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Forecasted Yield Responses of Carrot, Celeriac and Red Beet to Sprinkler Irrigation Under Climate Change in a Highly Water-Deficient Area of Central Poland

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Abstract

Drought events are a major constraint on vegetable production in central Poland, one of the country's most water-deficient agricultural regions. Supplemental irrigation is considered a key adaptation strategy to mitigate drought-induced yield losses, yet its future effectiveness under climate change remains uncertain. This study forecasts the yield responses of three important root vegetables—carrot, celeriac, and red beet—to sprinkler irrigation under two climate change scenarios (RCP 4.5 and RCP 8.5) for the period 2021–2100. Yield increments achievable through irrigation for normal, medium dry, and very dry years across four counties in central Poland were estimated using a linear model relating irrigation-induced yield gains to precipitation deficits during the critical water demand periods for each crop. The results show that irrigation will consistently enhance yields, with the largest increments occurring in very dry years. Across most counties, yield responses were higher under RCP 4.5 than under RCP 8.5, indicating that more severe climate change may reduce the relative benefits of irrigation. Regression analysis revealed a significant declining trend in yield increments under RCP 8.5 for all crops, whereas under RCP 4.5, slight but statistically insignificant increases were observed for celeriac and red beet in Wągrowiec county. The findings highlight irrigation as an essential tool for sustaining vegetable yields in drought-prone regions, while also emphasizing the need for broader adaptation strategies under future climate variability.

Keywords: *Apium graveolens* L.; *Beta vulgaris* L.; crop productivity; *Daucus carota* L.; evapotranspiration; global warming; precipitation deficit; water needs

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1. Introduction

Agricultural production in Poland, particularly in its central lowland regions, is increasingly exposed to unfavorable weather phenomena, among which drought plays a dominant role. These areas, which represent one of the country's most important zones of crop production, are highly vulnerable to climatic risks due to their limited water retention capacity and frequent rainfall deficits. Atmospheric droughts occur irregularly and often develop into soil droughts, and in extreme cases, even hydrological droughts [1–5]. This variability results from the temperate transitional nature of Poland's climate, characterized by considerable year-to-year fluctuations in weather conditions during the same calendar

periods. Although this variability affects all weather elements, precipitation amount and distribution remain the most critical factors influencing agricultural performance. The occurrence of drought during the periods of peak crop water demand reduces yields both quantitatively and qualitatively, primarily by causing water stress that impairs plant growth and development, limits nutrient uptake, and physiological processes, which can lead to accelerated senescence and reduced duration of active physiological functioning [4,5].

Field experiments conducted in highly water-deficient regions of central Poland, characterized by light soils with low retention, have consistently shown that drought episodes lead to significant yield losses in field crops [5–9]. Reported yield reductions range from 20% to as much as 80%, depending on drought severity, while extreme drought may even result in total crop failure [2,5,8,10,11]. Irrigation is therefore considered the most effective agronomic measure to mitigate the negative effects of drought, ensuring proper plant growth and development, physiological processes, enhancing yield quantity and stability, and improving quality attributes [5–9]. These challenges are expected to be further amplified under future climate change scenarios, which may alter both the frequency and severity of drought events.

Climate change further exacerbates the challenges of agricultural water management. Global shifts, including rising temperatures, altered precipitation patterns, and more frequent extreme events [12–17], are already being observed in Poland [18,19]. Together with the country's limited water resources, these changes are likely to significantly influence the future development of supplemental irrigation [5,10,11,20,21]. According to recent climate projections for Europe, mean annual air temperature is expected to increase by approximately 2–3 °C under RCP 4.5 and by 4–5 °C under RCP 8.5 by the end of the 21st century, accompanied by a higher frequency of heat waves and changes in precipitation distribution [22,23]. In Poland, as well as in Central Europe, these shifts are projected to reduce summer rainfall totals, extend dry periods, and enhance evapotranspiration rates, particularly in central and southern regions [24,25], leading to intensified seasonal precipitation deficits and greater challenges for sustainable agricultural production and irrigation management [10,11,26].

Across Europe and worldwide, similar challenges related to drought and irrigation needs are being widely reported. In southern Europe, regions such as Spain and Italy are already facing severe water shortages that threaten vegetable and fruit production [27–30]. Studies conducted in the Mediterranean region indicate that rising temperatures and declining precipitation are leading to reduced soil water availability and crop productivity, with irrigation becoming indispensable for maintaining stable yields [31–33]. In central Europe, including Germany, the Czech Republic, Slovakia, and Austria, recent research has also shown increasing evapotranspiration and prolonged dry periods during summer months, resulting in more frequent agricultural droughts and growing irrigation demand [34–38]. Similar trends are observed beyond Europe. In regions with temperate or continental climates, such as Canada and parts of China, projections under RCP 4.5 and RCP 8.5 scenarios indicate that rising temperatures and changes in precipitation patterns will intensify water deficits during the growing season [39–41]. These findings collectively emphasize that climate-induced drought represents a global challenge for agriculture, requiring adaptive strategies such as optimized irrigation management, improved soil water retention, and the use of drought-resistant crop varieties [22,42].

