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RESEARCH ARTICLE

Modelling of Genotype × Environment interaction for grain yield of late maturity maize hybrids in Serbia by climate variables

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ABSTRACT

With global climate change, including unpredictable geographic and temporal weather patterns causing significant Genotype × Environment interaction (GEI), modelling by climate variables can reveal their influence on phenophases of maize (*Zea mays* L.) development. The objectives of this study were dissection of the phenotypic variation of grain yield of late maturity maize hybrids grown in multi-environment trial, and quantification of the influence of climatic factors on the GEI for each vegetative and reproductive phenophase. Eight FAO 700 maize hybrids were evaluated across five locations in Serbia during 2020 and 2021 years. The hierarchy of sources of variation according to three-way ANOVA were: Year (Y) > Location (L) > Location×Genotype (G) > L×Y×G > G > L×Y > Y×G. The average maximum temperature (mxt, 22.1%), average minimum temperature (mnt, 19.2%), average mean temperature (mt, 18.2%) and relative humidity (rh, 15.1%) in April significantly influenced emergence stage. The mxt (21.1%) and mt (15.7%) in May influenced significantly vegetative phases V1-V9. June contributed the largest percentage of the sum of squares of the GEI with mxt (25.2%), mnt (20.9%), mt (16.1%) influencing vegetative phases V10-V18 and tassel emergence. In July mxt (17%), mt (15.6%), precipitation sum (15.2%), and sunshine hours sum (15.1%), influenced R1, R2, R3, and R4 reproductive phases. In August mxt (23.2%), mnt (20.8%), mt (15.7%), rh (17.1%) influenced R5 reproductive phase. The extreme heat as a stressor had a more critical role for late maturity maize hybrids production than drought in crucial phenophases of maize development.

Key words: Factorial regression, Genotype×Location×Year interaction, multi-environment trial, phenophases, *Zea mays*.

INTRODUCTION

The underlying cause of differences among cultivars in relation to performance stability is the Genotype×Environment interaction (GEI). The GEI has three adverse effects in plant breeding: i) Reducing the correlation between genotypic and phenotypic values and making the selection of superior and stable genotypes in a wide range of environments difficult; ii) as a component of a trait phenotypic variance, it decreases heritability, selection gain and hinders breeding for complex traits; iii) masking the potential benefits of exotic germplasm introgression (Branković et al., 2015). The partial least squares regression and the factorial regression of climate variables are models commonly used for the interpretation of GEI.

With global climate change, the mean temperature has increased by 1.2 °C since 1960, and the severity of drought stress has increased causing negative effects on maize grain filling and yield (Ge et al., 2022). Continual increases in air temperature expected to occur under climate change will have significant impacts on maize production (Hatfield, 2016). In Spain, the days with mean temperature over 15 °C during the first weeks after sowing have negative effect on maize grain yield, while the maximum temperature of September (up to 28.9 °C) when plants are on the stage of seed filling have a positive effect on yield (Katsenios et al., 2021). In Serbia, high mean temperature of July affected less the yield of medium early maturing hybrids than late maturing hybrids, while the amount of precipitation (rainfed cultivation) in June was significantly correlated with grain yield (Katsenios et al., 2021).

The late maturity hybrids can take more of the available heat units, which could be imperative when maize plants experience more heat events and an increase in evaporative demand due to climate change (Buhiniček et al., 2021). Comparable shifting to late maturity hybrids is expected in Southeast Europe according to series of Agricultural Production Systems Simulator (APSIM) simulations especially when water regime (irrigation) is appropriately imposed (Buhiniček et al., 2021).

The extreme heat as a stressor had a more critical role for maize production than drought in the US, corroborating previous studies of rainfed maize showing strong negative yield response to accumulation of extreme temperatures (> 30 °C), and relatively weaker response to seasonal rainfall (Lobell et al., 2013). The maize grain yield is reduced by 0.83 t ha^{-1} and 0.67 t ha^{-1} with a mean temperature and minimum temperature increase of 1 °C in different maize growing regions of China (Hou et al., 2021). The optimum temperatures in China for mid-summer maize growth and kernel filling are 21-27 °C and 27-32 °C, respectively (Ge et al., 2022).

