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Evaluation phenology, yield and quality of maize genotypes in drought stress and non-stress environments

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Abstract. The aim of the study is to examine the effect of agrometeorological indices (growing degree days, GDD; heliothermal unit, HTU; photothermal unit, PTU; hydrothermal unit, HYTU) on the phenology and yield (GY) of the Sushi (FAO 340) and Fornad (FAO 420) maize hybrids. Furthermore, it was also analysed how the amount of nitrogen and its application time affected the productivity and protein content (GP) of maize under drought stress (DS) and non-stress (NS) conditions. There were seven fertilizer treatments in the scope of the field experiment. Non-fertilized treatment (A_0) spring basic treatment with 60 and 120 N ha^{-1} (A_{60}, A_{120}), and following the basic treatments, 30 kg N ha^{-1} top-dressing was applied in the V6 ($V6_{90}$, $V6_{150}$) phenophase and then another 30 kg N ha^{-1} in the V12 ($V12_{120}$, $V12_{180}$) phenophase. Based on the GDD and PTU, length of the vegetation period of maize hybrids can be predicted. Under DS, the largest GY and GP was recorded in the same treatment for Sushi ($V6_{150}$ kg N ha^{-1}), and at different nutrient levels under NS: GY (A_{120}) and GP ($V6_{150}$). The highest GY of Fornad hybrid under DS was achieved with the A_{120} treatment while the highest GP with the $V6_{150}$; in the case of NS $V6_{150}$ kg N ha^{-1} was the most effective for both GY and GP. The + 30 kg ha^{-1} N fertilizer applied in the V12 phenophase did not improve GY and GP in either hybrid during the two growing seasons. The findings provide useful help for farmers to prepare for future environmental changes and to operate successfully.

Key words: agrometeorological indices, phenology, nitrogen fertilization, grain yield, grain protein content.

INTRODUCTION

In addition to wheat and rice, maize is the crop produced in the highest volume on global scale (Serna-Saldivar, 2019; Santpoort, 2020). It is also a key component of animal feed (Shiferaw et al., 2011; Malaviarachchi et al., 2014) and its role in human nutrition is also extremely important. Of the 300,000 edible plant species, 200 are consumed, of which maize, wheat and rice make up 60% of the diet. In countries struggling with hunger, 80–90% of maize is used for human consumption. Therefore, increasing the average yield, yield stability and quality of maize is of utmost importance.

There is still potential for the global increase of maize production, for which maize yields need to improve by at least 18% by 2030 to meet the growing demand for food for a growing population and a changing diet (FAO, 2017; Listman & Ordóñez, 2019) despite increasingly extreme environmental conditions due to climate change.

Currently, adverse weather extremes caused by climate change, drought and water scarcity are critical barriers to plant growth and development, yields and quality worldwide (Xu et al., 2008; Iversen & Norby, 2014; Lobell et al., 2014; Avramova et al., 2015; Song et al., 2018).

Of the three important climatic parameters, temperature, precipitation, and light, temperature is the primary factor influencing plant development (Marton et al., 2005; Girijesh et al., 2011; Hatfield & Prueger, 2015), which is responsible for potential productivity for yield and quality (Nagy, 2008; Hawkins & Sutton, 2011). Achieving a certain heat unit accumulation is required to reach each phenological stage of maize hybrids (Nandini & Sridhara, 2019; Ahmed & Saikia, 2020). The duration of phenophases determines the rate and distribution of dry matter accumulation in different parts of the plant (Hao et al., 2016; Mirosavljević et al., 2018; Shrestha et al., 2018) Temperature-based agrometeorological indices of (GDD, HTU, PTU, and HYTU) are widely used for plant growth, phenological development, and harvest time estimation (Rajput et al., 1987; Wurr et al., 2002; Roy et al., 2005). These indices are based on the idea that the rate of phenological development is linearly related to temperature in the range between base temperature and optimal temperature (Monteith, 1981). Quantifying heat use efficiency (HUE) is useful for assessing the yield potential of a plant in different environments (Singh et al., 2018). Even under the most favourable agro-climatic conditions, the total heat and radiation energy available to the plant is not completely converted to dry matter. HUE depends on sowing time, genetic factors, and the applied agro-technology (Rao et al., 1999; Rani et al., 2012).

Fertilizer use plays a central role in increasing maize yield (Nagy, 2008; Lucas et al., 2019). Nitrogen is the primary limiting factor for maize plant growth and yield (Berzsenyi 2009; Liu et al., 2013; Thomsen et al., 2014; Du et al., 2020). Nitrogen is an essential building block of plant proteins and as such is one of the most important influencers of quality parameters in addition to quantity (Mamatha et al., 2017; Litke et al., 2019; Széles et al., 2019b).

Nitrogen uptake is lowest during maize emergence and then intensifies as of the 6–7 leaf stage, after stem elongation and is the highest during silking (Ciampitti & Vyn, 2013). Nitrogen uptake and incorporation are also significant during grain filling (Blackmer & Schepers, 1996; Ciampitti & Vyn, 2013). Applying the right amount of spring N basic and top-dressing fertilizer in the appropriate time reduces nitrogen loss, increases the efficiency of nitrogen supply, and improves economical nutrient supply, yield amount, and production efficiency (Muthukumar et al., 2007; Sitthaphanit et al. 2010; Ványiné & Nagy, 2012; Széles et al., 2019a).