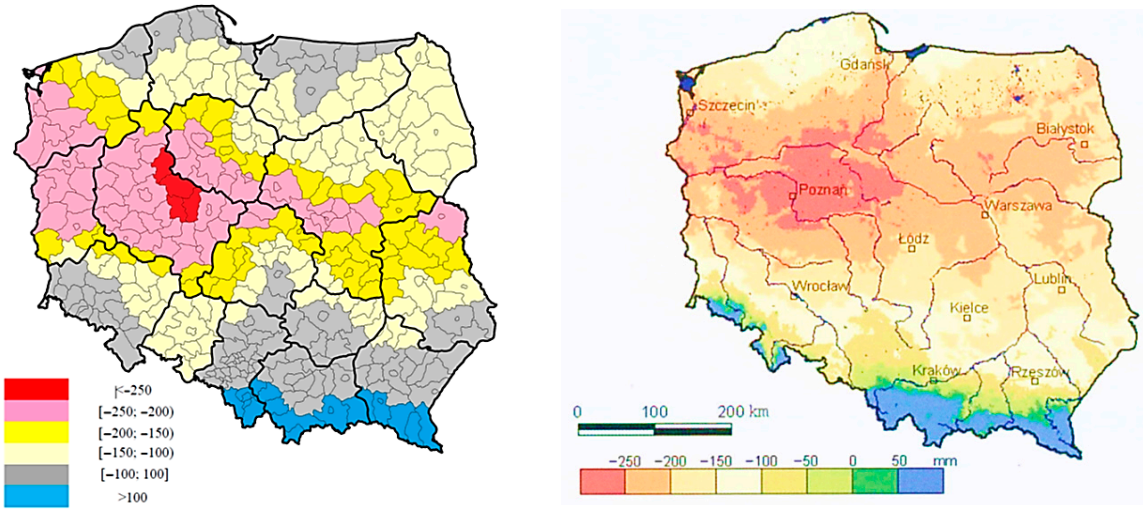
In this broader context, assessing the yield response to irrigation under projected climate scenarios becomes essential not only for Poland but also for other drought-prone agricultural regions across Europe. Given the increasing pressure on water resources due to both natural droughts and projected climate change, the practical implementation of irrigation systems in agriculture and horticulture ultimately depends on their economic

viability. From this perspective, quantitative assessment of yield increments under irrigation is essential for decision-making regarding investments in irrigation infrastructure. The yield gained from irrigation directly informs assessments of its economic efficiency and profitability [5].

The present study addresses this issue by forecasting the yield responses of three important vegetable crops—carrot (*Daucus carota* L.), celeriac (*Apium graveolens* L.), and red beet (*Beta vulgaris* L.)—to sprinkler irrigation under climate change conditions. The analysis focuses on one of the most water-deficient agricultural regions of central Poland and considers two climate change scenarios (RCP 4.5 and RCP 8.5) over the forecast period 2021–2100. The findings provide insights into the potential benefits of irrigation in mitigating drought-induced yield losses and offer a quantitative basis for evaluating the economic and agronomic rationale of irrigation practices in vegetable production under future climate variability.

2. Materials and Methods

In this study, calculations were performed to forecast root yield responses of carrot (*Daucus carota* L., Apiaceae), celeriac (*Apium graveolens* L., Apiaceae), and red beet (*Beta vulgaris* L., Amaranthaceae) to sprinkler irrigation. The analysis covered four counties in central Poland: Gniezno, Słupca, Wągrowiec, and Września, which are marked in red in Figure 1a. This region is highly water-deficient, resulting in substantial irrigation requirements for crops. Within the studied area, the climatic water balance from April to September is less than 250 mm (Figure 1a,b) [43,44], which indicates a deficit of atmospheric precipitation during the growing season. Therefore, supplementary irrigation is required for the cultivation of the studied vegetable species in these counties to ensure proper plant growth and development under optimal soil moisture conditions. This observation highlights and justifies the undertaken research, whose objective was to assess the yield response of selected vegetable crops.



(**a**) (**b**)

Figure 1. Location of the study area with the spatial distribution of the climatic water balance (mm) from April to September: (**a**) according to Łabędzki [43], with the study area marked in red; (**b**) according to Kozyra and Górski [44].

According to the national soil-agricultural maps developed by the Institute of Soil Science and Plant Cultivation (IUNG-PIB, Puławy, Poland), the dominant soils in these counties are light to medium-textured, mostly sandy loams and loams, with occasional

patches of lighter sands and heavier silty loams. Such soils are typically characterized by moderate to relatively low available water capacity, which increases their susceptibility to drought and enhances the need for irrigation during dry periods [45,46]. Detailed soil hydraulic parameters at the county scale were not available; therefore, these general soil characteristics were used to provide background information for interpreting irrigation demand results.

Forecasting was conducted under two climate change scenarios: RCP 4.5 and RCP 8.5 [47]. Data for the simulations were obtained from the Klimada 2.0 portal [48]. The RCP 4.5 scenario represents a moderate trajectory, assuming an increase in CO_2 concentration to 540 ppm by 2100, corresponding to a radiative forcing of 4.5 W m^{-2}. In contrast, RCP 8.5 is an extrapolative scenario, projecting a CO_2 concentration of 940 ppm by 2100 and a radiative forcing of 8.5 W m^{-2}.

The analysis was based on a linear relationship between yield increments resulting from sprinkler irrigation and precipitation during the critical water demand periods for the studied species, according to Equation (1) proposed by Grabarczyk [1]:

$$Q = q \times (P_{opt} - P_{act}), \quad (1)$$

where Q is the yield increment due to irrigation (kg ha^{-1}); q is the yield increase per 1 mm of precipitation deficit (kg ha^{-1} mm^{-1}); P_{opt} is the optimal precipitation during the period of high crop water demand (mm); and P_{act} is the actual precipitation during the same period (mm).

It should be noted that the yield increment model (1) assumes a linear increment per mm deficit, which may not hold under extreme water stress or heatwave conditions.

Yield increments under irrigation were determined for each decade within the forecast period (2021–2100). The equations applied for calculating yield increments of the studied root vegetables are presented in Table 1. These equations were derived from field experiments evaluating the effects of sprinkler irrigation on carrot, celeriac, and red beet yields [7]. The results of these earlier studies indicated that the critical water demand period for carrot occurred from May to July, whereas for celeriac and red beet it extended from July to August.

