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Prediction of soybean productivity based on the photothermal quotient

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Abstract

Climatic variables affect soybean yield components. Understanding how they are interrelated is essential for planning and boosting crop productivity. The aim of this study was to evaluate whether the photothermal quotient can be used to predict the productivity and 1000-grain weight of soybean. Five experiments were carried out at the Federal University of Santa Maria in growing seasons of 2013/14 to 2017/18 using the main cultivars (154) sown in the state of Rio Grande do Sul (RS), Brazil. The experiments were organized in a randomized block design with four replicates, evaluating grain productivity and 1000-grain weight. The results showed that years with the highest grain productivity and 1000-grain weight were associated with regular rainfall and high photothermal quotients (approximately 2.3 MJ m^{-2}). There was a positive and significant correlation between grain productivity and the average number of days without rainfall ($r = 0.98$). In addition, there was a negative correlation with air temperature ($r = -0.8$). Air temperature and days without rain are decisive factors for yield and grain weight. The photothermal quotient can be used as a basis for predicting soybean grain productivity.

Keywords: Sunlight; rainfall; solar radiation; temperature.
Abbreviations: PQ_ photothermal quotient, r_ Person coeficient of correlation, g_ gramas, TGW_Thousand grain weigth, NDWR_Numbers of day without rain, R_daily solar radiation, T_temperature.

Introduction

Soybean farming (*Glycine max* (L.) Merrill) ranks sixth in terms of yield and fourth in terms of cultivated area worldwide (FAOSTAT, 2019). In Brazil, the soybean area varies as the crop is incorporated into rotation systems with other crops and/or planted in new cultivation areas. The grain is rich in proteins and oils, and essential for global food security. It is consumed by humans and animals, and used to produce fuel and in the pharmaceutical industry. However, average productivity varies due to climatic fluctuations during the growing season (CONAB, 2019). The grain productivity and yield components vary depending on the environment.

The cultivation of soybean is among the human activities most vulnerable to climatic variables (Ramirez-Villegas and Challinor, 2012). Factors such as temperature, rainfall, sunlight and solar radiation directly and indirectly influence soybean crop cycle events (Ellwood et al., 2012). Climate variables affect the quantity and density of grains per unit area, in addition to impacting productivity (Talukder et al., 2013; Rose et al., 2016). Models have been defined in various studies to confirm that future productivity of agricultural crops will tend to fall based on the climatic prognoses (Sundström et al., 2014; Asseng et al., 2015; Bhattarai et al., 2017; Zhao et al., 2017). It is necessary to understand that climatic variables affect crop productivity, and that adaptating to each of these effects involves different physiological processes and requires specific agronomic management systems (Sadras et al., 2015). In addition, cultivars with longer cycles could facilitate adaptation by mitigating climatic stresses (Vadez et al., 2012). The environmental changes brought about by global warming means that plants are less able to mitigate biotic stresses caused by pests (Newton et al., 2012).

The air temperature acts as a growth and development regulator, the optimum temperature range for cropping soybean is from 20 to 30 °C, and the likelihood of reaching maximum yield potential increases if plants are exposed to temperatures close to 30 °C for longer periods (Smiderle et al., 2009). Plants grown within this temperature range perform better in terms of productivity (Devasirvatham et al., 2012; Kaushal et al., 2013). Solar radiation is essential for photosynthesis, triggering the formation of plant biomass (Sandaña and Pinochet, 2011). The availability of solar radiation is directly linked to latitude and time of year. The canopy's capacity to intercept this radiation is related to the phenological stage of the crop and sunlight availability. For soybean crop, solar radiation use efficiency is estimated to gradually increase up to stages R1 and R2, and is influenced by air temperature and water availability. However, the duration of the crop cycle is defined by the photoperiod (Nico et al., 2019), which is related to the relative maturity of the cultivar (Alliprandini et al., 2009), as well as the effects of factors such as temperature, radiation and rainfall (Abrahão and Costa et al., 2018).

Crop productivity is affected by water availability. Soil saturation by excess water impairs physiological functions

such as photosynthesis, phytohormone concentration and nutrient absorption (Valliyodan et al., 2017). Water deficiency impairs shoot growth (Yamaguchi and Sharp, 2010), even if root growth is continuous (Lenssen, 2012), resulting in a drop in yield potential (Song et al., 2016). The potential productivity of some crops is related to the photothermal quotient (PQ) (Ahmed et al., 2011), i.e. the ratio between average daily solar radiation and the average daily temperature, subtracted from the crop's base temperature (Silva et al., 2014). PQ is used to predict or explain grain productivity, since crop cycle events are determined by variations in climatic factors (Bassu et al., 2010).
Understanding of climatic factors that interrelate with soybean productivity is important for estimation of environmental change scenarios. Cultivar cycles are determined by the interaction between air temperature and photoperiod (Fietz and Rangel, 2008). Efficient management ensures that most sensitive stages of crop development do not coincide with periods of climatic stress and/or the definition of yield potential covers climatic factors compatible with crop requirements (Donnatelli et al., 2017).
Therefore, the aim of this study was to evaluate whether the photothermal quotient can be used to predict soybean crop productivity and 1000-grain weight.

