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The effect of meteorological conditions on the course of development stages and yield of winter wheat in southern Poland

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Abstract: Yield and the course of crop vegetation are the result of the interaction between the level of cultivation technology and the course of meteorological conditions, which are a variable production factor. The aim of the study was to quantify the effect of meteorological conditions on the course of development stages and yield of winter wheat cultivated in two technological variants (A1 – medium-intensive and A2 – intensive). The paper uses data on yield and timing of winter wheat development stages from four Experimental Stations for Variety Testing (Pol. Centralny Ośrodek Badania Odmian Roślin Uprawnych – COBORU) experimental stations from 2007–2016 located within the Upper Vistula and Upper Oder River basins. To determine the dependence of the length of development stages of winter wheat on the values of selected meteorological elements, the linear regression metod, correlation coefficient. It was found that the lengths of the selected developmental stages are positively correlated with air temperature and negatively correlated with the sum and number of days with precipitation in these stages. A 1°C increase in air temperature resulted in a shortening of the shooting – heading and heading – full maturity periods by 2.5 and 2.8 days respectively. An increase of 100 mm of precipitation in the periods sowing – full maturity and heading – full maturity resulted in an increase of these periods by 5 and 10 days. Increasing the number of days with precipitation by 10 days in the sowing – full maturity and heading – vax maturity stages resulted in extending these stages by 4.1 to 4.4 and 7 to 7.5 days for the A1 and A2 cropping technologies, respectively.

Keywords: crops, length of phenophases, number of days with precipitation, precipitation, temperature, wheat

INTRODUCTION

There is growing evidence of negative impacts of observed climate change on crop yields, crop quality and food security prospects at a global scale (e.g., Newton, Johnson and Gregory, (2011), Challinor *et al.* (2014), Ray *et al.* (2019)]. A study by Wing, Cian De and Mistry (2021), which examined the risk to global crop yields from climate warming with projections constructed using an ensemble of 21 climate model simulations, suggests that under strong warming, climate change could reduce global crop yields by 3 to 12% by mid-century and by 11 to 25% by the end of the century. Variability in weather elements determines conditions for plant growth and development, triggering genotype-environment interactions in plants (Kołodziej and Kulig, 2007; Weber *et al*., 2011; Jadczyszyn and Bartosiewicz, 2020). The course and length of phenophases and crop yields are influenced by rainfall and temperature variability, as well as by photoperiodism, i.e. the response of plants to the length of the day (long-day or photoperiodically indifferent varieties) (Dubcovsky *et al*., 2006).

Poland is located in the zone of temperate transitional climate, which is characterised by high variability of meteorological conditions (temperature and precipitation) (Wójcik and Miętus, 2014; Ziernicka-Wojtaszek, 2020). In recent decades, there has been an increase in the number of days with low precipitation and a decrease in the number of days with higher precipitation (>10 mm) and stable annual precipitation totals with an increasing temperature trend (Skowera, Kopcińska and Bokwa, 2016; Ziernicka-Wojtaszek and Kopcińska, 2020). The climate changes observed in Poland in recent decades are manifested by an increase in the average annual temperature of about 0.3°C per 10 years, against the background of a global temperature increase at a rate of 0.2°C per 10 years (IPCC, 2007). The effect of these changes is the observed and projected changes in sowing and harvesting dates, as well as crop yields (Kołodziej and Kulig, 2007; Weber *et al*., 2011, Jadczyszyn and Bartosiewicz, 2020).

Yield and the course of crop vegetation are the result of the interaction between the level of cultivation technology and the course of meteorological conditions, which are variable production factors (Kołodziejczyk, Szmigiel and Kulig, 2009). Common wheat is one of the most important crops. Its global area is about 215.9 mln ha (Global…, 2021/2022; FAO STAT, no date). In Poland, more than approximately 2 mln ha of winter wheat are grown (GUS, 2022). Fluctuations in winter wheat yields are most often caused by variability in meteorological conditions, especially the amount and frequency of precipitation during the growing season, and to a lesser extent by extreme temperatures. Among the meteorological elements, precipitation is subject to the greatest fluctuations and shows positive correlations with the length of developmental stages of winter wheat in the period from the beginning of vegetation to flowering (Galant and Andruszczak, 2004). The main period of water demand for winter wheat is during the shooting and earing stages and slightly less during grain formation and filling. In Poland, these periods are between the end of April and middle of July (Podolska, 2018). The first, direct source of water for plants in field conditions is their resources in the soil; the second, indirect source is precipitation. For 1 tonne of grain with an adequate amount of straw, wheat uses about 30 mm of water. During the winter dormancy period, the optimum rainfall is 10 mm per decade. After the resumption of vegetation, the water requirement varies from 195–230 mm of precipitation depending on the soil type (Kaczmarczyk and Nowak, 2006). An important and variable element of the environment is climate which determines the course and length of phenophases and plant yield. Ye *et al*. (2020), Xiao and Tao (2014) showed a shift in the timing of the occurrence and duration of phenophases of winter wheat in response to increasing temperatures, which is most often manifested by a shortening of the flowering and maturation period of this species. However, the length of the entire vegetation cycle is rather stabilised. Yue, Zhang and Shang (2019) showed that a 1°C increase in temperature during the growing season results in a 3–10% reduction in yield. An increase in temperature with low precipitation results in a shortening of the developmental phases of plants especially at the generative stage; from stem elongation/shooting to stem maturity (Kanapickas *et al*., 2022).