The continuous process of breeding in Serbia implies the creation of maize hybrids with higher genetic yield potential, greater adaptability, resistance and tolerance to the most prevalent diseases and pests. Maize hybrids of late maturity groups are better adapted to better agro-ecological growing conditions in Serbia.

Compared with traditional statistical analysis methods, crop model research can more accurately express the relationship between crop growth and various factors, which have obvious advantages in assessing the impact of climate change on crop growth and yield, and has become an efficient tool to assist agricultural production decision-making (Zhou et al., 2022). The objectives of this study were dissection of the phenotypic variation of grain yield of late maturity maize hybrids grown in multi-environment trial, and quantification of the influence of climatic factors on the GEI for each vegetative and reproductive phenophase.

MATERIALS AND METHODS

Plant material, field trials and experimental design

Seven maize (*Zea mays* L.) hybrids (ZP1-ZP7) created at the Maize Research Institute “Zemun Polje”, together with widely grown commercial hybrid (Ch) used as a control, were tested at five locations in Serbia during two cropping seasons, 2020 (20) and 2021 (21) as post-registration multi-environment trial. All of the examined hybrids belong to FAO 700 maturity group. The locations used for field trials were: Zemun Polje (ZPO) (44°51'41.72" N, 20°20'17.63" E, 80 m a.s.l.), Kukujevci (KU) (45°4'10.96" N, 19°20'26.59" E, 93 m a.s.l.), Bačka Topola (BT) (45°49'0.62" N, 19°38'27.85" E, 102 m a.s.l.), Požarevac (PO) (44°37'16.79" N, 21°11'16.15" E, 81 m a.s.l.), and Rimski Šančevi (RS) (45°19'12" N, 19°50'3.98" E, 84 m a.s.l.). Haplic Chernozem (CHha) soil is at the ZPO, KU, BT, RS locations, whereas Dystric Fluvisol (FLdy) is at the PO (WRB, 2014). Standard agrotechnical measures were applied at all test locations during both vegetation seasons. Integral protection against pests and weeds was successfully accomplished by a proper use of adequate pesticides.

The experimental design used in this study was a randomized complete block design with two replicates. Planting density was 63.492 plants per hectare. Plot length was 5 m, with inter-row distance of 0.75 m. The elementary plot consisted of eight rows, while only measurements from four internal rows were used for statistical analysis. Sowing and harvesting were done mechanically, using Wintersteiger specialized trial equipment. The sowing dates were in the range from 9 to 21 April 2020 and from 5 April to 7 May 2021.

The harvesting dates were in the range from 15 September to 7 October 2020 and 20 September to 1st October 2021.

Climatic conditions at the field locations

Climatic variables were measured during the vegetation period of tested maize hybrids at the field locations from April to August. The average values of maximum temperature (mxt, °C), minimum temperature (mnt, °C), mean temperature (mt, °C), relative humidity (rh, %), sunshine hours sum (sh, h), and precipitation sum (pr, mm), for April (1), May (2), June (3), July (4), and August (5) were recorded and calculated starting from the date of sowing for each location (Table 1) and each vegetative and reproductive phase.

Table 1. Climatic conditions during two vegetation seasons (2020 and 2021) at five Serbia locations: Zemun Polje (ZPO), Kukujevci (KU), Bačka Topola (BT); Požarevac (PO), Rimski Šančevi (RS).