Results and discussion

Climate correlations

Based on the averages for the climatic variables and average productivity values, the highest average productivity was found in the following years: 2017/2018, 2016/17, 2014/15, 2013/2014 and 2015/16, respectively (Table 1). There was a positive and significant correlation between grain productivity and the average number of days without rainfall (r=0.98). Solar radiation is the factor that triggers photosynthesis and the formation of carbon skeletons. Therefore, greater the availability of solar radiation cause greater capacity for the formation of carbohydrates subsequently translocated to the grains. Other factors are also related to grain productivity, such as the regularity of rainfall during the crop cycle. The soybean crop needs cumulative rainfall of 450 to 800 mm during the growth cycle (Franke and Dorfman, 2000). In this study, the rainfall in all years was greater than this minimum. However, in years in which rainfall was lower but still sufficient to meet the demands of the crop and distributed evenly, grain productivity is higher. However, climate variability means that even with rainfall very close to the minimum required, but more uniformly distributed (Figure 1), productivity is boosted (Valliyodan et al., 2017). Thus, the more days with rainfall, the lower the productivity (r=0.72), indicating that when rainfall occurs mainly during the day, there is less photosynthetically active radiation capable of generating net photosynthesis that will be converted into biomass (Mariano, 2011). This is aggravated by high nighttime temperatures, resulting in high transpiratory rates that reduce the accumulation of biomass (Vadez et al., 2012).

Photothermal quotient

The ratio of soybean productivity to the photothermal quotient is high (r=0.96 *), indicating that average daily temperature is an important climatic variable (r= -0.80). The photothermal quotient is more representative in increase in grain productivity (Ahmed et al., 2011). In other words, the higher average daily temperature is usually coincides with more direct solar radiation, boosting the average productivity of the soybean crop due to relationship between sunlight and solar radiation (r= 0.97). Dreccer et al. (2014) point out that the average temperature for the soybean crop to reach high yield potential is between 20 and 30 °C. In average daily temperatures above 30º C, evapotranspiration from the canopy is high, resulting in a drop in average grain productivity (r.0.8). The temperatures in this experiment do not cover extreme data recorded during the day, which would require hourly or even instantaneous temperature readings. Between December and February, the temperature peaked between midday and 4 pm. It exceeded 30 °C and the frequency of occurrence of these peak temperatures had an impact on grain productivity. Jumrani et al. (2017) concluded that the highest rate of photosynthesis occurs when the average maximum and minimum daily temperatures are between 28 ºC and 22.4 °C. The photosynthetic activity falls if these averages rise.
Thousand-grain weight is significantly influenced by cultivar genetics, but the environment also influences this characteristic. The number of rainy days (r= -0.93 *) and cumulative rainfall have an adverse effect on this variable. It can be seen that an increase in the number of days between rains (0.98 *) together with higher grain productivity helps to increase 1000-grain weight.
Based on the linear relationships in Figure 2 for 1000-grain weight over the five-year experimental period, the variations was in PQ: 23.66%, sunlight: 36.26%, temperature: -6.49% and rainfall: -39.31% resulted in fluctuations in this variable of 30.75 g, 34.68 g, 22.05 g and 31.62 g, respectively. Thus, in descending order of importance, they are temperature, rainfall, sunshine and photothermal quotient. For each 1% increase in average air temperature and rainfall, there would be a respective drop of 3.4 g and 0.8 g in the 1000-grain weight, so that for each 1% increase in sunshine and the photothermal quotient, the 1000-grain weight increases by a respective 0.95 g and 1.3 g.
This is because, with an increase in temperature, the beginning of florescence will be speeded up, reducing the growth period and increasing crop evapotranspiration, contributing to the lower grain weight (Vadez et al., 2012). Similarly, high rainfall impairs soybean development, reducing oxygen levels in plant tissues and roots, and impairing nutrient absorption from the soil (Valliyodan et al., 2017). This effect is intensified when high rainfall occurs at the grain filling stage, since it changes the plant's source/sink ratio. In other words, grains are formed but grain density can be impaired as results of environmental conditions that reduce translocation and consequently 1000-grain weight. The cumulative number of sunlight hours is directly dependent on the number of days with rainfall (Figure 1), raising the photothermal quotient, which could explain the variations in the 1000-grain weight (144.5 g to 186 g). Bassu et al. (2010), explained the variation in the weight of ears of wheat in terms of the variation in the photothermal quotient (Figure 2).
TGW is known to be the last yield component defined and it is highly influenced by genetic factors, with the result that environmental factors must be very intense to change this variable. It is dependent on the partitioning of the carbohydrates formed and temporarily stored in the plant for subsequent translocation to the grains, which begins at stage R5.1. As a result, if environmental conditions cause a

Table 1. Averages and correlation between grain productivity and climatic variables (NRD: number of rainy days, CR: cumulative rainfall during the cycle, RAD: cumulative radiation, CS: number of hours of cumulative sunshine, ADWR: average days without rainfall, SD: standard deviation for days without rainfall, AR: average rainfall, PTQ: photothermal quotient, TM: average cycle temperature, GP: average grain productivity in each experiment, and TGW: 1000-grain weight).

