Effects of deficit irrigation on the productivity of the common bean (*Phaseolus vulgaris* L.)

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Abstract: Although historically cultivated by small farmers, bean crops are now cultivated in large scale to increase productivity, which involves varied levels of technology in practices such as irrigation and direct sowing, as well as developed soil management and traditional practices. Along with the adoption of these techniques, an increase in irrigation efficiency has occurred, which aims to meet the water requirements of the crop throughout its life cycle without water wastage. The main objective of this study was to study the effects of different irrigation depths during two phases of the bean crop cycle and the behavior of *cv.* IAC-Alvorada during winter in the first and second year of direct sowing in Botucatu – SP, a southeastern region of Brazil. The experimental soil was classified as a red distroferric nitosol with a clayey texture. The delineated experimental design consisted of complete randomized blocks (each: 1.8×4.0 m), 16 treatments, and a witness with four replications. Irrigation treatments were performed daily with the assistance of a Class A tank. The following characteristics were evaluated: the productivity of the grains, number of pods per plant, number of grains per plant, number of grains per pod, grain yield, weight of 100 grains, empty pods per plant, and water use efficiency. The number of pods and the grain yield decreased with an increase in water stress at a 5% probability. Reductions in the applied water depth in the vegetative phase did not interfere with grain productivity. Reductions in water in the reproductive phase had the greatest effect on the productivity of grains and the number of pods per plant. The highest productivity was 3,322.27 kg ha^{-1} and resulted from the combination of an application depth of 40% in the vegetative phase and 100% in the reproductive phase.

Keywords: red distroferric nitosol, water stress, water use efficiency

Citation: Carvalho, J. J., J. C. C. Saad, M. B. Teixeira, F. A. L. Soares, N. F. D. Silva, M. S. D. Campos, F. N. Cunha, and L. N. S. D. Santos. 2018. Effects of deficit irrigation on the productivity of the common bean (*Phaseolus vulgaris L.*). Agricultural Engineering International: CIGR Journal, 20(3): 24–34.

1 Introduction

The common bean (*Phaseolus vulgaris* L., Fabaceae) is one of the main crops in Brazil; however, the average productivity rate of the country is substantially limited as a result of the low usage of inputs or efficient technology. The current average productivity rate is 910 kg ha^{-1} (Conab, 2014). However, productivities above 3 t ha^{-1} can be achieved in irrigated crops and with the use of technological cultivation (Lopes et al., 2011).

Brazil is the world's largest common bean producer, generating approximately three million tons per year with

Received date: 2017-10-05 **Accepted date:** 2018-05-15

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an average consumption of 17.5 kg per habitant^{-1} year^{-1} (Silva et al., 2011). These grains represent a vital source of protein and minerals and are of great importance, both economically and socially, to the Brazilian population.

The winter bean is one of the most widely grown crops using productive systems under managed sprinkler irrigation in the "Cerrado" due to its attractive profitability and rapid economic returns (Azevedo et al., 2008). Bean crop harvests depend on a full or complementary irrigation process, especially during the most sensitive growth phases. The basic purpose of irrigation is to supply water to the crop to meet all of the hydric requirements throughout its cycle (Santana et al., 2009). Irrigation not only reduces the risk of crop failure but also increases the productivity of beans with larger harvests during the year.

In a direct sowing system, the presence of chaff reduces crop evapotranspiration during the initial growing stage when the canopy does not entirely cover the ground, thereby reducing the need for irrigation (Stone et al., 2006). Currently, beans are the main crop that constitutes an irrigated agricultural system in the Midwest and Southeast areas of Brazil (Silveira et al., 2003), with grain yields of approximately 3,000 to 4,000 kg ha^{-1}.

Like other crops, bean crops are subjected to multiple factors that can directly or indirectly affect the yield. Santana et al. (2009) discovered that the maximum economic yield for bean crops was 3,242.73 kg ha^{-1} with an irrigation depth of 575.4 mm, resulting in a profit margin of R$1,304.86 ha^{-1}.

Bean crops are very sensitive to weather conditions, air temperature, as well as competitors such as weeds, especially during their early stage of growth. Bean crops are also susceptible to pests and diseases (Oliveira and Kluthcouski, 2009), and have demanding nutritional requirements that must be met in order to obtain satisfactory and profitable production (Gonzaga and Barbosa, 2012).