The quality of maize grains is determined by climatic factors (Izsáki, 2007; Hegyi et al., 2008; Széles et al., 2018; Butts-Wilmsmeyer et al., 2019). Temperatures above 35 °C negatively affect protein production and alter the chemical structure of proteins (Monjardino et al., 2005; Rahman, 2005; Ristic et al., 2009).

The aim of the present study was to determine the heat demand and heat utilization efficiency of two different FAO number maize hybrids by means of various agrometeorological indices (GDD, PTU, HTU, HYTU). Furthermore, the intention was to explore the correlation between weather factors and nitrogen basic and top dressing, as well as the yield and quality of maize in the given crop production environment.

MATERIAL AND METHODS

Site description

The experiments were performed in the eastern part of Hungary, at the Experimental Site of the University of Debrecen (47° 33 'N, 21° 26' E, altitude 111 m), in moderately warm, dry growing area, on calcareous chernozem soil (Mollisol-Calciustoll or Vermustoll, clay loam; USDA) in a multivariate, four-replicate, stripped small-plot field trial in 2018 and 2019 with natural precipitation, involving hybrids with different genetic composition and different FAO numbers (Fornad, FAO 420 and Sushi, FAO 340).

Soil data

The average pHKCl of the soil is 6.6 (weakly acidic). In the upper (20 cm) layer of the soil Arany's plasticity index is 39, carbonated lime content in the upper 80 cm of the soil is around 0% (lime deficient) but from 100 cm it is 12% (moderately calcareous). The organic matter content in the upper 20 cm layer of the soil is 2.3% and at a depth of 120 cm it does not exceed 1.0%. The soil has a good potassium supply and a medium P supply. The soil has a favourable water absorption and significant water retention capacity. In the soil profile (0–2 m), which is decisive for the water supply of the plants grown in the long-term experiment, the soil is able to retain about 600–700 mm of water, of which approximately 65% is the amount of water available. The average depth of groundwater in the experimental area is 3–5 m (Pepó & Csajbók, 2014).

Weather data

To evaluate the weather conditions of the maize production experiments, the daily data of an automatic meteorological station operated by the Agrometeorological and Agroecological Monitoring Centre of the University of Debrecen near the experimental plots (500 m distance) was used. The climate data of the Debrecen Airport Station of the National Meteorological Service for the period of 1981–2010 (OMSZ, 2020) served as a reference for the examination of the deviations from the multi-year average.

The research included the examination of the cumulative values of different agrometeorological indices, growing degree days (GDD), photothermal units (PTU), heliothermal units (HTU) and hydrothermal units (HYTU) for each phenological stage of the experimental maize stocks.

In addition to the important emergence-tasseling (VE-VT) and emergence-physiological maturation (VE-R6) phases, emergence-6 leaf (VE-V6), emergence-12 leaf (VE-V12), emergence-silking (VE-R1), emergence–dough (VE-R4), tasselling-physiological maturity (VT-R6), silking-physiological maturity (R1-R6) are also evaluated.

Growing degree days (GDD*)*

$$\mathrm{GDD} = \sum\left(\frac{(\mathrm{T_{max}} + \mathrm{T_{min}})}{2} - \mathrm{T_b}\right) \tag{1}$$

where, T_{max} (°C) is the daily maximum temperature, T_{min} (°C) is the daily minimum temperature, T_b (°C) is the base temperature. If the daily average temperature is lower than the base temperature, i.e if $\frac{(T_{max}+T_{min})}{2} < T_b$ then $\frac{(T_{max}+T_{min})}{2} = T_b$ was used for the calculation, thus the given daily value of thermal heat unit is 0 (McMaster & Wilhelm, 1997). T_b is the temperature below which the rate of development is considered 0. The heat sum was calculated with $T_b = 10$ ºC in accordance with the scientific literature data (Davidson & Campbell, 1983; Gallagher, 1979).

Photothermal units (PTU)

$$\mathrm{PTU} = \sum \mathrm{DL} \cdot \left(\frac{(T_{max}+T_{min})}{2} - T_b\right), \tag{2}$$

where, DL (hours) is the length of day. The daily value of PTU is the product of the daily heat unit and the length of the given day (McMaster & Smika, 1988).

Heliothermal units (HTU)

$$\mathrm{HTU} = \sum \mathrm{SH} \cdot \left(\frac{(T_{max}+T_{min})}{2} - T_b\right), \tag{3}$$

where, SH (hour) is the daily duration of sunlight, the value of HTU is the product of the daily heat unit and the sunny hours of the given day. Data from direct sunlight measurements (with a Campbell-Stokes measuring device) were not available, thus sunlight duration data calculated from the global radiation by the Debrecen station of the National Meteorological Service were used.

Hydrothermal units (HYTU)

$$\mathrm{HYTU} = \sum \mathrm{RH} \cdot \left(\frac{(T_{max}+T_{min})}{2} - T_b\right), \tag{4}$$

where, RH (%) is the daily mean value of relative humidity, the daily value of HYTU is the product of the daily heat unit and the average relative humidity of the given day. The daily mean value of relative humidity was calculated from hourly data.

