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Effect of Selected Meteorological Factors on the Growth Rate and Seed Yield of Winter Wheat—A Case Study

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Abstract: Recent years have seen a significant increase in weather anomalies in Central Europe (51°22′ N, 22°64′ E), which makes it more difficult to predict yields of winter wheat and to estimate prices on world exchanges. Eight-year (2007–2015) field observations of winter wheat cv. Turnia were carried out in order to determine the relationship between selected meteorological indicators (e.g., the values of average daily air temperature, daily sums of precipitation, and the number of days with precipitation) and the biometric traits and seed yield of winter wheat. In addition, an attempt was made to identify the meteorological parameters that determine an increase in stem elongation during the growing season. The relationship between yield parameters and biometric parameters was evaluated using Spearman's non-parametric correlation coefficients. The regression models for analysis of the dependence of yield parameters and biometric parameters on meteorological elements (temperature, precipitation totals, and days with precipitation) in each development period was used. The study showed that from the beginning of vegetative growth to the flowering stage, growth and development were most advanced in plants for which the average temperature was about 8–9 °C, and the number of days with precipitation was about 41. During generative growth, spike length is 80% determined by the precipitation total. Grain weight is 68% negatively determined by the temperature during dormancy (the higher the temperature during dormancy, the lower the weight of the kernel). A positive relationship was shown between yield and the precipitation total during the period from sowing to the onset of dormancy (r = 0.37). Winter wheat yield was 69% dependent on the density at harvest (the greater the density, the higher the final yield). On the basis of the 8-year results of the study, we conclude that the weather is highly variable from year to year, and therefore breeders should direct their research towards creating variants with much greater plasticity and high tolerance for unfavourable weather patterns.

Keywords: winter wheat; yield; temperature; precipitation; plant development

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1. Introduction

The level of yield of winter wheat largely depends on the course of the weather during the growing season, which is often the cause of suboptimal conditions during plant growth and development. Important weather factors influencing crop yield and quality include temperature and precipitation conditions. Recent years have seen negative climate impact in many parts of Europe, i.e., a significant increase in the average annual air temperature and a reduction in the amount of precipitation. Suboptimal weather conditions often increase the risk level of cultivation of cereal crops, including winter wheat, due to disturbances of physiological processes induced by abiotic stress and affecting the entire phenology of plants, such as the time and duration of development stages [1]. The many newly introduced varieties of winter wheat vary in their sensitivity to variable weather conditions due to the imperfect methods and tools used in breeding cereal plants, including winter wheat [2–4].

The effect of global warming on the production of four crop species of key importance for meeting the global demand for food (wheat, rice, maize, and soybean) has long been analysed by a variety of methods (global grid models, local models, and field warming experiments) and mathematical models [5–7]. The results of these methods consistently show that temperature negatively affects crop yields on a global scale [6]. According to literature reports, a global air temperature increase of 1 °C would reduce the average global yield of wheat by 6.0%, rice by 3.2%, maize by 7.4%, and soybean by 3.1% [6,8]. The results of research in various geographic regions are highly heterogeneous, but multidimensional analyses increase the certainty of the assessment of the effect of climate change on these crops. To ensure food security for the growing world population, adaptation strategies for C3 plants are proposed, adjusted for individual regions of the world [6].

Wheat is one of the most important commodity crops in the world due to the multiple uses of its grain, including human consumption, fodder, and industrial purposes. Owing to the versatility of the plant, global wheat production covers 221 million ha and amounts to 758 million tonnes (FAO 2019). Wheat production is determined by genetic and environmental factors. Biological advances have contributed to a significant increase in wheat yield, as confirmed by FAO data [9]. Average global yields amount to 3.43 t ha^{-1} [10]. In Europe, wheat yields are varied. The highest yields are obtained in Western Europe, and the lowest in the east of the continent [5]. Weather conditions during the growing season have a decisive influence on wheat yield. In Central Europe, in the temperate climate zone characterised by highly variable weather conditions, cultivation of winter wheat, which is more fertile, is predominant. Fertility, however, is determined by the biology of the plant as well as environmental conditions, including low temperatures inducing the tillering process. Research by Kamran et al. [11] and Zikhali and Griffiths [12] on the effect of temperature on wheat development has shown that genes (Eps) inducing specific responses to environmental stimuli are activated in the vernalisation process. Besides the biochemical processes taking place in plants as a result of low temperature, an increase in temperature is considered to be another factor accelerating the growth and development of plants, irrespective of cultivar [13,14]. Wheat yield is also determined by genetic–environmental factors (G–E), described many times in the scientific literature [13,14]. While explaining the genetic determinants affecting the elongation and productivity of wheat is an easy task [15,16], it is much more difficult to identify environmental factors (mainly meteorological) which determine the intercalary growth of plants during ontogenesis and influence the final yield. Among meteorological elements, air temperature and the amount of precipitation have been shown to significantly influence plant growth [14,17]. Many researchers have partially investigated the effect of meteorological elements on the phenology of cereal crops. Slafer et al. [14] showed that stem elongation is a critical stage in yield formation. Due to numerous scientific reports of a relationship between plant growth and yield, methods of biometric evaluation of plants have included phenotyping technology, of which a crucial element is monitoring of plant growth in field conditions [18–21]. Despite the proven effect of temperature on plant growth, there are limited studies [20] that take a comprehensive approach to quantifying the effect of meteorological elements (air temperature, precipitation totals, and number of days with precipitation) during selected development stages of winter wheat on the course of its intercalary growth, yield, and yield structure.

In this study, an attempt was made to determine the relationship between selected temperature and precipitation parameters and the biometric traits and yield of winter wheat.

An attempt was also made to identify the meteorological parameters which determine stem growth during the growing season.

2. Material and Methods

2.1. Field Experiment

A field experiment was carried out in 2007–2015 at the Experimental Station in Felin (51°22′ N, 22°64′ E) in the south-eastern part of the Lublin region (Figure 1).