The research hypothesis is that not only contemporary climate change, but also the level of intensity of cultivation technology influences the yield and the timing of developmental stages in cereals. Therefore, the aim of the study was to quantify the effect of meteorological conditions on the timing and length of development phases and yield of winter wheat grown in two technological variants (A1 – medium-intensive and A2 – intensive) in the Upper Vistula and Upper Oder River basins (southern Poland) in the period 2007–2016.

STUDY MATERIALS AND METHODS

In this study, we used data on yield and timing of developmental stages of winter wheat (*Triticum aestivum ssp. vulgare*) from the period 2007–2016 from four Experimental Stations for Variety Testing (Pol. Centralny Ośrodek Badania Odmian Roślin Uprawnych – COBORU): Słupia Jędrzejowska, Węgrzce, Pawłowice and Przecław. These stations were selected for their location within the Upper Vistula and Upper Oder River basins and for their altitude below 300 m a.s.l. (Fig. 1).

These stations were selected for their location in the Upper Vistula and Upper Oder River basins and for their altitude below 300 m a.s.l. Elevation data come from the European Digital Elevation Model (EU-DEM), which is part of the European Union's Copernicus Land Monitoring Service. Data on voivodship boundaries and river basins have been downloaded according to the "Public data opening programme" of the Polish Ministry of Digital Affairs (Pol. Ministerstwo Cyfryzacji).

According to the climatic norm 1991–2020, provided by the Institute of Meteorology and Water Management – PIB (Pol. Instytut Meteorologii i Gospodarki Wodnej – IMGW-PIB), the annual air temperature in the area was in the range of 8 to 9°C, in winter 0 to −2°C, in summer the average temperature was 18–19°C. Precipitation was relatively high here compared to the Central Polish Lowlands. Annual precipitation averaged 600–700 mm, in autumn about 160 mm, in winter about 100 mm, while from the beginning of the meteorological growing season until the end of July, i.e. reaching full maturity of the wheat, average precipitation amounts to 320–360 mm.

The research was conducted for two winter wheat cultivation variants; medium-intensive A1 and intensive A2. The A2 level was characterised by 40 kg higher nitrogen fertilisation compared to A1 (100–120 at A1 and 140–160 kg N·ha^{-1} at A2). Phosphorus and potassium fertilisation was the same at 60 and 90 kg P_2O_5 and K_2O, herbicides and insecticides were used at A1 sites and herbicides, insecticides and fungicides were used at A2 sites. The sowing date at the stations in question fell within the optimal date for these locations, i.e. between September 23 and October 8, while harvesting took place between July 20 and August 10. The occurrence of the other periods is presented in the results chapter.

Based on the data collected, the length of the main interphases of winter wheat was determined. These were the following periods: sowing – emergence, emergence – tillering A1, A2, stem shooting – heading A1, A2; heading – wax maturity A1,

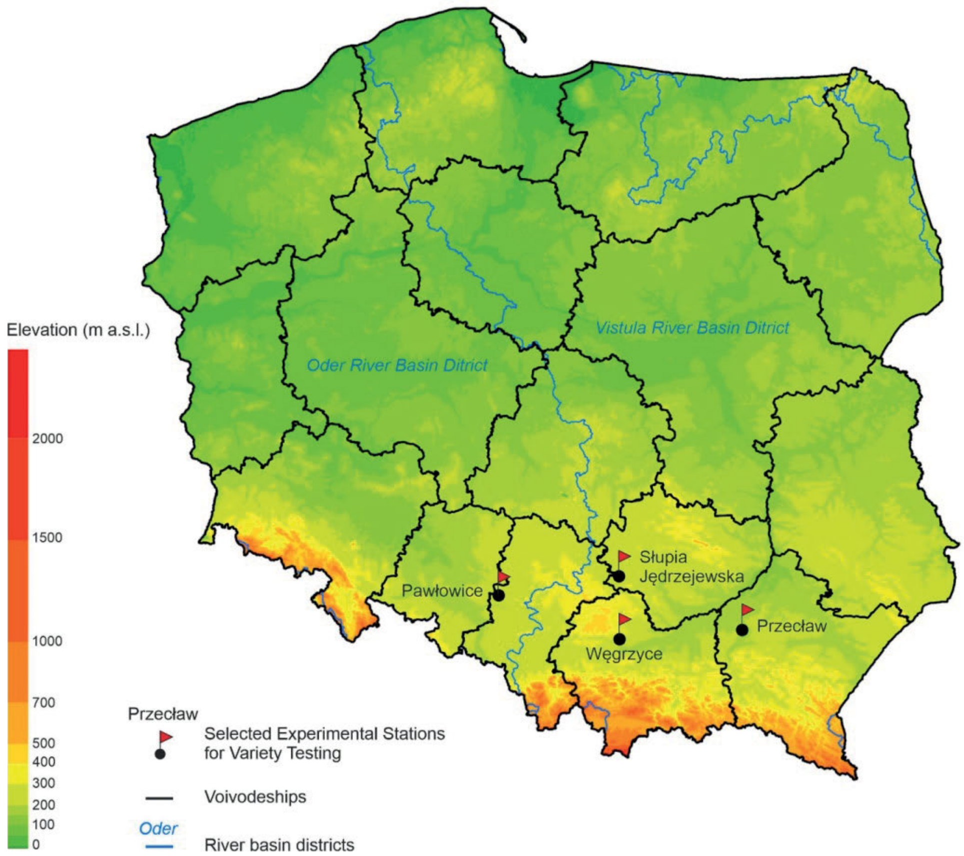

Fig. 1. Location of selected Experimental Stations for Variety Testing; source: own elaboration