Table 1. Equations used to calculate root yield increments of the studied vegetables under sprinkler irrigation during periods of increased water demand [7].

Species	Critical Water Demand Period	Regression Equation
Carrot	1 May–31 July (V–VII)	$Q = 294\ (242 - P_{V–VII})$
Celeriac	1 July–31 August (VII–VIII)	$Q = 177\ (190 - P_{VII–VIII})$
Red Beet	1 July–31 August (VII–VIII)	$Q = 81\ (225 - P_{VII–VIII})$

To assess the probability and intensity of drought occurrence during the critical crop water demand periods, we applied the method proposed by Ostromęcki [49,50], which relates long-term variability in precipitation and evapotranspiration to precipitation deficits of different probabilities.

In this study, the potential evapotranspiration (ETp) was not calculated directly. Following Ostromęcki's approach [49,50], only the precipitation component ($Bp\% \times P$) was used to estimate precipitation totals corresponding to selected probability levels (50%, 25%, and 10%), since the regression equations employed in this research (Table 1) depend solely on precipitation during the critical water demand periods for the analyzed vegetable species.

The empirical coefficient B reflects the variability in precipitation for the selected probability level (p%). According to Ostromęcki [49,50], B for p = 10% ranged from 0.51 to 0.80 (average 0.70), while for p = 25% it ranged from 0.67 to 0.90 (average 0.80), and for p = 50% it was assumed to be 1.0. These values were applied to estimate the expected precipitation amounts for the respective probability categories in the analyzed region. For reference, the general form of the Ostromęcki equation is (2):

$$Np\% = Ap\% \times ETp - Bp\% \times P, \quad (2)$$

where Np% is the precipitation deficit (mm per period), ETp is the long-term mean evapotranspiration (mm), P is the mean precipitation (mm), and Ap% and Bp% are empirical coefficients expressing the variability in evapotranspiration and precipitation for the selected probability level.

In this study, only the precipitation-related term ($Bp\% \times P$) of the above equation was used, as ETp values were not directly computed. Drought intensity was expressed by the magnitude of Np%, with larger positive values indicating more severe precipitation deficits. This approach allows for quantifying both the frequency (probability) and severity (intensity) of drought conditions in the studied region. This calculation was further used to estimate the expected precipitation deficits. The precipitation deficits were calculated as the difference between the optimal precipitation (*Popt*) and the precipitation determined using the Ostromęcki method [49,50] for normal, medium dry, and very dry years. The optimal precipitation values used in the regression equations (Table 1) were based on long-term field irrigation experiments [5,7,51]. For celeriac and red beet, *Popt* was 225 mm and 190 mm, respectively, during the period from 1 July to 31 August, while for carrot it was 242 mm during 1 May–31 July. Each millimeter of rainfall deficit below these values increased root yield by 294 kg·ha^{-1} for carrot, 81 kg ha^{-1} for celeriac, and 177 kg ha^{-1} for red beet.

For each vegetable species, county, and climate change scenario (RCP 4.5 and RCP 8.5), linear regression analysis was performed to describe the temporal trends in yield increments attributable to sprinkler irrigation over the forecast period 2021–2100. The dependent variable (y) represented the decadal mean yield increment (t ha^{-1}) due to irrigation, and the independent variable (x) denoted the decade number within the projection period.

Trends in sprinkler irrigation efficiency (yield increments attributable to irrigation) were analyzed for each decade of the forecast period (2021–2100). A linear regression analysis was applied, with the calculation of correlation (r) and determination (R^2) coefficients. The significance of the correlation coefficients was assessed at confidence levels of p = 0.1 and p = 0.05 [52]. In addition, a statistical characterization of root yield increments was performed, including the following descriptive statistics: minimum, maximum, mean, and median values (t ha^{-1}), as well as the standard deviation (t ha^{-1}) and coefficient of variation (%). These parameters were calculated separately for each vegetable species, climate change scenario, and county to assess the variability and stability of yield responses to sprinkler irrigation. Statistical analyses were conducted using Microsoft Excel 365 (Microsoft Corporation, Redmond, WA, USA).

3. Results

Table 2 presents the statistical characteristics of yield increments depending on the species, climate change scenario, and county. Among the three tested species, carrot exhibits the greatest variability in yield response to sprinkler irrigation, followed by red beet, whereas celeriac showed the lowest variability. This is evidenced by the values of both the standard deviation and the variability coefficient. The RCP 8.5 scenario generated greater variability than RCP 4.5 for each species and each county. The negative minimum

values observed for carrot yield increments require clarification. They result solely from the mathematical nature of the calculation. In practical field vegetable production, such situations do not occur, since irrigation is not applied when natural precipitation is sufficient to fully meet the crop water requirements. In Poland, irrigation serves primarily as a supplementary practice to compensate for rainfall deficits.

Table 2. Statistical characterization of root yield increments due to sprinkler irrigation as affected by vegetable species, climate change scenario, and county.