	Environment									
Month	ZPO20	ZPO21	KU20	KU21	BT20	BT21	PO20	PO21	RS20	RS21
	Maximum temperature (°C)									
April	6.7	-	21.9	19.0	21.2	15.4	22.7	20.5	22.0	17.1
May	21.3	22.2	21.4	22.4	21.4	20.8	22.3	23.2	22.0	21.9
June	25.4	29.0	25.8	29.8	25.8	29.3	26.2	30.0	26.2	29.8
July	28.7	31.4	28.7	31.4	27.9	31.0	28.7	32.3	28.3	32.0
August	30.2	29.0	30.3	28.6	29.5	28.6	30.0	29.2	30.0	28.9
	Minimum temperature (°C)									
April	-0.6	-	6.5	9.3	6.6	4.1	3.7	6.4	6.3	6.6
May	10.6	12.0	10.1	10.6	10.0	9.7	10.0	10.2	10.3	10.6
June	15.6	16.4	14.6	15.1	15.7	15.5	14.6	13.8	15.6	15.5
July	16.9	19.9	15.1	18.4	16.3	18.4	15.0	17.7	15.7	19.1
August	18.4	16.8	16.9	15.3	17.5	15.6	16.5	14.5	17.3	15.9
	Mean temperature (°C)									
April	2.7	-	14.6	13.8	14.0	9.5	13.7	13.2	14.37	12.0
May	16.3	16.9	15.9	16.2	15.6	15.2	15.9	16.6	16.1	16.0
June	20.4	23.5	20.1	22.7	20.4	23.2	20.2	22.3	20.7	23.3
July	23.2	25.9	21.8	24.4	22.4	25.0	22.0	25.0	22.4	25.5
August	24.3	23.1	22.9	21.4	23.4	21.9	22.9	22	23.2	22.1
	Relative humidity (%)									
April	80.4	-	55.7	73.0	49.7	65.9	51.6	70.0	53.3	73.0
May	66.0	62.3	70.0	67.0	61.0	72.0	68.0	65.0	64.0	67.0
June	73.0	57.0	76.0	62.0	74.0	63.0	72.0	64.0	73.0	61.0
July	63.0	60.0	72.0	67.0	68.0	63.0	71.0	64.0	69.0	64.0
August	64.0	60.0	74.0	68.0	66.0	64.0	71.0	66.0	71.0	67.0
	Precipitation sum (mm)									
April	21.1	-	3.1	7.4	2.8	10.3	9.2	11.0	11.1	26.7
May	71.2	71.9	66.3	49.0	28.4	53.6	188.9	50.3	47.3	62.9
June	129.4	26.6	70.5	7.2	107.4	41.2	217.4	22.0	161.9	23.9
July	20.2	83.5	44.1	105.9	94.4	81.9	287.6	175.4	77.3	114.4
August	126.6	35.9	104.1	30.1	51.4	47.4	274.6	57.5	137.5	46.4
	Sunshine hours sum (h)									
April	69.8	-	96.0	27.1	209.8	315.6	201.3	34.5	166.8	83.9
May	157.7	135.6	187.5	236.8	220.6	246.5	94.9	243.1	217.7	255.0
June	182.0	254.9	212.2	297.8	204.6	361.9	104.7	308.5	223.0	348.1
July	304.4	255.3	281.3	283.1	317.7	323.4	142.4	305.2	334.3	325.8
August	279.6	260.4	293.4	293.3	296.6	291.9	94.0	270.9	314.2	302.0

Agro-meteorological conditions in the spring of 2020 (March-May) started with warmer weather than usual and with higher amounts of precipitation than average for Serbia. As the main characteristic of the month of March is fluctuating temperatures, after a period of warm weather with temperatures over 25 °C, at the end of the month there was a cooling down, followed by light to moderate spring frosts and the appearance of snow from 5 to 35 cm. In the rest of the spring, the weather was warm and mostly dry, so the moisture reserve in both the surface and deeper layers of the soil was reduced, which made it difficult to prepare the soil for sowing of spring crops. The dry period ended in the first days of May, and the rainfall that arrived was beneficial and valuable for the sprouting and uniform growth of the sown spring crops. The end of spring was marked by fresher and wetter weather, followed by daily rains. The summer of 2020 (June-August) was warmer and wetter than average conditions. The beginning of summer was cooler with frequent rain. In June, 50 to 400 mm precipitation was measured in Serbia. Humidity conditions in Serbia, estimated on the basis of the standardized precipitation index (SPI-3), show that conditions of increased humidity prevailed during the summer. However, because of abundant rainfall at the beginning of summer, excellent conditions were created for an exceptional harvest and yield of spring crops. Frequent rains enabled the creation of moisture reserves in the deeper layers of the soil, which created a precious reserve that the plants used in the dry and hot part of the summer. The average warm weather, with frequent precipitation and without occurrence of extremely high temperatures, remained throughout the summer. The most economically important crop in Serbia, maize, was suited to these weather conditions and allowed the smooth flow of the grain filling phase.