A2; heading – full maturity A1, A2; sowing – full maturity A1, A2. The average air temperature, total precipitation and number of days with precipitation were then calculated for each period. Meteorological data for the analysed Experimental Stations for Variety Testing were obtained from the Prediction of Worldwide Energy Resource (POWER) Project (no date) via the Data Access Viewer. The meteorological parameters provided by the POWER project are based on NASA Goddard's Global Modeling and Assimilation Office (GMAO) (NASA LaRC, no date) assimilation model, the Modern Era Retrospective-Analysis for Research and Applications (MERRA-2) (Gelaro *et al.*, 2017).

Statistical tools, i.e. the linear regression method of the, the r-Pearson correlation coefficient, were used to determine the dependence of the length of development periods of winter wheat grown in two technological variants on the values of selected meteorological elements.

The results of statistically significant dependences ($p \leq 0.05$) are presented in the paper. Box-and-whisker plots show the mean values and range of selected traits, i.e. yield for two technological levels (A1 and A2), locations and years, length of developmental stages (*LDS*), and values of mean temperature (T), total precipitation (P) and number of days with precipitation (Ndp) in selected developmental periods. The non-parametric Kruskall–Wallis test (KW-H) was used to statistically assess the variation in air temperature, precipitation and the number of days with precipitation in the heading – full maturity stage of winter wheat.

In order to determine the total, indirect and direct effect of meteorological parameters on the length of development periods, Wright's path analysis was used, which is a certain extension of regression analysis (Gozdowski, Martyniak and Mądry, 2008; Wójcik, Kuriata and Lewandowska, 2012). While simple regression analysis only examines direct relationships between the dependent variable, e.g. y, and the independent variables x_1, ..., x_n, path analysis additionally takes into account the so-called indirect interactions of these variables. Indirect interactions also result from the interdependence between each other, i.e. between the independent variables x_1, ..., x_n. The essence of this method is to decompose the correlation coefficients into direct and indirect effects through other variables for each of the independent variables (Eq. 1):

$$\begin{array}{c} r_{y1} = p_1 r_{1,1} + p_2 r_{1,2} + \ldots + p_n r_{1,n} \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ r_{yn} = p_1 r_{n,1} + p_2 r_{n,2} + \ldots + p_n r_{n,n} \end{array} \tag{1}$$

where: r_{yi} – the correlation coefficient between the variable y and the variable x_i, i.e. the total influence of the variable x_i on the dependent variable y (the length of the interphase studied), while $r_{i,j}$ – the correlation coefficient between the independent variables i, j i.e. the strength of the interactions between the variables x_i and x_j (our meteorological parameters). By solving the above system of equations due to p_i, we determine the direct and indirect interactions through each of the structural variables.

RESULTS AND DISCUSSION

In the Upper Vistula and Upper Oder River basins, meteorological conditions in 2007–2016 (Tab. 1), were similar to the climatic requirements of winter wheat given by Podolska (2018), but differed significantly in subsequent years (Fig. 2b, d, f). In the shooting – heading period, the highest air temperature occurred in Słupia Jędrzejowska (13.7°C) and the lowest in Węgrzce (12.6°C), while the highest temperature in this period occurred in 2012 (15.3°C) and the lowest in 2016 (11.9°C) (Tab. 1, Fig. 2a, b). For precipitation totals, the highest totals and number of days with precipitation occurred in Węgrzce (612 mm and 121 days) and the lowest in Pawłowice (567 mm and 115 days), while the highest precipitation totals and number of days with precipitation were observed in 2011 and the lowest in 2015. Detailed data for the development stages are presented in (Tab. 1, Fig. 2c–f).

The duration of one of the main development phases (heading – full maturity) is shown in Figure 3a; it ranged from 58 days in variants A1 and A2 in Przecław to 67 days in variant A1 in Pawłowice. No significant differences in the duration of this period were found in the study area (Fig. 3a). On the other hand, in successive seasons of the study period (2007–2016), the duration of this interphase differed significantly, being the shortest in 2016; it was 52 days, while the longest in 2011; it was 72 and 73 days in technology variants A1 and A2, respectively (Fig. 3b), which was confirmed by the results of the non-parametric Kruskall–Wallis test.

The results of the Kruskall–Wallis test, regression analysis and Wright's path analysis in the Upper Vistula and Upper Oder River basins during the decade under study showed significant, year-to-year variation in the influence of weather elements on the course of development periods (Tab. 2, 3 and Figs. 2a–f, 3) and winter wheat yield (Tab. 4, and Fig. 4a, b).

In the regression analysis presented here, the dependent variable was the length of development stages and the independent variables were mean air temperature, total precipitation and number of days with precipitation in the respective period. The highest, statistically significant correlation coefficients were obtained for the stages: sowing – full maturity, stem shooting – heading, heading – wax maturity and heading – full maturity (Tab. 2). Table 2 shows the linear regression equations for the significant relationships.