Statistical Description	County							
	Gniezno		Słupca		Wągrowiec		Września	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Carrot								
Minimum (t ha^{-1})	1.9	−2.3	−1.7	−4.1	3.5	−1.7	5.0	−0.7
Maximum (t ha^{-1})	9.4	7.6	5.9	5.9	10.3	8.1	11.7	9.6
Mean (t ha^{-1})	6.1	3.6	3.3	1.8	7.0	4.0	8.5	5.4
Median (t ha^{-1})	6.0	3.2	3.2	1.6	6.9	3.6	8.7	5.5
Standard Deviation (t ha^{-1})	2.422	3.204	2.535	3.325	2.467	3.031	2.407	3.095
Variability Coefficient (%)	39.9	89.0	76.8	186.2	35.3	76.3	28.4	56.9
Celeriac								
Minimum (t ha^{-1})	6.4	5.8	5.9	5.7	6.6	5.7	6.8	5.9
Maximum (t ha^{-1})	7.2	6.9	6.8	6.9	7.5	6.9	7.7	7.2
Mean (t ha^{-1})	6.8	6.5	6.3	6.3	7.0	6.4	7.2	6.7
Median (t ha^{-1})	6.8	6.5	6.2	6.3	7.0	6.5	7.2	6.8
Standard Deviation (t ha^{-1})	0.250	0.451	0.307	0.397	0.261	0.482	0.294	0.465
Variability Coefficient (%)	3.7	7.0	4.9	6.3	3.7	7.5	4.1	7.0
Red Beet								
Minimum (t ha^{-1})	7.8	6.5	6.6	6.3	8.3	6.2	8.6	6.8
Maximum (t ha^{-1})	9.6	9.0	8.7	8.9	10.2	8.9	10.7	9.6
Mean (t ha^{-1})	8.6	7.9	7.5	7.5	9.1	7.9	9.5	8.4
Median (t ha^{-1})	8.6	8.1	7.3	7.6	9.1	8.0	9.5	8.7
Standard Deviation (t ha^{-1})	0.547	0.985	0.672	0.868	0.570	1.053	0.642	1.017
Variability Coefficient (%)	6.4	12.4	8.9	11.6	6.3	13.4	6.7	12.1

Table 3 presents the yield increments of carrot roots achievable through sprinkler irrigation in normal, medium dry, and very dry years. The results indicate that under the RCP 4.5 scenario, carrot yields will increase to a greater extent compared with RCP 8.5. This pattern was consistent across all year categories and in all analyzed counties. The largest yield increments were observed in very dry years, smaller in medium dry years, and the smallest in normal years. Among the four counties, the greatest increase in carrot root yield between very dry and normal years was found in Wągrowiec county, while the lowest was in Słupca county.

For celeriac, yield increments due to irrigation under the RCP 4.5 scenario were higher compared with RCP 8.5 in three of the four counties, although the differences were relatively small, and in Wągrowiec county, no difference was observed (Table 4). In all counties, the lowest yield gains were expected in normal years, higher in medium dry years, and the highest in very dry years. The magnitude of celeriac yield increments in very dry years compared with normal years was similar across all counties.

Table 3. Forecasted carrot root yield increments under sprinkler irrigation (t·ha^{-1} and % relative to yield increase in normal years = 100%) in normal, medium dry, and very dry years under the RCP 4.5 and RCP 8.5 scenarios in four counties of central Poland.

Year Category	Probability of Precipitation Occurrence (*p*)	Climate Change Scenario			
		RCP 4.5		RCP 8.5	
Gniezno County					
Normal	50%	6.1	100%	3.6	100%
Medium Dry	25%	19.1	313%	17.1	475%
Very Dry	10%	25.6	420%	23.9	664%
Słupca County					
Normal	50%	8.5	100%	5.4	100%
Medium Dry	25%	21.0	247%	18.6	344%
Very Dry	10%	27.3	321%	25.1	465%
Wągrowiec County					
Normal	50%	3.3	100%	1.8	100%
Medium Dry	25%	16.9	512%	15.7	872%
Very Dry	10%	23.7	718%	22.6	1255%
Września County					
Normal	50%	7.0	100%	4.0	100%
Medium Dry	25%	19.8	283%	17.4	435%
Very Dry	10%	26.2	374%	24.1	602%

Table 4. Forecasted celeriac root yield increments under sprinkler irrigation (t·ha^{-1} and % relative to yield increase in normal years = 100%) in normal, medium dry, and very dry years under the RCP 4.5 and RCP 8.5 scenarios in four counties of central Poland.

Year Category	Probability of Precipitation Occurrence (*p*)	Climate Change Scenario			
		RCP 4.5		RCP 8.5	
Gniezno County					
Normal	50%	6.8	100%	6.5	100%
Medium Dry	25%	9.1	134%	8.8	135%
Very Dry	10%	10.2	150%	10.0	154%
Słupca County					
Normal	50%	7.2	100%	6.7	100%
Medium Dry	25%	9.4	131%	9.0	134%
Very Dry	10%	10.5	146%	10.1	151%
Wągrowiec County					
Normal	50%	6.3	100%	6.3	100%
Medium Dry	25%	8.7	138%	8.7	138%
Very Dry	10%	9.9	157%	9.9	157%
Września County					
Normal	50%	7.0	100%	6.4	100%
Medium Dry	25%	9.2	131%	8.8	138%
Very Dry	10%	10.4	149%	10.0	156%

Table 5 shows the potential yield increments of red beet roots under irrigation. According to the RCP 4.5 scenario, these increments were higher than under RCP 8.5 in three counties: Gniezno, Słupca, and Września. In Wągrowiec, however, yield increments were at

comparable levels across all year categories, regardless of the climate change scenario. The highest red beet yield increments were observed in very dry years, followed by medium dry years, with the lowest in normal years. The relative increase in yield between very dry and normal years was similar in all counties.

Table 5. Forecasted red beet root yield increments under sprinkler irrigation (t·ha^{-1} and % relative to yield increase in normal years = 100%) in normal, medium dry, and very dry years under the RCP 4.5 and RCP 8.5 scenarios in four counties of central Poland.