Year	NRD	AR	RAD	IA	ADWR	SD	AR	PTQ	TM	GP	TGW
2013/14	70.00	1055.70	3699.31	1379.50	3.00	2.77	15.08	1.98	24.22	2478	145.8
2014/15	60.00	968.60	3603.91	1345.70	3.73	3.29	16.14	2.07	23.53	3155	163.7
2015/16	76.00	1076.40	3208.66	1071.20	3.09	2.23	14.16	1.86	23.37	2491	144.5
2016/17	71.00	1084.00	3569.36	1287.70	3.83	3.16	15.27	2.27	22.63	3695	159.3
2017/18	52.00	657.90	3689.13	1459.60	4.52	3.33	12.65	2.30	22.88	4160	186.6
Correlation between cultivar average grain productivity and climatic variables											
	-0.72	-0.72	0.46	0.58	0.98*	0.80	-0.42	0.96*	-0.80	---	0.92*
Correlation between cultivar 1000-grain weight and climatic variables											
	-0.93*	-0.91*	0.52	0.68	0.98*	0.79	0.52	0.82	-0.57	0.92*	---

* Significant at 5% by Pearson's test.

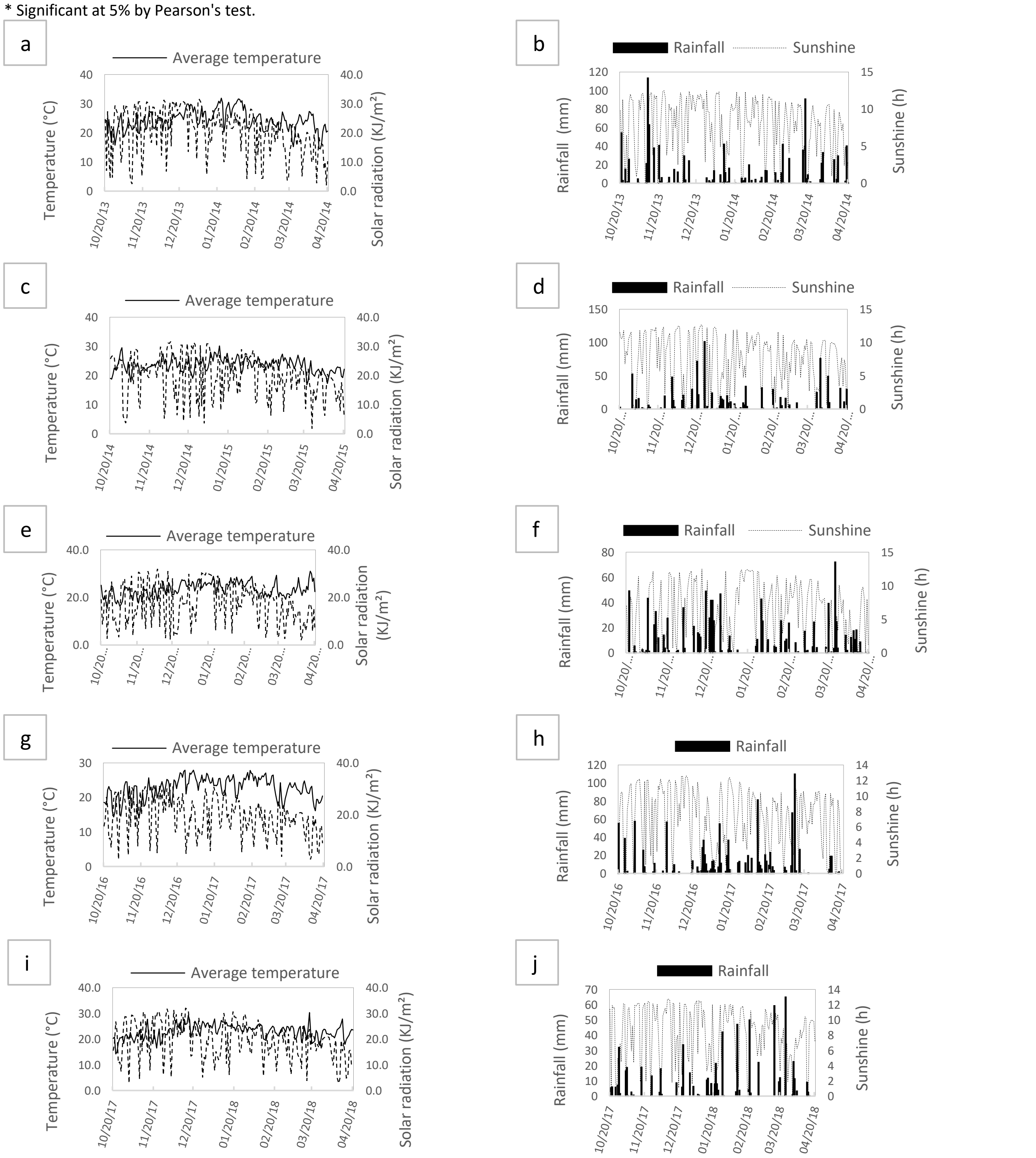

Figure 1. Average air temperature (ºC), solar radiation (MJ m^{-2}), rainfall (mm day^{-1}) and sunlight (hours), for soybean crops from 2013/14 to 2017/18 during the experiments in Santa Maria, Brazil.

Table 2. 1000-grain weight (TGW, g), grain productivity (PG, kg ha^{-1}), and percentage productivity compared to the average for soybean cultivars cropped in the state of Rio Grande do Sul (% x RS) in the 2013/14 growing season. Santa Maria, Brazil.

2013/14 Cultivars	Owner	RMG	TGW		GP		%xRS
Bmx Potencia RR	Brasmax	6.7	143.42	d	2750.88	c	101.96
Fun 65 RR	Fundacep	5.9	173.02	a	3139.63	b	116.37
TEC 5936 IPRO	Basf	6.1	163.41	b	2867.87	b	106.30
Bmx Turbo RR	Brasmax	5.8	153.13	c	3044.53	b	112.84