The bean crop has broad edaphoclimatic adaptability and can be cultivated all year round in almost all states of Brazil. Most bean cultivation occurs in micro regions with average temperatures ranges of 17ºC–25ºC; an optimal temperature range for this species. Temperatures above 35°C during the flowering stage greatly affects grain yield. Likewise, temperatures below 12°C can induce flower abortion, contributing to a lower return (Gonzaga and Barbosa, 2012).

Water stress reduces the size of the leaves and branches (Taiz and Zeiger, 2013) in the vegetative stage (V2) to (V4), reducing the size and development of the plant with an indirect effect on grain yield. Hydric deficiency in the pre-flowering to flowering stages decreases the ripening of the flowers and prolongs the bean crop cycle (Portes et al., 2009). During the flowering stage, the plant height and number of seeds/grains per pod are reduced (Silva and Ribeiro, 2009). During the pod formation stage (R7), water stress causes the abortion of the ovules, producing empty pods. During the pod filling stage (R8), it causes the abortion of young pods, resulting in shriveled pods. The suppression of irrigation during grain filling reduces the productivity and number of grains per pod (Miorini et al., 2011). The grain mass is reduced by water stress during the physiological maturation stage (R9) (Oliveira and Kluthcouski, 2009). An excess or deficiency of water during the flowering stage in the bean crop may cause losses of up to 60% in grain production (Silva et al., 2006). In summary, water stress shortens the crop cycle. Sousa and Lima (2010) evaluated the effect of hydric deficiency at different development stages of the common bean and witnessed reductions in productivity in the order of 80.49%, 69.14%, 68.61%, and 27.29%, during the phases of vegetative development, pre-flowering, full-flowering, and grain filling, respectively. Guimarães et al. (2011) established an average yield of 863 and 2,084 kg ha^{-1} under conditions with and without hydric deficiency, respectively, over two years, with an average reduction of 58.6% in productivity due to hydric deficiency.

Irrigation of bean crops results in significant gains in productivity, making drought the biggest factor in productivity loss (Aguiar et al., 2008). Conditions of low hydric availability in the soil are expected to impact the growth of agricultural crops, resulting in reduced productivity (Flexas et al., 2006). Excess water is also a factor in productivity loss because it can cause damage to the crop, especially from rains during harvest time.

The aim of this study was to assess the effect of different levels of hydric replacement during the two phases (i.e., reproductive and vegetative) of the bean crop (cultivar IAC-Alvorada) cycle during winter cultivation in the first and second year of direct sowing.

2 Material and methods

2.1 Description and characterization of the study area

The experiment was conducted over two consecutive years (2010 and 2011) with a direct seeding system during the winter months, April to September, on an experimental farm known as Lageado, belonging to the Paulista State University "Julio Mesquita Filho" – Botucatu/São Paulo/Brazil. This University is located in the Midwestern region of São Paulo (22°51′S, 48°26′W) at an altitude of 786 m.

According to Cepagri (2016), Köppen's classification, the climate type is Cwa, and characterized as a warm-temperate mesothermal climate with rains in the summer and drought during the winter.

The soil in the experimental area is classified as a red distroferric nitosol, with clayey texture (Embrapa, 2013). The chemical and physical characteristics were evaluated four months prior to the commencement of the experiment in the field, and obtained from twenty-four trenches. Samples of the soil were taken from the layers between 0 to 0.1 m and 0.1 to 0.2 m depths, which were sent for chemical and physical characterization of the soil. The soil chemical evaluations were based on the methodology of Van Raij et al. (2001), and the physical soil properties in Embrapa (2011). Before the experiment was conducted, the area was fallowed, with residues of Brachiaria and, corn was planted to elevate the straw content and organic soil matter.