Year Category	Probability of Precipitation Occurrence (*p*)	Climate Change Scenario			
		RCP 4.5		RCP 8.5	
Gniezno County					
Normal	50%	8.6	100%	7.9	100%
Medium Dry	25%	13.6	158%	13.1	166%
Very Dry	10%	16.1	187%	15.6	197%
Słupca County					
Normal	50%	9.5	100%	8.4	100%
Medium Dry	25%	14.3	151%	13.5	161%
Very Dry	10%	16.8	177%	16.0	190%
Wągrowiec County					
Normal	50%	7.5	100%	7.5	100%
Medium Dry	25%	12.7	169%	12.7	169%
Very Dry	10%	15.4	205%	15.3	204%
Września County					
Normal	50%	9.1	100%	7.9	100%
Medium Dry	25%	14.0	154%	13.0	164%
Very Dry	10%	16.5	181%	15.6	197%

Across all vegetables and counties, linear regression analysis under the RCP 8.5 scenario revealed a decreasing temporal trend in irrigation-induced yield increments (Table 6). By contrast, under RCP 4.5, a slight, though statistically insignificant, increasing trend was observed for celeriac and red beet yields in Wągrowiec county.

Table 6. Trend line equations for carrot, celeriac, and red beet root yield increments under sprinkler irrigation during the forecast period 2021–2100, based on the RCP 4.5 and RCP 8.5 climate scenarios in four counties of central Poland.

Species	Climate Change Scenario			
	RCP 4.5		RCP 8.5	
Gniezno County				
Carrot	y = −0.2342x + 7.1211	↓	y = −1.1046x + 8.5722	↓
Celeriac	y = −0.01x + 6.8147	↓	y = −0.0722x + 6.7858	↓
Red Beet	y = −0.0219x + 8.6964	↓	y = −0.1578x + 8.6332	↓
Słupca County				
Carrot	y = −0.4483x + 10.481	↓	y = −1.0658x + 10.231	↓
Celeriac	y = −0.0781x + 7.5423	↓	y = −0.0827x + 7.0609	↓
Red Beet	y = −0.1707x + 10.286	↓	y = −0.1707x + 10.286	↓

Table 6. *Cont.*

Species	Climate Change Scenario			
	RCP 4.5		RCP 8.5	
Wągrowiec County				
Carrot	y = −0.0798x + 3.6593	↓	y = −1.1452x + 6.9395	↓
Celeriac	y = 0.0156x + 6.2072	↑	y = −0.0964x + 6.6993	↓
Red Beet	y = 0.0341x + 7.3689	↑	y = −0.2107x + 8.4442	↓
Września County				
Carrot	y = −0.4186x + 8.8736	↓	y = −1.0749x + 8.8095	↓
Celeriac	y = −0.0628x + 7.2839	↓	y = −0.0938x + 6.8546	↓
Red Beet	y = −0.1372x + 9.7217	↓	y = −0.205x + 8.7836	↓

Table 7 presents the Pearson linear correlation coefficients calculated for the expected yield increments of carrot, celeriac, and red beet roots under irrigation across four counties in central Poland and under both climate scenarios. The highest and statistically significant (p = 0.05) correlation coefficients were obtained for carrot yield increments under the RCP 8.5 scenario in all counties. Additionally, high and significant correlations (p = 0.1) were found for celeriac and red beet yield increments in Słupca county under RCP 4.5.

Table 7. Linear correlation coefficients for root yield increments of the studied vegetables expected under irrigation according to two climate change scenarios in four counties of central Poland.

Species	Climate Change Scenario	
	RCP 4.5	RCP 8.5
Gniezno County		
Carrot	0.237	0.845 **
Celeriac	0.098	0.393
Red Beet	0.098	0.393
Słupca County		
Carrot	0.456	0.843 **
Celeriac	0.651 *	0.435
Red Beet	0.651 *	0.651
Wągrowiec County		
Carrot	0.077	0.844 **
Celeriac	0.124	0.595
Red Beet	0.124	0.595
Września County		
Carrot	0.416	0.869 **
Celeriac	0.589	0.477
Red Beet	0.589	0.477

* significant at p = 0.1; ** significant at p = 0.05.

Figure 2 illustrates the statistically significant temporal trends in yield increments of carrot, celeriac, and red beet, based on the regression and correlation analysis presented in Table 6. Table 6 provides all regression equations describing the temporal trends in yield increments under sprinkler irrigation for three vegetable species, two climate change scenarios (RCP 4.5 and RCP 8.5), and four counties in central Poland, whereas Figure 2 illustrates only the statistically significant cases as representative examples to enhance clarity and readability. Figure 2a–d illustrate the regression functions determined for carrot

root yield increments under the RCP 8.5 scenario in all counties. The analysis indicates that in each successive decade of the forecast period (2021–2100), carrot root yield increments resulting from irrigation will decrease by approximately 1.1 t ha^{-1} (p = 0.05). According to the RCP 4.5 scenario, in each subsequent decade of the projected period, the yield increases in carrot roots resulting from irrigation will remain unchanged. In contrast, for celeriac and red beet under the RCP 8.5 scenario, the yield increases due to irrigation will also remain stable, whereas under the RCP 4.5 scenario, the irrigation-induced yield increases for celeriac and red beet will decrease by approximately 0.08 t ha^{-1} and 0.17 t ha^{-1} (p = 0.1), but only in one of the analyzed counties—Słupca County (Figure 2e,f).