Energy use efficiency: Knowing the average yield of each treatment, the value of heat unit efficiency indices were calculated from the value of the previously presented agrometeorological indices summarized for the growing season (VE-R6) as follows:

$$\text{Heat Use Efficiency (HUE, kg ha}^{-1}\ {}^{\circ}\text{C}^{-1}\ \text{day}^{-1}) = \text{Yield/GDD} \tag{5}$$

where, Σ GDD = Cumulative growing degree days

$$\text{Photothermal Use Efficiency (PTUE, kg ha}^{-1}\ {}^{\circ}\text{C}^{-1}\ \text{day}^{-1}\ \text{hr}^{-1}), = \text{Yield/PTU} \tag{6}$$

where, Σ PTU = Photothermal units

$$\text{Heliothermal Use Efficiency (HTUE, kg ha}^{-1}\ {}^{\circ}\text{C}^{-1}\ \text{day}^{-1}\ \text{hr}^{-1}), = \text{Yield/HTU} \tag{7}$$

where, Σ HTU = Heliothermal units

$$\text{Hydrothermal Use Efficiency (HYTUE, kg ha}^{-1}\ {}^{\circ}\text{C}^{-1}\ \text{day}^{-1}\ \%^{-1}) = \text{Yield/HYTU} \tag{8}$$

where, Σ HYTU = Hydrothermal units.

Experimental details

In the field experiment, in addition to the treatment without fertilization (control), the fertilizer doses were applied as basic and top fertilizer divided as follows:

– Base fertilization: $A_{(0)}$ = non-fertilized control; A_{60} = 60 kg N ha^{-1}; A_{120} = 120 kg N ha^{-1},

– Top-dressing in the V6 phenophase: $V6_{90} = A_{60} + 30$ kg N ha^{-1}; $V6_{150} = A_{120} + 30$ kg N ha^{-1},

– Top-dressing in the V12 phenophase: $V12_{120} = V6_{90} + 30$ kg N ha^{-1}; $V12_{180} = V6_{150} + 30$ kg N ha^{-1}

The number of plants was 73 thousand plants ha^{-1}, the green crop was maize. The maize was sown on 23/04/2018 and 10/04/2019. The harvest was took place on 27/09/2018 and 09/10/2019. Harvested grain yield was corrected for 14% moisture content.

From the yield of maize hybrids in both years, samples were collected from each treatment and the protein content of the grains was determined with a Foss Infratec^{TM} 1241 device based on the near-infrared-transmittance (NIT) measurement method.

Statistical analysis

The effect of treatments on yield was examined using a general linear model (GLM) (Huzsvai & Vincze, 2013). Within GLM, evaluation was performed based on the Repeated Measurement Model. Mean values of the treatments were compared by means of the Duncan's test to avoid accumulation of Type I error. Within the homogeneous group, the yields did not differ with a significance level of 5%. The evaluation was performed with the statistical software package SPSS for Windows 21.0.

RESULTS AND DISCUSSION

Development of agrometeorological indexes

The 2018 growing season of maize was characterized by high mean temperature and low amount of precipitation, while drought stress (DS) was developed. It was 1.9 °C warmer than the 30-year average (17.5 °C) and had a precipitation deficit of 30 mm compared to the average (346 mm). The weather in 2019 was non-stress (NS), its average temperature (17.8 °C) was almost the same as the temperature characteristics of the years of the region, its precipitation supply was above average (+ 43 mm).

GDD, PTU, HTU, and HYTU developed differently for each hybrid under DS and NS conditions (Table 1).

The combined effect of cultivation conditions and hybrids on heat unit (GDD) was significant in all phenological phases, similar to the results of Malo & Ghosh (2018). Under DS conditions, the longer maturity Fornad maize hybrid required a higher amount of heat (GDD) than the shorter maturity Sushi maize hybrid during the entire growing season to reach each developmental stage. The largest difference was in the vegetative (VE-V12) phase, the accumulated GDD value difference being 84 day °C, coupled with only a 7 mm precipitation excess (Fig. 1). Silking is related to the average air temperature and acts as an important factor on flower formation (Iannucci et al., 2008). The Sushi hybrid reached the R1 phenophase with a lower GDD (594 day °C) than the Fornad hybrid (621 day °C). The difference in GDD between the two hybrids was also significant in the reproductive phase. The difference between the GDD value was 54 day °C in the VT-R6 phase and 46 day °C in the R1-R6 phase. There was a significant difference in precipitation during these phenophases. The Fornad hybrid had a 62 mm precipitation surplus. From emergence to physiological maturity (VE-R6), the Fornad hybrid required 1,446 day °C, while the Sushi hybrid required 1,373 day °C.

