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Research article

Irrigation management of common bean cultivars with contrasting growth habits

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ABSTRACT: A study was undertaken comparing the water requirements of two common bean (*Phaseolus vulgaris* L.) cultivars to generate specific recommendations aimed at optimizing water use. To accomplish this work, the agronomic performance, responsiveness to water and water productivity of these two common bean cultivars of determinate and indeterminate growth habits were identified. The 2-year experiment was carried out during the winter growing season in the southeast of Brazil. Cultivars IAC Imperador, with an early season of determinate growth habit, and IPR Campos Gerais, having a mid-season of indeterminate growth habit, were subjected to five irrigation levels (54, 70, 77, 100, and 132 % of the crop evapotranspiration). Water deficit affected agronomic performance, reducing plant height (by up to 29 %), leaf area index (by up to 40 %), soil cover fraction (by up to 28 %), and grain yield (GY - by up to 31 %), in both cultivars. In contrast, excess water was more detrimental to cultivar IAC Imperador. Cultivar IPR Campos Gerais produced 18 % more than GY, showing superior water productivity and response to irrigation depth than IAC Imperador. Out of all the variables evaluated, the soil cover fraction correlated the most with grain yield in both common bean cultivars during the 2-year study. In other words, cover fraction evaluation in common bean allows for estimating crop production potential, which helps producers and technicians in their decision making regarding management practices. Thus, a cultivar directly affects water use in common bean production, thereby suggesting the need for a or water conservation strategy and sustainability of irrigated common bean production.

Keywords: *Phaseolus vulgaris* L., cover fraction, water deficit, leaf area index, grain yield

Introduction

Irrigation systems, management, soil cover, and tillage are often considered factors in optimizing water use in irrigated areas (Rahil and Qanadillo, 2015; Silva et al., 2019). The cultivar is commonly a neglected factor, even though selecting the suitable cultivar for an irrigated production system can increase yield and water productivity by more than 15 % (Santos et al., 2020).

Water use optimization in crop production is not always about the consumption (FAO, 2017) but also involves efficiency and responsiveness. Efficiency is the capacity to produce sufficiently well under conditions of limited resources. At the same time, responsiveness refers to the capacity of a given plant to increase its production as a result of its response to that resource (Fageria et al., 2013). Thus, efficient and responsive cultivars should be expected to optimize their use of resources.

Common bean (*Phaseolus vulgaris* L.) is widely grown during the winter in tropical regions due to the lower temperature and precipitation conditions at this time of year, which reduces the risk of a wet harvest time and disease and pests (Lemos et al., 2015). As for 2021, approximately 600,000 ha of common bean were grown during winter in Brazil (CONAB, 2021), when a scarcity of rain calls for irrigation and proper management to obtain satisfactory yields.

Growth habits and season length of cultivars can interfere with their responsiveness and efficiency to water use and grain yield (Emam et al., 2012). Early season cultivars of determinate growth habit require less water and might be more efficient but produce less than mid-season cultivars of indeterminate growth habit (Filla et al., 2020; Nunes et al., 2020). However, such benefits have not been comprehensively studied.

It was hypothesized that (i) common bean cultivars of determinate and indeterminate growth habits have different responsiveness to water and water productivity, and (ii) cultivars of indeterminate growth habit outperform determinate growth habit cultivars in terms of agronomic characteristics and grain yield. The objectives of this study were to determine and compare the agronomic performance, responsiveness to water, and water productivity of common bean cultivars with contrasting growth habits.

Materials and Methods

The experiment was carried out in the winter growing season of 2019 and 2020 in Jaboticabal, São Paulo, Brazil (21°14′44″ S, 48°17′00″ W, altitude 545 m). The regional climate was classified as Aw tropical with a dry winter, summer rains, an average annual temperature of 22 °C, and average annual precipitation of 1,425 mm (Alvares et al., 2013). The soil in the experimental area (Tables 1 and 2) was classified as an Oxisol (Soil Survey Staff, 2014).

The experimental design consisted of a strip-block design, with four replications in a split-plot arrangement. The main factor was the irrigation level (L1, L2, L3, L4 and L5), and the secondary factor was common bean

Table 1 – Soil physical attributes and particle size distribution of the experimental area.

Layer	Ds	Moisture FC	Moisture PWP	Clay	Silt	Sand
m	g cm^{-3}	——— m^3 m^{-3} ———		——— g kg^{-1} ———		
0-0.20	1.33	0.357	0.171	492	279	229
0.20-0.40	1.24	0.325	0.166	536	266	198

*Ds = soil density; FC = field capacity; PWP = permanent wilting point.

Table 2 – Soil chemical attributes (0-0.20 m soil layer) of the experimental area in 2019 and 2020.

Year	pH $CaCl_2$	H+Al	Al	K	Ca	Mg	SB	CEC	V
		——————— mmol$_c$ dm^{-3} ———————							%
2019	5.7	26	0	5.7	47	12	64.7	91	71
2020	5.9	25	0	5.1	50	14	69.1	94	74
Year	OM	Presin	S	B	Cu	Fe	Mn	Zn	
	g dm^{-3}	——————— mg dm^{-3} ———————							
2019	25	59	8	0.77	6.6	31	47.3	3.5	
2020	24	66	5	0.46	4.5	16	25.8	3.2	

OM = organic matter; SB = sum of bases; CEC = cation exchange capacity; V = base saturation.

cultivar (determinate and indeterminate). Each subplot was 6.75 m long × 2.4 m wide and accommodated 15 rows. Six rows were used for harvest and the remainder for destructive analysis.

A line-source sprinkler was used, allowing for the distribution of the irrigation water with variable application depths as the treatment moved away progressively from the central sprinkler line (Hanks et al., 1976). A field test made possible a definition of the distribution fractions of the sprinkler precipitation. Senninger 4023-2 sprinklers and ¾″ M 08Qx05 nozzles were used, spaced 6 m apart on the line (service pressure = 250 KPa).