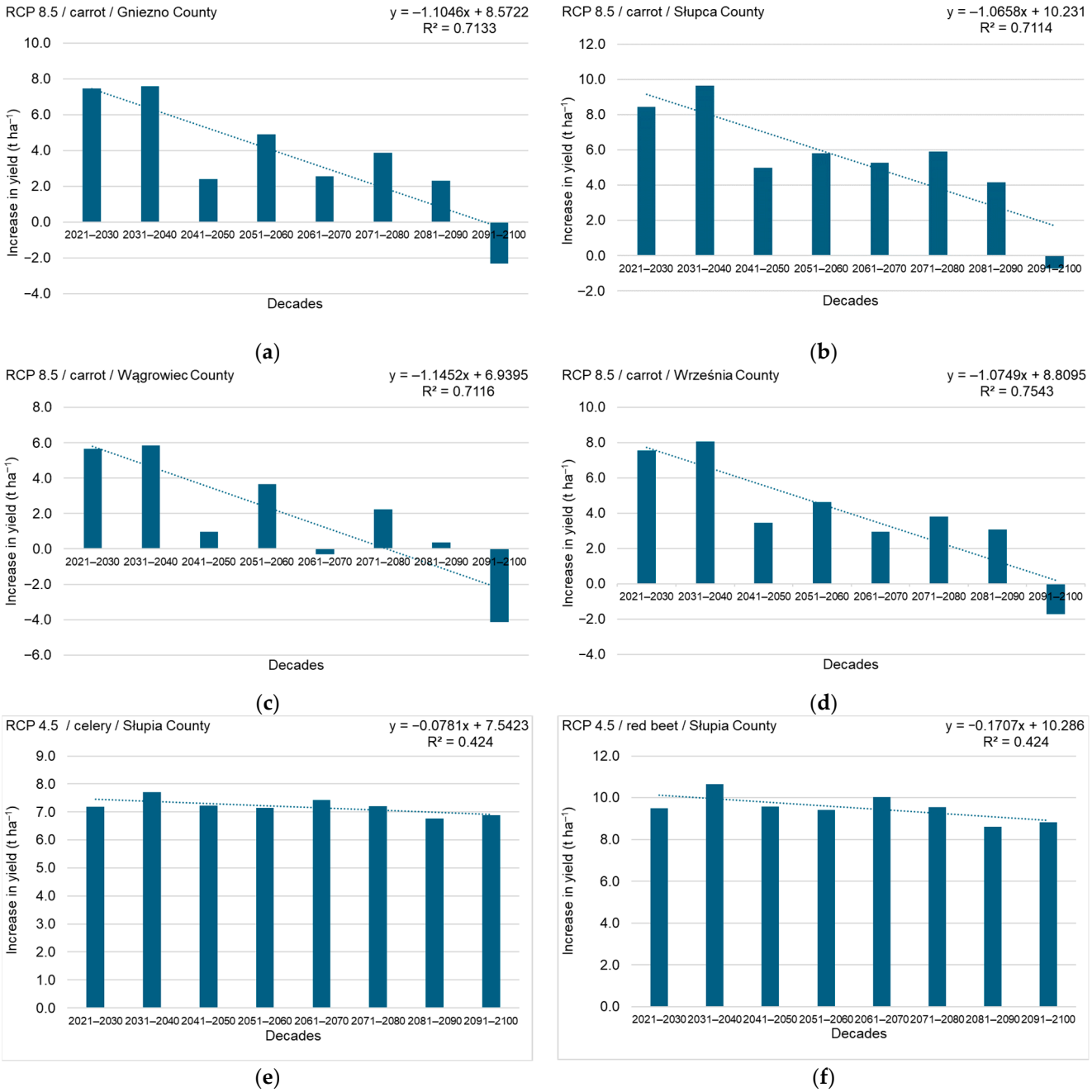


Figure 2. Temporal trends in yield increments under irrigation in successive decades from 2021 to 2100 for carrot according to the RCP 8.5 scenario in the following counties of central Poland: (**a**) Gniezno, (**b**) Słupca, (**c**) Wągrowiec, and (**d**) Września, as well as for (**e**) celeriac and (**f**) red beet according to the RCP 4.5 scenario in Słupca county.

Precipitation deficits during the periods of critical water demand varied across species, counties, and climate scenarios (Table 8). Overall, carrot experienced the smallest deficits, celeriac intermediate, and red beet the largest, reflecting differences in water requirements and drought sensitivity among the species. Across all crops and scenarios, the highest deficits were consistently observed in Słupca county, while the lowest occurred in Wągrowiec county. Precipitation deficits were generally lower under RCP 8.5 than under RCP 4.5 for all species, which reflects the projected changes in precipitation distributions and evapotranspiration intensity under more extreme climate conditions.

Table 8. Precipitation deficits (N; mm) during periods of critical water demand for the studied vegetables in four counties of central Poland.

Species	County							
	Gniezno		Słupca		Wągrowiec		Września	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Carrot	20.6–87.0	12.3–81.2	28.8–92.8	18.5–85.5	11.2–80.5	6.1–76.9	23.8–89.2	13.5–82.1
Celeriac	48.6–91.0	44.8–88.3	53.8–94.6	47.6–90.3	42.5–86.8	42.4–86.6	51.4–93.0	44.4–88.1
Red Beet	83.6–126.0	79.8–123.3	88.8–129.6	82.6–125.3	77.5–121.8	77.4–121.6	86.4–128.0	79.4–123.1

4. Discussion

The projections obtained in this study align with earlier evidence showing that sprinkler irrigation effectively mitigates yield losses of root vegetables under water-limited conditions in central Poland. Long-term field experiments have consistently shown that carrot, red beet, and celeriac respond positively to supplemental irrigation, with yield gains often proportional to the severity of drought stress [1,7,8,53,54]. These findings support the methodological approach adopted in our work, in which yield increments were modeled as a linear function of precipitation deficits.

Kaniszewski and Knaflewski [55] reported that in certain years, particularly when substantial amounts of irrigation water were applied, carrot yields could even decline by about 5.7 t·ha^{-1} (12.4%). At the same time, maximum yield increases reached up to 18.4 t·ha^{-1} (50%), with water applications ranging between 50 mm and 190 mm. For red beet, irrigation resulted in yield improvements of 3–30 t·ha^{-1} (11–111%), corresponding to a productivity index of 0.45–2.6 t·ha^{-1} per 10 mm of applied water. For celeriac, yield increases ranged from 0.6 t·ha^{-1} to 20.6 t·ha^{-1}, with irrigation productivity indices between 0.12 t·ha^{-1} and 3.01 t·ha^{-1} per 10 mm of water applied. Such variability illustrates that irrigation efficiency depends not only on total water applied but also on its timing and uniformity, as excessive irrigation can lead to leaching and temporary oxygen deficits in the root zone.