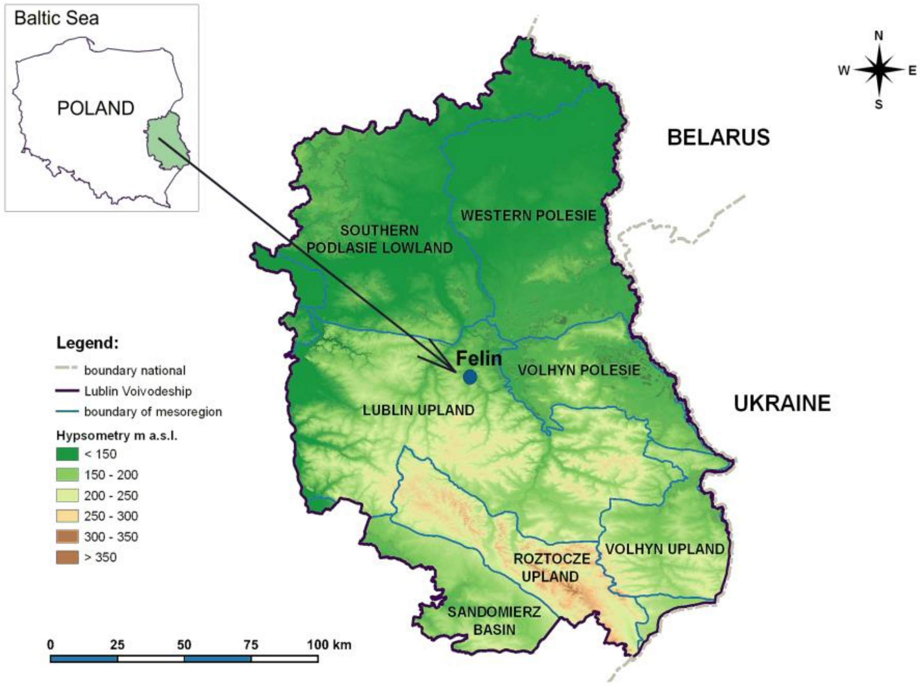


Figure 1. Localisation of Felin Experimental Statio.

The experiment was set up on Orthic Luvisol formed of loess-derived silt, classified as good wheat complex. The soil had a high content of nutrients. The contents of P, K, and Mg were 76, 119, and 55 mg·kg^{-1} of soil, respectively, and the pH in the KCl solution was 6.3 [22]. Soil cultivation was typical for ploughing. Harvest of the forecrop (red clover) was followed by skimming and medium ploughing, and the soil for sowing was prepared with a seedbed cultivator. The fertilisers applied before sowing were 70 kg·ha^{-1} P_2O_5 in the form of superphosphate (40%) and 100 kg·ha^{-1} K_2O as potash (60%). In spring, 60 kg·ha^{-1} N in the form of ammonium nitrate (34%) was applied before the onset of plant growth and 40 kg·ha^{-1} N during the beginning of stem elongation. Winter wheat cv. Turnia was sown at 500 seeds per m^2 using a seed drill. Row spacing was 11 cm, and seeds were sown at a depth of 3 cm. Cultivar Turnia is the very common cultivar (Małpolska Hodowla Roślin-breeder company, Kraków, The Republic of Poland) for cultivated for consumption purposes. Turnia is characterised by high resistance to pathogens, high winter hardiness, and medium-to-high water requirement and medium-to-high productivity. The plot size was 18 m^2. Plant cultivation procedures (herbicides Chwastox Extra 300SL at 1.5 L·ha^{-1}, KuzarActiv 1 kg·ha^{-1}) were carried out in accordance with plant protection principles. Before harvest, the plant density was determined on each plot, and then 20 stems of winter wheat were collected. The weight and length of the stems and spikes were measured, and the number of internodes and grain number per spike were determined. From each plot, every year, the same 20 selected stems were measured during the entire vegetation period. Plant height was measured from the onset of plant growth, and spike length from the time of heading.

Wheat was harvested with a plot combine machine during the full grain maturity stage. Following grain harvest (seed yield in unite t·ha^{-1}) the 1000-grain weight (TGW) was determined.

This study used the available values of average daily air temperature, daily sums of precipitation, and the number of days with precipitation. These data were used to determine the effect of meteorological conditions on the winter wheat plant development in specific periods (1–4) from sowing to harvest. These data came from the Agrometeorological Station located in the Experimental Station in Felin (51°22′ N, 22°64′ E). Three basic meteorological indicators were used, because among the meteorological parameters, the main yield-generating factors are weather parameters, e.g., daily air temperature, daily sums of precipitation, and the number of days with precipitation. In essence, the precipitation consists of the "income" in the water balance. Air temperature is the second the most important parameter for yielding, which corresponds to evapotraspiration and effects the values of climate water balance.

2.2. Meteorological Background of the Experiment

The climate of the given region is located in the transitional temperate zone. The long-term average (1981–2010) annual air temperature at the Felin experimental station was 7.8 °C, and the precipitation total during that period was 544 mm (Figure 2). The climatic water balance in Poland during the growing season is negative. In the region where the Felin Experimental Station is located, the average values of the climatic water balance in the warm half-years (from April to September) are negative and amount to −63 mm; in the month of April to July, the average of climatic water balance is about 43 mm [23]. During the study period, i.e., 2007–2015, the air temperature was higher than the 1981–2010 climate normal in all months of the year. Precipitation in April and August during the study period was lower than normal for these months, while in other months of the year, it was higher than normal (Figure 2).

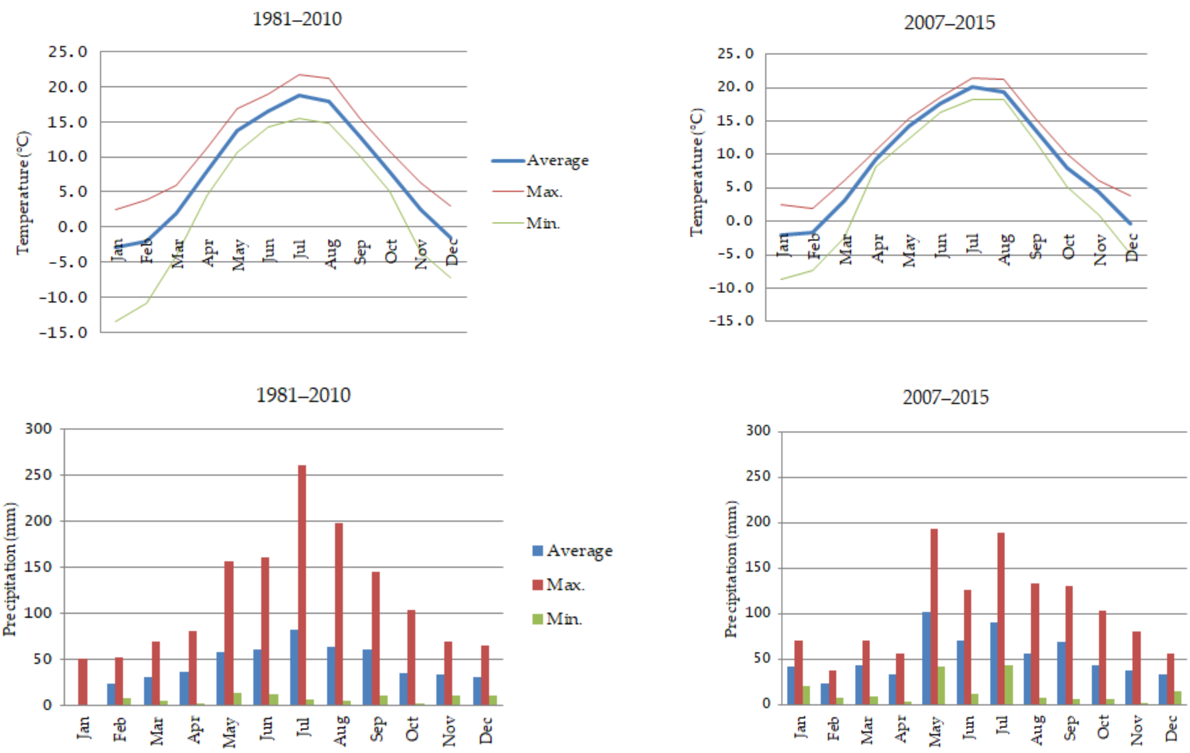


Figure 2. Monthly air temperature (°C) and precipitation (mm) from the Felin experimental station during the 2007–2015 study period in comparison with the 1981–2010 long-term average.