Bmx AtivaRR	Brasmax	5.6	166.39	b	3521.29	a	130.51
TEC 5833IPRO	Soytech	5.8	163.40	b	2793.26	b	103.53
TEC 6029IPRO	Soytech	5.7	180.84	a	2678.81	c	99.29
Bmx TornadoRR	Brasmax	6.2	125.48	f	2490.23	d	92.30
Bmx Força RR	Brasmax	6.2	147.66	d	2455.46	d	91.01
TEC 5718 IPRO	Basf	5.7	133.51	e	2667.35	c	98.86
TEC 6070 RR	Basf	6.3	134.36	e	1990.48	d	73.78
Bmx Magna RR	Brasmax	6.2	142.12	d	2826.60	b	104.77
Bmx Apolo RR	Dom Mário	5.5	135.30	e	2437.49	d	90.34
Fun 57 RR	Fundacep	6.7	175.83	a	1552.25	d	57.53
Fun 66 RR	Fundacep	6.0	153.58	c	2362.94	d	87.58
NK 7059 RR	Syngenta	6.4	136.37	d	2380.04	d	88.21
V-TOP RR	Syngenta	5.9	153.63	c	2484.23	d	92.08
TEC 5958 IPRO	Basf DM	5.8	145.20	d	2243.10	d	83.14
TEC 7166 IPRO	Basf BMX	6.6	131.70	e	2093.31	d	77.59
Syn 1363 IPRO	Syngenta	6.3	140.51	d	2297.56	d	85.16
Syn 1163 RR	Syngenta	6.3	132.56	e	2254.40	d	83.56
TEC 6563 IPRO	Basf DM	6.3	146.46	d	2175.79	d	80.64
TEC 6458 IPRO	Basf DM	5.8	119.85	f	2102.79	d	77.94
Syn 1258 RR	Syngenta	5.8	119.48	f	2558.98	d	94.85
Syn 1263 RR	Syngenta	6.3	127.09	f	2293.04	d	84.99
TEC 6160 IPRO	Basf	6.0	139.08	d	2485.94	d	92.14
DM 7.01	Dom Mário	7.0	127.29	f	2226.09	d	82.51
Syn 1365 RR	Syngenta	6.5	138.53	d	2429.89	d	90.06
NS 6411RR	Nidera	6.4	149.25	d	2608.33	c	96.68
NS 4823 RR	Nidera	4.8	151.92	c	2128.55	d	78.89
NS 5909 RG	Nidera	6.2	144.45	d	2237.25	d	82.92
A 4725 RG	Nidera	4.9	169.61	b	2745.42	c	101.76
Overall Average.			145.8		2478.87		91.88
Average for RS					2698.00		
CV (%)			5.75		12.21		

CV (%): Percentage coefficient of variation. RMG: relative maturity group.