Table 1. Development of agrometeorological indices in the phenological stages of maize hybrids of different genotypes under drought stress (DS) and non-stress (NS) conditions

Phenological phases	2018 (DS)				2019 (NS)			
	Accumulated							
	GDD (day °C)	PTU (day °C hour)	HTU (day °C hour)	HYTU (day °C %)	GDD (day °C)	PTU (day °C hour)	HTU (day °C hour)	HYTU (day °C %)
	Sushi hybrid							
VE-V6	186	2,754	2,109	9,967	193	2,916	1,574	14,191
VE-V12	466	7,155	4,966	28,400	463	7,216	4,831	32,935
VE-VT	580	8,970	5,892	35,827	644	10,100	7,268	44,157
VE-R1	594	9,198	5,944	36,812	682	10,693	7,692	46,162
VT-R6	793	11,967	8,071	47,727	780	11,374	8,247	49,225
R1-R6	779	11,740	8,019	46,742	742	10,781	7,823	47,221
VE-R4	832	12,954	8,357	51,231	961	14,980	10,597	65,053
VE-R6	1,373	20,937	13,964	83,554	1424	21,474	15,515	93,383
	Fornad hybrid							
VE-V6	202	3,005	2,288	11,019	214	3,251	1,797	15,680
VE-V12	550	8,493	5,549	34,075	488	7,621	5,129	34,846
VE-VT	598	9,272	6,000	37,104	667	10,456	7,582	45,273
VE-R1	621	9,626	6,179	38,552	700	10,990	7,890	47,056
VT-R6	847	12,668	8,632	50,989	777	11,279	8,082	49,201
R1-R6	825	12,314	8,453	49,541	743	10,746	7,774	47,418
VE-R4	882	13,735	8,702	54,849	1,007	15,670	11,029	68,389
VE-R6	1,446	21,940	14,633	88,093	1,444	21,735	15,665	94,474

Under NS conditions, the cumulative GDD of the Fornad hybrid was higher until the end of the vegetative developmental stage than that of the Sushi hybrid. The difference ranged from 21 day °C to 25 day °C. In the reproductive stage, the difference became balanced. For the entire growing season, the Fornad hybrid accumulated a higher GDD value (1,444 day °C) than the Sushi hybrid (1,424 day °C). There was no difference in the amount of precipitation among the developmental stages, except for the VE-V12 stage, however that it was not significant (6 mm).

PTU, HTU, and HYTU were higher in the case of the Fornad hybrid than the Sushi

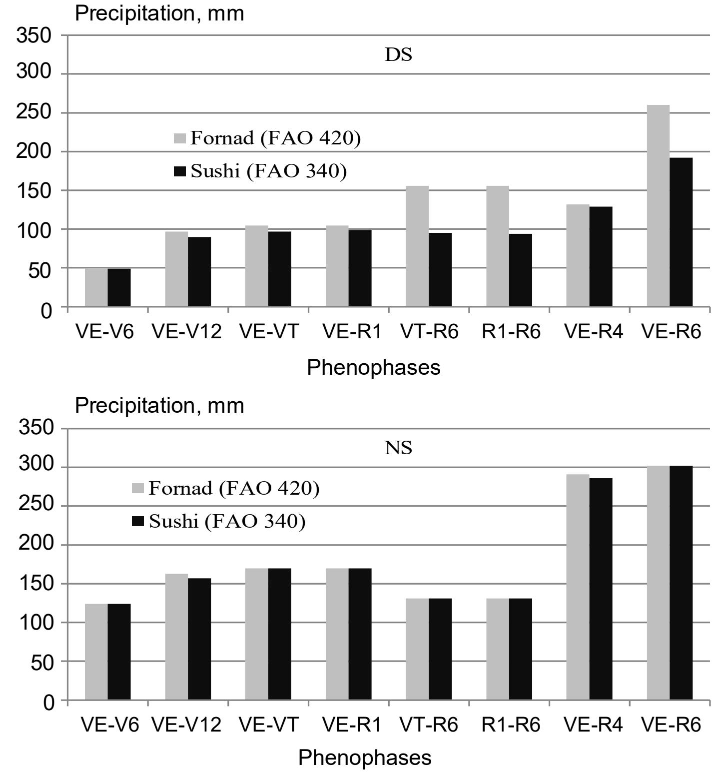

Figure 1. Amount of precipitation in the phenological phases of maize hybrids of different genotypes under drought stress (DS) and non-stress (NS) conditions.

hybrid during the growing season (VE-R6) under both DS and NS conditions. Between the vegetative (VE-VT) and reproductive (R1-R6) stages, more PTU, HTU, and HYTU accumulated under DS conditions for the Fornad hybrid, while under NS conditions there was more accumulation for the Sushi hybrid.

Abiotic stress tolerance and the effect of basic fertilization and top-dressing on maize yield

Under DS, yield of the Fornad maize hybrid without fertilization was 7,114 t ha^{-1}, the 60 kg N ha^{-1} applied as a base treatment increased the yield by 40.9% ($P < 0.05$), while the 120 kg ha^{-1} by 78.5% ($P < 0.05$) (Table 2). The 26.7% difference between A_{60} and A_{120} treatments was significant ($P < 0.05$). In the V6 and V12 phenophases, additional fertilizer application did not result in a significant yield increase. The maximum yield was ensured by the $V12_{120}$ treatment (13.614 t ha^{-1}), but based on the Duncan's test, the 12.695 t ha^{-1} result of the A_{120} treatment proved to be the best. The Sushi maize hybrid responded very strongly to the A_{60} treatment, with a yield increase of 71.2% ($P < 0.05$). Increasing the 60 kg N ha^{-1} applied as a base treatment in the V6 and V12 phenophases by an additional 30 + 30 kg N ha^{-1} did not result in a significant yield increase. The highest yield and the statistically confirmed maximum yield coincided in the case of the Sushi hybrid, which was achieved as a result of the $V6_{150}$ treatment (13.167 t ha^{-1}; $P < 0.05$).

