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Effects of solar radiation and night temperature on potential maize yield in two different crop years

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Abstract: Hungary's climate is undergoing change, and the heat unit (GDD) values have increased annually in the past nearly 50 years. In this study, we evaluate the performance of a maize hybrid in normal (2021) and drought (2022) crop years, along with the optimal agrotechnical factors (drip irrigation and high nutrient). In the potential experiment, we obtained a yield of 20.65t/ha in 2021 and 13.8t/ha in 2022. We examined the reasons for the large (33%) yield difference between the two years. By breaking down the weather data daily, it can be determined that the solar radiation (SR) and sunshine duration during the V6-V8 stage have an effect, and cloud cover affects the development of the reproductive organs of maize (ear differentiation). In the two years studied, we measured a significant difference in the SR value in the V6-V12 development stages (36% and 30% less SR was measured in 2022 vs 2021). The higher temperature (R1-R6) (2022) accelerated the phenological development of maize, so maize reached the black layer formation faster. The results indicate that in the future, we must also address the responses of maize to temperature changes with different levels of solar radiation and their dry matter incorporation dynamics.

Keywords: maize; GDD; solar radiation; NDVI; SPAD; yield; temperature

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1. Introduction

The impacts of climate change on agriculture are manifold. Over the past 50 years, the maize heat unit map of Hungary has undergone significant changes (GDD increase), with a parallel increase in average temperatures, along with a decrease in precipitation and its hectic occurrence. Maize production faces negative impacts such as yield reduction, vegetation period, temporal changes in developmental stages, deterioration in quality, and changes in the appearance of pests, diseases and weeds (in time and space).

The final yield of maize is influenced by many factors from the beginning, i.e. the choice of sowing date to the nutrient and water supply during grain filling. The amount and duration of sunlight, in addition to temperature and precipitation, play a significant role in the growth and development of maize. Tracking temperature and precipitation deficits by season is often easier to detect than seasonal sunlight accumulation.

Sunlight is an essential component of photosynthesis, which results in the production of carbohydrates used for plant growth and grain development. Reducing the amount of light available to plants during key growth stages can negatively impact yield and pose a greater risk to the plants. Low solar radiation has the greatest impact on yield during flowering and grain development. In experiments where maize was artificially shaded to approximately 50% solar radiation, yield was reduced by 12–20% when shaded during the R1 phase and by 19–21% when shaded during grain development [1]. Shading during flowering resulted in abnormal ear development (abortion) or fewer kernel per row, while shading during ear set resulted in reduced ear weight (thousand-kernel weight) [2].

Maize can experience several agronomic problems when sunlight is limited during ear set [3]. During ear set, limited photosynthesis signals the plant to move assimilates back from the stem to the ear, which weakens the stem (stem cannibalism). This problem can be further exacerbated if near-perfect growth conditions during ear size determination (number of kernel rows for V6 and rows/grain for V12) and pollination are followed by below-average sunlight during ear development. Favorable growing conditions during flowering induce plants to have higher yield potential and induce higher carbohydrate demands during ear set than the plant can meet under limited light [4].

The potential yield is the yield that a crop can achieve under good growing conditions, without being limited by water, nutrients, or stress and disease caused by pathogens and pests [5]. Under optimal growing conditions, the yield potential of a given crop depends on meteorological factors of the growing region, such as solar radiation and temperature [6]. Solar radiation, the driving force for plant growth and development, is closely related to plant morphogenesis and ear formation [7, 8]. As the solar energy utilization decreases, the yield also decreases [9].

Nowadays, mainly in China (due to air pollution, global warming), several shading experiments have been conducted to study the yield of maize at different solar radiation levels. Significant yield reductions were observed due to the reduction in solar radiation. Yang et al. (2019, 2021) [4, 10] observed a >50% reduction in maize yield when solar radiation was artificially reduced by 50% (by shading). Similarly, Hashemi-Dezfouli and Herbert (1992) [11] observed a yield reduction from 23% to 66% with a 50% reduction in solar radiation, shading starting on the 44th day after emergence and continuing until the physiological maturity of the plant. Various studies have shown that the yield reduction caused by reduced solar radiation also depends significantly on the timing of the reduction in solar radiation during the maize growing season. Liu and Tollenaar (2009) [1] found 21%, 29%, and 23% reductions in maize grain yield for shading treatments applied at the beginning, middle, and end of female flowering, respectively.