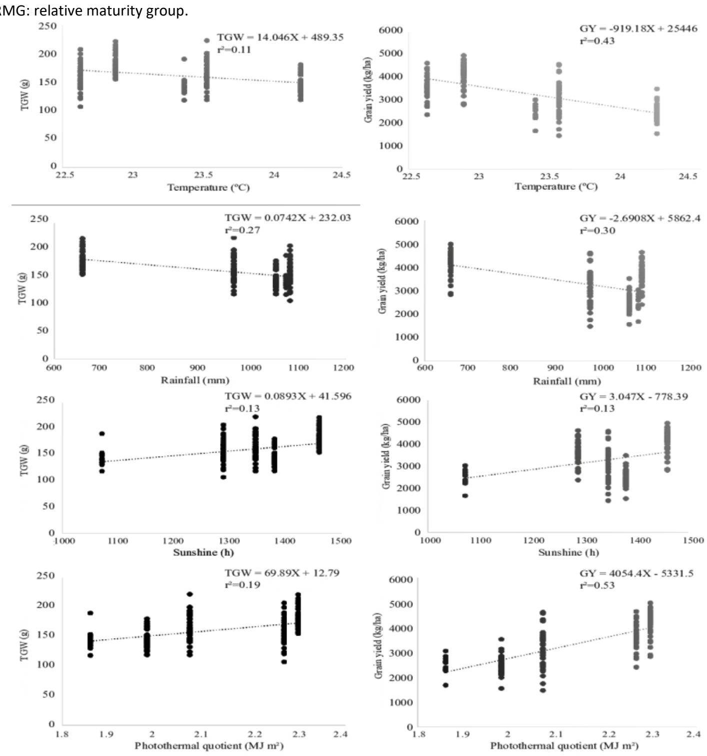

Figure 2. Grain productivity and 1000-grain weight (TGW) correlated with cumulative rainfall, average daily temperature, cumulative sunlight and photothermal quotient for the experimental cropping period.

Table 3. 1000-grain weight (TGW, g), grain productivity (PG, kg ha^{-1}), and percentage productivity compared to the average for soybean cultivars cropped in the state of Rio Grande do Sul (% x RS) in the 2014/15 growing season. Santa Maria, Brazil.

2014/15 Cultivars	Owner	RMG	TGW		GP		%xRS
SYN 1359 IPRO	Syngenta	5.9	156.0	d	2765	c	105.78
SYN 1365 RR	Syngenta	7.1	187.0	c	4317	a	165.15
SYN 1258 RR	Syngenta	5.8	142.0	e	2994	c	114.54
SYN 1163 RR	Syngenta	6.3	145.0	e	2244	d	85.85
SYN 13671 IPRO	Syngenta	7.3	144.0	e	3140	b	120.12
SYN 13561 IPRO	Syngenta	5.6	156.0	d	3014	c	115.30
V-TOP RR	Syngenta	5.9	164.0	d	3779	b	144.57
FUNDACEP 65 RR	Fundacep	5.9	165.0	d	3539	b	135.39
FUNDACEP 57 RR	Fundacep	6.7	145.0	e	2449	c	93.69
FUNDACEP 66 RR	Fundacep	6.0	223.0	a	3548	b	135.73
TEC IRGA 6070 RR	Basf	6.3	143.0	e	2552	c	97.63
TEC 9295 RR	Basf	6.8	146.0	e	2401	c	91.85
TEC 5718 IPRO	Basf	5.7	142.0	e	2562	c	98.01
TEC 5833 IPRO	Basf	5.8	188.0	c	2768	c	105.89
TEC 5936 IPRO	Basf	5.9	195.0	b	1467	d	56.12
TEC 6029 IPRO	Basf	6.0	194.0	b	2980	c	114.00
TEC 6702 IPRO	Basf	6.7	189.0	c	3336	b	127.62
TEC 7849 IPRO	Basf	7.8	119.0	f	1751	d	66.99
BMX ATIVA RR	Brasmax	5.6	191.0	c	3676	b	140.63
BMX VANGUARDA IPRO	Brasmax	6.0	158.0	d	2509	c	95.98
BMX TORNADO RR	Brasmax	6.2	153.0	d	3300	b	126.24
BMX VALENTE RR	Brasmax	6.7	174.0	c	2313	d	88.49
BMX MAGNA RR	Brasmax	6.2	175.0	c	3347	b	128.04
BMX PONTA IPRO	Brasmax	6.6	157.0	d	3117	b	119.24
BMX POTÊNCIA RR	Brasmax	6.7	145.0	e	2873	c	109.91
BMX TURBO RR	Brasmax	5.8	200.0	b	3695	b	141.35
M 5917 IPRO	Monsoy	5.9	161.0	d	3472	b	132.82
M 5947 IPRO	Monsoy	5.9	160.0	d	4260	a	162.97
M 6210 IPRO	Monsoy	6.2	141.0	e	3590	b	137.34
M 6410 IPRO	Monsoy	6.4	148.0	e	3144	b	120.28
DM 5958 RSF IPRO	Dom Mário	5.8	181.0	c	4606	a	176.21
DM 6563 RSF IPRO	Dom Mário	6.3	170.0	c	2891	c	110.60
DM 6458 RSF IPRO	Dom Mário	5.8	180.0	c	3543	b	135.54
NS 6006 IPRO	Nidera	5.7	186.0	c	3514	b	134.43
NS 6700 IPRO	Nidera	6.7	125.0	f	2051	d	78.46
NS 5106 IPRO	Nidera	5.1	166.0	d	3454	b	132.13
NA 5909 RR	Nidera	6.2	156.0	d	3516	b	134.51
NS 6209 RR	Nidera	6.2	133.0	f	3592	b	137.41
NS 5290 RR	Nidera	5.2	148.0	e	3138	b	120.05
NS 5258 RR	Nidera	5.3	160.0	d	3605	b	137.91
TMG 7062 IPRO	Tmg	6.2	201.0	b	4563	a	174.56
FPS URANO RR	Fps	6.2	165.0	d	3804	b	145.52
Overall Average.			163.7		3155.5		120.71
Average for RS					2614.00		
Cv (%)			6.59		11.81		