Based on the *t-test*, a significant difference between the two hybrids was observed as a result of the A_{120} and $V12_{120}$ treatments. The longer maturity Fornad hybrid outperformed the shorter maturity Sushi hybrid by 1.393 t ha^{-1} ($P < 0.01$) in the A_{120} treatment and by 2.201 t ha^{-1} ($P < 0.001$) in the $V12_{120}$ treatment.

Table 2. Effect of base fertilization and top-dressing on grain yield of maize hybrids under DS and NS conditions

Hybrids	Year	Treatments						
		A_0	A_{60}	A_{120}	$V6_{90}$	$V6_{150}$	$V12_{120}$	$V12_{180}$
Sushi	DS	6.039a	10.341bc	11.303c	11.707bc	13.167d	11.414	12.945bc
	NS	8.910a	11.157c	13.527e	11.328c	12.062d	10.565bc	10.109b
		***	ns	***	ns	ns	***	***
Fornad	DS	7.114a	10.023b	12.695c	9.767b	13.105c	13.614c	12.939c
	NS	9.161a	12.124bc	12.711c	11.808bc	14.023d	11.033b	12.227bc
		***	**	ns	ns	**	***	ns

Note: Within each line, different lowercase letters indicate the difference between fertilizer treatments under DS and NS conditions based on *Duncan's test* ($P < 0.05$). Within the columns, based on the *t-test*, *** $P = 0.001$%, ** $P = 0.01$%, ns = non-significant notations indicate the difference between DS and NS.

Heat use efficiency was influenced by different weather conditions and nutrient levels as confirmed by the findings of Rao et al. (1999) and Malo & Ghosh (2018). For the Fornad hybrid, it ranged from 4.92 kg ha^{-1} $°C^{-1}$ day^{-1} (non-fertilized) to 9.42 kg ha^{-1} $°C^{-1}$ day^{-1} ($V12_{120}$). For the Sushi hybrid, the values are between 4.40–9.59 kg ha^{-1} $°C^{-1}$ day^{-1} (non-fertilized and $V6_{150}$). Due to the shorter maturity and the lower heat demand, it was possible that despite the lower average yield, the maximum value of heat use was higher than in the case of the Fornad hybrid. The lowest PTUE, HTUE, and HYTUE values for both hybrids were recorded in the non-fertilized (A_0) treatment, while the highest PTU, HTUE, and HYTUE values were recorded in the

V12$_{120}$ for the Fornad hybrid and in the V6$_{150}$ treatment the Sushi hybrid. For the Fornad and Sushi hybrids, PTUE varied between 0.32–0.62 to 0.29–0.63 kg ha^{-1} °C^{-1} day^{-1} hr^{-1}, HTUE was 0.49–0.93 to 0.43–0.94 kg ha^{-1} °C^{-1} day^{-1} hr^{-1}, and HYTUE ranged from 0.081–0.155 to 0.072–0.158 kg ha^{-1} °C^{-1} day^{-1}%$^{-1}$ for each fertilization treatment (Table 3).

Table 3. Thermal use efficiencies of maize hybrids in terms of grain yield, under DS and NS conditions

	2018 (DS)				2019 (NS)			
	Accumulated							
Treatments	HUE (kg ha^{-1} °C^{-1} day^{-1})	PTUE (kg ha^{-1} °C^{-1} day^{-1} hr^{-1})	HTUE (kg ha^{-1} °C^{-1} day^{-1} hr^{-1})	HYTUE (kg ha^{-1} °C^{-1} day^{-1} %$^{-1}$)	HUE (kg ha^{-1} °C^{-1} day^{-1})	PTUE (kg ha^{-1} °C^{-1} day^{-1} hr^{-1})	HTUE (kg ha^{-1} °C^{-1} day^{-1} hr^{-1})	HYTUE (kg ha^{-1} °C^{-1} day^{-1} %$^{-1}$)
	Sushi hybrid							
A$_0$	4.398	0.288	0.432	0.072	6.259	0.415	0.574	0.095
A$_{90}$	7.532	0.494	0.741	0.124	7.837	0.520	0.719	0.119
A$_{120}$	8.232	0.540	0.809	0.135	9.502	0.630	0.872	0.145
V6$_{120}$	8.527	0.559	0.838	0.140	7.957	0.528	0.730	0.121
V6$_{150}$	9.590	0.629	0.943	0.158	8.473	0.562	0.777	0.129
V12$_{150}$	8.313	0.545	0.817	0.137	7.421	0.492	0.681	0.113
V12$_{180}$	9.428	0.618	0.927	0.155	7.101	0.471	0.652	0.108
	Fornad hybrid							
A$_0$	4.920	0.324	0.486	0.081	6.346	0.421	0.585	0.097
A$_{90}$	6.932	0.457	0.685	0.114	8.398	0.558	0.774	0.128
A$_{120}$	8.781	0.579	0.868	0.144	8.805	0.585	0.811	0.135
V6$_{120}$	6.755	0.445	0.667	0.111	8.180	0.543	0.754	0.125
V6$_{150}$	9.064	0.597	0.896	0.149	9.714	0.645	0.895	0.148
V12$_{150}$	9.416	0.621	0.930	0.155	7.636	0.507	0.704	0.117
V12$_{180}$	8.949	0.590	0.884	0.147	8.470	0.563	0.781	0.129