The reduction in maize yield caused by the reduction in solar radiation is largely due to the reduction in the photosynthetic rate of plants [12] and the total plant biomass [1,13]. Mbewe and Hunter (1986) [14] observed a 21%, 30% and 27% reduction in total plant biomass for seasonally accumulated solar radiation reductions of 23%, 20% and 24%. Similarly, Yang et al. (2021) [10] observed a 4.5%, 10.7% and 20.2% reduction in total plant biomass in maize for 15%, 30% and 50% shade treatments, respectively. The reduction in photosynthetic rate, plant biomass and assimilates in maize, especially during the female flowering and early grain filling stages, caused delayed female flowering [2,11], with increased aborted grains, reduced kernel number and reduced weight [13]. In addition, reduced solar radiation affects stem strength, increasing the frequency of plant collapse due to reduced plant photosynthesis and the withdrawal of larger assimilates from the stem

[3]. It is important to assess how longer-term weather data and environmental conditions affect maize growth and yield. Conditions such as heat and drought, solar radiation and the intra-seasonal distribution of heat unit accumulation can affect crop growth and yield [15].

Chang (1981) [16] reported that high nighttime temperatures reduce maize yields by about 30%. The main climatic factors that affect plant growth and development can be divided into two categories: water balance and thermal and radiative systems. The latter include sunshine duration, temperature and solar radiation. Temperature also affects photosynthesis, respiration and translocation, as well as crop development, especially during the grain-filling period.

High temperatures promote respiration. The average rate of respiration is about 25% of the rate of photosynthesis in temperate climates, compared with 35% in the tropics. The most important effect of temperature, however, is that high temperatures, especially at night, shorten the time to maturity, thus greatly reducing the achievable crop size [17]. The optimum temperature for plant growth and development is not the same as the optimum for high grain yield. Environments with lower but similar daytime temperatures accelerate development, reducing the growing season and the time for each developmental stage to develop.

The purpose of this review is to summarize the impact of long-term weather patterns on maize production, identify management considerations to mitigate potential losses, and suggest areas for future research to improve yield when similar weather conditions are experienced.

In this study, we compared solar radiation, cloud cover, daytime and nighttime temperatures during vegetation with the developmental stages of a mid-maturing maize hybrid, the dynamics of SPAD and NDVI, as well as with crop-forming elements and yield. A deeper understanding of these interactions will allow for better quantitative estimation of biomass and early yield prediction using spectral sensing, considering daily and seasonal variations. It may provide an opportunity to carry out various interventions that help eliminate abiotic stress factors (shading by lime painting, biostimulants, targeted nutrient applications).

2. Materials and Methods

University of Debrecen in the so-called "potential" experimental field, where we applied optimal cultivation technology for maize in order to create an ideal growth environment. The soil of the area is calcareous chernozem, the upper soil layer of which exceeds 80 centimeters on average. The humus content is between 2.7-3%. The pH of the soil is 5.8 (slightly acidic). During the study, plant physiological parameters and yield parameters were analyzed, including the recording of SPAD and NDVI data; a more detailed description is provided in Balaout et al. (2022) [18].

Characteristics of the maize hybrid tested in the experiment

The Sc4140 hybrid matures in the second half of the FAO400 group (FAO 450-470). It is a tall hybrid in terms of stature, with an average plant height of 283.5-331.8 cm in the years studied. Its taproot height was 126.4-145.1 centimeters in the year studied. It has good root and stem properties, with an average stem diameter of 19.8 mm. Its agronomic properties are favorable, its germination vigor and early development are fast. It reached physiological maturity on September 13 in 2021, while on August 27 in 2022. Its thousand-kernel weight was high, averaging 379.6 grams.

Agrometeorological evaluation of the experimental site

The weather data were evaluated based on the data measured and recorded by the automatic weather station located in the experimental area and with the Syngenta meteoblue® historical data source. The GDD (Growing Degree Days, growing degree days) calculation was performed by Széles et al. (2022) [19].

In 2021, the winter half-year preceding the growing season did not show any extremes, both in terms of temperature and precipitation, it was in line with the multi-year average. The 196 mm of precipitation that fell over 6 months was only 18 mm below the average value. The initial water reserves of the soil in spring reached an acceptable level, partly thanks to the rainy summer of 2020.