CV(%): Percentage coefficient of variation. RMG: relative maturity group.

Table 4. 1000-grain weight (TGW, g), grain productivity (PG, kg ha^{-1}), and percentage productivity compared to the average for soybean cultivars cropped in the state of Rio Grande do Sul (% x RS) in the 2015/16 growing season. Santa Maria, Brazil.

2015/16 Cultivars	Owner	RMG	TGW		GP		%xRS
BMX TORNADO RR	Brasmax	6.2	131.1	b	2744.92	a	92.081
BMX VALENTE RR	Brasmax	6.7	144	b	2612.35	a	87.633
TEC IRGA 6070 RR	Basf	6.3	135.1	b	2291.25	b	76.862
TEC 7849 IPRO	Basf	7.8	118.5	b	1675.73	c	56.214
TEC 6702 IPRO	Basf	6.7	190.6	a	2387.73	b	80.098
SYN 13671 IPRO	Syngenta	7.3	148.3	b	3049.1	a	102.284
NS 5258 RR	Nidera	5.2	151.1	b	2254.32	b	75.623
NS 5106 IPRO	Nidera	5.2	153.9	b	2590.02	a	86.884
NS 5909 RR	Nidera	6.2	139.5	b	2635.91	a	88.424
NS 6700 IPRO	Nidera	7.1	136.1	b	2843.36	a	95.383
M 5917 IPRO	Monsoy	5.9	141	b	2319.24	b	77.801
Overall Average.			144.5		2491.26		83.571
Average for RS					2981.00		
CV (%)			8.28		12.53		

CV (%): Percentage coefficient of variation. RMG: relative maturity group.

Table 5. 1000-grain weight (TGW, g), grain productivity (PG, kg ha^{-1}), and percentage productivity compared to the average for soybean cultivars cropped in the state of Rio Grande do Sul (% x RS) in the 2016/17 growing season. Santa Maria, Brazil.

2016/17 Cultivars	Owner	RMG	TGW		GP		%xRS
BMX Potência RR	Brasmax	6.7	151.4	d	4218.1	a	128.25
BMX Ponta IPRO	Brasmax	6.6	152.4	d	3891.32	a	118.31
BMX Garra IPRO	Brasmax	6.3	162.6	c	3239.64	b	98.50
BMX Lança IPRO	Brasmax	5.8	140.9	d	3649.59	b	110.96
BMX 5855 RSF IPRO	Brasmax	5.5	152.4	d	3571.31	b	108.58
BMX IconeIPRO	Dom Mário	6.8	191.1	b	3664.83	b	111.43
M 6410 IPRO	Monsoy	6.4	124.1	e	3176.86	b	96.59
M 5892 IPRO	Monsoy	5.8	121.1	e	3792.77	a	115.32
DM 61I59 RSF IPRO	Dom Mário	5.9	167.1	c	3395.36	b	103.23
BMX TornadoRR	Brasmax	6.2	145.9	d	3379.44	b	102.75
BMX VALENTE RR	Brasmax	6.7	182.7	b	3369.92	b	102.46
DM 6368 RSF IPRO	Dom Mário	6.8	143.6	d	3626.26	b	110.25
BMX 50I51 RSF IPRO	Brasmax	5.1	178.1	c	3740.78	b	113.74
DM 5947 IPRO	Dom Mário	5.9	145.9	d	3658.73	b	111.24
BMX ATIVA RR	Brasmax	5.6	130.9	e	3500.75	b	106.44
NS 6209 RR	Nidera	6.2	139.3	d	4106.04	a	124.84
TMG 7063 IPRO	Tmg	6.3	200.2	a	2934.85	c	89.23
TMG 7262 RR	Tmg	6.2	187.9	b	3913.02	a	118.97
TMG 7363 RR	Tmg	6.3	170.2	c	3382.32	b	102.84
TMG 7062 RR	Tmg	6.2	207.9	a	3887.8	a	118.21
AS 3539 IPRO	Agroeste	6.0	160.7	c	3427.96	b	104.22
NS 5959 IPRO	Nidera	5.9	161.3	c	4047.67	a	123.07
NS 6535 IPRO	Nidera	6.5	155.6	d	3674.8	b	111.73
NS 6700 IPRO	Nidera	6.7	139.7	d	2750.44	c	83.63
NS 5258 RR	Nidera	5.3	141.8	d	2806.7	c	85.34
NA 5909 RG	Nidera	6.2	148.2	d	4425.13	a	134.54
NS 6006 IPRO	Nidera	5.7	169.9	c	3575.56	b	108.71
SYN 1562IPRO	Syngenta	6.2	174.6	c	4360.41	a	132.58
SYN 1561IPRO	Syngenta	6.1	168.8	c	4092.84	a	124.44
SYN 13671IPRO	Syngenta	7.3	163.2	c	4401.28	a	133.82
SYN 1050RR	Syngenta	6.3	169.9	c	4648.48	a	141.33
SYN 13561IPRO	Syngenta	5.6	156.7	d	4447.3	a	135.22
Overall Average.			159.3		3695.76		112.37
Average for RS					3289.00		
Cv (%)			6.71		12.44		