Under NS conditions, the Fornad hybrid responded to the A$_{60}$ base treatment with a 32.2% yield increase. The yield difference resulting from the two base treatments is not significant. An additional 30 kg of N ha^{-1} (V6$_{150}$) in the V6 phenophase proved to be effective after the A$_{120}$ treatment ($P < 0.05$). For the Sushi hybrid, both base treatments significantly increased yield compared to the control treatment, however, the application of additional N was not effective. The A$_{120}$ treatment (13.527 t ha^{-1}) is considered justified (Table 2).

The Fornad hybrid was more effective than the Sushi hybrid in the V6$_{150}$ treatment with 1.961 t ha^{-1} ($P < 0.001$) and in the V12$_{180}$ treatment ($P < 0.01$). The *t-test* for the other treatments showed no significant difference between the hybrids.

Under NS conditions, there was little difference in the length of the cultivation period of the two hybrids, thus the differences in the individual accumulated heat unit values are also negligible. HUE values differed less between treatments, ranging from 6.35 to 9.71 for the Fornad hybrid and 6.26–9.50 kg ha^{-1} °C^{-1} day^{-1} for the shorter maturity genotype. The lowest PTUE, HTUE, and HYTUE values for both hybrids were recorded for the non-fertilized (A_0) treatment, while the highest PTU, HTUE, and HYTUE values for Fornad hybrid were achieved in the $V6_{150}$, while the Sushi hybrid reached it in the A_{120} treatment. For Fornad and Sushi hybrids, PTUE was 0.42–0.64 and 0.42–0.63 kg ha^{-1} °C^{-1} day^{-1} hr^{-1}, HTUE was 0.59–0.90 and 0.57–0.87 kg ha^{-1} °C^{-1} day^{-1} hr^{-1}, and HYTUE was 0.097–0.148 and 0.095–0.145 kg ha^{-1} °C^{-1} day^{-1}% $^{-1}$ for each fertilization treatment (Table 3).

The effect of weather factor was the most significant in the case of both hybrids in the control treatment. Under the influence of NS, the natural nutrient utilization capacity of the Sushi hybrid was 47.5% higher ($P < 0.001$), while that of the Fornad hybrid was 28.8% ($P < 0.001$) higher than under DS conditions (Table 2). In the case of the Fornad hybrid, the lowest applied base treatment of 60 kg N ha^{-1} (A_{60}) ($P < 0.01$) and the $V6_{90}$ N ha^{-1} ($P < 0.001$) treatment resulted in a yield increase of 21–21% under NS conditions. In the case of the Sushi hybrid, the effect of NS was significant in the A_{120} treatment (19.7%, ($P < 0.001$)). Utilization of the fertilizers applied in the V6 and V12 phenological phases was not significantly helped by NS.