On the basis of the obtained relationships, it was found that the average air temperature significantly affected the duration of the interphases of stem shooting – wax maturity. On the basis of the correlations obtained, it was found that an increase of 1°C in air temperature resulted in a shortening of the stags of stem shooting – heading – full maturity from –2.54 to –2.84 days on average. Slightly stronger relationships were obtained for the A1, i.e. medium-intensive technological variant (r –0.551 and –0.493) respectively (Tab. 2). Similar results were obtained by Dížková *et al.* (2022) in the Czech Republic. They showed earlier occurrence of development phases of winter wheat and correlation with air temperature. In the case of the dependence of the length of development stages on the sum of precipitation and the number of days with precipitation in these periods, these parameters result in longer interphases. Similar results were obtained by Kanapickas *et al.* (2022) in Lithuania. They found that there was a shortening of the developmental phases of stem shooting and earing and a negative correlation between the length of the stage of stem shooting and grain formation with mean May temperature, and a positive correlation from stem shooting to grain formation.

A stronger correlation with rainfall compared to temperature was observed for both interphase length (from $r = +0.552$ to $r = +0.771$) and number of days with precipitation (from $r = +0.387$ to $r = +0.813$). According to the study, precipitation amount had a greater effect on developmental stage duration, with an average extension of 0.5 to 1.0 days per 10 mm and 4.1 to 7.5 per 10 days with precipitation. Significant correlations occurred in the stages: stem shooting – heading A1, heading – full maturity A1 and A2, and sowing – full maturity A1 and A2.

Table 1. Average values of air temperature (T, °C), total precipitation (P, mm) and number of days with precipitation (Ndp, day) and length of development stages (LDS) of winter wheat grown at Experimental Stations for Variety Testing (2007–2016)

Development stage	Experimental Stations for Variety Testing															
	Pawłowice				Węgrzce				Słupia Jędrzejowska				Przecław			
	T	*P*	*Ndp*	*LDS*	*T*	*P*	*Ndp*	*LDS*	*T*	*P*	*Ndp*	*LDS*	*T*	*P*	*Ndp*	*LDS*
Sowing[1)]	–	–	–	275	–	–	–	277	–	–	–	271	–	–	–	274
Sowing – emergence	11.5	18	4	15	11.2	27	4	13	12.4	23	5	16	11.5	30	5	16
Emergence – tillering	11.5	78	12	39	6.2	95	20	47	4.8	59	12	46	8.5	83	18	40
Stem shooting – heading A1	13.0	91	15	37	12.6	102	15	32	13.7	86	13	31	13.5	96	16	34
Stem shooting – heading A2	13.2	101	17	40	12.7	106	16	33	13.8	87	14	32	13.7	97	16	35
Heading – vax maturity A1	18.5	129	19	45	17.9	146	25	49	18.3	124	22	44	18.8	128	22	44
Heading – vax maturity A2	18.6	130	18	44	18.0	143	26	49	18.4	125	23	45	18.9	135	23	45
Heading – full maturity A1	19.0	194	33	67	18.2	201	34	66	18.7	174	30	61	19.0	186	30	59
Heading – full maturity A2	19.2	187	32	65	18.3	196	34	65	18.7	174	30	61	19.1	190	31	59
Sowing – full maturity A1	8.4	567	115	304	7.9	612	121	300	8.1	570	115	305	8.1	573	116	298
Sowing – full maturity A2	8.5	567	115	304	7.9	612	121	300	8.1	572	116	306	8.2	578	117	298

[1)] Day of the year.
Explanations: A1 = medium-intensive, A2 = intensive.
Source: own study.