CV (%): Percentage coefficient of variation. RMG: relative maturity group.

Table 6. 1000-grain weight (TGW, g), grain productivity (PG, kg ha^{-1}), and percentage productivity compared to the average for soybean cultivars cropped in the state of Rio Grande do Sul (% x RS) in the 2017/18 growing season. Santa Maria, Brazil.

2017/18 Cultivars	Owner	RMG	TGW		GP		%xRS
M5892 IPRO	Monsoy	5.7	155.47	d	4546.25	a	152.05
M5947IPRO	Monsoy	5.9	166.92	d	4988.22	a	166.83
M6410IPRO	Monsoy	6.4	162.80	d	4337.87	a	145.08
59I60 RSF IPRO	Brasmax	5.9	157.72	d	4548.67	a	152.13
68I70 RSF IPRO	Brasmax	6.8	207.87	a	4023.85	a	134.58
6968 RSF RR	Brasmax	6.7	187.47	b	4388.27	a	146.76
BRS 6203 RR	Embrapa	6.2	164.65	d	4312.65	a	144.24
DELTA IPRO	Brasmax	5.9	171.75	c	4497.90	a	150.43
ELITE IPRO	Brasmax	5.5	179.75	c	4555.92	a	152.37
GARRA IPRO	Brasmax	6.3	191.00	b	4284.95	a	143.31
GARRA IPRO	Brasmax	6.3	187.87	b	4682.20	a	156.60
LANÇA IPRO	Brasmax	5.8	186.85	b	4777.22	a	159.77
M5730 IPRO	Monsoy	5.7	174.25	c	4376.50	a	146.37
M5947 IPRO	Monsoy	5.9	162.57	d	4200.67	a	140.49
M6410 IPRO	Monsoy	6.4	168.75	c	4205.07	a	140.64
NA 5909 RG	Nidera	6.2	178.82	c	4666.27	a	156.06
NS 5258RR	Nidera	5.3	186.32	b	4109.32	a	137.44
NS 5445 IPRO	Nidera	5.4	187.75	b	4148.15	a	138.73
NS 5959 IPRO	Nidera	5.9	176.47	c	4819.50	a	161.19
NS 6006 IPRO	Nidera	5.7	187.45	b	3898.17	b	130.37
NS 6209 RR	Nidera	6.2	171.12	c	4601.37	a	153.89
NS 6535 IPRO	Nidera	6.5	188.77	b	4541.10	a	151.88
NS 6601 IPRO	Nidera	6.6	170.20	c	4241.07	a	141.84
NS 6700 IPRO	Nidera	6.7	182.10	c	3636.57	b	121.62
NS 6909 IPRO	Nidera	6.3	197.27	b	4447.02	a	148.73

POTÊNCIARR	Brasmax	6.7	173.65	c	3813.19	b	127.53
RAIOIPRO	Brasmax	5.0	185.87	c	3411.72	b	114.10
TEC 7849 IPRO	Basf	7.8	158.40	d	3817.65	b	127.68
TEC IRGA 6070 RR	Basf	6.3	171.75	c	2834.30	c	94.79
TMG 1759 RR	Tmg	5.9	179.47	c	4356.65	a	145.71
TMG 7061 IPRO	Tmg	6.1	197.42	b	4159.02	a	139.10
TMG 7062 IPRO	Tmg	6.2	221.85	a	4139.45	a	138.44
TMG 7063 IPRO	Tmg	6.3	206.47	a	3874.60	b	129.59
TMG 7067 IPRO	Tmg	6.7	210.85	a	2886.12	c	96.53
TMG 7262 RR	Tmg	6.2	215.57	a	3826.37	b	127.97
DM 61I59 RSF IPRO	Dom mario	6.1	201.25	a	3206.92	c	107.25
DM5958 IPRO	Dom mario	5.8	182.07	c	3462.95	b	115.82
Overall Average.			186.6		4160.10		139.13
Average for RS					2990.00		
Cv (%)			6.432		9.663		