Agro-meteorological conditions in the spring of 2021 (March-May) started with drier and warmer weather than usual, and from mid-March there was a significant cooling, accompanied by precipitation and the appearance of morning frosts. Such weather conditions persisted until the last days of March. During that cold period, there was also the appearance of snow. Unfavorable weather conditions continued in the rest of the spring, when after a period of slightly warmer weather at the end of March, occurrences of late spring frosts of weak to moderate intensity were recorded during the first half of April. Also, the cold and wet weather with frequent rainfall hindered and delayed the preparation of the soil for sowing, as well as the actual sowing of spring crops. In the rest of the spring, mostly optimal weather conditions prevailed, which enabled the unhindered sprouting, growth and development of all spring crops. The summer of 2021 (June-August) was warmer with less precipitation compared to average conditions. The humidity conditions in Serbia estimated on the basis of the SPI-3 show that in the summer of 2021, the usual humidity conditions prevailed in the largest part of the territory of Serbia. It was warm at the beginning of summer, and from the second half of June it was significantly warmer than usual for this month with little precipitation. Extremely hot and dry weather lasted until mid-July, which had an unfavorable effect on all agricultural crops. In the middle of July, there was a cooling with precipitation and these rains benefited all agricultural crops. The continuation of the summer was characterized by mostly dry and warm weather with maximum daytime temperatures that during most of August ranged from 30 to 38 °C, and in some places even up to 40 °C. In the last week of August, it was cold with rain. For maize these precipitations were late and could not significantly improve the yield and quality. The vegetation period of 2021 (April-September) was warmer and drier compared to average conditions. Accumulated heat sums in the vegetation period were higher by 120 to 280 degree days compared to average conditions. From April to September an average of about 285 mm of precipitation were recorded for Serbia, which is about 70% of the average precipitation. Production in the 2021 year, from the point of view of agrometeorological conditions, was not favorable for many agricultural crops. Maize yield was 30% to 40% lower than the multi-year average.

Statistical analyses

The three-way ANOVA done as the tests between-subjects effects was obtained by the use of IBM SPSS 27.0 program (IBM, Armonk, New York, USA). Environment represented Year×Test location combination. The multiple factorial regressions (van Eeuwijk et al., 1996) following "forward" procedure of climatic variables inclusion were used for the explanation of GEI for grain yield of tested maize hybrids in the multi-environment trial. The factorial regression was done within R computing environment 4.2.0 (R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

The three-way analysis of phenotypic variation (ANOVA) for grain yield of late maturity maize hybrids grown in multi-environment trial during two consecutive seasons were presented as tests of between-subjects effects in Table 2.

Table 2. Tests of between-subjects effects for grain yield of late maturity maize hybrids from multi-environment trial. [a]R^2 = 0.952 (adjusted R^2 = 0.904).

Source	Type III sum of squares	df	Mean square	F	Sig.	Partial η^2
Corrected model	1055.66[a]	79	13.36	19.92	0.000	0.952
Intercept	20614.05	1	20614.05	30730.19	0.000	0.997
Location (L)	166.28	4	41.57	61.97	0.000	0.756
Year (Y)	762.29	1	762.29	1136.37	0.000	0.934
Genotype (G)	22.38	7	3.20	4.76	0.000	0.294
L×Y	22.02	4	5.51	8.21	0.000	0.291
L×G	41.23	28	1.47	2.20	0.003	0.434
Y×G	9.87	7	1.41	2.10	0.053	0.155
L×Y×G	31.60	28	1.13	1.68	0.037	0.371
Error	53.66	80	0.67			
Total	21723.38	160				
Corrected total	1109.33	159				

The statistical significance was proved for effects on location (L) ($P < 0.001$), year (Y) ($P < 0.001$), genotype (G) ($P < 0.001$), L×Y interaction ($P < 0.001$), L×G interaction ($P < 0.01$), and L×Y×G interaction ($P < 0.05$). The Y×G interaction was nonsignificant. The hierarchy of importance of sources of variation for the grain yield of late maturity maize hybrids from multi-environment trail according to partial η^2 from three-way ANOVA was: Y > L > L×G > L×Y×G > G > L×Y > Y×G. As the external sources of variation from environment, and L×G interaction and L×Y×G interaction, prevailed in the total structure of phenotypic variation for grain yield of late maturity maize hybrids it justified the need to include climatic variables modeling by the use of factorial regression for the interpretation of GEI.

Environmental variables included in the final model explaining GEI for grain yield of tested late maturity maize hybrids over 10 environments, obtained by the use of multiple factorial regressions are presented in the Table 3.