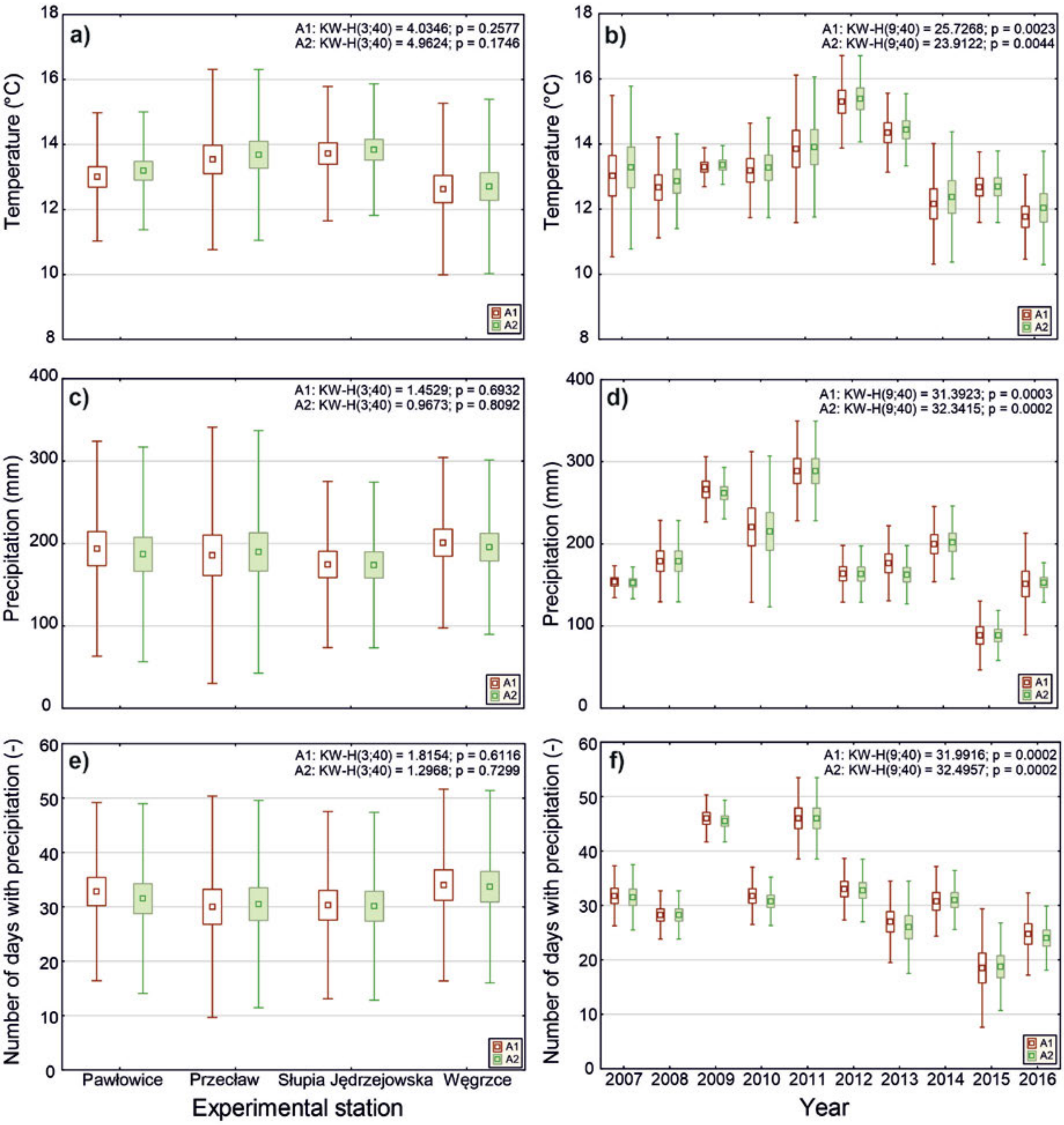

Fig. 2. Mean values of temperature (*T*), total precipitation (*P*) and number of days with precipitation (*Ndp*) at the one of main developmental stages of winter wheat (stage of heading – full maturity) in two technological variants (A1 = medium-intensive and A2 = intensive): a), c), e) at the experimental stations; b), d), f) in 2007–2016; KW-H = Kruskall–Wallis test, p = probability ($p > 0.05$ not statistically significant, $p \le 0.05$ statistical significance); source: own study

A significant relationship with the number of days with precipitation in the case of stem shooting – flowering stage A1 and A2 (Tab. 2) was also found. The strongest effect of the precipitation and the number of days with precipitation on the length of the developmental stage of heading – full maturity A1 (*r*: +0.764, +0.805) and A2 (*r*: +0,771, +0.813) was observed, with a stronger effect found at the intensive level (A2) (Tab. 2). According to the results of the simple regression analysis, the shooting-heading interphase length showed the strongest correlation with temperature (*T*), with correlations of –0.551 (A1) and –0.538 (A2). While the length of the head-to-full maturity interphase showed a correlation with both the total amount of rainfall (*P*) and the number of days with precipitation (*Ndp*); *P*: +0.764, +0.771, *Ndp*: +0.805, +0.813 respectively for A1 and A2 level (Tab. 2).

Based on the regression analysis, it was found that an increase of 10 mm in precipitation in the stages of earing – wax maturity, earing – full maturity and sowing – full maturity caused these periods to be prolonged by 0.5 and 1.0 days (for the latter), respectively. An increase of 10 days in the number of precipitation in these periods resulted in an increase of 2.6 to 2.8) and 7 to 7.5 days for A1 and A2 cropping technologies, respectively (Tab. 2). In our study, it was observed that all the studied traits, i.e. lengths of development stages and yields in the two technology variants (A1, A2) differed statistically significantly

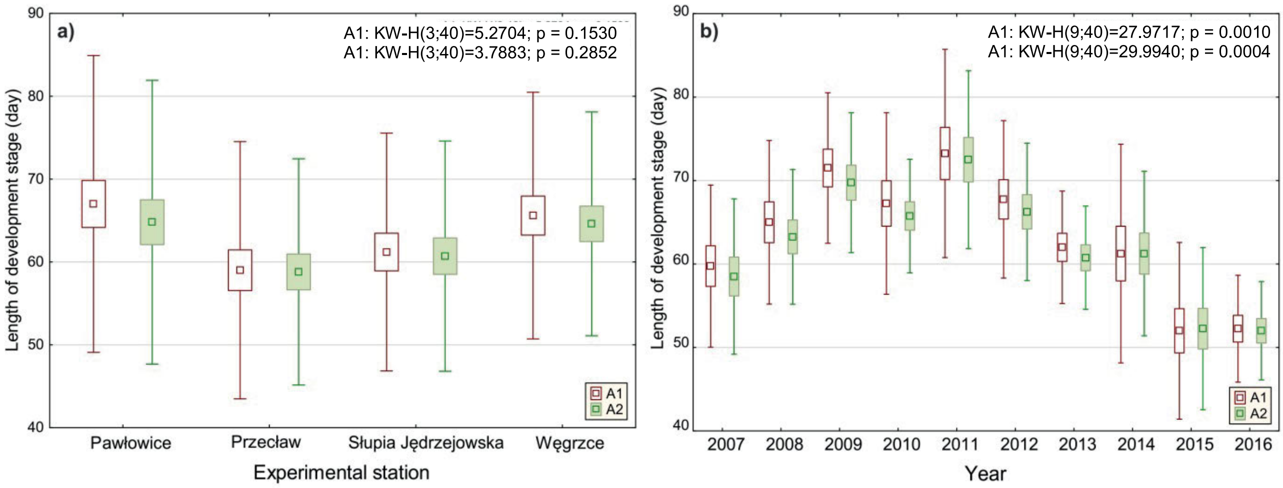

Fig. 3. Mean length of the development stage (*LDS*) of heading–full maturity of winter wheat in the Upper Vistula and Upper Oder River basins in two technological variants (A1, A2): a) in the experimental stations, b) in 2007–2016; A1, A2, KW-H, *p* as in Fig. 2; source: own study