Irrigation treatments consisting of five levels (L1, L2, L3, L4, and L5) were established after adjustments based on the irrigation fraction of the individual sprinklers in the line. L4 received 100 % of crop evapotranspiration (ETc), and L5 132 % of the ETc, while L3, L2, and L1 received 77, 70, and 54 % of ETc, respectively.

Common bean was sown in an area previously cultivated with corn. Limestone (1.5 Mg ha^{-1}) with a relative total neutralizing power of 95 was applied 30 days before corn sowing in both years and soil-incorporated with a plowing harrow at a depth of 0.20 m.

Two common bean cultivars from the 'Carioca' commercial group of contrasting growth habits were sown on 07 May 2019 and 18 May 2020. IAC Imperador is an early season cultivar of 75 days of determinate growth habit (Type I) and erect architecture (Chiorato et al., 2012). IPR Campos Gerais is a mid-season cultivar of 90 days of indeterminate growth habit (Type II) and erect architecture (Moda-Cirino et al., 2012). Both cultivars were sown with an inter-row, 0.45 m apart. The seeds were treated with pyraclostrobin (5 g a.i. ha^{-1}) + thiophanate-methyl (45 g a.i. ha^{-1}) + fipronil (50 g a.i. ha^{-1}) and inoculated with *Rhizobium tropici*.

Sowing fertilization consisted of 8 kg ha^{-1} of N, 40 kg ha^{-1} of P_2O_5 and 40 kg ha^{-1} of K_2O according to the soil analysis and recommendation from Ambrosano et al. (1997). It was applied in the sowing furrow during both years, with 04-20-20 formulated fertilizer as the source. Top-dressing fertilization consisted of 90 kg ha^{-1} of N applied 0.1 m from the sowing row at the V_{4-3} stage of development (Fernández et al., 1985) during both years, with urea as the N source (Ambrosano et al., 1997) followed by an irrigation of 10 mm for all treatments (Espindula et al., 2021).

The crop water needs (ETc) were obtained using the FAO 56 method from daily weather data obtained from an automated weather station located 1,500 m away from the experiment. The reference evapotranspiration (ETo) was estimated daily using the FAO 56 method (Allen et al., 1998). The ETc was calculated using the product of ETo multiplied by the crop coefficients (Kc) (Allen et al., 1998). The Kc values used were 0.40 (0 to 10 % of soil cover), 0.40 to 1.15 (10 to 80 % of soil cover), 1.15 (80 to 100 % of soil cover), and 0.35 (physiological maturity). The Kc values were obtained considering the season length of each cultivar. Each cultivar was irrigated with an irrigation line, allowing for irrigation management based on the ETc of each area.

Irrigation was triggered when the readily available water estimated at 18 mm was reached. This was calculated according to soil attributes (Table 1) and crop phenology considering an effective root depth of 0.25 m and a water availability factor of 0.40 (Allen et al., 1998). Two irrigations of 15 mm each were applied across treatments as the initial establishment. Irrigation was carried out until each cultivar's physiological maturity (R_9 phenological stage) was reached.

Soil moisture was determined weekly at three points per subplot in the 0.00-0.20 m layer, using the time domain reflectometry (TDR) technique (Fellner-Feldegg, 1969) and a HydroSense II Handheld Soil Moisture Sensor (Campbell Scientific).

The leaf area index (LAI) was obtained with the LI-3100C, a destructive method applied throughout the growing season requiring the removal of three plants per subplot each time. The soil cover fraction of common bean treatments was determined on the same day of each LAI evaluation using the Canopeo mobile app (Patrignani and Ochsner, 2015), which provides the percentage of soil covered by the green crop canopy through image processing. Plant height was also obtained at the R_6 stage for ten plants per subplot.

The final population was estimated from three rows per plot. Seven consecutive plants were collected to determine the number of pods per plant and the number of grains per pod. The 100-grain weight was determined using samples from the previous evaluation to count four subsamples of 100 grains per subplot, standardizing moisture content to 0.13 kg kg^{-1}. Grain yield was estimated by harvesting six rows, standardizing moisture to 0.13 kg kg^{-1}.

The accumulated growing degree-days in total (GDD) was calculated according to Arnolds (1959) Eq. (1). A base temperature (Tb) of 10 °C was used (Wutke et al., 2000). The GDD calculation started at crop emergence and ended at physiological maturity (R9).

$$GDD = \frac{T\max + T\min}{2} - Tb \quad (1)$$

where: GDD = growing degree-days Tmax = maximum temperature, Tmin = minimum temperature, Tb = base temperature (10 °C) (Wutke et al., 2000).

The irrigation water productivity (WP) of treatments was calculated by the ratio of grain yield to irrigation depth for each treatment (kg m^{-3}).

As in this study, the variables were levels (quantitative factor), all the analyzed variables were subjected to polynomial regression analysis as a function of the irrigation depths applied to each cultivar. Analyses were performed using the SigmaPlot software. To verify which variables interfered most with the common bean grain yield, correlation analysis was performed. This analysis was performed for each cultivar and year, in which all analyzed variables were correlated with GY. For variables with non-significant regressions in the two cultivars, the F-test ($p < 0.05$) was used for mean comparison between cultivars.

Results and Discussion

Low temperatures from 05 to 08 July 2019 (Figure 1A and Table 3) caused a frost on 07 July 2019. As a result, all treatments were irrigated on 06, 07, and 08 July 2019 with 20, 40, and 20 mm, respectively to minimize frost-related injuries to crops. Average maximum and minimum temperatures during 2019 were 27.8 and 13.9 °C (Figure 1A). In 2020, the average maximum and minimum temperatures were 28.4 and 13.9 °C (Figure 1B), respectively. The accumulated precipitation during 2019 was 48.7 mm (Figure 1C) and 35.0 mm in 2020 (Figure 1D).