Models of climatic variables significantly interpreted (> 80.3%) GEI for grain yield of late maturity maize hybrids by months of vegetation season before maturity. June contributed the largest percentage of the sum of squares (89%) of the GEI with its prevailing climatic variables-average maximum temperature (25.2%) and average minimum temperature (20.9%). Maybe the least percentage of the sum of squares (80.3%) of the GEI contributed with its prevailing climatic variables: Average maximum temperature (21.1%), average minimum temperature (14.2%), and average mean temperature (15.7%). The average minimum temperature had the highest contribution of 20.9% to the GEI for grain yield during June. The precipitation sum, and sunshine hours sum had the highest contribution of 15.2%, and 15.1%, respectively, to the GEI for grain yield during July.

Table 3. Multiple factorial regressions of climatic variables explaining Genotype×Environment Interaction (GEI) for grain yield of tested late maturity maize hybrids over 10 environments. Variable significance is tested against error mean square $P < 0.01$. mxt: Average maximum temperature; mnt: average minimum temperature; mt: average mean temperature; rh: average relative humidity; pr: precipitation sum; sh: sunshine hours sum. All reported values are given as a percentage of sums of squares of explained variance of GEI by the term.

Month	mxt	mnt	mt	rh	pr	sh	Residual (%)
April	22.1	19.2	18.2	15.1	5.7	7.1	12.6
May	21.1	14.2	15.7	12.1	10.1	7.1	19.7
June	25.2	20.9	16.1	12.8	8.9	5.1	11.0
July	17.0	10.1	15.6	14.1	15.2	15.1	12.9
August	23.2	20.8	15.7	17.1	7.1	3.7	12.4

DISCUSSION

The average mean yield per environment of eight late maturity maize hybrids from Serbia tested in multi-environment trial was 32.3% lower in the 2021 season in comparison to 2020 season corroborating the influence of variable climatic factors that led to the grain yield variation. Changes of temperature and precipitation levels affect physiological processes in plants leading to grain yield variations (Branković et al., 2015). When explicit information about the environment is available, it can be used directly in the factorial regression model by including it in the form of explanatory variables and GEI is then described as differential genotypic sensitivity to environmental factors such as temperature, precipitation, water availability, etc. (Malosetti et al., 2013). The different combinations of environmental variables could result in similar models in terms of the sum of squares of explained variance of GEI.

The vegetation cycle of maize encompasses V18 vegetative (V) phases until tassel emergence (VT) and transitioning into the reproductive (R) phases of growth. Taking into regard sowing dates, from this research, plant emergence (VE) is time-framed in April, and vegetative phases V1-V9 in May, V10-V18 in June, and VT in the first week of July.

When maize seedlings emerge from the soil and no leaf collars have formed, plants are in the VE stage which occurs 4 to 5 d after planting under ideal conditions, but up to 2 wk or longer under cool or dry conditions (Nielsen, 2019). According to obtained model of climatic variables that affected grain yield of late maturity maize hybrids average maximum temperature (mxt), average minimum temperature (mnt), average mean temperature (mt) and relative humidity (rh) in April significantly influenced VE stage. The correlation between mean temperature and maize yield was positive in the seeding (from sowing to emergence) and maturity phases (from milk to maturity), while it was negative in the vegetative (from emergence to flowering) and flowering phases (from flowering to milk) (Yin et al., 2016). The effect of ecological conditions at sowing on the maize seed size was even over 70% ($R^2 > 0.70$) in the investigation of Tabakovic et al. (2021) of variations in seed morphology that are results of different sowing dates in relation with agroecological conditions of cultivation.

The mxt and average mean temperature in May influenced significantly vegetative phases V1-V9. At V1 vegetative phase, round-tipped leaf on first collar appears and nodal roots elongate; by V2 vegetative phase, plant relies on the energy in the seed; V3 vegetative phase begins 2 to 4 wk after VE, and plant switches from grain reserves to photosynthesis and nodal roots begin to take over. By the V5 vegetative phase, the number of potential leaf and ear shoots is determined. The V6-V8 vegetative phases have the growing point above the soil surface, increasing susceptibility to hail, frost or wind damage. The V7 vegetative phase has rapid growth phase and start of stem elongation, number of grain rows is determined and potential grains per row begin and continues through V15/16 (Nielsen, 2019).