In 2022, the winter half-year following the 2021 growing season also saw little rainfall. The 144 mm of rainfall over six months was 70 mm less than the multi-year average. The recharge of the deeper layers of the soils was not satisfactory. The total of 32 mm of rainfall from January to March, coupled with sunny, windy weather, also definitely started the drying of the upper layers of the soils. All this foreshadowed the possibility of an even more severe drought.

Table 1. Temperature, precipitation (Debrecen-Látókép) in different development phases during the vegetation period in 2021-2022

Year	Period	Temperature	Temperature	Temperature	Precipitation
	Unit	Max average °C	Min average °C	Average °C	∑ mm
2021	Before sowing (from April 01)	12.72	3.39	8.31	24
2022	Before sowing (from April 01)	14.44	4.09	9.48	54.6
	Difference 2022-2021	1.72	0.7	1.17	30.6
2021	Between sowing and germination [VE]	17.65	7.72	12.78	41.3
2022	Between sowing and germination [VE]	21.62	9.92	15.87	13.3
	Difference 2022-2021	3.98	2.21	3.09	-28
2021	V6 status	20.7	10.11	15.72	56
2022	V6 status	25.42	12.28	19.16	19.1

	Difference 2022-2021	4.73	2.17	3.44	-36.9
2021	V12 status	29.6	16.82	23.68	17.4
2022	V12 status	26.11	14.7	20.55	35
	Difference 2022-2021	-3.49	-2.13	-3.13	17.6
2021	Male flowering [VT]	30.85	18.11	24.76	24.3
2022	Male flowering [VT]	30.95	16.42	24.46	4.6
	Difference 2022-2021	0.1	-1.69	-0.3	-19.7
2021	Female Flowering [R1]	32.83	21.48	26.54	6.9
2022	Female Flowering [R1]	34.12	20.93	27.38	0.5
	Difference 2022-2021	1.3	-0.55	0.84	-6.4
2021	R2 status	32.63	20.54	26.85	21.6
2022	R2 status	28.62	16.48	22.77	4.4
	Difference 2022-2021	-4	-4.06	-4.08	-17.2
2021	R6 status	27.93	15.46	21.72	72.3
2022	R6 status	31.78	18.12	25.04	52.2
	Difference 2022-2021	3.85	2.66	3.32	-20.1
	∑Difference 2022-2021	-0.15	0.36	-0.12	147.1
2021	Average VE-R6	27.45	15.75	21.72	34.26
2022	Average VE-R6	28.38	15.55	22.18	18.44
2021	Drip irrigation V8-R4				304
2022	Drip irrigation V8-R4				456.8

2021

April was relatively poor in sunshine, in May the sunshine duration did not show any significant difference compared to the long-term average. At the beginning of June, a definite turn occurred in the weather (Table 1). The first two months of the summer were sunny and significantly warmer than average, all of which were associated with very little precipitation. The temperature in June was exceptionally warm. July developed under more balanced temperature conditions. The number of sunny hours in June was above the long-term average, and July was also a month rich in sunlight. As a result of the warm weather, the development of maize accelerated in June, however, due to the lack of precipitation, drip irrigation (304mm) played a life-saving role and helped the experimental population to a moderate stress state. There was no precipitation in September that significantly increased the water resources of the soil. All this provided suitable conditions for ripening, grain shedding and drying. The maize harvest took place in the experimental area, mostly in the last decade of September, under favorable weather conditions that did not hinder work.

2022

April was characterized by slightly cool, averagely rainy weather, but it was less cold than April 2021. In May, however, warm, dry weather prevailed from the beginning of the month. Overall, conditions were favorable for sowing and emergence in the spring of 2022. Daily average soil temperatures rose steadily towards the plant's base temperature (10°C) from April 12 and reached a stable 15°C by the end of the month. With the exception of a few days, the air temperature remained several degrees below the soil temperature, and the excess soil temperature was clearly visible. The entire summer period was very hot and extremely dry. Monthly average temperatures were relatively uniformly 2-3°C above average in all three summer months. Total summer precipitation fell short of the low value recorded in 2021. Daily precipitation above 10 mm fell only twice, but due to the very high evaporation capacity of the air, these could not significantly contribute to the water supply of the maize. 456.8 mm was applied with drip irrigation! The daily temperature fluctuations were large. The air usually cooled to around 20°C during the night hours, but the number of hot days (max ≥ 30°C) was very high in the summer. An extremely severe drought developed in the Debrecen region (and in most of Hungary) during the summer. Since the beginning of large-scale maize production, there has not been a crop loss of a similar magnitude to that of 2022. The maize crop was completely destroyed over a large area on the region's high-quality and water-efficient chernozem soils. A significant turn in the weather occurred in September. A very large amount of precipitation fell. The moisture condition of the soil also hindered the harvest, which in many places could only take place in October.