Table 2. Dependence of length of development stages (Y) of winter wheat grown in two technological variants (A1, A2) on the values of selected weather elements

Development stage	Regression equation	*r*	*F* (1.38)	*p*<	Range of significance
Dependence of the length of the development stages (Y) of winter wheat on air temperature (T)					T (°C)
Stem shooting – heading A1	$Y = -2.700T + 69.246$	–0.551	16.588	0.00023	10.9–16.3
Stem shooting – heading A2	$Y = -2.838T + 72.880$	–0.538	15.441	0.00035	11.0–16.3
Heading – vax maturity A1	$Y = -2.542T + 92.057$	–0.493	12.188	0.00124	16.2–20.2
Heading – vax maturity A2	$Y = -2.742T + 96.223$	–0.474	10.988	0.00202	16.5–20.2
Heading – full maturity A1, A2	no statistically significant relationship				
Sowing – full maturity A1, A2					
Dependence of the length of the development stages (Y) of winter wheat on the total precipitation (P)					P (mm)
Stem shooting – heading A1, A2	no statistically significant relationship				
Heading – vax maturity A1	$Y = 0.082P + 34.580$	0.716	39.963	0.00000	45–226
Heading – vax maturity A2	$Y = 0.088P + 33.890$	0.762	52.731	0.00000	45–243
Heading – full maturity A1	$Y = 0.104P + 43.630$	0.764	53.164	0.00000	71–316
Heading – full maturity A2	$Y = 0.097P + 44.049$	0.771	55.956	0.00000	71–316
Sowing – full maturity A1	$Y = 0.050P + 272.792$	0.568	18.056	0.00013	402–901
Sowing – full maturity A2	$Y = 0.046P + 275.194$	0.552	16.699	0.00022	402–901
Dependence of the length of the development stages (Y) of winter wheat on the number of days with precipitation (Ndp)					Ndp (day)
Stem shooting – heading A1	$Y = 0.434Ndp + 27.101$	0.460	10.173	0.00285	8–32
Stem shooting – heading A2	$Y = 0.449Ndp + 27.971$	0.479	11.328	0.00176	8–32
Heading – vax maturity A1	$Y = 0.258Ndp + 39.660$	0.387	6.728	0.01340	0–41
Heading – vax maturity A2	$Y = 0.284Ndp + 39.284$	0.419	8.115	0.00705	0–41
Heading – full maturity A1	$Y = 0.754Ndp + 39.236$	0.805	70.101	0.00000	11–50
Heading – full maturity A2	$Y = 0.699Ndp + 40.248$	0.813	73.909	0.00000	13–50
Sowing – full maturity A1	$Y = 0.440Ndp + 250.362$	0.690	34.534	0.00000	80–151
Sowing – full maturity A2	$Y = 0.411Ndp + 253.990$	0.669	30.743	0.00000	82–151

Explanations: r = correlation coefficient, F = Fisher's statistic, p = probability, Y = length of the development stages, T = average air temperature at a given stage, P = total precipitation at a given development stage, Ndp = number of days with precipitation >0.1 mm at a given stage, A1, A2 as in Tab. 2.
Source: own study.

Table 3. Interrelation of the length of selected development stages of winter wheat (*LDS*) with meteorological parameters (*T*, *P*, *Ndp*)

Parameter	Medium-intensive variant A1				Intensive variant A2			
	total	*T*	*P*	*Ndp*	total	*T*	*P*	*Ndp*
	Shooting – heading stage							
T	–0.56	–0.36	0.14	–0.34	–0.54	–0.32	0.20	–0.42
P	0.24	0.06	–0.91	1.00	0.24	0.06	–1.08	1.26
Ndp	0.46	0.10	–0.84	1.20	0.48	0.10	–0.99	1.37
	Heading – wax maturity stage							
T	–0.49	–0.20	–0.40	0.11	–0.48	–0.10	–0.41	0.03
P	0.72	0.10	0.80	–0.18	0.76	0.05	0.75	–0.04
Ndp	0.39	0.08	0.56	–0.25	0.42	0.04	0.45	–0.07

Explanations: *T*, *P*, *Ndp* as in Tab. 2.
Source: own study.