June contributed the largest percentage of the sum of squares of the GEI with following descending hierarchy of climatic variables by importance: mxt > mnt > mt > rh > precipitation sum (pr) > sunshine hours sum (sh) and influenced vegetative phases V10-V18 and VT. From V10 phase new leaves appear every 2 to 3 d and ear shoots are developing; V12 vegetative phase is characterized with maize being in high demand of nutrients and water to meet growth needs; V15 vegetative phase is approximately 2 wk after tassel is in near full size, but not visible and moisture and nutrient deficiencies in this phase can reduce the number of potential grains per row resulting in shorter ears and lower yield potential (Nielsen, 2019). The VT vegetative phase represents critical period where successful pollination is required to convert potential grains into viable, developing grains and pollen shed begins and continues for 1 to 2 wk (Nielsen, 2019). The negative effects of high solar radiation during the flowering phase may be linked to high temperature stress, since high solar radiation during the period of low soil water availability will increase canopy temperature and this will affect seed setting negatively during this sensitive period (Yin et al., 2016). When solar radiation was combined with other factors in the analysis, solar radiation mainly had significantly positive effects on maize yield in the vegetative and maturity phase, while it had significantly negative effects on the maize yield in the flowering phase (Yin et al., 2016). The drought stress during flowering affect seriously photosynthetic ability and seed sink capacity, as well as ear size and the number of kernels per ear (Yin et al., 2015). The exposure to high temperatures above 30 °C at pollination reduced grain number and grain yield (Hatfield, 2016). The maize plants tend to respond to high water demand during critical period from anthesis to grain filling because of increased leaf area combined with high evapotranspiration associated with other physiological processes which contribute to grain yield such as number of ears per plant and number of grains per ear (Oke, 2016). Water deficit in all growing phases would reduce yield and the effects of drought stress was particularly strong in the seeding and flowering phases (Yin et al., 2016). Higher mean temperature in the seeding and maturity phases was beneficial for maize yield whereas excessive rainfall would damage maize yield, in particular in the seeding and flowering phases (Yin et al., 2016).

The hierarchy of climatic variable in July mxt > mt > mnt > pr > sh > rh in our study showed influence on grain yield of late maturity hybrid through effects on R1, R2, R3, and R4 reproductive phases. High-temperature stress always decrease the chlorophyll index, reduce the net rate of photosynthesis and short the maize grain filling duration, with a maximum temperature over 35 °C possibly causing grain abortion due to the prevention of sugar-starch conversion (Ge et al., 2022). Drought stress stimulate leaf senescence, and inhibit the photosynthetic electron transport of photosystem II and leaf photosynthetic capacity, leading to shortened the grain filling duration and reduced grain weight (Li et al., 2022). The R1 reproductive phase is silking representing one of the most critical phases in determining yield potential and it was completed in the first decade of July. The R2 blister reproductive phase starts when silks darken and dry out and grains are white and form a small blister containing clear fluid and it lasted until the end of the second decade of July. Stress (especially drought) at this stage can reduce yield potential by causing grain abortion (Nielsen, 2019). The R3 milk reproductive phase is when grains are yellow and clear fluid turns milky white as starch accumulates and lasted until mid of the last decade of July. The effects of stress are not as severe after this stage, but can still result in shallow grains, stalk breakage, or lodging (Nielsen, 2019). The R4 dough reproductive phase is with the starchy liquid inside the grains with a dough-like consistency and was completed until the end of July. Stress during this phase can produce light weight ears with poorly filled, shrunken kernels (Nielsen, 2019).

