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DEPENDENCE OF THE CROP YIELDS OF MAIZE, WHEAT, BARLEY AND RYE ON TEMPERATURE AND PRECIPITATION IN HUNGARY

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Abstract: Temperature and precipitation are the most important meteorological variables influencing crop yields of cereals. In the paper we use and compare two procedures, namely Factor analysis with special transformation and multiple linear regression analysis with stepwise method in determining the influence of monthly mean temperatures and monthly precipitation amounts of April, May, June, July and August for determining the crop yields of maize, wheat, barley and rye. When comparing the results received on the two methods, those variables were retained that were concurrently significant for determining the crop yields for both cases. It is found that for maize yield the most important variables in decreasing order are August mean temperature with negative, as well as July and June precipitation amounts with positive association. For wheat yield, June and May mean temperatures, while for barley yield the same but in reverse order are the most important variables, all with negative relationship. Concerning rye yield, April precipitation amount with positive and June mean temperature with negative association are the decisive variables. Among the examined cereals, maize yield is the most sensitive to precipitation. The here-mentioned significant relationships may have a predictive power in projecting the actual crop yield.

Key words: climate change, environmental factors, agriculture, cereals, food consumption

1. INTRODUCTION

The global demand for food will increase for at least in the next 40 years (Nelson et al., 2014). Warming climate and increasing frequency of extreme meteorological events (Rosenzweig et al., 2002) transform the regional rates of food production serving an ever growing threat to food security (Rosenzweig et al., 2014; IPCC, 2019). Without adequate adaptation, increasing losses in aggregate production of wheat, rice and maize are expected in both temperate and tropical regions as warming increases (Challinor et al., 2014, Asseng et al., 2015). However, observed yields are function of not only environmental but social factors that largely vary by farm and region. At the same time, agricultural activities intensify warming of the climate when greenhouse gases (GHGs) are released, for example, due to rice production, keeping and breeding of cattles, furthermore land clearing (e.g. stubble burning), inappropriate use of fertilizers, and other practices that are harmful for the environment (Beddington et al., 2012; Nelson et al., 2014).

Climate models project an estimated 0.3-1.7°C increase in global average temperature for the lowest emissions scenario [Representative Concentration Pathway (RCP2.6), van Vuuren et al., 2011] and a 2.6-4.8°C increase for the highest emissions scenario (RCP8.5) over the 21st century (Riahi et al., 2011). For the three highest of the four RCPs, the increase of the global average temperature is projected to exceed 2°C by 2050, compared to the pre-industrial levels (UNFCCC, 2009; Collins et al., 2013). Annual average land temperature over Europe is projected to increase higher than that of the global land area (Jacob & Podzun, 2010; Collins et al. 2013; Jacob et al., 2014). At the same time, global mean precipitation increases in all scenarios, due to the intensification of the hydrological cycle (Collins et al., 2013). Because of global warming, the climate of Hungary will become drier and sunnier during the initial few decades of warming; while later, the moisture supply improves and is expected to approach or exceed the current values (Faragó et al., 2010). Whilst globally, climate variability accounts for roughly a third (32-39%) of the yield variability of maize and wheat (Ray et al., 2015); in Hungary, climate accounts for 33%-67% of yield variability, and a 1°C temperature increase reduced wheat yield almost two times higher than the global average during the last 30 years (Liu et al., 2016; Pinke & Lövei, 2017).

Projected future temperature rise and decline in rainfall amount may decrease cereal crop yields. Global wheat production is estimated to decrease by 6% for each °C of further temperature increase and its spatial and temporal variability increases (Asseng et al., 2015). According to model calculations (Allen et al., 1998; Paltineanu et al., 2011; Pirttioja et al., 2015) yields decline with higher temperatures and low precipitation amounts; furthermore, they increase with higher precipitation and evapotranspiration. However, climate risk of crop yields can be reduced by shifting optimum planting windows to earlier dates (Ottman et al., 2012). A major reason of significant decrease in crop yields associated with ever prolonging dry periods may be attributed to increased leaf senescence, owing to exceeding the physiologically critical temperature value (T_{crit}) (Asseng et al., 2011). A further risk is that high temperatures and prolonged dry period in the ripening stage reduces the duration of the grain-filling period and thus the kernel weight. In spite of this, e.g. the yield of winter rye is going to be increasing from the mid 1980s due to the higher crop density and kernel number, caused probably by the higher temperatures in winter months and the earlier start of the growing season (Chmielewski & Köhn, 2000). Concerning maize, daily water shortage in July, as a critical month, is three times more sensitive to 2°C warming than to a 20% decrease of precipitation (Lobell et al., 2013). Peltonen-Sainio et al., (2010) confirmed a species dependent negative effect of increased temperatures on wheat, barley and rye both in the pre- and post-anthesis phases. The response is probably associated with water shortage, as a limiting factor of yield, particularly at the beginning of the growth phase (Peltonen-Sainio et al., 2010).