2.3. Statistical Calculations

The relationship between yield parameters and biometric parameters was evaluated using Spearman's non-parametric correlation coefficients. This method was used because one of the meteorological elements (precipitation totals) did not fit a normal distribution. Next, yield elements and biometric parameters were analysed by analysis of variance. The statistical significance between years of the study was determined using the non-parametric Kruskal–Wallis test (K–W) for a significance level of $\alpha = 0.05$.

A path coefficient analysis was described by Sewall Wright in 1920 and allows for the analysis of the interdependencies between explanatory and explained variables in a complex biological system [24,25]. In the case when one of the analysis component (variable y = yield) depends on several independent variables: x1, . . . , xn (variables xn = components of the yield structure), which additionally interact in some way, this method relies on decomposition matrix of correlation coefficients [24,25].

The regression models for analysis of the dependence of yield parameters and biometric parameters on meteorological elements (temperature, precipitation totals, and days with precipitation) in each development period was used. Backward stepwise regression was used [26]. Before performing the regression, two dimensional diagrams of their dispersion were analysed for dependence (linear and non-linear) of the examined variables. Regression models were created on the basis of a forward procedure. It consisted in changing the model from the previous step by removing the predictor according to a specific step criterion [26]. The removal of effects of the model were determined using the critical values for $p = 0.05$, wherein the actual values used to control the removal of effects from the model were 1-p values. For the obtained models, the values of the determination coefficients (R^2) were also given. The calculations were performed using Statistica 14 software.

3. Results

3.1. Meteorological Characteristics of the Study Period and the Course of Selected Periods of Wheat Development

To analyse the development of winter wheat plants (from sowing to harvest) in relation to the course of average daily temperatures in 2007–2015, four development periods were distinguished.

The meteorological characteristics of the periods of development of winter wheat at the Felin station are presented in Table 1. Differences in meteorological conditions and the dates of each period of development of winter wheat were observed between years of the experiment (Figure 2, Table 1).

Table 1. Meteorological characteristics of the periods of development of winter wheat (1–4) at the Felin experimental station.

Wheat Development Period	Parameter	2007/2008	2008/2009	2009/2010	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015
Sowing to onset of dormancy ($t_p \geq 3$ °C) (1)	Sowing date	3 Oct	20 Oct	10 Oct	14 Oct	13 Oct	4 Oct	4 Oct	3 Oct
	D (1)	33	32	20	41	27	23	41	21
	t (1)	6.8	7.3	5.7	7.0	5.5	9.1	9.7	11.8
	P (1)	20.7	24.1	93.6	37.8	4.8	39.3	62.1	25.6
	NdP (1)	8	8	18	21	6	14	16	5
Dormancy period ($t_p < 3$ °C) (2)	Dormancy period date	5 Nov	21 Nov	30 Oct	24 Nov	9 Nov	27 Oct	14 Nov	24 Oct
	D (2)	109	126	139	107	128	165	93	141
	t (2)	−0.2	−0.8	−2.0	−3.3	−1.5	−1.0	0.2	−1.2
	P (2)	87.7	171.5	167.2	101.6	94.8	260.7	121.7	143.3
	NdP (2)	41	65	77	62	70	84	40	46
Vegetative growth of plants ($t_p \geq 3$ °C) (3)	Vegetative growth date	22 Feb	27 Mar	18 Mar	11 Mar	16 Mar	10 Apr	15 Feb	13 Mar
	D (3)	112	91	92	89	80	68	100	89
	t (3)	9.1	12.6	12.8	11.3	11.5	14.6	8.8	8.5
	P (3)	230.5	200.2	228.2	79.7	123.6	186.5	215.1	199.4
	NdP (3)	53	37	46	23	29	29	41	34
Generative growth of plants (4)	Generative growth date	13 June	26 June	18 June	8 June	4 June	17 June	26 May	10 June
	D (4)	55	46	50	59	65	51	74	59
	t (4)	18.2	20.0	20.3	18.3	20.3	20.0	18.9	16.2
	P (4)	111	86.1	150.8	260	112.9	172.5	250.1	54.9
	NdP (4)	23	17	16	37	28	15	31	15
	Harvest date	6 Aug	10 Aug	6 Aug	5 Aug	7 Aug	6 Aug	7 Aug	7 Aug

Legend: t_p—average daily temperature, D—length of period, t—temperature, P—precipitation, NdP—number of days with precipitation.

The autumn vegetation period, i.e., the period from sowing to the onset of dormancy (period 1), lasted from 20 to 41 days. Period 1 was shortest in the 2009/2010 season (20 days) and longest in the 2010/2011 and 2013/2014 seasons (41 days) (Table 1). The 2009/2010 season was relatively cold (5.7 °C) and wet, with the highest and most frequent precipitation. The longest seasons differed in temperature and moisture conditions: in the 2013/2014 season, it was much warmer and wetter than in 2010/2011. This period in the 2011/2012 season was the coldest and driest (Table 1), with only 4.8 mm of precipitation and 6 days with precipitation.

The dormancy period (2) lasted from 93 days (season 2013/2014) to 165 days (season 2012/2013). This period was wettest in the 2012/2013 season and warmest in 2013/2014, with an average temperature of +0.2 °C. The dormancy period in 2013/2014 had the lowest frequency of precipitation (only 40 days). Period 2 was longest in the 2012/2013 and was wet.

During the period of vegetative growth (3), measurements of the growth of winter wheat plants were made. The length of this period was varied: from 68 days (2012/2013 season) to 112 days (2007/2008). The 2007/2008, 2013/2014, and 2014/2015 seasons were much colder than the others. Period 3 was the driest and warmest in the 2010/2011 season. In 2012/2013, the onset of vegetative growth was delayed in comparison to the other years of the study. However, the delay was compensated for by higher temperatures, and the precipitation total and frequency can be considered average. In comparison to the other seasons, the precipitation total in period 3 was <40%.

The final period of development of winter wheat was the period of generative growth (4), which lasted from 46 days (2008/2009) to 74 days (2013/2014). In all seasons, the plants were harvested between 6 and 10 August. In the 2008/2009 period, period 4 was the shortest and was dry and warm. In the 2010/2011 and 2013/2014 seasons, the period of generative growth was relatively cold and wet, and it was longest in the 2013/2014 season. The 2014/2015 season was the coldest and driest (Table 1).