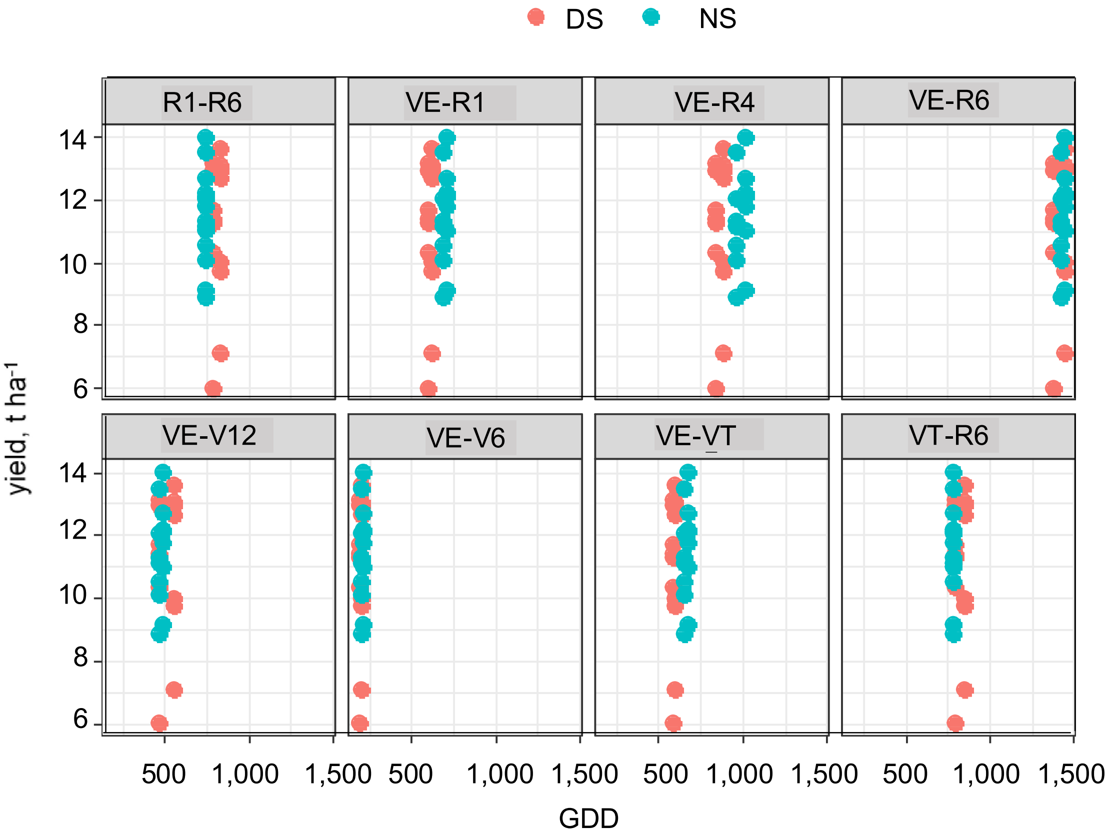

Figure 2. Development of GDD and yield in the average of maize hybrids under drought stress (DS) and non-stress (NS) conditions.

In the control treatment, the heat utilization efficiency of the Sushi hybrid was 42% higher under NS conditions than in the drought stress (DS) crop year. Due to the higher heat sum in the NS crop year, this increase is below the increase of natural nutrient utilization capacity. In the case of the Fornad hybrid, due to the nearly identical heat sum of the two crop years, the 29% difference in HUE is essentially the same as the difference in yield averages. Mainly due to the more favourable water supply, HYTU was 11–12% higher in the NS growing season than in the DS growing season. Consequently, HYTUE differs by 32% in the two crop years in the non-fertilized treatments of Sushi and by 20% in the treatments of the Fornad hybrid, which is significantly below the differences in the average yield. Under more favourable conditions, heat efficiency is higher, but not as much as the increase in natural nutrient utilization.

Overall, the study confirmed the results of Nandini & Sridhara (2019) and Ahmed & Saikia (2020), namely that nearly the same GDD is required for each phenological phase every year (Fig. 2).

Abiotic stress tolerance and the effect of basic fertilization and top-dressing on the protein content of maize grains

Under DS conditions, GP ranged from 6.9 to 9.6 g (100 g dm.)$^{-1}$ (Table 4). As a result of N fertilizer applied at different times and doses GP increased compared to control treatment. The rate of growth varied among the applied hybrids. The hybrid GP of Fornad responded to the A_{120} fertilizer dose with a reliable difference (11.4%, $P < 0.05$). An additional 30 kg N ha^{-1} ($V6_{90}$) applied after 60 kg N ha^{-1} A_{60} base treatment in the V6 phenophase resulted in a 26.0% ($P < 0.05$) increase in GP. The A_{120} treatment which was the most effective in terms of GP, was 18.0% lower than the $V6_{90}$ treatment which provided the highest GP. For Sushi, both base treatments reliably increased GP compared to the control treatment. The 120 kg N ha^{-1} (A_{120}) was more effective, the growth rate was 23.2% ($P < 0.05$). The application of + 30 kg N ha^{-1} after the 120 kg base treatment in V6 phenophase resulted in an additional 11.8% ($P < 0.05$) increase. This treatment provided the highest GP statistically.

Table 4. Effect of basic fertilization and top-dressing on the grain protein content of maize hybrids under DS and NS conditions

Hybrids	Year	Treatments						
		A_0	A_{60}	A_{120}	$V6_{90}$	$V6_{150}$	$V12_{120}$	$V12_{180}$
Sushi	DS	7.0a	7.3a	7.8b	9.2d	8.6c	8.7c	8.5c
	NS	6.9a ns	7.4b ns	8.5c ***	8.5c *	9.5e ***	9.1d *	9.6e ***
Fornad	DS	7.9a	9.4bc	8.8b	9.3bc	9.9c	9.9c	10.0c
	NS	8.1a ns	8.7b ns	9.3c ***	9.9d *	10.2e ns	10.2e **	10.0de ns

Note: Within each line, different lowercase letters indicate the difference between fertilizer treatments under DS and NS conditions based on *Duncan's test* ($P < 0.05$). Within the columns, based on the *t-test*, *** $P = 0.001\%$, ** $P = 0.01\%$, *$P = 0.05\%$, ns = non-significant notations indicate the difference between DS and NS.

There was no significant difference between the two hybrids in the control and A_{60} treatments based on the *t-test*. The GP value of the Sushi hybrid was reliably higher than that of the Fornad hybrid, except for the $V6_{90}$ treatment. The largest difference was in the $V6_{150}$ treatment (10.5%, $P < 0.001$).