Table 4. Dependence of the yield of winter wheat (*Y*) grown in two technological variants (A1, A2) on the values of selected weather elements

Development stage	Regression equation	*r*	*F* (1.38)	*p*<	Range of significance
Dependence of winter wheat yield (*Y*) to air temperature (*T*)					no statistically significant relationship
Dependence of the yield of winter wheat (*Y*) on total precipitation (*P*)					*P* (mm)
Shooting – heading A1	$Y = -0.007P + 8.856$	–0.330	4.636	0.0377	30–313
Shooting – heading A2	no statistically significant relationship				
Heading – vax maturity A1, A2					
Heading – full maturity A1, A2					
Sowing – full maturity A1	$Y = -0.005P + 11.035$	–0.446	9.422	0.00394	402–901
Sowing – full maturity A2	$Y = -0.005P + 12.064$	–0.435	8.867	0.00503	402–901
Dependence of the yield of winter wheat (*Y*) on number of days with precipitation (*Ndp*)					*Ndp* (day)
Sowing – heading A1	$Y = -0.064Ndp + 9.184$	–0.316	4.208	0.04717	8–32
Shooting – heading A2	no statistically significant relationship				
Heading – vax maturity A1, A2					
Heading – full maturity A1, A2					
Sowing – full maturity A1	$Y = -0.028Ndp + 11.477$	–0.353	5.412	0.02543	80–151
Sowing – full maturity A2	$Y = -0.028Ndp + 12.558$	–0.347	5.196	0.02834	82–151

Explanations: *r*, *F*, *p*, *Y*, *T*, *P*, *Ndp* as in Tab. 2.
Source: own study.

between years. This was due to the variation of the weather (meteorological parameters) in the different years of the study (Fig. 3). These results are consistent with those obtained by Węgrzyn *et al.* (2022).

Wright path analysis is used in genetics and agricultural sciences, for example, assess elements of yield structure on plant yield or gene–gene interactions (Gozdowski, Martyniak and Mądry, 2008; Wójcik, Kuriata and Lewandowska, 2012; Węrzyn *et al.*, 2022). To the authors' knowledge, Wright path analysis has so far not been used to assess the influence of meteorological elements on plant development. In our study, the influence of meteorological parameters (*T*, *P* and *Ndp*) on the length of the most important interphases, i.e. the shooting period – heading and heading – wax maturity stage, was assessed in more detail using this method. *T* was found to have a negative effect on the length of these periods (Tab. 2).

The total effect (A1 = –0.56, A2 = –0.54) and the direct effect of *T* on the length of the stem shooting stage are both negative (A1 = –0.36, A2 = –0.32). In the case of total precipitation, a comparable positive total effect was found in variants A1 and A2 (0.24) on the length of this interphase. The direct effect of *P* is strongly negative (A1 = –0.91, A2 = –1.08) but offset by a strongly positive (A1 = 1.00, A2 = 1.26) effect of *Ndp*. The different development of the direct and indirect effects of total precipitation and number of days with precipitation in the above-mentioned agrotechnical levels may be due to: higher

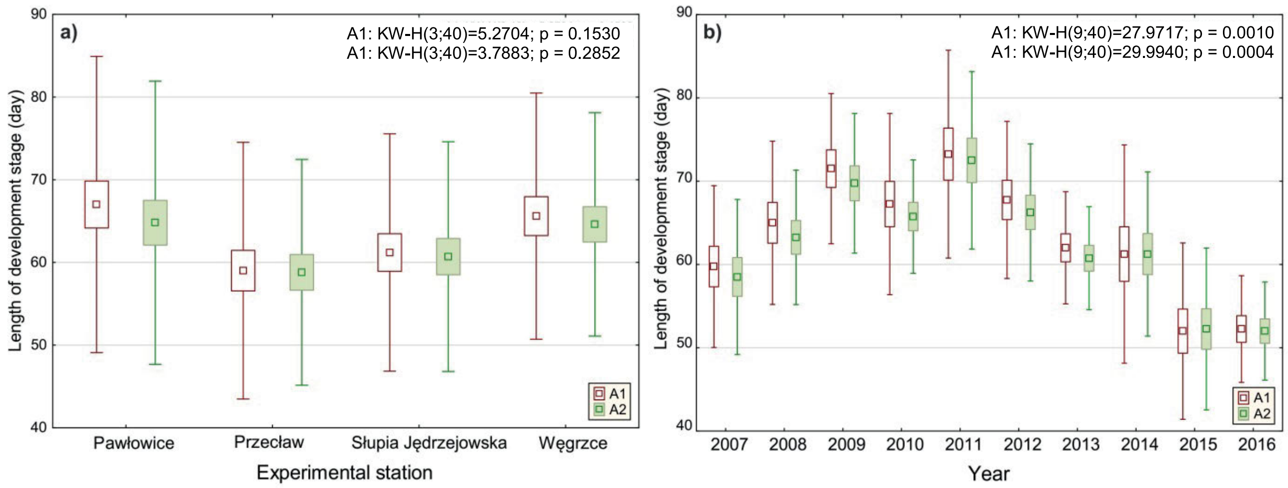

Fig. 4. The yield of winter wheat (t·ha^{-1}): a) at the experimental stations, b) in 2007–2016 in two technology variants (A1, A2); A1, A2, KW-H, *p* as in Fig. 2; source: own study

nitrogen fertilisation rate, use of antifungals and fungicide protection at A2 level. A different relationship appeared for the effect of *Ndp* on the length of the stem shooting – heading stage: the total effect of this parometer is positive, similar in both variants (A1 = 0.46, A2 = 0.48). However, it should be noted that the direct effect (A1 = 1.20, A2 = 1.37) of the parameter *Ndp* is much greater than the total effect, as it is compensated by the indirect negative effect of P (A1 = –0.84, A2 = –0.99) (Tab. 3).