3.2. Effect of Selected Meteorological Parameters on the Growth Rate of Winter Wheat

3.2.1. Growth Rate of Winter Wheat

From 2007 to 2015, the rate of stem growth measured from the onset of vegetative growth to maturity was varied, sometimes extremely, e.g., in 2009/2010 and 2014/2015 (Figure 3). The rate of stem growth was determined by the weather during period 3, i.e., the period of vegetative growth. In 2008, the average air temperature was low (9 °C), and the precipitation total was high (230.5 mm) during this development period (Table 1). This significantly prolonged the period of plant growth to 112 days. The plants formed long stems (Figure 3a). In 2013, high (about 14 °C) average temperatures were noted during the period of vegetative growth (period 3), which shortened this period to 68 days and accelerated the transition to generative development (Table 1). These plants formed the shortest stems (Figure 3f).

Intercalary growth significantly depended on the length of the entire growing period (D), especially the period of vegetative development of winter wheat D (3) and the number of days with precipitation during this period NdP (3), while during the period from sowing to winter dormancy (1), high temperatures negatively affected plant growth (r = −0.34) (Table 2).

Table 2. Correlations between plant growth and selected meteorological parameters and the length of development periods.

Varible	P (1)	P (2)	P (3)	P (4)	t (1)	t (2)	t (3)	t (4)	NdP (1)	NdP (2)	NdP (3)	NdP (4)	D	D (1)	D (2)	D (3)	D (4)
Increase in length (ΔL)	0.24	−0.16	0.33	−0.25	−0.34 *	−0.16	−0.03	−0.10	0.08	−0.09	0.58 *	-	0.70 *	−0.10	−0.08	0.55 *	-

Legend: ΔL—increase in length (cm), D—length of period from sowing to harvest, D (1)—length of period from sowing to onset of dormancy, D (2)—length of dormancy period, D (3)—length of vegetative growth period (when plant growth was measured), D (4)—length of generative growth period. * Correlation coefficients in red are significant at $\alpha \leq 0.05$.

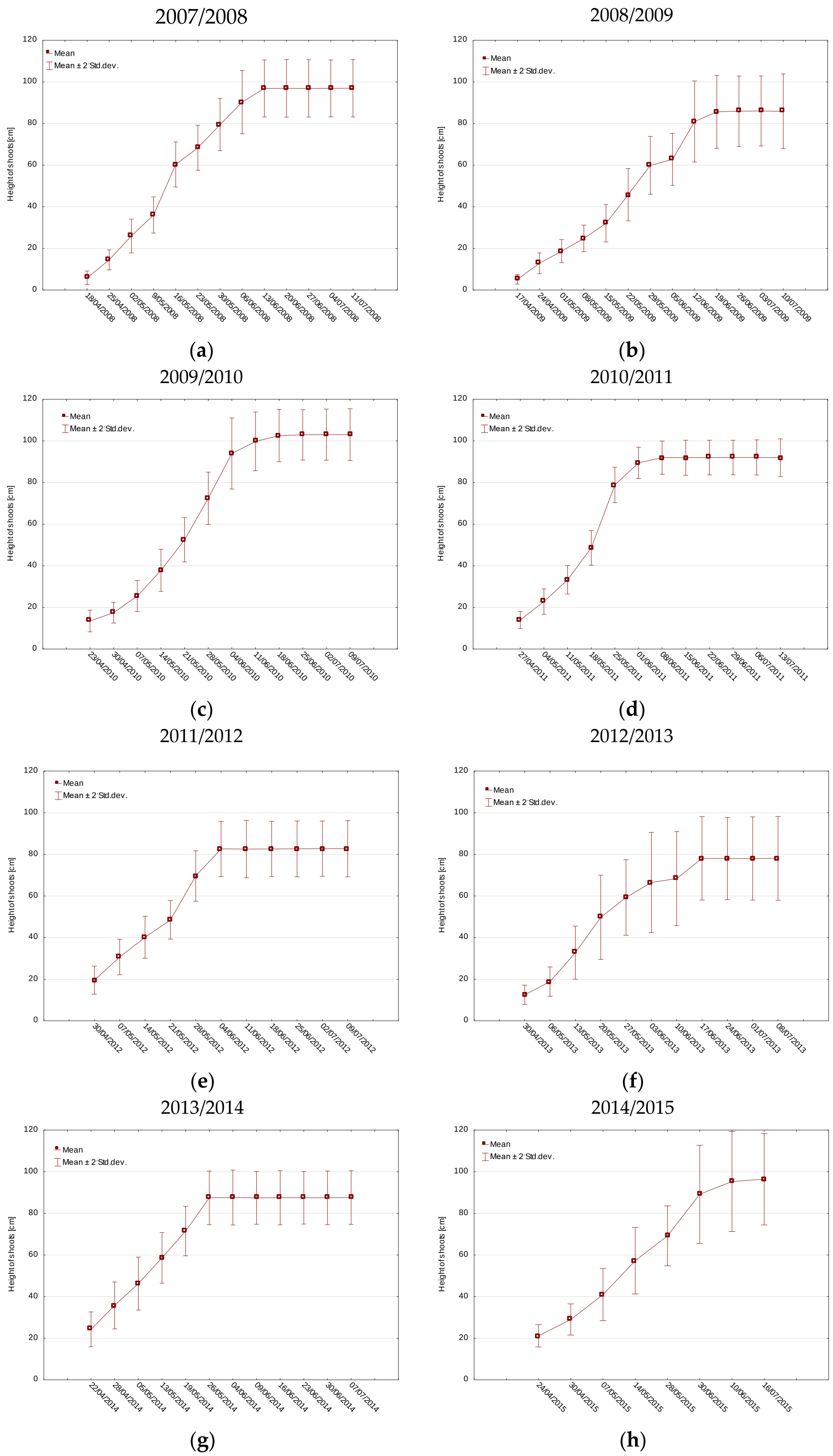


Figure 3. Hight of shoots in following vegetation seasons (**a**–**h**).

3.2.2. Biometric Parameters of Winter Wheat

The statistical analysis of the biometric parameters of winter wheat in the years 2007–2015 showed that the 2014/2015 season stood out in terms of stem growth (Figure 4). In that season, the plants had an increased internode number, plant weight, and straw weight, but a reduced spike length, grain number per spike, and 1000-grain weight (Figures 4 and 5).