Obviously, several factors can contribute to the quality and quantity of cereal crop yields, like environmental factors, such as meteorological variables, soil types, consistency (bulk density) of the soil, available water capacity, gold crown value of the soil (a land rating value, an indicator of the net income of a unit area, concerning fertility, location, and cultivability), geomorphology (slope of the cultivated area), as well as social factors, such as land size, and -extent, fertilization, use of pesticides, mechanization, precision farming, etc.). In the following, we will simplify the above-mentioned complex relationship and will only stay (1) at quantity of cereal crop yields and (2) at temperature and precipitation among meteorological variables. The reason of this simplification is that (1) for supplying population, quantity of the cereal is much more important than its quality and (2) among the meteorological factors these two components contribute most to the yields of cereal crops (Waha et al., 2013). The role of temperature and precipitation, as major factors of crop yields, has been analyzed in several aspects. However, to our knowledge, no papers have been published in demonstrating the order of importance of these meteorological elements in determining the crop yield of different cereals. Hence, in the paper, based on two procedures, we aimed at calculating the order of importance of the mean monthly temperatures and monthly precipitation amounts of April, May June, July and August in determining of the crop yields of maize, wheat, barley and rye for Hungary. The results received on the two methods will be compared and then evaluated.

2. MATERIALS AND METHODS

2.1. Location and data

According to the climatic classification system of Köppen, the majority of Hungary belongs to the Cf climate zone characterized by temperate-warm climates with an almost even distribution of precipitation (Köppen, 1931), or that of Trewartha's D.1 climate zone characterized by continental climates with long warm seasons (Trewartha, 1943). Temperate-warm / continental climates are the most suitable for growing cereals.

Hungary is an important country for producing cereals in Europe (Fig. 1, prepared in Excel 16 software). The ratio of the agricultural production is gradually decreasing in the national gross domestic product (GDP) (2000: 5.4%, 2010: 3.8%, 2018: 3.6%) (Hungarian Central Statistical Office, 2010; 2018). However, in 2018, the production area accounted for 79.1% of the country's territory, and a significant part of the production area (57%) was agricultural land (only UK, as former EU-member, has a bigger ratio) (Hungarian Central Statistical Office, Statistical Mirror, 2018). According to the same source, Hungary has 58 hectares of agricultural land per 100 inhabitants, which equls to the average of the EU-countries. This also indicates that the agriculture of Hungary is capable of exporting agricultural products in addition to supplying the local population. In 2010, only 4.4% of total cereal production in the EU-27 was produced in Hungary, while per capita cereal production was more than twice of the EU-27 average and the second highest after Denmark (Hungarian Central Statistical Office, 2010; 2018). Wheat and maize performed well above the EU-average in Hungary, ranking 7th and first in the ranking of EU-27 based on the specific value of yield, respectively (Hungarian Central Statistical Office, 2010; 2018).

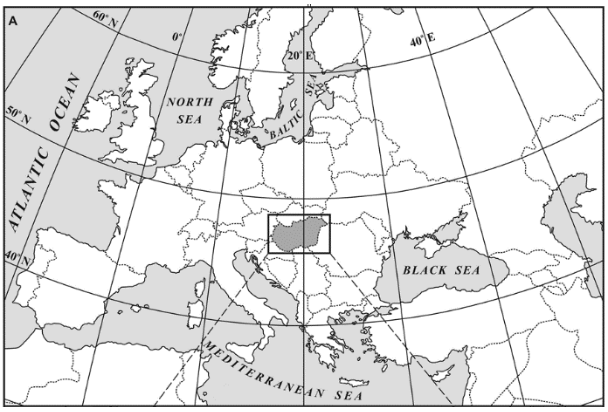

Figure 1. Location of Hungary in Europe

Since temperature and precipitation are the most important meteorological variables influencing crop yield, we took into account both mean monthly temperatures and monthly precipitation amounts for April, May, June, July and August, respectively.