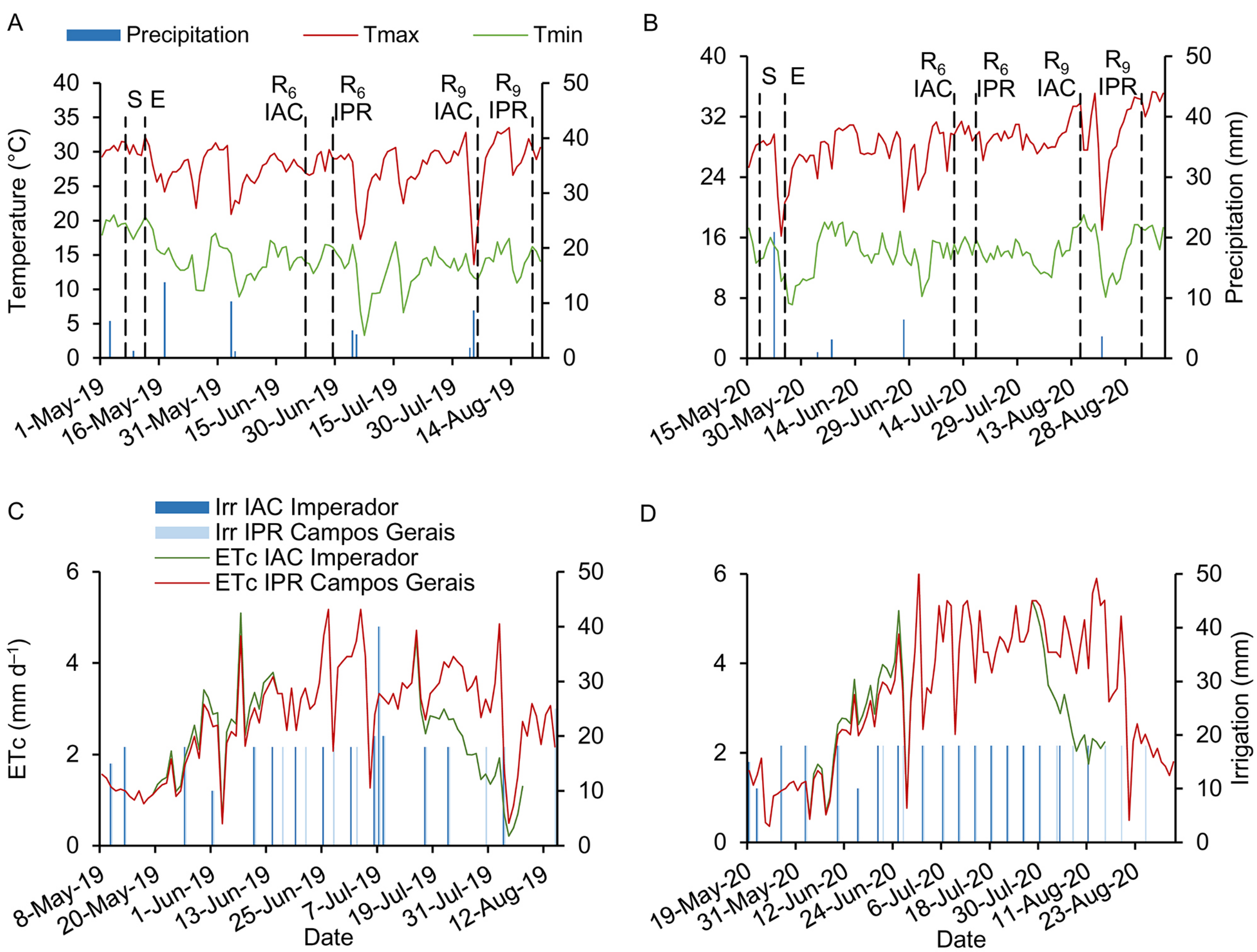

Figure 1 – Daily maximum temperature (Tmax), minimum temperature (Tmin), precipitation (A and B), crop evapotranspiration (ETc), and irrigation (Irr) (C and D) of common bean cultivars IAC Imperador and IPR Campos Gerais during the experimental period from 7 May 2019 to 19 Aug 2019 (A and C), and 18 May to 1 Sept (B and D). S = sowing; E = emergence; R6 = full bloom; R9 = physiological maturity; Irr = irrigation; ETc = crop evapotranspiration.

Table 3 – Mean and mean standard deviation of the 15-day period values of maximum temperature (Tmax), minimum temperature (Tmin), and global solar radiation (GSR) during the experimental period from 2019 and 2020.

DAE	2019	2020	2019	2020	2019	2020
	Tmax	Tmax	Tmin	Tmin	GSR	GSR
0-15	28.5 ± 2.3	25.4 ± 3.8	16.9 ± 2.4	11.5 ± 2.7	15.9 ± 2.1	15.6 ± 4.2
16-30	27.4 ± 3.6	28.6 ± 2.2	13.6 ± 3.0	15.9 ± 2.0	15.5 ± 3.9	13.9 ± 2.7
31-45	27.6 ± 1.4	26.9 ± 2.9	13.8 ± 2.0	13.8 ± 1.3	16.3 ± 1.3	13.9 ± 3.3
45-60	28.1 ± 2.2	28.9 ± 2.5	14.5 ± 1.3	13.7 ± 2.4	14.3 ± 3.2	15.5 ± 1.2
61-75	25.7 ± 3.7	29.3 ± 1.2	10.2 ± 3.6	14.2 ± 0.9	16.9 ± 1.1	17.2 ± 0.5
75-90	28.0 ± 4.5	29.7 ± 2.3	13.8 ± 1.2	13.8 ± 2.4	14.5 ± 4.7	18.1 ± 1.4
90-105	29.4 ± 3.9	28.9 ± 4.8	14.2 ± 2.0	13.8 ± 3.5	16.5 ± 4.3	17.9 ± 5.5

DAE = days after emergence; T = °C; GSR = MJ m^{-2} d^{-1}.