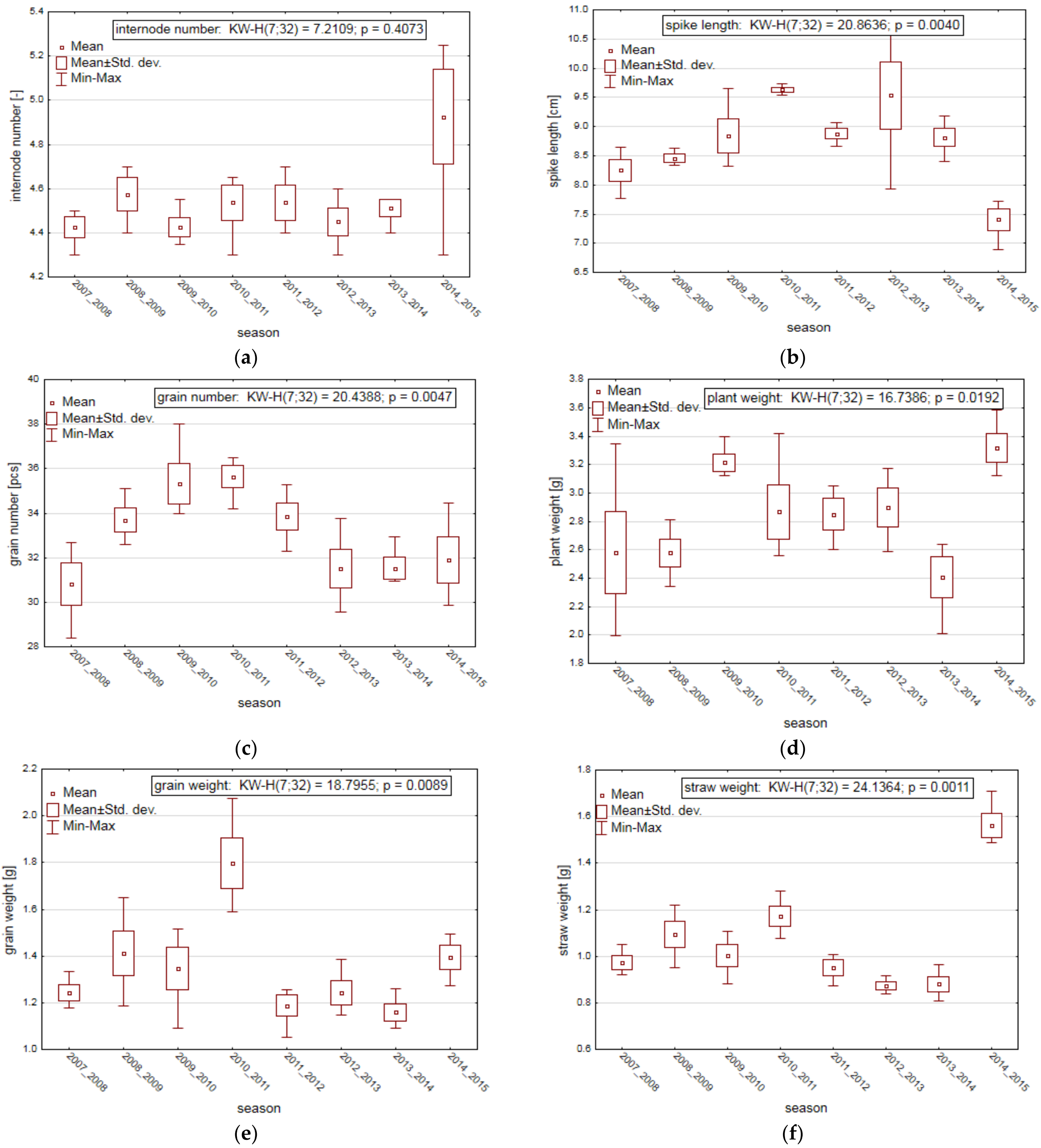
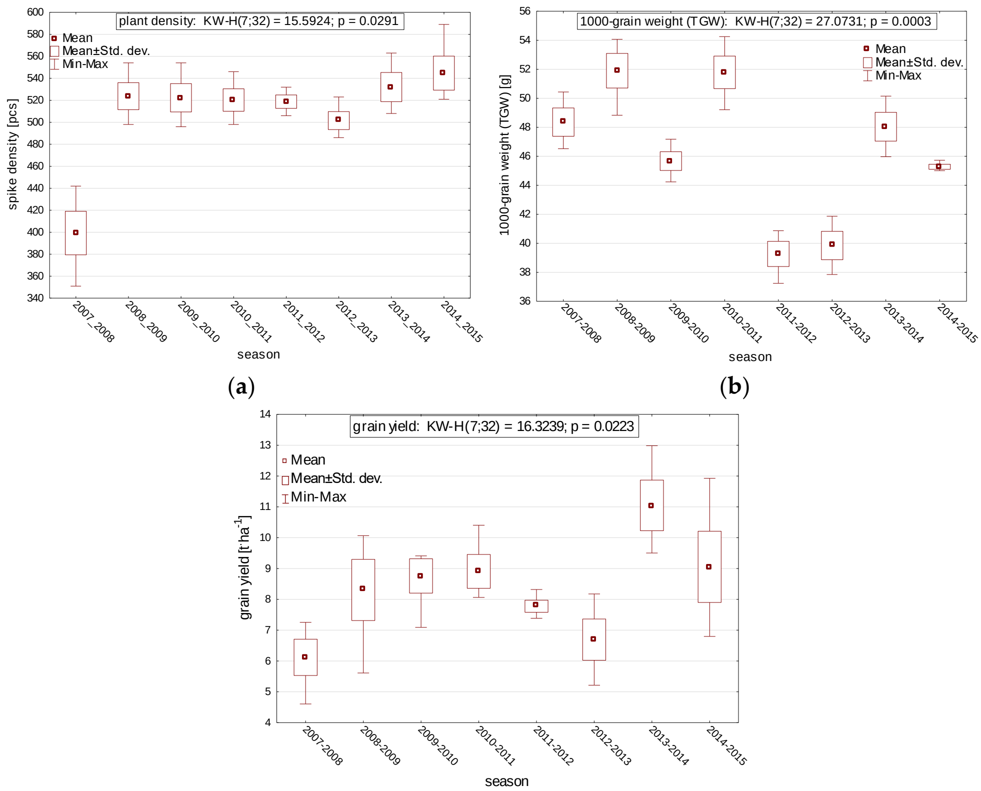


Figure 4. Statistical characterisation of biometric parameters of winter wheat in 2008–2015: (**a**)—internode number, (**b**)—spike length, (**c**)—grain number, (**d**)—plant weight, (**e**)—grain weight, (**f**)—straw weight.



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

(**c**)

Figure 5. Basic statistical parameters of spike density (**a**), 1000-grain weight (TGW) (**b**), and grain yield in t·ha^{-1} (**c**) of winter wheat in the years of the study.

Correlation coefficients between selected meteorological parameters (average air temperature, precipitation total, and number of days with precipitation) and the biometric parameters of winter wheat are presented in Table 3.

Table 3. Correlation coefficients between biometric parameters of winter wheat and meteorological parameters.