Data of temperature and precipitation were used from the latest 30-year period (1981-2010) (Hungarian Meteorological Service, 2016). We used mean monthly amounts of precipitation and monthly mean values of temperature calculated on five meteorological stations in Hungary: namely, Budapest (47.5°N, 19.0°E), Debrecen (47.5°N, 21.6°E), Szeged (46.2°N, 20.1°E), Pécs (46.0°N, 18.2°E) and Szombathely (47.2°N, 16.6°E) that are distributed evenly throughout the country (Pinke & Lövei, 2017). These meteorological data are homogenized for the above-mentioned cities (Peterson et al., 1998; Szentimrey, 1999).

Regarding crop data, annual average yields (t/ha) of maize, wheat, barley and rye were used (Hungarian Central Statistical Office 2012). For maize, temperature and precipitation data between April-August; for wheat and barley, between April-June; while, for rye between April-July were considered. All statistical computations were performed in Excel (version 16) software.

2.2. Methods

2.2.1. Factor analysis with special transformation

Factor analysis (FA) identifies linear relationships among subsets of examined variables and this helps to reduce the dimensionality of the initial database without substantial loss of information. First, a factor analysis was applied to the initial dataset consisting of different number of variables. Namely, for maize, 11 variables were used [10 explanatory variables, i.e. 5 temperature and 5 precipitation variables between April-August, in addition 1 resultant variable, i.e. maize]. For wheat and barley, 7-7 variables were applied [6 explanatory variables, i.e. 3-3 temperature and precipitation variables between April-June; furthermore, 1 resultant variable, i.e. wheat and barley, respectively. Finally, for rye, 9 variables were used [8 explanatory variables, i.e. 4-4 temperature and precipitation variables between April-July, besides 1 resultant variable, i.e. rye)]. Then, these original variables were transformed to fewer variables. These new variables (called factors) can be viewed as latent variables explaining the joint behaviour of weather – crop yield variables. The optimum number of the retained factors is determined by different statistical criteria (Jolliffe, 1993). The most common and widely accepted one is to specify a least percentage (80%) of the total variance in the original variables that has to be achieved (Liu, 2009). Note that though we have altogether four target variables; however, in one factor analysis we use only one of them. Therefore, we will perform altogether four factor analyses for the four target variables, respectively.

After performing factor analysis, a special transformation of the retained factors was performed to find out: (1) to what degree the above-mentioned explanatory variables affect the resultant variable and (2) what is the order of importance of their influence on the crop yields as resultant variables (Fischer & Roppert, 1965; Jahn & Vahle 1968; Jolliffe, 1993).

Following the transformations – after aggregating all the weights of the retained factors at the place of both the explanatory variables and the target variable into one factor – the significance thresholds belonging to the factor loadings are determined as follows. Introducing the *0*-hypothesis, according to which a given factor loading is *0*, that is, this factor loading does not play a role in determining the target variable, the

$$t = \sqrt{\frac{r^2(n-2)}{1-r^2}} \qquad (1)$$

statistics follows Student's *t*-distribution with $n–2$ degrees of freedom, where r is the value of the given factor loading and n is the number of data pairs. From here, in the knowledge of t belonging to the chosen probability level and the calculated degree of freedom, the threshold r can be calculated (Csépe et al., 2014; Makra et al., 2016; Matyasovszky et al., 2011; Matyasovszky & Makra, 2012).

*2.2.2. **Multivariate linear regression and stepwise regression***

The task is (1) to establish a relationship between the explanatory variables and the resultant variable; furthermore, (2) to calculate the order of importance of the explanatory variables in determining the resultant variable. As the variables exhibit annual trends, regression coefficients in the linear relationship have annual courses described by sine and cosine functions with yearly and half-yearly periods. This latter cycle was introduced to describe the asymmetries of the annual courses. The coefficients of these periodic functions were estimated using the least squares principle (Draper & Smith, 1981).

In order to determine the order of importance of the explanatory variables, the above-mentioned 5 temperature variables (mean monthly temperatures for April, May, June, July and August) and 5 precipitation variables (monthly precipitation amounts for April, May, June, July and August) were used to evaluate which of them influence mostly the annual crop yield of the examined four cereals. Using the above-mentioned 10 explanatory variables an iteration was performed with the aim of assessing the annual crop yield. Then the error of the assessment was calculated. In the next step of the iteration, one variable was omitted and the assessment was performed again. This iteration was performed in all possible ways.