On average, the growing season of IAC Imperador was 15 days and 187 GDD less than IPR Campos Gerais (Table 4). The growing season of both cultivars under irrigation levels L1 and L2 was five and three days less than the L4 level. This is because water deficit commonly anticipates the growing season (Coelho et al., 2020) due to the accumulation of oxidative substances on tissues (Taiz et al., 2017).

The L4 irrigation depth in 2020 was 30 % higher than in the previous year for both cultivars (Table 5). Overall, the amount of water applied to the IPR Campos Gerais cultivar was 17 % higher than IAC Imperador.

Plant height (PH) increased quadratically as a function of irrigation depths, with IPR Campos Gerais presenting the highest values (Figures 2A and B). The maximum PH for IAC Imperador (0.59 m) and IPR Campos Gerais (0.69 m) in 2019 was obtained with 279 and 340 mm of irrigation, respectively, while the maximum PH for IAC Imperador (0.54 m) and IPR Campos Gerais (0.65 m) in 2020 was obtained with 333 and 382 mm of irrigation, respectively.

Total dry mass at harvest showed a quadratic increase for both cultivars as a function of irrigation depths (Figures 2C and D). Maximum dry mass for IAC Imperador (8.6 Mg ha^{-1}) and IPR Campos Gerais (11.8 Mg ha^{-1}) in 2019 was obtained with 291 and 349 mm of water, respectively. In 2020, the maximum dry mass was 11.0 Mg ha^{-1} (IAC Imperador) and 12.3 Mg ha^{-1} (IPR Campos Gerais) at irrigation depths of 344 and 414 mm, respectively.

Overall, there was no variation in the final plant population (FP) as a function of irrigation depths for the two cultivars in 2019 and IPR Campos Gerais in 2020 (Figures 3A and B). IAC Imperador showed quadratic increments for FP in 2020, with the maximum value (267,500 plants ha^{-1}) at the irrigation depth of 307 mm.

The number of grains per pod (NGP) was not affected by irrigation depths and cultivars in 2019 (Figure 3C). Increases in NGP were found in 2020, with a quadratic variation for IAC Imperador and a linear increment for IPR Campos Gerais (Figure 3D). The maximum NGP for IAC Imperador (4.6) was obtained at an irrigation depth of 334 mm, while the IPR Campos Gerais showed increases in NGP of 0.23 for each 100 mm of irrigation depth.

Table 4 – Accumulated growing degree-days (GDD) of common bean cultivars grown without water stress during two growing seasons.

Stage	IAC Imperador				IPR Campos Gerais			
	2019		2020		2019		2020	
	GDD	Days	GDD	Days	GDD	Days	GDD	Days
$V_1 - V_4$	199	0-18	202	0-19	199	0-18	202	0-19
$V_4 - R_5$	139	18-32	146	19-32	177	18-35	171	19-35
$R_5 - R_6$	104	32-41	151	32-47	147	35-48	201	35-53
$R_6 - R_8$	150	41-55	143	47-59	186	48-69	185	53-69
$R_8 - R_9$	286	55-85	272	59-82	341	69-99	357	69-99
Total	877		914		1049		1116	

Table 5 – Irrigation depths (mm) per cultivar and year used in this study.

	IAC Imperador		IPR Campos Gerais	
	Irrigation depth (2019)	Irrigation depth (2020)	Irrigation depth (2019)	Irrigation depth (2020)
L1	152	189	175	218
L2	182	231	212	269
L3	194	248	228	290
L4	235	305	278	359
L5	294	387	351	459

The number of pods per plant (NPP) showed quadratic increments for both cultivars in 2019 and IAC Imperador in 2020 (Figures 3E and F). No NPP variation was verified in 2020 for IPR Campos Gerais. The maximum NPP values for IAC Imperador (17.6) and IPR Campos Gerais (21.7) in 2019 were obtained at irrigation depths of 220 and 298 mm, respectively. On the other hand, the maximum NPP for IAC Imperador (26.5) in 2020 was obtained at an irrigation depth of 427 mm.

As regards the 100-grain weight (100W), only the IPR Campos Gerais showed variation in 2019 (Figure 3G and H), with a linear increase of 1.59 g for each 100 mm of water applied. The mean was the parameter that best represented 100W as a function of irrigation depths for the other treatments.