Agrotechnical characteristics of the experiment

The precursor crop for the "potential" yield experiment was maize. The soil preparation of the experimental field and the autumn nutrient application were as follows in 2021; 500 kg/ha of CAN (27-7-5) was applied, and 300 kg/ha of NPK (8-24-24) was applied in the autumn of 2022. 500 kg/ha of CAN was applied in the spring of 2022 (March 29). Sowing was done on April 20 in 20241 and on April 26 in 2022 with a plant density of 85,000 seeds/ha. The emergence and GDD (growth degree days) will be detailed later. In both years, the drip irrigation system was installed in each row after inter-row cultivation. The total amount of irrigated water during the growing season was 304 mm in 2021, applied 38 times (between June 16 and August 29), and 456.8 mm of irrigation water was applied in 2022 (between May 17 and August 11). Along with the irrigation water, liquid fertilizer was applied on June 10, 2022 in the following macroelement amount: 100 kg NPK 3-5-40 (3 kg N, 5 kg P 2 O 5 , 40 kg K 2 O) and then on July 12 in a dose of 50 kg. Harvesting took place on October 1 in 2021 and on October 10 in 2022 using a small-plot harvester. The experimental area was free of weeds, diseases and pests.

Statistical evaluation of results

To evaluate the results, we used one- and multivariate analysis of variance and Fisher 's least significant difference (LSD) test.

3. Results

3.1. The effect of temperature and GDD values in the two years studied

The natural rainfall of the experiment during the period before sowing and between emergence and sowing was considered good for germination in both years. In 2021, 24 and 41.3 mm of precipitation fell, while in 2022, 54.6 and 13.3 mm of precipitation fell in the indicated periods (Table 1). The greatest impact on germination during this period is the soil temperature [20] and the rainfall. In 2021, at the normal sowing time (April 20), the average soil temperature was 12.6 °C, while in 2022, with the sowing time on April 26, this value was much higher at 15.9 °C (Table 2). The accumulated GDD values from sowing to emergence were 62.6 and 77.1 °C, which are lower or equal to the national average. The number of days since sowing was 17 and 12 days, respectively, and here too the increase in soil temperature and atmospheric temperature had a major impact on the values.

Examining the vegetative (VE-VT) and reproductive (R1-R6) stages of the Sc4140 hybrid, significant differences can be discovered between the two vintages. Available precipitation as a factor did not play a role in the different developmental stages, through a potential experiment, due to drip irrigation. The development of reproductive organs (ear and crest initiations are determined by V4-V7, ear grain number, while the formation of ear length and the expected number of grains are formed between the V6-V12 stages) are greatly influenced by optimal weather conditions [21]. The accumulated GDD was higher in both years in 2021, with a significant 144 °C increase in the V6-V12 stage. The appearance of the hybrid crest occurred on the 80th day from sowing in 2021, while in 2022 it was already on the 76th day. The female inflorescence, the appearance of the pistils, then occurred after 3 and 2 days. The flowering temperature (at a non-critical level) was higher in 2021 between the R1 and R2 phases, which shortened the duration of this stage. Then, between the R2 and R6 phases, in the most critical period for bud set, the average temperature in 2022 exceeded the same period in 2021 by more than 3 degrees, and a higher heat sum than the GDD values was associated with 2022. The rapid accumulation of heat units may accelerate bud development, which results in a shorter bud set time [15]. Thus, in this reproductive stage, 58 days passed between the bladder stage and the formation of the black layer in 2021, while in 2022 only 45 days passed. This, as we will discuss later, had a major impact on crop size and individual ear performance due to the shorter time it took for assimilates to be incorporated. As a result, the weather conditions in 2022 were not optimal for the formation of the reproductive organs (ear length, ear size) as discussed above.