Variable	IN	SL	PW	GN	GW	SW	P (1)	P (2)	P (3)	P (4)	t (1)	t (2)	t (3)	t (4)	NdP (1)	NdP (2)	NdP (3)	NdP (4)
IN	1.00	0.06	0.19	0.07	0.10	0.24	−0.14	0.02	−0.24	−0.16	0.23	−0.05	−0.24	−0.20	−0.22	−0.14	−0.23	0.02
SL		1.00	0.04	0.43 *	0.09	−0.32	0.25	0.02	−0.43 *	0.74 *	−0.28	−0.31	0.42 *	0.41 *	0.59 *	0.32	−0.44 *	0.40 *
PW			1.00	0.31	0.23	0.24	0.18	0.17	−0.12	−0.16	0.00	−0.50 *	0.04	0.04	−0.07	0.30	−0.12	−0.42 *
GN				1.00	0.58 *	0.36 *	0.11	0.02	−0.32	0.23	−0.42 *	−0.68 *	0.27	0.34	0.38 *	0.32	−0.29	0.26
GW					1.00	0.84 *	0.04	0.09	−0.29	−0.01	0.04	−0.51 *	−0.02	−0.23	0.21	0.06	−0.30	0.03
SW						1.00	−0.20	−0.07	−0.18	−0.40 *	0.15	−0.38 *	−0.36 *	−0.47 *	−0.20	−0.18	−0.16	−0.07

Legend: P (1–4)—precipitation total during a given period, t (1–4)—average temperature during a given period, NdP (1–4)—number of days with precipitation during a given period, IN—internode number, SL—spike length, GN—grain number, PW—plant weight, GW—grain weight, SW—straw weight. * Correlation coefficients are significant at $\alpha \leq 0.05$.

The values of the correlation coefficients indicated that the temperature and precipitation conditions during the analysed development periods of winter wheat affected the biometric parameters of the plants, particularly spike length (SL). SL was shown to be negatively correlated with the precipitation total in period 3 (vegetative growth), with r = −0.43, but positively correlated in period 4 (generative growth), with r = 0.74. The number of days with precipitation (NdP) also significantly influenced this biometric parameter. The number of days with precipitation was found to be significantly positively correlated with SL in periods 1 and 4 (r = 0.59 and r = 0.40, respectively) and negatively correlated in period 3 (r = −0.44). The air temperature significantly influenced spike length (SL) in periods 3 (r = 0.42) and 4 (r = 0.41) (Table 3).

Plant weight (PW) depended on air temperature and on the number of days with precipitation. Negative correlations were shown between PW and temperature during the dormancy period (2) (r = −0.50) and between PW and the number of days with precipitation (NdP) in the generative development period (3) (r = −0.42). Grain number (GN) was negatively correlated with temperature during period 1 (r = −0.42) and during dormancy (2) (r = 0.68), and positively correlated with the number of days with precipitation in period 1 (r = 0.38). Grain weight (GW) was negatively correlated with temperature during dormancy (2) (r = −0.51). Straw weight (SW) was negatively correlated with the precipitation total in period 4 (r = −0.40) and with air temperature during dormancy (2) (r = −0.38), vegetative development (3) (r = −0.36), and generative development (4) of winter wheat (r = −0.47).

3.3. Effect of Selected Meteorological Parameters on Yield of Winter Wheat

Yield is the product of three components: plant density at harvest, mean grain number per spike, and 1000-grain weight (TGW). One of the most important parameters determining the final yield of wheat is plant density, which was significantly influenced by the weather.

The weather was found to be associated with the grain yield and certain biometric parameters (Table 3). Yield was highest in the 2013/2014 season, at 110 dt/ha, while low yield was obtained in the 2007/2008 season, at 60 dt·ha^{-1}. Conditions for the growth and development of winter wheat were most favourable in 2013/2014. The least favourable conditions for wheat were noted in 2007/2008, which resulted in the low yield of 60 dt·ha^{-1}.

The lowest plant density at harvest was recorded in the 2007/2008 season, which in comparison to the other years was characterised by unfavourable meteorological conditions (Tables 1 and 4). While plant density was not determined by the weather in the season, as confirmed by the statistically non-significant result of the K-W test, TGW and yield were found to be dependent on the weather (Figure 5, Table 4).

Table 4. Correlations between elements of the yield of winter wheat and selected meteorological elements.

Variable	TGW	Yield	P (1)	P (2)	P (3)	P (4)	t (1)	t (2)	t (3)	t (4)	NdP (1)	NdP (2)	NdP (3)	NdP (4)
Plant density at harvest (PDH)	0.15	0.75 *	0.19	0.18	−0.23	−0.02	0.26	−0.19	−0.21	0.01	−0.03	−0.07	−0.21	0.04
TGW	1.00	0.26	0.05	−0.13	0.21	0.10	0.11	0.15	−0.24	−0.39 *	0.38 *	−0.49 *	0.21	0.45 *
Yield		1.00	0.37 *	0.08	−0.08	0.25	0.27	−0.03	−0.26	−0.01	0.26	−0.26	−0.067	0.28

P (1–4)—precipitation totals in respective periods, t (1–4)—average temperature in respective periods, NdP (1–4)—number of days with precipitation in respective periods. * Correlation coefficients in red are significant at $\alpha \leq 0.05$.

The greatest reduction in final plant density and the lowest yield were observed in the 2007/2008 season (Figure 5a,c). In that season, the weather conditions during the period of vegetative development (3) were the most divergent from the other years of the study, with the highest and most frequent precipitation (Table 1). The significant influence of weather conditions on 1000-grain weight was confirmed by the correlations obtained and the Kruskal–Wallis test (Figure 5b, Table 4). The highest 1000-grain weight was observed in the years 2008/2009 and 2010/2011, which was linked to temperature conditions and the precipitation total and distribution. The most favourable weather conditions were observed in the 2010/2011 season (Table 1), in which period 1, from sowing to the onset of dormancy, was long (41 days), with relatively high levels of precipitation, while the dormancy period (2) was the coldest, with moderate precipitation. Period 3, vegetative development, from the end of dormancy to the end of plant growth, was warm and relatively dry, while the final period, generative development (4), was characterised by unfavourable precipitation conditions.

The correlations linking plant density (PDH), 1000-grain weight (TGW), and yield of winter wheat with selected meteorological elements are presented in Table 4.

A statistically significant positive correlation (r = 0.37) between yield and precipitation totals was noted only in the first of the four development periods (from sowing to the onset of dormancy). In the case of 1000-grain weight (TGW), weather elements had a greater influence—1000-grain weight was negatively correlated (r = −0.39) with temperature in the generative development period (4). Varied (positive/negative) statistically significant effects of the weather on 1000-grain weight were observed in the case of precipitation distribution among development periods, expressed as the number of days with precipitation (NdP). Positive correlations between NdP and TGW were noted in the period from sowing to the onset of dormancy (r = 0.38) and the generative development period (r = 0.45), and a negative correlation was found during the dormancy period (r = −0.49).