The measured values of the chemical characteristics of the soil, in the layer from 0 to 0.2 m, before the test installation, were as follows: 4.7 pH in $CaCl_2$; 21 g dm^{-3} of organic matter; 4.7 mg dm^{-3} of P_{resina}; 1.7, 13.0, 7.0, 30.0, and 1.0 $mmol_c$ dm^{-3} of K, Ca, Mg, 'H+Al', and Al, respectively; 41.5% base saturation (V%); and 0.16, 11.55, 38.5, 13.85, and 1.15 mg dm^{-3} of B, Cu, Fe, Mn, and Zn, respectively. During the second year, in the same layer from 0 to 0.2 m, before the test installation, the values were as follows: 4.85 pH in $CaCl_2$; 24 g dm^{-3} of organic matter; 24 mg dm^{-3} of P_{resina}; 1.9, 29.0, 14.0, 40.0, and 1.0 $mmol_c$ dm^{-3} of K, Ca, Mg, 'H+Al', and Al, respectively; 51% base saturation (V%); and 0.3, 11.9, 43.5, 16.5, and 1.2 mg dm-3 of B, Cu, Fe, Mn, and Zn, respectively. The clayey texture had 423.1, 444.7, and 132.1 g kg^{-1} of sand, silt, and clay, respectively.

In the first and second cultivation year, the soil density at a depth of 0 to 0.15 m was 1.35 and 1.38 g cm^{-3}, and 1.39 and 1.41 g cm^{-3}, respectively.

2.2 Cultural practices and experimental treatments

Liming was performed before sowing in order to increase the base saturation (V%) to 70%; the appropriate level of the bean crop. The lime was manually distributed on the soil surface. The direct sowing of the bean crop (cv. IAC-Alvorada) was conducted on 04/09/2010 and 05/10/2011 in a space of 0.45 between rows, with 13 seeds per meter in order to obtain a final density of 200,000.0 to 240,000.0 plants per ha^{-1}. A model JM 2980 PD Jumil seeder was used, following the curve of the terrain. Crop fertilization was based on a chemical analysis of the soil, with added fertilization of 321 and 145 kg ha^{-1}, with a formulation of 8-28-16 + Zn and 70 kg of N applied for coverage and divided in two applications for an expected productivity of 2.5-3.5 t. The culture and phytosanitary treatments were made in accordance with the general recommendations for bean crops, whenever necessary. The delineated experimental design consisted of complete randomized blocks (each: 7.2 m^2, 1.8×4.0 m), with four repetitions in a factorial scheme of 4×4+a witness. The utilized factors were 4 levels of fluid replacement 100%, 80%, 60%, and 40% of crop evapotranspiration (ETc) applied at two stages during the crop cycle (Phase I – vegetative, and Phase II - reproductive) (Table 1).

The same levels applied in Phase I was repeated in Phase II. Each 7.2 m^2 plot (or block) consisted of four rows of beans, with three lateral irrigation lines between the rows. The spacing between the blocks was 2.0 m, and in between the plots was 1.5 m. For evaluation purposes, the external lines of each plot were considered to be the margin. Furthermore, the margin was considered to be 1 m by adding the two ends of each plot.

Table 1 Treatments used to assess the effect of four levels of fluid replacement: 100%, 80%, 60%, and 40% of crop evapotranspiration (ETc), applied at two phases during the bean crop cycle: Phase I – vegetative, and Phase II - reproductive

Treatments	Symbol	Phase I	Phase II
		ETc (%)	
Treatment 0	T_0	-	-
Treatment 01	T_{01}	40	40
Treatment 02	T_{02}	40	60
Treatment 03	T_{03}	40	80
Treatment 04	T_{04}	40	100
Treatment 05	T_{05}	60	40
Treatment 06	T_{06}	60	60
Treatment 07	T_{07}	60	80
Treatment 08	T_{08}	60	100
Treatment 09	T_{09}	80	40
Treatment 10	T_{10}	80	60
Treatment 11	T_{11}	80	80
Treatment 12	T_{12}	80	100
Treatment 13	T_{13}	100	40
Treatment 14	T_{14}	100	60
Treatment 15	T_{15}	100	80
Treatment 16	T_{16}	100	100