Table 2. Weather and GDD data of the growth stages of the Sc4140 hybrid in the two years studied (Debrecen-Látókép)

Growth stages	Years	Temperature	Temperature	Temperature	Soil temperature	Period	GDD
		°C	°C	°C	°C	Days	°C
		Max	Min	Mean	0-7 cm mean	Mean	Mean
VE	2021	17.65	7.72	12.78	12.69	17	62.6
	2022	21.62	9.92	15.87	15.93	12	77.1
V6	2021	20.70	10.11	15.72	15.81	27	152.2
	2022	25.42	12.28	19.16	19.17	15	138.2
V12	2021	29.60	16.82	23.68	23.72	26	344.4

	2022	26.11	14.70	20.55	20.72	29	200.4
VT	2021	30.85	18.11	24.76	25.24	10	140.7
	2022	30.95	16.42	24.46	24.95	20	277.5
R1	2021	32.83	21.48	26.54	27.54	3	47.7
	2022	34.12	20.93	27.38	28.64	2	32.9
R2	2021	32.63	20.54	26.85	27.22	6	96.5
	2022	28.62	16.48	22.77	24.09	10	124.2
R6	2021	27.93	15.46	21.72	22.59	58	665.8
	2022	31.78	18.12	25.04	25.45	45	648.9

3.2. The effect of cloud cover, sunshine duration and solar radiation

In the years studied, the different developmental stages were greatly influenced by solar radiation. In addition to water and nutrients, solar radiation (sunlight duration) is essential for plant growth. Plants can only utilize a portion of the solar radiation spectrum. This portion is called photosynthetically active radiation (PAR) and is estimated to account for 43-50% of the total radiation. The amount of PAR available to the plant decreases with cloud cover. PAR decreased from 25% to 50% on partly cloudy or overcast days and by more than 60% on rainy days [22]. It is therefore not surprising that cloudy, rainy periods can have a significant impact on crop yield during sensitive stages of plant development. Based on Tables 2 and 3, studying the development stages of VE and V6, in 2021, due to higher cloud cover and thus lower sunlight duration and solar radiation, the initial development was slower in the Sc4140 hybrid, and the individual phenophases, both emergence and reaching the 6th leaf collar, took significantly longer than in 2022. However, in the stage of development of critical reproductive organs (V6-V12), the average percentage of cloud cover was 41.34% in 2022 compared to 29.22% in 2021, which of course had an impact on the reduction in sunlight duration and a significant negative reduction in solar radiation (on average 2.84 MJm^2 /day). Since the experiment also served to exploit the genetic potential of the field and the applied plant population was much higher than the national average (84000 plants/ha), it can be assumed that the effect of greater cloud cover and decreasing solar radiation may be more pronounced with such a high plant population. This empirical fact is also confirmed by the study of Yang et al. (2019) [4], in which, with increasing shading conditions (30 and 50%), higher plant populations showed a significantly greater yield reduction. In their study, Gao et al. (2017) [23] observed a 24% yield reduction with a decrease in solar radiation before the R1 phase (V6 and VT).

Table 3. Cloud cover, sunlight duration, solar radiation and accumulated GDD data of the Sc4140 hybrid growth stages in the two years studied (Debrecen-Látókép)

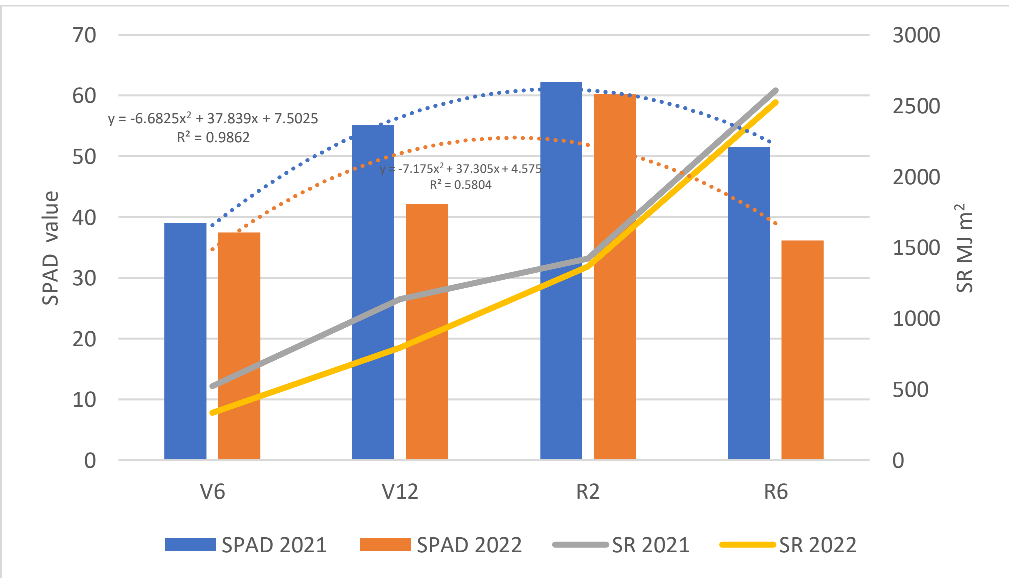
Growth stages	Years	Cloud cover total	Sunshine duration	Solar radiation	Accumulated GDD
		%	hour	MJ/m^2	°C
		Mean	Mean	Mean	Mean
VE	2021	43.20	7.92	19.07	62.6
	2022	37.63	8.34	20.78	77.1
V6	2021	42.92	8.30	20.09	214.7
	2022	29.45	9.99	22.32	215.3