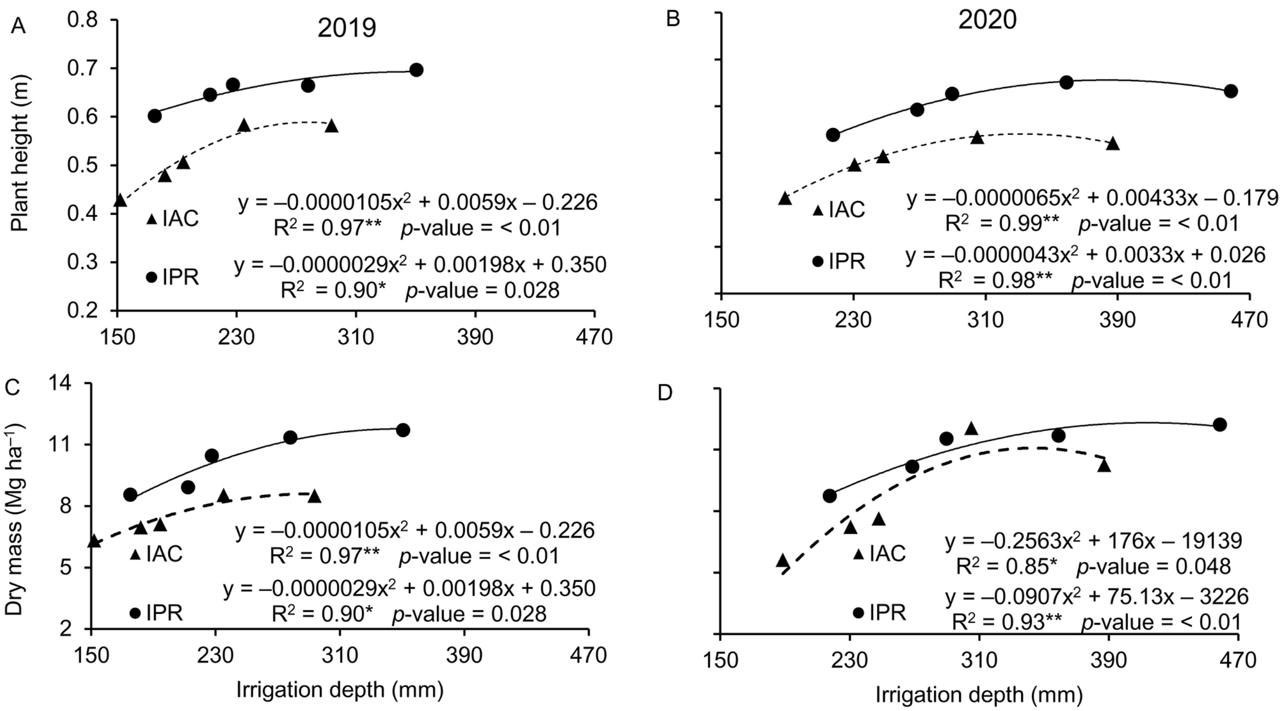

Figure 2 – Variation in plant height (A and B), and dry mass of plants (C and D) as a function of irrigation depths for two common bean cultivars in two years (2019 and 2020).

Cultivar IAC Imperador showed quadratic increases regarding grain yield (GY) in both years, with a maximum of 3,961 kg ha^{-1} in 2019 and 3,802 kg ha^{-1} in 2020, with irrigation depths of 281 and 378 mm, respectively (Figures 4A and B). Cultivar IPR Campos Gerais showed linear behavior, with an increase of 512 kg ha^{-1} for every 100 mm applied in 2019 and 476 kg ha^{-1} in 2020. On average, IPR Campos Gerais presented a higher GY than IAC Imperador.

Water productivity (WP) decreased linearly for both cultivars in both years (Figures 4C and D). In 2019, WP reduced 0.47 and 0.45 kg m^{-3} for every 100 mm of irrigation depth to the IAC Imperador and IPR Campos Gerais, respectively. However, this reduction reached 0.20 and 0.21 kg m^{-3} for IAC Imperador and IPR Campos Gerais, respectively, in 2020.

The maximum leaf area index (LAI) between irrigation levels varied from 2.39 to 4.05 in 2019 and 1.47 to 2.44 in 2020 for IAC Imperador and from 2.45 to 3.01 in 2019 and 2.23 to 2.91 in 2020 for IPR Campos Gerais (Table 6). The maximum cover fraction (CF) for IAC Imperador ranged from 82 to 94 % in 2019 and 79 and 97 % in 2020, and from 88 to 99 % in 2019 and 77 to 93 % in 2020 for IPR Campos Gerais.

In the first year, the variables that most correlated with IAC Imperador grain yield were PH, maximum LAI, maximum CF, dry mass (DM), and 100W. In contrast, in the second year, they were PH, maximum LAI, maximum CF, DM, NPP, and NGP (Table 7). For IPR Campos Gerais, the variables that most correlated with GY in the first year were maximum CF, NPP, and 100W, while in the second year, they were maximum CF, DM, and NGP.

Soil moisture was affected by the L1, L2, and L3 irrigation levels in both cultivars (Figure 5A-D). These treatments delivered less water throughout the season, especially post 25 DAE. The water deficit was more severe from flowering (R6), and in 2020. In addition, irrigation levels under water deficit (L1 to L3) showed soil moisture lower than levels L4 and L5. Moreover, night irrigation in 2019 to reduce frost injuries to crop on 07 July 2019 resulted in similar soil moisture between treatments 60 to 68 DAE (Figure 5A and C).

Overall, the agronomic performance of the IPR Campos Gerais cultivar was better compared to the IAC Imperador cultivar, showing a maximum GY of up to 18 % higher, mainly because IPR Campos Gerais has a 15 day longer growing season. This difference occurred at the reproductive stages, as both cultivars had similar development until R_5 (appearance of flower buds). Thus, intermediate cultivars have a longer time for forming pods and grain filling (R_8), directly affecting GY. Results from this study help advance our understanding of the irrigation needs of common bean cultivars of different growth habits.

The GY of early cultivars tends to be lower than cultivars of the mid cycle. IAC Imperador grain yield may be up to 38 % higher than IPR Campos Gerais (Filla et al., 2020). In a study with sixteen common bean cultivars, the