3. RESULTS

3.1. Factor analysis with special transformation

After performing a factor analysis equally for maize, wheat, barley and rye, as target variables, as well as for temperature and precipitation as explanatory variables for the months mentioned in section 2.1, 6 factors were retained for each of the four crop yields, respectively. In order to calculate the rank of importance of the explanatory variables for determining the resultant variable, loadings of the retained factors were projected onto Factor 1 (with a special transformation) (Table 1) (Jahn & Vahle, 1968).

As regards the crop yields as target variables, maize is more sensitive to precipitation than the remaining three cereals (Table 1). Concerning the meteorological variables, monthly precipitation amounts in June, July and August show very strong positive relationship with the crop yield of maize ($p<0.01$). In addition, mean temperatures in May and August exert significant negative influence on the

Table 1
Special transformation.
Effect of the explanatory variables on crop yields as resultant variables and the rank of importance of the explanatory variables on their factor loadings transformed to Factor 1 for determining the resultant variable (thresholds of significance for the weights: underlined: $x_{0.05} = 0.361$; **bold:** $x_{0.01} = 0.462$; **bold underlined:** $x_{0.001} = 0.570$;

Explanatory variables	maize			wheat			barley			rye		
	weight	rank	p-value	weight	rank	p-value	weight	rank	p-value	weight	rank	p-value
APR,temp	-0.019	10	>0.900	-0.197	5	0.297	-0.215	6	0.258	0.039	8	0.838
MAY,temp	-0.410	5	0.026	**-0.722**	2	<0.001	**-0.784**	2	<0.001	**-0.627**	2	<0.001
JUN,temp	-0.317	7	0.090	**-0.861**	1	<0.001	**-0.810**	1	<0.001	**-0.619**	3	<0.001
JUL,temp	-0.166	9	0.382	–	–	–	–	–	–	-0.041	7	0.830
AUG,temp	**-0.614**	1	<0.001	–	–	–	–	–	–	–	–	–
APR,prec	0.315	8	0.092	0.114	6	0.550	0.244	5	0.188	**0.750**	1	<0.001
MAY,prec	0.319	6	0.088	0.352	4	0.058	0.386	4	0.038	0.280	5	0.141
JUN,prec	**0.525**	3	0.005	0.382	3	0.040	**0.515**	3	0.006	0.421	4	0.022
JUL,prec	**0.551**	2	0.003	–	–	–	–	–	–	0.176	6	0.355
AUG,prec	**0.515**	4	0.006	–	–	–	–	–	–	–	–	–

Legends: APR,temp = mean April temperature; MAY,temp = mean May temperature; JUN,temp = mean June temperature; JUL,temp = mean July temperature; AUG,temp = mean AUG temperature; APR,prec = mean April precipitation amount; MAY,prec = mean May precipitation amount; JUN,prec = mean JUN precipitation amount; JUL,prec = mean July precipitation amount; AUG,prec = mean AUG precipitation amount;

maize yield. Note that May and June mean temperatures have a significant negative effect on the crop yields of wheat, barley and rye, respectively (for each case: $p<0.001$). Moreover, wheat is sensitive to June precipitation amount (significant positive effect), barley to May and June precipitation amounts (significant positive relationship) and rye both to April and June precipitation amounts (significant postive effects) (Table 1).

3.2. Multivariate linear regression and stepwise regression

When performing multivariate linear regression, crop yields were estimated in the function of the examined meteorological variables. The order of importance of the examined meteorological variables in determining the crop yields were calculated through the application of stepwise regression (Table 2).

3.3. Comparison of the results

The order of importance of the meteorological characteristics as explanatory variables in determining the target variables as crop yields for the examined cereals calculated by the two above-mentioned procedures are compared using Spearman rank correlation. According to this method, the order of importance of the meteorological variables show significant similarity for maize [$r_{s,\ maize}$ = 0.770 (p-value: 0.010)], rye [$r_{s,\ rye}$ = 0.834 (p-value: 0.011)] and barley [$r_{s,\ barley}$ = 0.829 (p-value: 0.044)], while for wheat [$r_{s,\ wheat}$ = 0.600 (p-value: 0.210)] we cannot say similarity in the orders of importance.