The descending hierarchy of climatic variables by importance mxt > mnt > mt > rh > pr > sh in August in our study influenced R5 dent reproductive phase. The heat stress degree days (SDD) during the grain filling and during full vegetation season were the most tightly associated with grain yield and that the high precipitation of 101.6 mm in August had a positive effect on recovery during grain filling and eventually on grain yield across the five FAO maturity groups in maize (Buhiniček et al., 2021). The same authors also concluded that experimental and simulation data demonstrate that grain yield in Southeast Europe is more affected in early maize hybrids than late ones apparently due to omnipresent heat stress. Oke (2016) found only highly significant ($P < 0.01$) correlations between maximum rh and maize grain yield ($r = 0.990$), mean rh and maize grain yield ($r = 0.870$) for whole vegetation cycle, and significant ($P < 0.05$) correlations between pr for grain filling period (61-100 DAP) and maize grain yield ($r = 0.902$) for maize grown in Nigeria. According to Subbulakshmi (2022) the minimum temperature at vegetative, silking, milking, dough and maturity stages affected negatively grain yield, and precipitation sum at vegetative stage and rh at all the growth stages affected the grain yield of maize hybrids grown in India, positively, under rainfed conditions. The same authors (Subbulakshmi, 2022) showed that increase in maximum temperature at knee high and milking stage increased the plant height and leaf area index, and that increase in minimum temperature at knee high stage increased the leaf area index, but at milking stage, drastically reduced the yield. Radiation is an important climatic factor that strongly influences maize grain yield via biomass accumulation and grain weight (Yang et al., 2021; Ge et al., 2022). Insufficient sunshine hours result in reductions in leaf area index and photosynthesis, thus limiting the development of grains and inhibiting starch formation during grain filling, leading to lower grain weight (Guo et al., 2020). Higher grain yield levels are calculated for locations where the level of solar radiation is high during grain filling and the average temperature is relatively low, which results in a long period of grain filling, and lower yields for locations with higher temperatures and less solar radiation (Hatfield and Dold, 2018).

The R6 black layer reproductive phase was achieved at the beginning of September, when physiological maturity is reached, and grains have attained maximum DM.

Without adaptation, approximately 53% of the cultivation areas would require hybrid renewal before 2050 under RCP 4.5 and RCP 8.5 emission scenarios (Zhang et al., 2021). The yield loss would be 2.3% in 2030s under RCP 4.5 for late maturing maize hybrids but tripled (7.1%) for early maturing hybrids (Zhang et al., 2021). The late maturing hybrids did not consistently suffer from greater yield losses under the climate change, suggesting that other traits may be at work, such as heat and drought resistance, grain filling rate and light use efficiency according to Xiao et al. (2020). Caubel et al. (2018) concluded that whatever the planting date, higher temperatures in the future will be favorable for late maturity maize varieties in the northern part of France.

The rising temperatures increase the rate of phenological development, leading to a smaller plant and reduced productivity because of the shortened growth cycle (Hatfield et al., 2018). Significant GEI is a consequence of variations in the extent of differences among genotypes in diverse environments (quantitative or absolute differences between genotypes) or variations in the comparative ranking of the genotypes (qualitative or rank changes) (Fasahat et al., 2015). When genotypic performance in different environments is extremely different, GEI becomes major challenge to selection and genetic improvement. Katsenios et al. (2021) showed that grain yield variation is explained predominantly with the effect of GEI (80.36%) for five maize hybrids evaluated in a 2 yr field experiment at six locations, then with genotype (12.79%) and the rest with the environment (6.85).

CONCLUSIONS

The descending hierarchy of importance of sources of variation on grain yield of late maturity maize hybrids were: Year (Y) > Location (L) > L×Genotype (G) > L×Y×G > G > L×Y > Y×G. The average maximum temperature, average minimum temperature, average mean temperature and relative humidity in April significantly influenced VE stage. The average maximum temperature and average mean temperature in May influenced significantly vegetative phases V1-V9. June contributed the largest percentage of the sum of squares of the Genotype×Environment interaction (GEI) with average maximum temperature, average minimum temperature, average mean temperature influencing largely vegetative phases V10-V18 and VT.

In July average maximum temperature, average mean temperature, precipitation sum, and sunshine hours sum, significantly influenced R1, R2, R3, and R4 reproductive phases. In August average maximum temperature, average minimum temperature, average mean temperature, relative humidity influenced R5 reproductive phase. The main conclusion is that extreme heat as a stressor had a more critical role for late maturity maize hybrids production than drought.

Author contribution

Conceptualization: J.P., N.D. Methodology: J.P. Software: N.M. Validation: N.M., J.P., Z.Č., N.G. Formal analysis: N.D. Investigation: J.P, Z.Č., S.B., N.G. Writing-original draft preparation: G.B. Writing-review and editing: G.B., J.P. Supervision: N.D. All co-authors reviewed the final version and approved the manuscript before submission.

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