V12	2021	29.22	10.94	23.56	559.1
	2022	41.34	8.68	20.72	415.7
VT	2021	30.76	10.81	22.12	699.8
	2022	19.31	12.67	25.96	693.2
R1	2021	24.75	12.17	22.47	747.5
	2022	20.52	12.28	24.77	726.1
R2	2021	25.79	11.96	22.34	844.1
	2022	42.19	9.09	21.70	850.3
R6	2021	31.85	9.48	18.51	1413.4
	2022	29.87	10.08	21.09	1375.0

3.3. Solar radiation and NDVI values in the two years studied

In both years, we compared the NDVI values in the different growth stages of the Sc4140 hybrid (Figure 1.). In 2021, we found higher NDVI values in all growth stages. This indicates that in 2021 we can see a continuously healthy stand, under near ideal conditions, while in 2022 the hybrid was burdened by constant weather anomalies during the vegetation period. At the V6 developmental stage, we measured a value of 0.46 compared to 0.33 in 2022, in the case of V12 it showed a value of 0.84 vs 0.8, but in the R6 phase it was 0.7 vs The value of 0.49 also shows that in 2022, there was a strong drying out, a high degree of abiotic stress due to the drought in the studied genotype. The amount of solar radiation can also be well monitored in the given phenophases , in 2021 the amount of solar radiation significantly exceeded the data of 2022. In the V6 phase, the accumulated value was 522 vs 334 MJm^2 from emergence, while in V12 we measured 1135 vs 795 MJm ^{2} (between V6-V12) and then these data were balanced in the remaining stages. The accumulated solar radiation value was 5689 vs 5019.1 MJm^2 in 2021 and 2022. Gong and Gong (2020) [24] quantified that a decrease in total solar radiation by 1 kJ/cm^2 (1 kJ/cm^2 = 10 MJm^2) during the maize growing season corresponds to a decrease in maize biomass yield of 337.5 kg/ha. A decrease in solar radiation has a significant impact on maize growth, development, and yield.

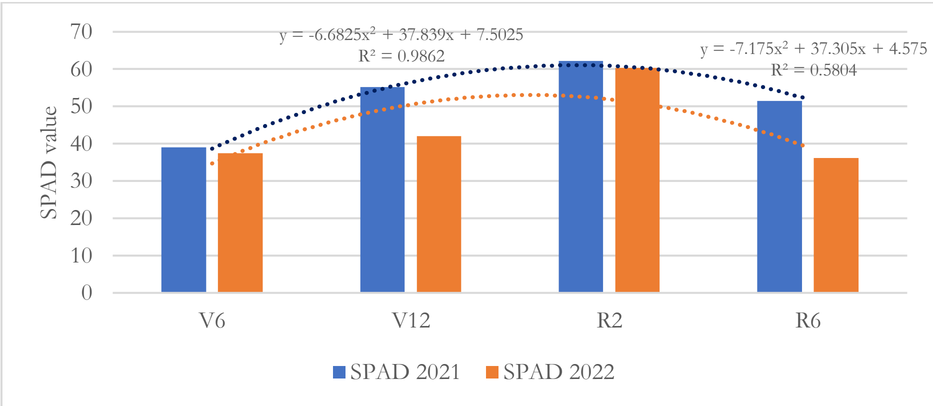
Figure 1. Change of NDVI and Solar Radiation (SR) values in different growth stages of maize (Debrecen-Látókép, 2021-2022).