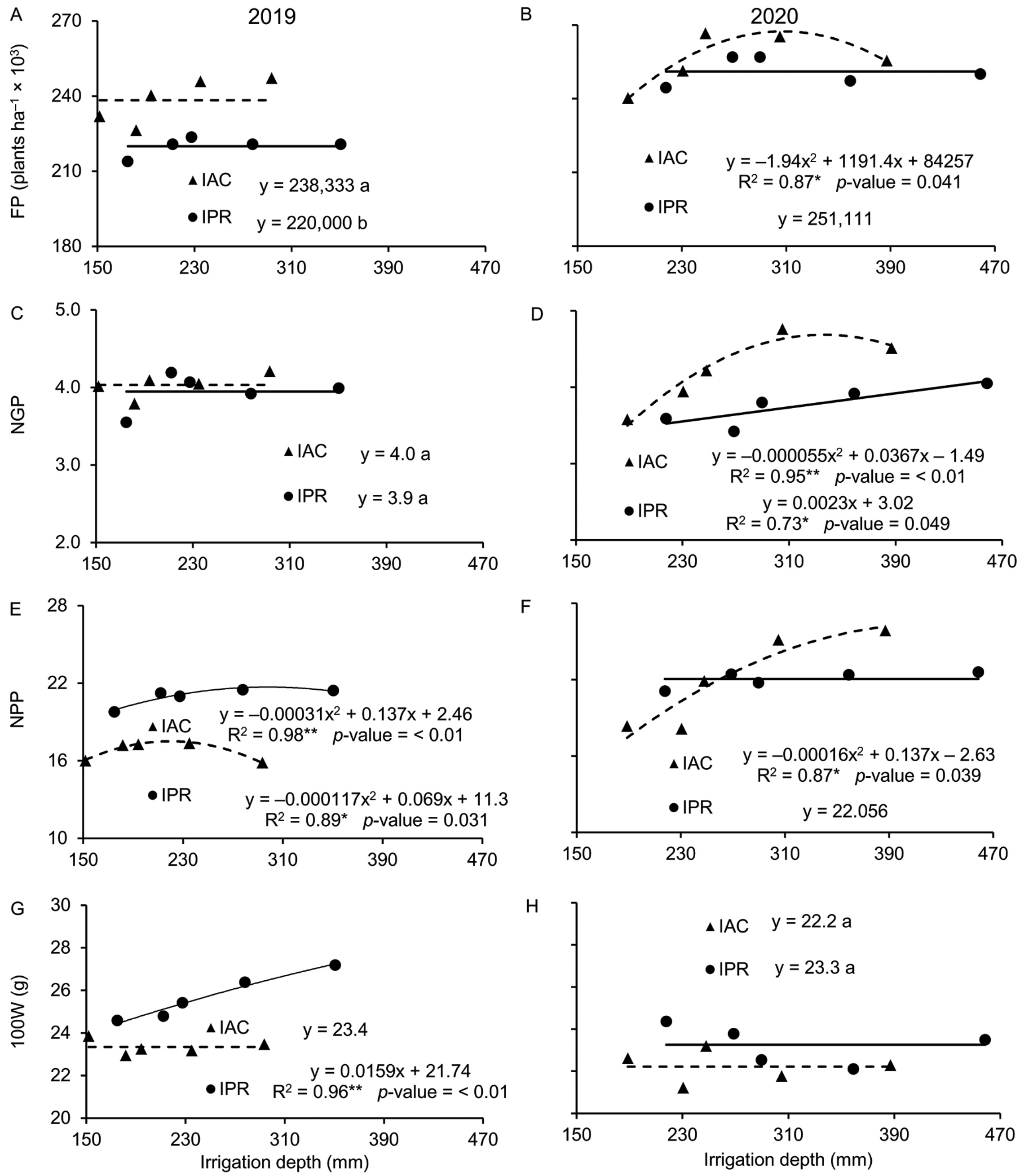

Figure 3 – Variation in the final plant population (FP, A and B), number of grains per pod (NGP, C and D), number of pods per plant (NPP, E and F), and 100-grain weight (100W, G and H) as a function of irrigation depths for two common bean cultivars evaluated in two years (2019 and 2020).

authors verified that cultivars with a mid and late cycle presented, on average, 40 % higher GY than early cycle cultivars (Nunes et al., 2020).

In Brazil, common bean IAC Imperador is considered a standard genotype for studying water deficit tolerance due to its high stomatal conductance (Gonçalves et al., 2019), production of biochemical substances (Andrade et al., 2016), and advanced development of its root system (Dipp et al., 2017). In this study, IPR Campos Gerais showed a higher GY than the IAC Imperador at the lowest irrigation levels, characterizing the efficiency of producing sufficiently well under conditions of low water availability (Fageria et al., 2013). Moreover, IPR Campos Gerais showed linear GY increments as a function of irrigation levels, At the same time, IAC Imperador had a quadratic increase, characterizing the response in the increment of GY with the increased availability of the studied resource (Fageria et al., 2013). Even with GY