Among the six of biometric variables: SL, PW, GN, TGW, SW, IN, the greatest influence on GW was TGW, followed by GN (Figure 6). The above-mentioned influences were directed. On the other hand, IN had the lowest impact on GW, and additionally varied significantly over the years; therefore, it must be strongly dependent on weather conditions. It is very interesting that SL, PW, and SW also had a large influence on GW, but they were indirectly influenced by GN and TGW.

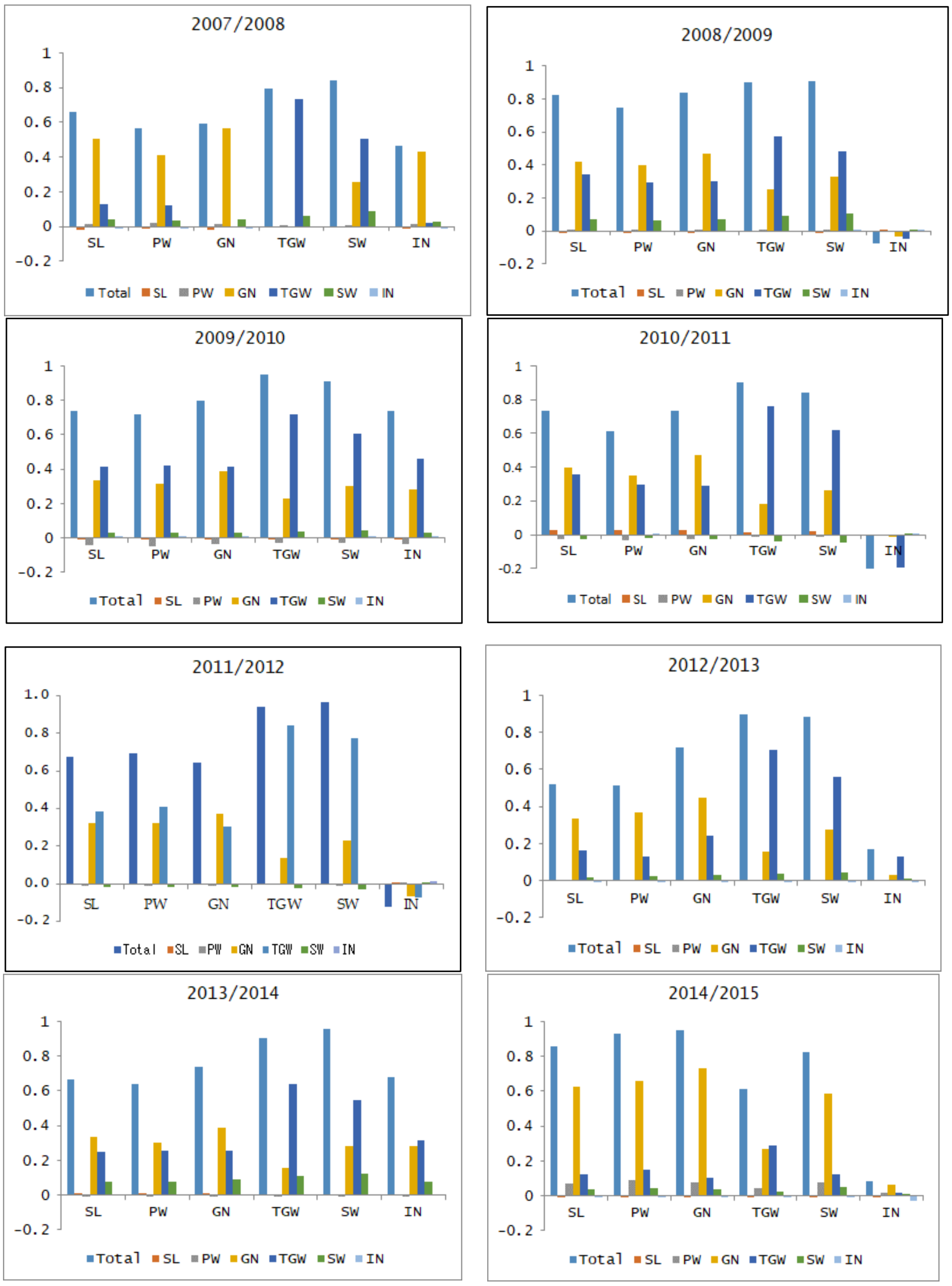


Figure 6. Interrelation of biometrical parameters of yield.

An interesting observation was also the fact that although in many scientific studies the yield parameters are negatively correlated with yield, our studies revealed interesting relations among yield parameters and yield.

The analysis of Wright's paths proved that although TGW was arithmetically inversely proportional to GN, the results indicate that both parameters of yield had a strong positive effect on yielding and they were mainly direct impact themselves; however, they had low correlation with each other.

3.4. Association between Biometric Parameters and Yield of Winter Wheat and Meteorological Parameters

The backward multiple regression models quantified the dependence of the basic biometric parameters of winter wheat on meteorological parameters (Table 5). The paper presents only those equations in which the independent variables, e.g., air temperature (t), sum (P), and distribution (NdP) of precipitation had a statistically significant influence on a given biometric treats and were qualified for the model in the back regression procedure. On the basis of the obtained models, we gained information at which growth stages (1–4) and the meteorological parameters had a statistically significant impact on given dependent variables and whether it was a positive (+) or negative (−) effect.

Table 5. Relationships linking biometric parameters of winter wheat and yield elements with selected meteorological parameters.

Dependent Variable	Regression Equation	Determination Coefficient R^2	F Statistic	Probability *p*
Spike length (SL)	Y = 0.19·t (3) + 0.01·P (4) + 5.56	0.80	25.97	0.00003
Straw weight (SW)	Y = −0.09·t (2) − 0.114·t (4) − 0.001·P (4) + 3.32	0.89	37.05	0.00000
Plant weight (PW)	Y = −0.16·t (2) + 2.64	0.40	5.84	0.02186
Grain weight (GW)	Y = −0.016·t (2) + 1.16	0.68	26.52	0.00001
1000-grain weight (TGW)	Y = −0.013·NdP (2) + 54.25	0.43	6.85	0.01377
Yield (dt)	Y = 0.27·PDH − 57.18	0.69	27.51	0.000012

Independent variables: t (1, 2, 3, 4)—average temperature in respective development periods; P (1, 2, 3, 4)—precipitation total in respective development periods; NdP(1, 2, 3, 4)—number of days with precipitation in respective development periods; PDH—plant density at harvest.

Spike length was 80% dependent on air temperature in the vegetative growth period t (3) and the precipitation total in the generative growth period P (4). Both elements of the model positively influenced spike length (the higher the temperature in the vegetative growth period and the precipitation total in the generative growth period, the longer the spike).