Significant relationships of crop yield vs metorological variables received on both procedures were selected and their concurrent occurrences were collected (Table 3). For maize, August mean temperature, as well as June and July precipitation amounts have significant role on both procedures. For wheat and barley, the importance of May and June mean temperatures were confirmed by both methods. At the same time, for rye, June mean temperature and April precipitation amount are the clearly highlighted variables (Table 3). Note that significant relationships shown by using stepwise regression can be experienced in case of factor analysis with special transformation, as well. In addition, the latter method detected 7 more significant relationships. This assumes that factor analysis with special transformation is a more refined procedure for exploring hidden crop yield vs meteorological variables relationships (Table 3).

4. DISCUSSION

Climate conditions are the most important meteorological factors affecting agricultural production. Dependence of the crop yields of the main cereals on meteorological variables have been extensively studied in the international special literature (Ji et al., 2017; Kheiri et al., 2017; Maaz et al., 2017; Pinke & Lövei, 2017). Multiple linear regression analysis (Mosaedi & Kaheh, 2008; Klink et al., 2014), via e.g. Enter and Stepwise methods (Mosaedi & Kaheh, 2008) is a known procedure for studying weather dependent crop yield of different cereals. However, factor analysis with special transformation has not yet been applied for this aim.

Xiao & Tao (2016) revealed that introducing effective agronomic and management practices raised the maize yield; however, the climate change related loss reached 46-67% of the increased yields in North China Plain, between 1981-2009. According to Akpalu

Table 2

Explanatory variables with their p-value and the order of importance of the explanatory variables for determining the resultant variable i.e. crop yields, via stepwise regression (<u>underlined</u>: significant at the 5% probability level; **bold**: significant at the 1% probability level; **<u>bold underlined</u>**: significant at the 0.1% probability level)

Explanatory variables	maize		wheat		barley		rye	
	p-value	rank	p-value	rank	p-value	rank	p-value	rank
APR,temp	0.389	7	0.641	5	0.738	4	0.797	7
MAY,temp	0.808	9	<u>0.024</u>	2	**0.009**	1	0.286	3
JUN,temp	0.182	5	**0.002**	1	<u>0.012</u>	2	<u>0.033</u>	2
JUL,temp	0.954	10	–	–	–	–	0.764	6
AUG,temp	**<u><0.001</u>**	1	–	–	–	–	–	–
APR,prec	0.256	6	0.628	4	0.840	6	<u>0.014</u>	1
MAY,prec	0.428	8	0.469	3	0.760	5	0.834	8
JUN,prec	**0.003**	3	0.670	6	0.494	3	0.461	4
JUL,prec	**0.001**	2	–	–	–	–	0.731	5
AUG,prec	0.115	4	–	–	–	–	–	–

Legends: the same as at that of Table 1;

The most influencing factors in determining crop yield of maize are August mean temperature, as well as June and July precipitation amounts, while those for wheat and barley are May and June mean temperatures, respectively. Concerning rye, the only significant factors influencing crop yield are June mean temperature and April precipitation amount (Table 2).

Table 3
Concurrent significant relationships of crop yield vs meteorological variables (conc. sign. rel. ●) by using factor analysis with special transformation (FA+sptr) and stepwise regression (stregr) and their order of importance (rank)

Explanatory variables	maize			wheat			barley			rye		
	conc. sign. rel.	rank		Conc. sign. rel.	rank		conc. sign. rel.	rank		conc. sign. rel.	rank	
		FA+ sptr	stregr		FA+ sptr	stregr		FA+ sptr	stregr		FA+ sptr	stregr
APR,temp												
MAY,temp				●	2	2	●	2	1			
JUN,temp				●	1	1	●	1	2	●	2	2
JUL,temp				–	–	–	–	–	–			
AUG,temp	●	1	1	–	–	–	–	–	–	–	–	–
APR,prec										●	1	1
MAY,prec												
JUN,prec	●	3	3									
JUL,prec	●	2	2	–	–	–	–	–	–			
AUG,prec				–	–	–	–	–	–	–	–	–