The differentiation between the treatments, with regards to the irrigation per drip, began 8 d after the previous sowing. Irrigation treatments were applied using a conventional sprinkler irrigation system. The lateral lines of the dripping hoses had a wall thickness of 625 mm, were spaced 0.2 m apart, had a flow rate of 7.5 L h^{-1} m^{-1}, and a pressure of 100 kPa. The exponent of the equation of the emitter flow (x) was equal to 0.461. The lateral lines were distributed across a space of 0.45 m between the lines of the bean crop, which formed a wet continuous band on the usable area of the plot. A pump assembly was used, coupled with the irrigation system, with lateral lines, registers, a disk filter, and a gauge. The storage capacity of groundwater was 18.9 mm for an effective soil depth of 0.3 m. For the treatment with 100% ETc in both study phases, 1.15 h of irrigation was necessary to achieve field capacity, with a system efficiency of 90%, to reach the irrigation depth of the bean plant roots at 0.3 m. The irrigation management was based on a calculation of the evapotranspiration reference (ET_0) from the Class A pan evaporation (CAP), which was obtained daily (at 150 m distance from the experimental area) using a micrometer, and these values were corrected by the correction coefficient (Kp) according to Allen et al. (1998), as per Equation (1). The CAP methodology was preferred due to its simplicity, low acquisition cost, and minimal need for climatic data compared to the FAO standard method (Penman-Monteith equation), making it possible for use in various Brazilian conditions.

$$ETo_{CAP} = Kp \times ECA \qquad (1)$$

where, $Kp = 0.108 - 0.0286U + 0.0422\text{Ln}(F) + 0.1134\text{Ln}(F) - 0.0006331[\text{Ln}(F)]^2\text{Ln}(H)$; U = represents the wind speed at 2 m height (km d^{-1}); F = is the distance from the border area (10 m); H = is the humidity as a daily average (%).

The values of Kc were: 0.4, 1.15, and 0.35 in the phases of initial, average, and final, respectively, and the maximum height of the culture was 0.4 m according to Allen et al. (1998).

The T_{16} treatment was kept as a reference without water restriction, both in the initial phase (Phase I - vegetative) and the final phase (Phase II - reproductive). In the other treatments, a depth reduction was observed in one of the two phases after germination. Phase I began in stage V_2 (22 d after emergence - DAE) to flowering (40 DAE), over an average period of 18 d. Phase II began in the flowering to physiological maturity stage of the grains (40-60 DAE), with an average period of 20 d. In the field, the depth applied in each plot was controlled based on the time of issuing water flow to each plot (drippers flow of the plot, divided by the area of the plot). The irrigation time was determined daily to reference plot with 100% of the ETc, applied in Phase 1 and 2. Then, the corresponding times for others depths were obtained (80%, 60%, and 40% of ETc). Daily irrigations were conducted.

2.3 Evaluation and analysis

The following variables were evaluated: grain productivity (PG), weight of 100 grains (MG), number of pods per plant (NVP), number of seeds/grains per pod (NGV) and number of empty pods (NVC). Parameters were evaluated along two transects of 2 m in each plot. Threshing was performed manually. The grain yield (or PG) and weight of MG were adjusted to 13% moisture. The water use efficiency of the crop was calculated as the ratio between the average PG and the total volume of water received during the 94 d of the crop cycle.

The results were subjected to analysis of variance by F test, and the means were compared by the Tukey test at 5% probability using the SISVAR program (Ferreira, 2011). The joint analysis was conducted with Statistical Analysis Systems GENES software (Cruz, 2013).

3 Results and discussion

The pluvial precipitation during Phases I and II in 2010 was 5.26 mm and 9.12 mm (total: 14.38 mm), and 5.19 mm and 9.64 mm in 2011 (total: 14.83 mm), respectively (Figure 1).

The total irrigation depth applied was calculated by adding the applied irrigation and the effective precipitation that occurred during Phases I and II. The maximum irrigation depth applied, i.e., for T_{16}, was 191.22 mm and 217.99 mm during 2010 and 2011, respectively (Table 2). The applied depths in Phases I and II were found to be higher in the 2011 cultivation cycle. The effective precipitation (T_0) and depth values applied in each phase for each treatment (T_{01} – T_{16}) are described in Table 2.