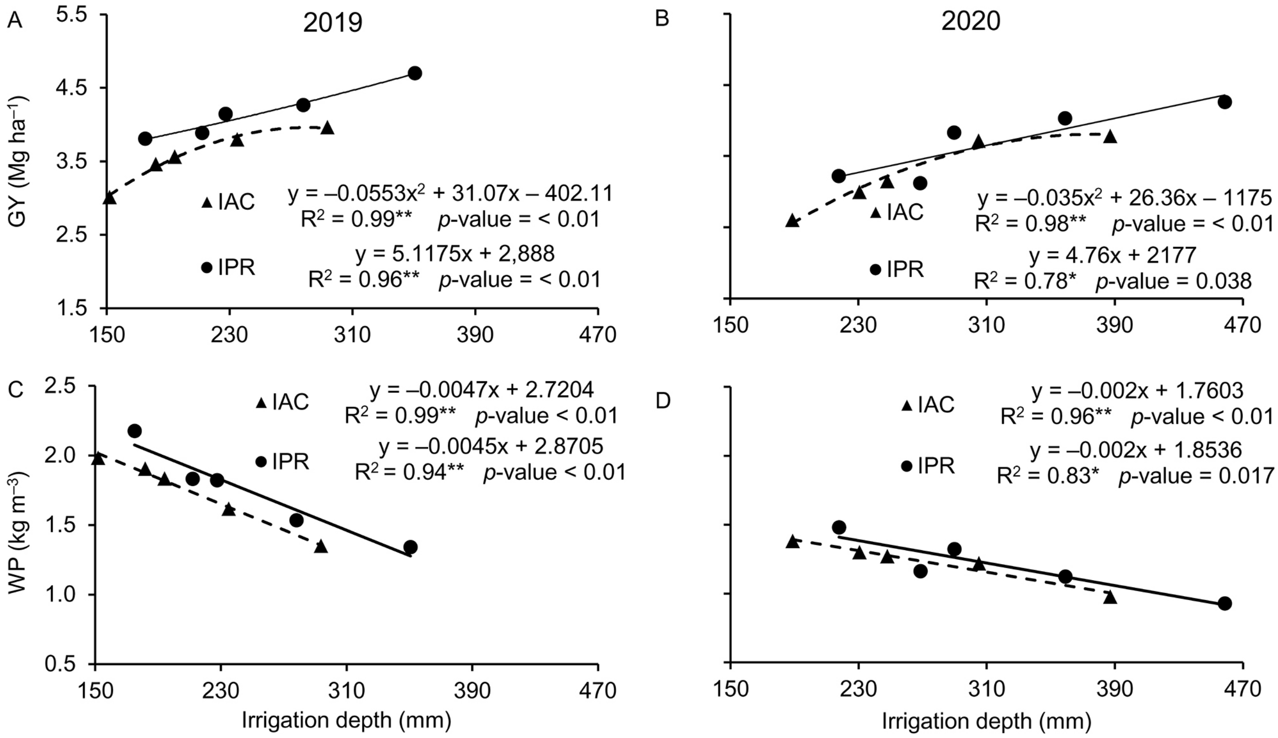

Figure 4 – Variation in grain yield (GY, A and B), and water productivity (WP, C and D) as a function of irrigation depths for two common bean cultivars evaluated in two years (2019 and 2020).

Table 6 – Maximum leaf area index (LAI) and cover fraction (CF) for common bean cultivars IAC Imperador and IPR Campos Gerais subjected to five irrigation levels during two growing seasons (2019 and 2020).

Irrigation level	IAC Imperador							
	2019		2020		2019		2020	
	LAI max.	DAE	LAI max.	DAE	CF max.	DAE	CF max.	DAE
L1	2.39	61	1.47	60	82	59	79	63
L2	2.68	62	1.91	61	85	58	88	68
L3	2.87	62	1.87	62	88	61	93	70
L4	4.05	63	2.43	65	94	58	95	71
L5	3.97	62	2.44	67	93	59	97	76
Irrigation level	IPR Campos Gerais							
	2019		2020		2019		2020	
	LAI max.	DAE	LAI max.	DAE	CF max.	DAE	CF max.	DAE
L1	2.45	69	2.29	69	88	67	77	58
L2	3.03	69	2.23	67	90	67	83	60
L3	2.96	68	2.55	71	94	70	88	70
L4	2.96	68	2.85	73	98	72	93	76
L5	3.01	68	2.91	75	99	74	93	78

DAE = days after emergence; CF = cover fraction (%).

lower than the IPR Campos Gerais, the IAC Imperador GY was higher than the regional average for the winter crop (2.323 kg ha^{-1}), regardless of the irrigation level (CONAB, 2021).

It has been reported that IPR Campos Gerais has a high level of efficiency and responds to several inputs, especially water and nitrogen. IPR Campos Gerais is recommended for breeding programs aiming to develop highly productive cultivars simultaneously tolerant to water deficit (Arruda et al., 2019). In the literature, IPR Campos Gerais has been highlighted as being one of the common bean genotypes with higher stability and agronomic performance (Zanella et al., 2019). In addition, in a study that evaluated the efficiency and response of common bean cultivars to N use, IPR Campos Gerais was more efficient and responsive than IAC Imperador (Nunes

Table 7 – Pearson's coefficient of correlation of grain yield and traits of common bean.

Year	IAC Imperador							
	PH	LAI	CF	FP	DM	NPP	NGP	100W
2019	0.568*	0.498*	0.606**	–0.066^{ns}	0.542*	–0.346^{ns}	0.193^{ns}	0.531*
2020	0.764**	0.681**	0.748**	0.277^{ns}	0.735**	0.696**	0.692**	–0.163^{ns}
Year	IPR Campos Gerais							
	PH	LAI	CF	FP	DM	NPP	NGP	100W
2019	–0.101^{ns}	0.296^{ns}	0.649**	–0.316^{ns}	0.249^{ns}	0.599**	0.051^{ns}	0.808**
2020	0.566*	0.441^{ns}	0.731**	0.208^{ns}	0.551*	0.088^{ns}	0.562*	–0.306^{ns}

PH = plant height; LAI = maximum leaf area index; CF = maximum cover fraction; FP = final population; DM = total dry mass; NPP = number of pods per plant; NGP = number of grains per pod; 100W = 100-grain weight; **Significant at 0.01; *Significant at 0.05; ^{ns}Not significant.