As a result of NS, there was an increase in GP, ranging from 7.9 to 10.2 g (100 g dm.)$^{-1}$ (Table 4). For the Fornad hybrid, the A_{60} treatment was more effective than the control (19%, $P < 0.05$) of the basic treatments. There was no significant difference between the two basic treatments, however, increasing the 120 kg N ha^{-1} dose in the V6 phenophase by 30 kg N ha^{-1} significantly improved GP (+12.5%, $P < 0.05$). The amount of N applied in the V12 phenological phase no longer had a GP-increasing effect. In the case of the Sushi hybrid, both basic treatments reliably increased GP compared to control, the A_{120} (14.8% $P < 0.05$) treatment increased it by a higher degree. The GP value was significantly affected by the + 30 kg N ha^{-1} applied after the basic 120 kg N ha^{-1} (A_{120}) treatment in the V6 stage; the growth rate was 9.7% ($P < 0.05$). The amount of N fertilizer applied in the V12 phenophase did not further increase the GP value.

The *t-test* showed significant difference between the hybrids in the A_{120}, $V6_{90}$ and $V12_{120}$ treatments. In all cases, the GP value of the Sushi hybrid was higher. The largest difference was recorded in the $V6_{90}$ treatment (6.5%, $P < 0.05$)

The *weather factor* greatly affected both hybrid GPs. In the non-fertilized (control) treatment, the GP value of the Fornad hybrid under NS conditions was 12.9% ($P < 0.001$) higher than under DS. In the case of the Sushi hybrid, the effect of NS was more significant (17.4%, $P < 0.001$). For the Fornad hybrid, the largest GP modifying effect of NS was recorded in the A_{60} (28.8%, $P < 0.01$) treatment. There was no significant difference between DS and NS in the $V6_{90}$ treatment, in other treatments the effect of NS was reliably higher ($P < 0.001$) in all cases (Table 4).

The GP value of the Sushi hybrid significantly increased in both the basic and top-dressing treatments under the influence of NS. The rate of increase was significant at 0.1% level, with the exception of the $V12_{180}$ treatment. The largest difference, similar to the Fornad hybrid, was recorded in the A_{60} (17.6%) treatment.

CONCLUSIONS

Examining the heat sum values for the whole growing season, it can be stated that there was no significant difference between the years (Sushi 3.7%), and in the case of the Fornad hybrid (0.1%) there was essentially no difference. These findings are in line with the essence of the heat sum concept, i.e. the occurrence of a phenological phase is expected when the value of the heat sum reaches the heat demand of the given plant (species, variety, hybrid) required for the given phenological phase (Rao et al. 1999; Malo & Ghosh, 2018; Bonhomme, 2000).

The difference in growing time between hybrids (FAO 420-FAO 340) was shown by the heat sum, although under NS conditions it was lower than under DS conditions. Although the hybrid with a higher FAO number required a higher amount of heat to achieve silking than the hybrid with a lower FAO number, there was no difference in the amount of heat required in the reproductive phase. Under DS conditions, the need for a larger amount of heat in the case of the Fornad hybrid was demonstrated in both subphases.

Photothermal units can be used to estimate phenophase length for some plants with less error than GDD (McMaster & Smika, 1988; Bouzo & Favaro, 2014). In the two years of the experiment, the values of PTU for the growing season were also almost the same in the two years, the differences (Sushi hybrid 2.6%, Fornad hybrid 0.9%) were significantly lower than the relative differences in the number of growing days. Consistent with the conclusion of Malo & Ghosh (2018), the findings suggest that this agrometeorological index may also be suitable for estimating the length of the phenological phase in the case of maize. However, the limited validity and applicability of PTU remains, as it does not take into account the change in photoperiodic sensitivity over time, the critical length of day, or even significant differences in sensitivity between genotypes. More complex, well-parameterizable formulas than PTU can be used to describe the combined effect of photoperiod and temperature (Birch et al., 1998; Yan et al., 1998; Bonhomme, 2000). Large differences in HTU and HYTU units (7–12%) between the two growing seasons suggest that they are not suitable for estimating the length of phenological phases.

Heat use efficiency (HUE) for grain yield was similar to that described by Rao et al. (1999) and Malo & Ghosh (2018), it showed a difference between the hybrids. The minimum HUE for both hybrids was shown by the unfertilized treatment regardless of weather factors. The maximum HUE was developed for different fertilizer treatments in the case of the two hybrids hybrid.

The suggested amount of N-fertilizer and time of application to achieve the highest yield developed differently for the two hybrids, which was also influenced by environmental factors. In the case of the Fornad hybrid, the A_{120} treatment is recommended under DS and the $V6_{150}$ treatment under NS conditions. However, for the earlier maturity Sushi hybrid, the $V6_{150}$ treatment is suggested under Ds and the A_{120} treatment under NS conditions. DS caused the highest yield loss in the case of the later maturity Fornad hybrid.

The studied maize hybrids adapted to DS conditions by reaching physiological maturity in a shorter time, thereby minimizing the effect of DS.

N top-dressing promoted GP growth of maize grains. Under drought stress (DS), the Fornad hybrid provided the highest GP up to 90 kg N ha^{-1} ($V6_{90}$) and the Sushi hybrid up to 150 kg N ha^{-1} ($V6_{150}$). Under non-stress (NS) conditions, increasing the base dose of 120 kg N ha^{-1} for both hybrids in theV6 phenological phase by an additional + 30 kg N ha^{-1} proved to be an appropriate treatment ($V6_{150}$) to achieve high GP.

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