The present findings reaffirm the necessity of irrigation in vegetable cultivation in central Poland. This conclusion is consistent with earlier studies highlighting that the region is characterized by pronounced irrigation requirements due to frequent rainfall shortages and persistently negative climatic water balances [54,56–63].

Previous work also indicates that the largest yield benefits occur in very dry years, followed by medium dry years, with the smallest gains in normal years. A comparable pattern was observed in red beet cultivation in central Poland, where irrigation in very dry years produced yield increases exceeding 20 t·ha^{-1}, while the benefits were smaller in medium dry or normal years [5]. Similar results were reported for sugar beet, with irrigation combined with nitrogen fertilization producing yield gains of around 18 t·ha^{-1} [64]. These observations correspond well with the projections of this study, which showed that yield increments were most pronounced under conditions of severe water deficit.

Comparable studies conducted in other European regions confirm that climate change will increasingly constrain vegetable production by intensifying drought stress and irrigation needs. In Mediterranean countries such as Spain and Italy, rising air temperatures and declining rainfall have already been linked to yield reductions in root and leafy vegetables, particularly under RCP 8.5 conditions [29–31]. Modeling studies for southern Europe predict that without adaptive irrigation strategies, average vegetable yields could decline by 10–30% by the end of the century due to increased evapotranspiration and lower soil water availability [28]. In Central Europe, including the Czech Republic and Germany, similar results were obtained, indicating that supplemental irrigation may partly compensate for the yield losses projected under future climate scenarios [34–38,65]. Research by Zhang et al. [39] in China also supports these findings, demonstrating that under RCP 8.5, crop water deficits during the growing season will intensify, particularly for high water-demand crops. These results collectively highlight that irrigation remains one of the most effective adaptive measures to sustain vegetable production under future climate variability, although its efficiency will depend on soil properties, crop type, and regional water availability.

Differences between climate scenarios are also noteworthy. The analysis revealed an increase in irrigation demand under both RCP 4.5 and RCP 8.5 scenarios compared to the reference period. Yield increments were consistently higher under the moderate RCP 4.5 scenario, whereas under RCP 8.5, the benefits of irrigation declined across successive decades. This tendency likely reflects the more severe water deficits and higher evaporative demand associated with stronger warming, conditions under which irrigation may be insufficient to fully offset crop water stress [65]. These results suggest that under more moderate warming (RCP 4.5), yield stability can still be maintained through adaptive irrigation management, while under RCP 8.5, structural changes in water allocation and storage may become necessary.

Nonetheless, in some cases—such as celeriac and red beet yields in Wągrowiec county under RCP 4.5—a slight though statistically insignificant increasing trend was observed, suggesting that under moderate climate change, irrigation combined with sound management practices could continue to stabilize or even improve productivity. The use of two Representative Concentration Pathways (RCP 4.5 and RCP 8.5) allows for assessing water requirements under contrasting climate trajectories. RCP 4.5 represents a stabilization pathway where greenhouse gas emissions peak around mid-century and then decline due to mitigation efforts, whereas RCP 8.5 assumes continuously increasing emissions throughout the century [47,66–68]. Comparing these two scenarios provides insight into the range of possible future irrigation needs. Under RCP 8.5, higher temperatures and reduced effective precipitation intensify irrigation demand, highlighting the urgency for adaptive water management and the implementation of sustainable irrigation infrastructure. In contrast, the moderate changes projected under RCP 4.5 suggest that proactive mitigation and climate policies could effectively limit water stress in agriculture. Thus, scenario-based analysis can inform long-term agricultural planning and policy development, helping to balance crop productivity, water conservation, and climate adaptation strategies in southern Poland.

Although climatic conditions are the primary drivers of irrigation demand, differences in soil texture and water-holding capacity may also contribute to spatial variability among the studied counties. Areas with lighter-textured soils, such as sandy loams, tend to retain less water in the root zone, leading to faster soil drying and higher irrigation requirements, particularly under the projected climate scenarios. Conversely, loamy or silty soils can buffer short-term water deficits more efficiently. This variation in soil properties may therefore partly explain the differences observed in irrigation demand between the four counties [69]. Future research should integrate spatially explicit soil data or field-based

measurements of soil water retention to refine irrigation demand estimates and improve the representation of local-scale hydrological variability.

It should be noted that the present study fixed the water demand periods as May–July for carrot and July–August for celeriac and red beet, based on long-term field experiments. However, under climate change, these periods may shift due to earlier onset of plant development and extended periods of elevated evapotranspiration. Rising temperatures and altered precipitation patterns projected under both RCP 4.5 and RCP 8.5 scenarios could advance or prolong the critical water demand period, potentially affecting the magnitude and timing of yield increments attributable to irrigation. For instance, peak water demand may occur earlier in spring for carrot, while celeriac and red beet may experience prolonged periods of water stress in late summer. Such changes could influence the scheduling and volume of irrigation needed to maintain optimal yields. Future studies should therefore include dynamic, phenology-based models that capture potential shifts in crop water demand periods under changing climate conditions. Integrating these models with downscaled regional climate projections (e.g., CMIP6 or RCMs) would enhance the accuracy and operational value of irrigation forecasts. These results suggest that under more moderate warming (RCP 4.5), yield stability can still be maintained through adaptive irrigation management, while under RCP 8.5, structural changes in water allocation and storage may become necessary. Coupling such phenology-based models with irrigation–yield response frameworks will enable more accurate assessment of irrigation efficiency, crop performance under extreme conditions, and climate-adaptive water management strategies [70,71].