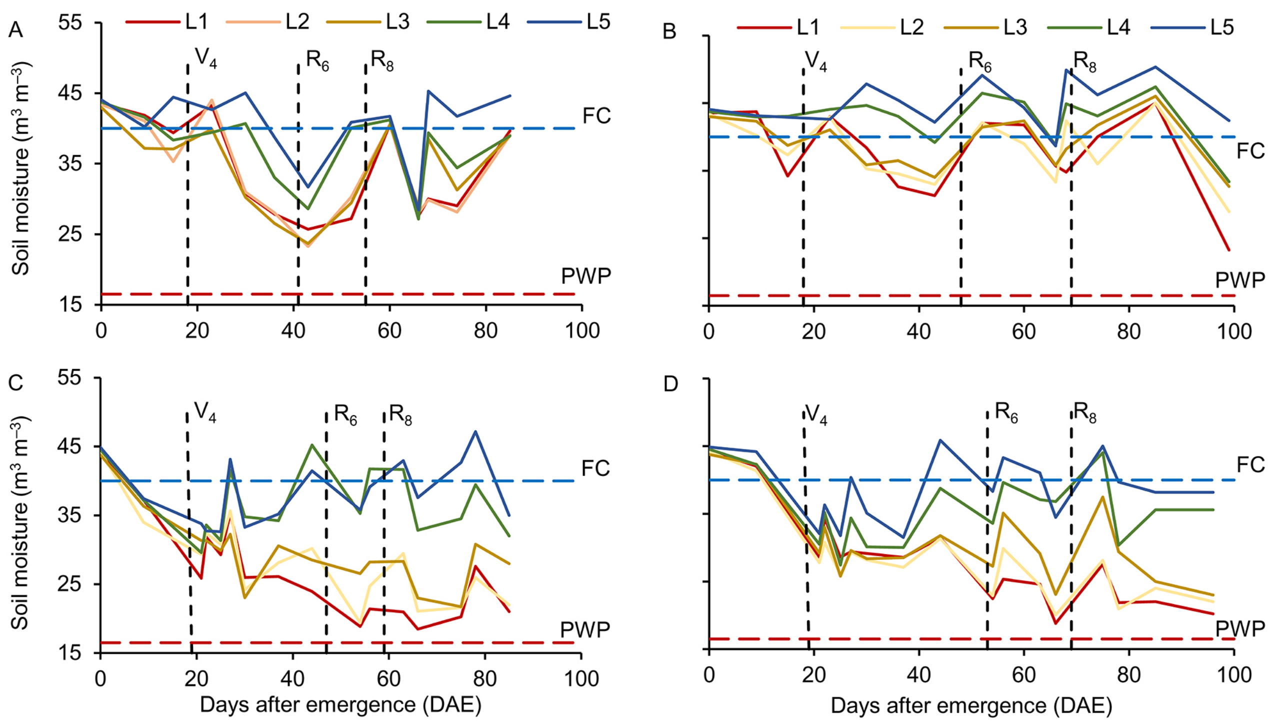

Figure 5 – Temporal variation in soil moisture for the cultivars IAC Imperador (A and B) and IPR Campos Gerais (C and D) in the two years (2019 and 2020). FC = field capacity; PWP = permanent wilting point.

et al., 2020). Such results suggest that IPR Campos Gerais is both high yield and responsive to water.

On average, in this study, water deficit reduced PH by up to 29 %, LAI by up to 40 %, CF by up to 28 %, and GY by up to 31 %. Water deficit was more severe and affected the yield of common bean cultivars mainly in 2020, principally on account of low soil moisture throughout the season (Figure 5B and D), which was also reflected in the most significant difference between the minimum and maximum yields of each cultivar in 2020. Moreover, irrigations for frost control in 2019 mitigated the effect of the water deficit at the end of the season.

Overall, the lowest GY in 2020 can be explained by the lower NGP and 100W for IPR Campos Gerais in 2020 compared to 2019 and the lower 100W for IAC Imperador. Low and high temperatures at the reproductive stages of common beans may affect the NPP, NGP, and 100W. The ideal temperature for common bean development ranges from 15 to 30 °C (Omae et al., 2012). Average maximum temperatures above 30 °C were not observed at the reproductive stages of common beans in either year (Table 3); however, an average minimum temperature of 10.2 °C was recorded in 2019 from 61 to 75 DAE, which represents a value 4 °C lower than that registered in 2020. Cultivar IAC Imperador was at the beginning of $R_{8,}$ and cultivar IPR Campos Gerais was at the pod formation stage (R_7) during this period (Table 4), a fact that may have contributed to the lower NGP for IAC Imperador in 2019 and NPP for IPR Campos Gerais.

The high temperatures between 61 to 75 DAE and 76 to 90 DAE in 2020, with average values of 4.0 °C and 1.7 °C higher compared to 2019, respectively, might have contributed to the lower 100W in 2020. High temperatures at the grain filling drastically affect 100W

(Silva et al., 2020). These high temperatures in 2020 may also have reduced soil moisture at the end of the season, compared to the same period in 2019 (Figures 5B and D), ultimately affecting grain filling.

Out of the variables correlated with GY, maximum CF was the only variable observed in both cultivars and both years (Table 6). Furthermore, maximum CF was one of the variables with the highest correlation value, regardless of the year and cultivar, with values and significance higher than maximum LAI. Cover fraction is an indirect indicator of plant vigor, growth, and light interception capacity, which are directly associated with GY (Patrignani and Ochsner, 2015). In this context maximum CF can more efficiently intercept solar radiation than maximum LAI. This is because LAI integrates all leaves, including those overlapped by the uppermost leaves that contribute little to net photosynthesis (Joggi et al., 1983). LAI increases from light saturation though not from the total light absorbed (Joggi et al., 1983), which also does not increase GY. Unlike LAI, CF does not increase indefinitely, and its saturation occurs at a determined soil cover rate.

Conclusions

Limited water reduces the agronomic performance of common bean, regardless of cultivar, decreasing plant height, leaf area index, cover fraction, and grain yield by up to 31 %. Cultivar IPR Campos Gerais of indeterminate growth habit had a maximum GY 18 % higher than cultivar IAC Imperador of determinate growth habit. With an average irrigation depth (mm) 17 % higher than that applied to IAC Imperador, IPR Campos Gerais was more efficient and responsive to water use. Irrigation management and common bean cultivar choice are essential to irrigated production systems, as they help farmers increase production.

Authors' Contributions

Conceptualization: Coelho, A.P.; Faria, R.T.; Lemos, L.B. **Data curation:** Coelho, A.P.; Reis, M.A.; Filla, V.A.; Bertino, A.M.P. **Formal analysis:** Coelho, A.P.; Faria, R.T.; Reis, M.A. **Funding acquisition:** Coelho, A.P.; Faria, R.T.; Lemos, L.B. **Investigation:** Coelho, A.P.; Reis, M.A.; Bertino, A.M.P. **Methodology:** Coelho, A.P.; Faria, R.T.; Reis, M.A. **Project administration:** Faria, R.T. **Resources:** Faria, R.T.; Lemos, L.B. **Supervision:** Faria, R.T. **Writing-original draft:** Coelho, A.P.; Reis, M.A.; Bertino, A.M.P. **Writing-review & editing:** Faria, R.T.; Lemos, L.B.; Filla, V.A.

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