CV (%): Percentage coefficient of variation. RMG: relative maturity group

drop in translocation, there will be a significant drop in TGW. Grain productivity is the result of combining various yield components and environment factors, and the interactions between them. Based on variations in climatic variables (PQ: 23.66%, sunlight: 36.26%, temperature: -6.49% and rainfall: -39.31%), grain productivity can be impacted by a respective 1783.94 kg ha^{-1}, 1181.01 kg ha^{-1}, 1491.2 kg ha^{-1} and 1146.5 kg ha^{-1} under the influence of these variables. The variables, in descending order of importance, for grain productivity proved to be similar to those influencing TGW. Each percentage increase in average air temperature and rainfall correlated with a respective drop of 229.85 kg ha^{-1} and 29 kg ha^{-1}. However, if the sunlight and the photothermal quotient increase by 1%, productivity will increase by a respective 32.57 kg ha^{-1} and 75.39 kg ha^{-1}. The multiple regression coefficients for estimating grain productivity is: PG = -2944.9203 + 705.6013 NDWR - 1706.3764 PQ ($p < 0.05$, r^2 = 0.98).

An increase in temperature significantly influences the duration of the soybean cycle by limiting the daily net production of biomass, which may result in a 15 to 30% drop in grain productivity (Deryng et al., 2011). In this sense, Tamang et al. (2014), found that high rainfall can cause soil water saturation, reducing productivity by up to 27% due to inhibited root growth, and reductions in net photosynthesis, concentration of phytohormones and absorption of nutrients (Valliyodan et al., 2017). Solar radiation availability and quality, expressed in terms of sunlight and the photothermal quotient, are essential for soybean productivity (Raines, 2011). According to Caron et al. (2018), grain productivity increases with the availability of radiation, and a 10% increase in the availability of radiation boosted grain productivity by 4.65%. The photothermal quotient has been shown to be directly proportional to soybean productivity. Ahmed et al. (2011) found the same relationship between PTQ and productivity for wheat crops, and this could also apply to pea (Poggio et al., 2005) and melon (Bouzo et al., 2015). Thus, PQ becomes an important tool to predict soybean productivity. The experimental results clearly indicate that the yield is directly proportional to PQ as long as all other resources are optimally available.

Material and methods

Field experiments

Five experiments were conducted at the Federal University of Santa Maria during the 2013/2014 to 2017/2018 growing seasons. The site is located at latitude 29 ° 42' South, longitude 53 ° 42' West, elevation 116 m. The soil classification is typical Red Dystrophic Argisol (EMBRAPA, 2013) or Ultisol (USDA, 2014). According to the Köppen system, the climate is Cfa (humid subtropical) (Alvares et al., 2013; Tapiador et al., 2019). The average temperature of the hottest month is 24.8ºC and of the coldest month 14.1ºC (Heldwein et al., 2009).

The main commercial soybean cultivars (cultivar assessment) available for each growing season were compared (Table 2 to Table 6) using a randomized block experimental design with four replicates. The experimental units consisted of five rows spaced 0.45m^2 giving a total area of 15.75 m^2. The experiments were managed according to the technical recommendations for soybean cropping in the South of Brazil, with target yields higher than 4 t ha^{-1}. The decision to harvest was based on the physiological maturity of the cultivars with the grain moisture adjusted to 13%. Two crop variables were evaluated: productivity and 1000-grain weight for the cultivars over the 5-year experimental period.

Climatic variables

The climatic variables evaluated were air temperature, solar radiation, sunlight and cumulative rainfall during the experimental period (OCT 20 to APR 20 in each year). Data were collected from the National Meteorological Institute (INMET) and from the conventional weather station run by the 8th Meteorological District of the National Meteorological Institute (DISME/INMET) situated approximately 1.4 km from the experimental site. The average air temperature was determined based on the arithmetic mean of all the average daily temperatures during the period. Photothermal quotient values (PQ, MJ m^{-2} day^{-1}) were determined for the period between sowing and harvesting (Oct 20 to Apr 20 in each growing season), according to the method proposed by Monteiro (2009): PQ: R/T, where "R" is the average daily solar radiation (MJ m^{-2} day^{-1}), and "T" is the average temperature for the same period (ºC). According to INMET (2009), the soybean base temperature is 14° C.

Statistical analysis

The climatic variables were subjected to position and spread analysis to characterize each year, and the correlation (r) between climatic variables and grain productivity tested. In each growing season, the cultivars were compared by analysis of variance (F-test) and Scott-Knott mean range testing at 5% significance using SISVAR® software (Ferreira, 2011).

Conclusions

The photothermal quotient is an adequate predictor of soybean grain productivity.

Grain productivity increases with solar radiation and sunlight and reduces with rainfall and average temperature, remaining closer to the optimal growth range.

It is essential to define environmental parameters if soybean is to be cropped in locations that maximize productivity.

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