of supplemental irrigation of soybean cultivation in the southern highlands of the USA was also confirmed. An extreme sensitivity to drought during the seed development stage was also found. Additionally, this study found that supplemental irrigation of soybean performed better than corn, but worse than cotton, sorghum, or wheat. Supplemental irrigation of soybean was also applied in the semi-humid area of Croatia, where the experiment was carried out in three different climatic years [69]. According to these studies, during average climatic years, fully irrigated plants had a lower seed yield than supplemental irrigated plants. Recent data according to FAOSTAT [70] on soybean productivity in the world, Europe, and Poland suggest that both the soybean cultivation area and its yield, measured in thousands of tons and in tons per hectare, remain constant (Tables S1–S3). This would suggest the use of an additional yield-creating factor, which is undoubtedly the irrigation of soybean crops. The beneficial effect of irrigation on production efficiency is confirmed by the latest research [52,71] in which the water use efficiency of two soybean cultivars irrigated supplementarily in critical development stages, 2013–2018, was in the range of 7.8 and 11.7 kg ha^{-1} mm^{-1} (Table S4). Based upon the above studies, it can be concluded that the use of supplemental irrigation allows for both the protection of water resources and the improved yield of soybean seeds.

On the basis of conducted research and literature data, Chmura et al. [72] found that the productivity of 1 mm of water from irrigation was lower than from rainfall by 40–90%. According to Dzieżyc [73], the efficiency of water used for irrigation shows an increasing tendency with a decrease in soil compactness. Concerning the efficiency of 1 mm of natural precipitation, RWUE is lower when the sum of precipitation during the vegetation period of a given plant is higher. The differences in the size of RWUE between years can reach even 200–300%. These results confirm the outcomes presented in our study. In the years 2016–2022, the average in central Poland RWUE of rainfed soybean plantations amounted to 6.6 kg ha^{-1} mm^{-1}; however, among individual years and provinces, there was up to three times the difference. In addition, the results presented in our study show that RWUE varies among different soybean cultivars.

5. Conclusions

Based on the results of the research presented above, on average, in the years 1981–2020, in four provinces of central Poland, the highest daily soybean water requirements were recorded in July (4.0 mm) and June (3.5 mm), and the water requirements of soybean in the entire growing season, i.e., from 21 April to 10 September, amounted to 384 mm.

In the studied forty-year period, a significant upward trend in the water requirements of soybean cultivated in central Poland was observed, both in the period from 1 May to 31 August and in the period from 1 June to 31 August.

In the climatic conditions of central Poland, precipitation in the growing season is not sufficient to fulfill the water needs of field crops. Calculated rainfall deficits indicate the amounts of water needed to be supplemented from soil water resources (retention) and irrigation to fulfill crop water requirements. In all the considered provinces of central Poland, rainfall deficits in soybean cultivation were found in the period from May to August, both in normal years (123 mm), medium dry years (212 mm), and very dry years (275 mm).

The water use efficiency calculated for production fields in rainfed cultivation systems in the years 2016–2022 in four provinces of central Poland amounted on average to 6.6 kg ha^{-1} mm^{-1}) and varied among years from 4.9 to 9.3 kg ha^{-1} mm^{-1}. The RWUE was the highest in the following scenarios: (i) in the years with good precipitation distribution in times when the yield was higher than the long-term average, (ii) in dry years, but with yield below the average, and (iii) when growing cultivars adapted to the given climatic conditions.

Worldwide, soy is considered an important crop, both economically and nutritionally. Unfortunately, significant climate changes recorded in central Europe caused periodic water deficits, which adversely affect the cultivation of soybean, a crop that is poorly adapted to drought stress. Therefore, to cover water deficits in soybean cultivation and to increase water use efficiency for this species in central Poland, as well as regions of the world with similar climate conditions, supplemental irrigation is recommended. Such irrigation, applied at critical growth stages, optimizes the yield of seeds and water use efficiency from year to year.

The results of this study may contribute to rational and economical water management (water protection) and the effective use of available water resources for precision irrigation (i.e., the use of precise amounts of water resulting from calculations carried out according to reliable methods).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13092429/s1, Table S1. Soybean acreage (unit = thousand ha) in 2016–2020 in the world, in Europe, and in Poland (according to FAOSTAT data). Table S2. Soybean harvest (thousand tons) in 2016–2020 in the world, in Europe, and in Poland (according to FAOSTAT data). Table S3. Soybean yields (tons per ha^{-1}) in 2016–2020 in the world, in Europe, and in Poland (according to FAOSTAT data). Table S4. Water use efficiency of irrigated soybean crops in central Poland.

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