3.4. Change in SPAD value in the two years examined

According to the SPAD values, the Sc4140 hybrid showed a continuous increase until the R2 phase in both years (Figure 2.). The highest values were shown at this time (62.2 and 60.3). The statistically different value of the chlorophyll concentration difference is striking in the V12 and R6 developmental phases, which confirms the anomalies read from the weather data by such measurements in 2022. Drip irrigation in 2022 was unable to reduce the rapid eye saturation and aging of the genotype, as shown by the NDVI and SPAD R6 phase values.

Figure 2. Change of SPAD values in different growth stages of maize (Debrecen-Látókép, 2021-2022).



3.5. Changes in dry matter accumulation during the grain-filling period

The dry matter incorporation of the genotype under study is shown in Table 4 from the theoretical R2 phase (0%) to the formation of the black layer (R6). It is striking that in 2021 the grain filling phase was 10 days longer than in 2022. This meant a significant amount of assimilate surplus accumulation. When evaluating the potential experimental result, it is essential to examine all environmental factors. It is known from the literature that higher than average night temperatures measured during the grain filling phase have a significant impact on the subsequent yield. Peters et al. (1971) [25] first established that high night temperatures can have a detrimental effect on maize yield. Maize grown at an average night temperature of 85ºF (29.4 °C) was able to yield 40% less than maize grown at an average night temperature of 62°F (18.3 °C). Badu-Apraku et al. (1983) [26] reported that increased nighttime temperatures reduced cob weight. Yields were further reduced when both day and nighttime temperatures were raised. In their study, elevated day temperatures were more detrimental than high nighttime temperatures, indicating that night and day temperatures affect yield independently. The yield loss was directly attributable to reduced kernel size. The smaller kernel size is likely a result of a shortened kernel development period. They measured a yield loss of 2.8 to 4.7 bu /A for each 1°F increase in nighttime temperatures in July and August in hybrids of that time. In summary, higher temperatures accelerate the phenological development of maize, allowing maize to reach black stage more quickly (R6). At the end of Table 4, looking at the average temperature data for the two years, in 2021, during the 64-day grain ripening period, the daytime temperature was 28.2 °C and the nighttime temperature was 15.4 °C, and drip irrigation until wax ripening helped to achieve the potential yield level. In 2022, the grain ripening period was reduced to only 54 days, and drip irrigation was not able to delay the ripening process even with drip irrigation. The daytime temperature was 31.9 °C, while the nighttime temperature was 18.1 °C, both values significantly exceeded the data measured during the same period in 2021.

Table 4. Dry matter incorporation dynamics (%) of the Sc4140 hybrid in different growth phases and temperature changes (Debrecen-Látókép, 2021-2022).

Year	Grain filling R1-R6	Max. Temperature	Min. Temperature	Dry matter	Daily Dry matter
	Days	°C, Mean	°C, Mean	%	%
2021	0	31.0	19.6	100	0.00
	18	30.3	19.1	30.5	3.86
	7	30.5	18.0	41.9	1.63
	7	30.5	17.4	49.9	1.14
	7	30.2	15.8	55.3	0.77
	7	26.7	14.9	58.7	0.49
	8	20.9	12.7	63.8	0.64
	6	25.2	9.9	64.8	0.17
	4	28.1	11.0	66	0.30
2022	0	31.2	17.2	100	0.00
	24	33.1	17.6	45.5	2.27
	8	32.3	18.7	53.24	0.97
	7	30.8	17.6	58.09	0.69
	7	33.1	19.0	63.72	0.80
	6	28.9	18.9	65.46	0.29
	2	33.9	17.5	67	0.77
2021	**∑64**	**28.2**	**15.4**		
2022	**∑54**	**31.9**	**18.1**		

3.6. Change in phenometric indicators

Based on the examination of the yield and phenometric characteristics of the two years, it can be said (Table 5.) that the examined weather factors (assuming that the stress and nutrient deficiency caused by the water available through drip irrigation did not affect the plant) had a great impact and continuous control on the results obtained.

In 2021, the Sc4140 hybrid achieved a yield of 20.65 t/ha, based on its fruit-forming components, ear differentiation could take place without stress and the subsequent ear length development and subsequent fertilization at flowering were also optimal. The tested ear samples were filled throughout, no tip back was observed and they were characterized by high thousand-kernel weight.