The equations used to estimate irrigation effects (Table 1) incorporated optimal rainfall thresholds derived from earlier studies [1,5,7]. For instance, the critical precipitation sums for the July–August period were 190 mm for celeriac and 225 mm for red beet, beyond which irrigation no longer contributed to yield increases. Similarly, the optimal rainfall for carrot during May–July was estimated at 242 mm. The models indicated that irrigation could enhance yields by approximately 177 kg·ha^{-1} (celeriac) and 81 kg·ha^{-1} (red beet) per millimeter of rainfall deficit below the respective thresholds. For carrot, the corresponding value was higher, at 294 kg·ha^{-1} per millimeter of deficit.

Precipitation deficits calculated for the period of peak crop water demand varied across species, counties, and climate scenarios, ranging from the smallest values in medium dry years to the largest in very dry years. These differences closely matched the ranges of irrigation-induced yield increments estimated in our study, further emphasizing the close link between rainfall deficits and the productivity of irrigation. The obtained results confirm that irrigation provides the greatest yield benefits under severe drought conditions, which is consistent with findings reported for similar temperate regions in Central Europe, including the Czech Republic, Poland or Germany, where comparable yield responses of root crops to supplemental irrigation were observed [64,65,71]. These results emphasize that improving water-use efficiency and optimizing irrigation scheduling remain crucial for maintaining stable yields in regions experiencing frequent water deficits, such as central Poland. Although an explicit economic evaluation was beyond the scope of this study, the quantitative estimates of yield gains obtained here provide a valuable foundation for future research on the cost-effectiveness and profitability of irrigation strategies under projected climate change scenarios [5,10,11,20]. Although the approach provided consistent and interpretable results, several limitations should be acknowledged. The assumed linear relationship between precipitation deficits and yield gains remains valid for moderate water shortages (up to approximately 50% of total crop water requirements). Beyond this threshold, crop responses become increasingly non-linear due to physiological constraints, such as impaired photosynthesis, reduced stomatal conductance, and irreversible reproduc-

tive damage. According to the well-established FAO 33 framework [72], this relationship is approximately linear only within moderate water deficit ranges. Field studies on carrot and sugar beet have shown that yield gains plateau or even decline when precipitation deficits exceed approximately 80–100 mm during the critical water demand period [64,73]. Similar threshold-type responses have been reported for other root and field crops under water-limited conditions [31,74–77]. These limitations emphasize the need for non-linear and process-based models capable of representing threshold-type responses under progressive drought stress.

Future research should therefore further develop the modeling framework by incorporating non-linear crop responses to water deficits. Potential approaches include the use of logistic or Mitscherlich functions to represent yield saturation, piecewise regression models to capture critical thresholds, or flexible machine-learning methods such as random forests and gradient boosting that can accommodate multiple interacting stressors [78,79]. Alternatively, process-based crop growth models such as AquaCrop, DSSAT, or APSIM, which explicitly simulate soil–plant–atmosphere interactions and water-stress dynamics, could be employed to evaluate non-linear responses across diverse soil and climate conditions [80]. To assess the impacts of climate change more comprehensively, such models could be coupled with outputs from downscaled regional climate models (RCMs) or bias-corrected CMIP6 ensemble projections. Climate forcing data (precipitation, evapotranspiration, and temperature) can be integrated with irrigation–yield response models through temporal disaggregation and bias correction to produce decade-scale irrigation scenarios under different RCP or SSP pathways [71,81]. This coupling would allow testing of model robustness under extreme drought or water scarcity conditions and enhance the applicability of the results for water-resource planning [26]. Furthermore, linking biophysical models with economic, hydrological, and policy modules would support integrated assessments of irrigation profitability, water allocation, and long-term adaptation strategies in water-deficient regions of central Poland [82].

In practice, however, irrigation potential is often constrained by water availability, infrastructure capacity, and regulatory or economic limitations. Moreover, soil heterogeneity, varietal differences, and local management practices may cause yield responses to deviate from regional-scale model estimates [83–90]. Future studies should therefore combine process-based and empirical approaches with field data to capture these local-scale variations and to identify cost-effective and sustainable irrigation strategies under projected climate change conditions. Ultimately, bridging biophysical, hydrological, and economic modeling approaches will be essential for designing resilient irrigation strategies that align with sustainable water management policies in Central Europe.

5. Conclusions

This study demonstrates that supplemental sprinkler irrigation can play a crucial role in stabilizing and improving the yields of carrot, celeriac, and red beet in one of the most water-deficient agricultural regions of central Poland. The analysis across four counties and three categories of growing seasons (normal, medium dry, and very dry) revealed consistent benefits of irrigation under both climate change scenarios (RCP 4.5 and RCP 8.5). The greatest yield improvements were observed in very dry years, confirming the role of irrigation as a key adaptation strategy to mitigate drought-induced yield losses. The results also highlighted regional variability, with Wągrowiec County showing the strongest responses, particularly for carrot, while other counties, such as Słupca, exhibited lower or more variable effects. Scenario-based comparisons indicated that yield responses were generally higher under RCP 4.5 than under RCP 8.5, suggesting that more severe climate conditions may reduce the effectiveness of irrigation in maintaining yield gains. This projected decline

under RCP 8.5 underscores the limitations of irrigation as a stand-alone adaptation measure. It highlights the need for integrated adaptation approaches that combine efficient irrigation with soil and crop management innovations. To ensure the long-term resilience and profitability of vegetable production in water-deficient regions, irrigation should be integrated into broader water management strategies that combine efficient irrigation scheduling with improved soil moisture conservation, the use of drought-tolerant cultivars, and precision farming techniques. Future research should focus on refining irrigation–yield models by incorporating non-linear crop responses, extreme drought scenarios, and soil–water–plant interactions to enhance the accuracy of yield projections under future climate extremes.

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