Legends: the same as at that of Table 1;

et al., (2008), the impact of precipitation on maize yield is stronger than that of temperature. Current warming with temperature increase and concurrent decrease in precipitation are of negative effect on maize yield (Akpalu et al., 2008). Liu et al., (2019) reported similar results; namely, vegetative growth period, reproductive growth period and whole growth period of maize was negatively associated to average temperature and positively related to precipitation and sunshine hours. Recent models, adapting global climate change, indicate an average decrease in maize yield between 13.2-19.1% during 2050s, compared to 1961-1990 (Tao & Zhang, 2010). Humidity/precipitation sensitivity of maize crop yield was also shown by Huang et al., (2015), who examined this relationship for the Eastern United States. Ceglar et al., (2016) detected a significant dependence between maize yield and monthly cumulated precipitation for France. The here-mentioned sensitivity of maize yield is in a negative relationship in accumulation of temperatures above 30°C [or extreme degree days (EDD)] (Lobell et al., 2013). In China, 1°C temperature increase in the growing season involved 25.1% reduction in maize yield (Wang et al., 2014).

According to our results, maize yield – meteorology relationship are consistent with those of other authors. Namely, the major meteorological components determining the yield in decreasing order are August mean temperature, furthermore July, June and August precipitation amounts, as well as May mean temperature by using FA and special transformation. However, by using both methods, the common significant variables influencing maize yield, in decreasing order, are August mean temperature, as well as July and June precipitation amounts. It is clear that temperature shows negative, while precipitation positive relationship with the maize yield, respectively.

Negative effect of temperature on cereal crop yields is widely reported. Some examples are as follows. Every 1°C increase in daily mean temperature reduces yield by 4.1-5.7% (Schelling et al., 2003). A 1°C increase in wheat growing season temperature reduces wheat yields by about 3-10% (You et al., 2009). A warming since the 2000s contributed to a 4.5% reduction in wheat yields in China (Asseng et al., 2011). When separating the impact of temperature from other components, variations of mean growing season temperatures of ±2°C may contribute to an up to 50% decrease in the crop yield of wheat in Australia (Asseng et al., 2011). Kheiri et al., (2017) found that spring meteorological variables influence the most the wheat yield. In addition, Holman et al., (2011) found a negative relationship between wheat crop yield and increased daily maximum temperatures; furthermore, a similar association was detected between winter wheat and mean monthly temperature for France, as well (Ceglar et al., 2016).

Our results are in accordance with those of the special literature. Namely, crop yields of wheat, barley and rye are in a significant negative relationship with both May and June mean temperatures, respectively. That is, high mean temperatures in these months predict poor harvest and vice versa. Significant dependence on precipitation is detected only between rye yield and April precipitation amount. The sequence of the meteorological variables in decreasing order for significantly determining (1) wheat crop yield: are June and May mean temperatures, (2) barley yield: are May and June mean temperatures, and (3) rye yield: are April precipitation amount and June mean temperature by using FA and special transformation.

5. CONCLUSIONS

For rainfed agriculture under Hungarian environmental conditions, temperature and precipitation are the most important meteorological variables influencing crop yields of maize, wheat, barley and rye. It was found that for maize yield the most important variables in decreasing order were August mean temperature with negative, as well as July and June precipitation amounts with positive association. For wheat yield, June and May mean temperatures, while for barley yield the same but in reverse order were the most important variables, all with negative relationship. Concerning rye yield, April precipitation amount with positive and June mean temperature with negative association were the decisive variables. Among the examined cereals, maize yield was the most sensitive to precipitation. The here-mentioned significant relationships may have a predictive power in projecting the actual crop yield.

Note that the relationship between the meteorological variables and crop yields is more complex than examined in this paper. As mentioned, the study applies to rainfed crops where irrigation and reference evapotranspiration were not investigated. For an in-depth approach, a phenophase specific analysis of the cereal crop yields with the meteorological elements would make a possibility for reaching more refined results. In addition, including further meteorological variables, such as accumulation of temperatures above 30°C [or extreme degree days (EDD)], or the occurrence of physiologically critical temperatures (T_{crit}) (34°C for wheat, 35°C for maize), diurnal temperature range, maximum temperature, accumulated cold degree days (ACDD), solar radiation, soil water content, change in the distribution of the growing period, especially during the grain-filling stage could be important components of crop yields. Furthermore, analysis of further yield dependent variables, such as spike number per plant (SNPP), grain number per spike (GNPS), 1000-grain weight (TGW) and grain yield per plant (GYPP) provides a further opportunity to explore the meteorological relationships of crop yields in more detail.

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