Straw weight was 89% determined by temperature in the dormancy period t (2) and by the temperature t (4) and precipitation total P (4) in the generative growth period. This means that the higher the temperature in the dormancy period and the temperature and precipitation total in the generative growth period, the lower the straw weight.

Plant weight and grain weight were 40% and 68% determined by negative dependencies on temperature t (2) during the dormancy period. This means that the higher the temperature in the dormancy period, the lower were the plant weight and grain weight.

The 1000-grain weight was 43% described by the regression model in which the lower the frequency of precipitation NdP (2) during the dormancy period (2), the higher the 1000-grain weight (TGW). The yield of winter wheat was 69% dependent on plant density at harvest: the higher the density, the higher the final yield.

4. Discussion

Rising temperatures are the determinant of the predicted negative effect of climate, i.e., a reduction in the growing period and yield of wheat [27,28]. However, only a detailed data analysis can show whether the negative effect of temperature on wheat yield is in fact the result of multiple environmental components or whether it is possible to identify the effect of a configuration of factors which significantly affect crop productivity in a given period. In this study, an attempt was made to determine the effect of weather on wheat development and to specify which meteorological factors determine the course of the development stages and morphological traits of wheat plants in eight growing seasons (2007–2015). During the seasons analysed, only a few biometric parameters, including grain number and TGW, were significantly affected by the air temperature and number of days with precipitation in the period up to the onset of dormancy. Grain number was found to be positively correlated with the number of days with precipitation and negatively with temperature. Low temperatures during this period reduced the number of grains formed per spike. The results are supported by research by Klimek-Kopyra et al. [29] and Zając et al. [30], who showed that the grain number per unit area is determined by environmental factors occurring throughout wheat growth and development. Low temperatures during winter dormancy were of greater importance for biometric parameters of plants in comparison with other stages. Low temperature was shown to cause a significant reduction in plant weight, grain weight, and straw weight. A lack or low frequency of precipitation and low temperatures in the period from the start of growth to mowing negatively affected spike length. The air temperature during dormancy was above freezing only in 2014, causing a significant increase in plant density, which resulted in higher yields. We showed that final plant density was primarily determined by the frequency of precipitation during dormancy and vegetative growth. The regression model confirms that it was 52% dependent on the number of days with precipitation during the stage from the start of vegetative growth to the flowering stage. Dreccer et al. [31] reported that the maximum number of stems per plant was positively correlated with the relative growth rate of the plants, the relative leaf appearance rate, the final leaf number (as previously shown by Kirby et al. [32] and Zając et al. [33]), and the rate and duration of tillering. Sadras and Slafer [34], defining the hierarchy of the phenotypic plasticity and heritability of traits, showed that the median for heritability of tiller number was the lowest (0.31), in comparison to spike number, grain number per spike, and kernel size, while the phenotypic plasticity of tillering (tiller number) was the highest. This means that the number of stems per plant is a highly variable trait with low heritability.

Among the biometric parameters analysed, increasing focus is placed on plant height as a significant determinant of yield and a trait that is easily determined in field conditions using new plant phenotyping techniques [18,34,35]. Kronenberg et al. [18] showed a significant correlation between plant height and temperature ($r = 0.85$). The authors established that among all components, the response to temperature was a significant factor influencing plant height during the stem elongation stage. High temperature delayed the onset of the stem elongation stage in wheat plants and modified its duration in comparison with genotypes responding less to temperature. Slafer and Rawson [36] showed that wheat genotypes have varied responses to temperature increases during development. According to the authors, accelerated plant development up to the flowering stage is correlated with a temperature increase up to 19 °C, whereas higher temperatures slowed down their development. Our study partially confirmed these findings and significantly elaborated on them. We showed that stem growth depends on temperature and on the number of days with precipitation during a given stage of development. Temperature significantly affects the growth rate of plants throughout its growing period, particularly in periods 1 (from sowing to dormancy) and 3 (from the start of spring growth to flowering).

Throughout the growing season, the number of days with precipitation is of more importance than the precipitation total in determining TGW. We showed that TGW was positively correlated with the precipitation total during autumn development ($r = 0.38$), during winter dormancy ($r = -0.49$), and during the generative development of plants ($r = 0.45$).

5. Conclusions

The rate of growth and development of plants is dependent on the temperatures during the 'autumn' period. Plants developed fastest at 9.0 °C, remaining in the tillering stage for a long time, while the period of winter dormancy was short, lasting about 93 days.

During the period from the onset of vegetative growth to the flowering stage, plants for which the average temperature was about 8–9 °C and the number of days with precipitation was about 41 were the most advanced in their growth and development.

Stem density before harvest, resulting from tillering efficiency, is determined by precipitation levels; the highest stem number, on average 540 per plant, was noted in conditions of 25–60 mm of precipitation and 30–40 days with precipitation.

The development of the spike of the main stem was closely synchronised with the development stage of plants; plants that began the vernalisation process sooner (due to a shorter first development period) formed shorter spikes (8.4 cm), while a later onset of vernalisation (2010/2011 vs. 2009/2010) resulted in longer spikes (9.6 cm) and a larger number of grains of greater weight.

Grain yield was determined by the precipitation total during the period from sowing to the onset of dormancy (r = 0.37) and was 69% dependent on the plant density at harvest.

Positive correlations between NdP and TGW were noted in the period from sowing to the onset of dormancy (r = 0.38) and the generative development period (r = 0.45), as well as a negative correlation during the dormancy period (r = −0.49). This finding proves that periods from sowing to the onset of dormancy and the generative development period are the most important for yield formation.

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Abbreviations

Dedicated to Plant Development

ΔL	increase in length [cm]
IN	internode number [№]
SL	spike length [cm]
GN	grain number [№]
PW	plant weight [g/plant]
GW	grain weight [g]
SW	straw weight [g]
PDH	plant density at harvest [№/m^2]
TGW	1000-grain weight [g]
(1)	the period from sowing until the onset of autumn dormancy, i.e., after three consecutive days of temperatures < 3°C, which is the threshold temperature for wheat
(2)	dormancy period was defined as the period from the onset of dormancy (average temperature < 3 °C) to the start of spring growth (average temperature ≥ 3 °C)

(3)	the vegetative growth period/the period from the start of spring growth to the end of intercalary growth (the date of full flowering was used), i.e., the end of vegetative growth
(4)	the generative growth period/the period from the end of vegetative growth to the day of harvest
D	length of period from sowing to harvest [№]
D (1)	length of period from sowing to onset of dormancy [№]
D (2)	length of dormancy period [№]
D (3)	length of vegetative growth period (when plant growth was measured) [№]
D (4)	length of generative growth period [№]
Dedicated to Meteorological Parameters	
P (1–4)	precipitation total during a given period
T (1–4)	average temperature during a given period
NdP (1–4)	number of days with precipitation during a given period [№]

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