In 2022, the same hybrid achieved a yield of 13.8 t/ha. Practitioners will of course immediately find the reason for this in the phenomenon of lack of rainfall and drought, but in a potential experiment where irrigation is given, a deeper and more sophisticated investigation is appropriate. Exploring the causes and effects can help mitigate the negative effects of similar situations in the future. In 2022, the ear and grain parameters were significantly below the similar data in 2021. The weaker factors obtained during ear differentiation, affecting sunlight and through it the photosynthesis mechanism, likely played a role in the development of the smaller ear size. The NDVI data and SPAD data obtained confirmed this, and the temperature anomalies during grain filling were supported by literature data. The negative differences of 30% or more in the size of the ears, grain weight, and thousand grains compared to 2021 explain the yield difference between the two years (33.2%).

Table 5. Yield and phenometric characteristics of the Sc4140 hybrid (Debrecen-Látókép, 2021-2022)

Phenometric characteristics	Years	
	2021	2022
	Yield (t/ha-1)	
	20.65	13.8
Thousand Kernel Weight (g)	370 a	264 b
Grain / ear(g)	231 a	163 b
Ear (g)	272 a	191 b
Length of ear (cm)	21,6 a	18,4 b
Number of kernels	17 a	16 a
Diametric of ear (mm)	55,5 a	53,6 b

Note: values marked with different letters are significantly different from each other at the $p<0.05$ level.

4. Discussion

In precision agriculture, in addition to the development of site-specific cultivation technology, great emphasis is placed on monitoring plants during vegetation and their response to abiotic stress factors. Rapid recognition of reactions under stressful conditions can provide an immediate opportunity for intervention.

In general, rising temperatures, increases in heat totals, decreasing precipitation and hectic changes in solar radiation can be observed in Hungary as well. Changes in this series of meteorological factors closely related to maize production will inevitably affect maize production in Central Europe, including the maize-producing regions of Hungary.

In this study, we investigated the reasons for the large (33%) yield difference between the two years studied. A deeper interpretation of the weather data suggests that the reduced solar radiation and sunlight duration during the vegetative growth stage, in parallel with cloud cover, can affect the reproductive phase of maize (smaller ear size, lower yield potential). After weighing the harvested ears, it can be determined that we obtained significantly smaller ear length and grain number, which indicates stress between the V6-V12 stage. In the two years studied, we measured a significant difference in the solar radiation value in the V6 and V12 developmental stages (36% and 30% less solar radiation was measured in 2022 compared to 2021). This was also measured in the NDVI and SPAD values, which were also higher in 2021 at the V6 and V12 stages. We monitored GDD values and the number of days between each phenological phase throughout the vegetation. In 2021, there were 64 days between flowering and physiological maturity, while in 2022 this grain-filling stage decreased to 54 days. The average daytime temperature of the grain-filling stage was 3.7°C higher than in 2021, and the nighttime temperature was also 2.7°C higher on average. In summary, the higher temperature accelerated the phenological development of maize, so that maize reached the black layer formation (R6) faster. The chlorophyll concentration of the leaves (SPAD) and the NDVI values in 2022 also showed the rapid maturation and aging process of the hybrid with high reliability. Examining the phenometric characteristics of the 2022 harvest, we obtained significantly lower thousand-kernel weight and ear weight compared to the same data in 2021. In 2022, drip irrigation (supplemented with nutrient solution) was not able to delay the ripening process.

In precision agriculture (PrA) technologies, weather sensors and the collection of accurate weather data are vital. They should be an integral part of big data. Year after year, more and more accurate and sophisticated data collection options are opening up in crop production, for example, recording different leaf zones of plants in the study of leaf temperature, leaf moisture and humidity. By analyzing such data, based on the information obtained in the study, day and night temperature data, and GDD, our goal in precision agriculture can be to improve the health of the maize stand and extend the grain filling period. The use of biostimulants applied during the ear differentiation period, based on the above information, can improve the development of reproductive organs. PrA technology effectively supports farmers in making informed decisions regarding nutrient application, timing of biostimulants, and irrigation, thereby maximizing yields and reducing negative impacts from weather.

The test results pointed out that in the future, it is necessary to address the responses of maize hybrids to different levels of solar radiation and to temperature changes during their dry matter incorporation dynamics. This is not only important during hybrid testing, but the production of low-light and heat stress-tolerant lines will also be a new challenge in plant breeding. Knowing the exact environment x genotype, with the help of appropriate weather forecasts, it becomes possible to carry out interventions that help eliminate abiotic stress factors (shading through "lime painting", application of biostimulants, targeted nutrients).

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