In the analysis of the dependence of the length of the earing – wax maturity stage on meteorological factors, analogous dependences were found as in the case of the heading – wax maturity stage (Tab. 3). The *T* negatively influences the length of this period both through total and direct effect, but additionally has a negative effect through the sum of *P* in this stage. However, the interaction between total *P* and the number of *Ndp* is different. The effect of total precipitation sum is strongly positive, meaning that as precipitation sum increases, the length of the period increases. This relationship is confirmed by the direct effect of total precipitation on the length of this stage, which is even stronger but partly compensated by the negative indirect effect of the number of days with precipitation (Tab. 3). In the case of the number of days with precipitation, a positive total effect of this parameter was found (A1 = 0.39, A = 0.42) resulting in a prolongation of the heading – wax maturity stage. However, the direct effect of this parameter is weak, negative (A1 = –0.25, A2 = –0.07) but offset by a positive indirect effect of *P* (Tab. 3).

According to Weber *et al.* (2011), on light soils and at low fertilisation rates, yields decreased due to rainfall deficiency, whereas on compact soils and high fertilisation, the yield decrease was smaller and was related to excess rainfall. The dependence of wheat yield (A1, A2) on meteorological conditions, as well as on the length of the development periods of this crop, was assessed on the basis of correlations with mean values of air temperature, total precipitation and the number of days with precipitation.

In the A2 variant, the yield was more than 1 t·ha^{-1} higher than in the A1 variant, although this difference proved not statistically significant (Fig. 4a, b). In individual years, the higher technical level (A2) stabilised yields, while the medium–intensive cultivation level A1 made the effect of meteorological conditions on yield more apparent, as manifested by greater yield variability between years (Fig. 4b). On the basis of regression analysis (Tab. 4), the effect of air temperature on wheat yield turned out to be statistically insignificant in the analysed interphases, while a significant effect of precipitation (from r = –0.330 to –0.435) and number of days with precipitation was observed in the stages from stem shooting to earing only in the A1 variant (r = –0.316), and in the stage from sowing to full maturity in both cultivation variants (r = –0.353 and –0.347). In both cases, a slightly stronger effect of total precipitation on wheat yield was observed than the number of days with precipitation in the mentioned interphases (Tab. 4). A 10 mm increase in precipitation sum caused a yield decrease of 0.05 to 0.07 t·ha^{-1} in these phases, while an increase in the number of days with precipitation by 10 days reduced the yield from 0.28 to 0.64 t·ha^{-1} depending on the level of technology. Lower yield and higher yield variability are observed for weaker soils and unfavourable rainfall distribution (Weber *et al.*, 2011). Globally, temperature negatively affects cereal yields, and a 1°C increase in air temperature can reduce global average wheat yields by 6.0% (Zhao *et al.*, 2017). However, research results on the effects of meteorological parameters on winter wheat yield and development in different geographical regions are heterogeneous. The variability of winter wheat grain yield is dominantly influenced by weather extremes, causing stressful conditions at specific stages of plant development, limiting their yield potential (Martyniak and Kaczyński, 2002; Ziernicka-Wojtaszek and Zawora, 2005; Pirttioja *et al.*, 2015).

CONCLUSIONS

As a result of the study, it was found that in the years 2007–2016 in the Experimental Station for Variety Evaluation located in the area of the Upper Vistula and Upper Oder River basins there were favourable conditions for winter wheat cultivation. The average grain yield over the study period was high, at 8.2 t·ha^{-1} in the medium-intensive variant and at 9.3 t·ha^{-1} in the intensive variant. Wheat yields in the intensive and medium-intensive variants were negatively correlated with the sum of precipitation and the number of days with precipitation in the sowing – full maturity period, while in the medium-intensive variant also in the stem shooting – heading stage. An increase of 10 mm in total precipitation caused a decrease in yield of 0.05 to 0.07 t·ha^{-1} in these phases, while an increase in the number of days with precipitation by 10 days reduced the yield by 0.28 to 0.64 t·ha^{-1}.

The impact of meteorological conditions on the length of development periods of winter wheat varied. Air temperature had a significant, negative effect on the length in two periods; stem shooting – heading and earing – wax maturity, which means a shortening of the developmental period of winter wheat at a higher temperature. An increase of 1°C in air temperature resulted in a shortening of the stages stem shooting to earing and earing to full maturity by 2.54 and 2.84 days, respectively.

The effect of total precipitation and the number of days with precipitation is strongly positive, implying a lengthening of wheat development periods. As total precipitation increased, the length of the periods: earing – wax maturity, earing – full maturity and sowing – full maturity increased, with these parameters most strongly positively related to the length of the earing – full maturity period. An increase of 10 mm of precipitation in the periods sowing – full maturity and earing – full maturity resulted in the lengthening of these stages by 0.5 and 1.0 days, respectively. The number of days with precipitation also significantly influenced the lengthening of the shooting – heading period. Increasing the number of days with precipitation by 10 days in the stages sowing – full maturity and earing – wax maturity resulted in a lengthening of these periods by 4.1 to 4.4 and 7 to 7.5 days for the A1 and A2 cropping technologies, respectively.

The results obtained proved that a higher level of cultivation intensity increases and stabilises winter wheat yields, and thus wheat yields depend less on weather variability and justify higher costs mainly incurred for plant protection. The observed negative effect of temperature causing shortening of wheat interphase duration confirms the need for multidirectional research in the aspect of breeding new winter wheat varieties characterised by a lower tendency to shorten the generative development period. However, please take into consideration that the negative effect of temperature on shortening the interfacial time is not reflected in the production effects of wheat.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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