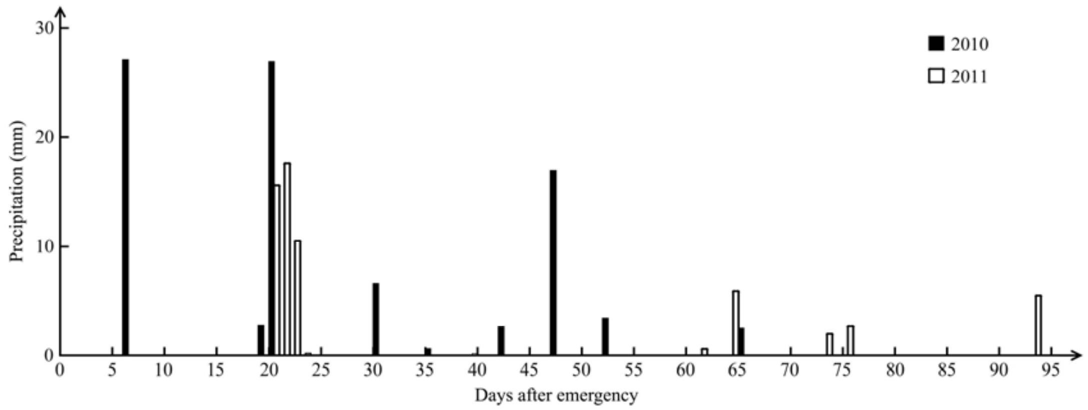

Figure 1 Pluvial precipitation during the bean crop (cv. IAC-Alvorada) cycle

Table 2 Irrigation depth applied (mm) in each phase of the bean crop cycle: Phase I – vegetative, Phase II – reproductive, and the total depth applied for each treatment in the first and second experimental years

Treatments	2010			2011		
	Phase I[(a)]	Phase II[(b)]	Total[(c)]	Phase I	Phase II	Total
T_0	-	-	14.38	-	-	14.83
T_{01}	26.42	44.31	85.11	32.02	49.24	96.06
T_{02}	26.42	66.47	107.27	32.02	73.86	120.71
T_{03}	26.42	88.63	129.43	32.02	98.40	145.25
T_{04}	26.42	110.79	151.59	32.02	123.10	169.95
T_{05}	39.63	44.31	98.32	48.08	49.24	112.15
T_{06}	39.63	66.47	120.48	48.08	73.86	136.77
T_{07}	39.63	88.63	142.64	48.08	98.40	161.31
T_{08}	39.63	110.79	164.80	48.08	123.10	186.01
T_{09}	52.84	44.31	111.53	64.05	49.24	128.12
T_{10}	52.84	66.47	133.69	64.05	73.86	152.74
T_{11}	52.84	88.63	155.85	64.05	98.40	177.28
T_{12}	52.84	110.79	178.01	64.05	123.10	201.98
T_{13}	66.05	44.31	124.74	80.06	49.24	144.13
T_{14}	66.05	66.47	146.90	80.06	73.86	168.75
T_{15}	66.05	88.63	169.06	80.06	90.40	185.29
T_{16}	66.05	110.79	191.22	80.06	123.10	217.99

Note: [(a)] Phase vegetative; [(b)] Phase reproductive; [(c)] Sum of the depth applied in the Phase I, Phase II and effective precipitation.

The bean harvest in the first cycle was conducted during 17-22 July 2010 (Table 3). The first-year crop cycle duration was 90-95 d among the various treatments. A treatment with 100% ETc in its two phases exhibited a cycle of 95 d, whereas the non-irrigated treatment exhibited a cycle of 90 d. In the second experiment, the harvest was conducted between August 3rd and September 3rd 2011. The second-year crop cycle duration was 100-107 d among the treatments.

Table 3 Period between the beginning (Start) of the experiment and the harvest, with the respective number of days (Cycle) for the evaluated treatments in the first and second experimental years

Treatments	2010			2011		
	Start	Harvest	Cycle	Start	Harvest	Cycle
T_0	19/04	17/07	90	20/05	31/08	101
T_{01}	19/04	20/07	93	20/05	01/09	104
T_{02}	19/04	20/07	93	20/05	02/09	105
T_{03}	19/04	22/07	95	20/05	03/09	106
T_{04}	19/04	22/07	95	20/05	05/09	107
T_{05}	19/04	20/07	93	20/05	01/09	104
T_{06}	19/04	20/07	93	20/05	02/09	105
T_{07}	19/04	22/07	95	20/05	03/09	106
T_{08}	19/04	22/07	95	20/05	05/09	107
T_{09}	19/04	20/07	93	20/05	01/09	104
T_{10}	19/04	20/07	93	20/05	01/09	105
T_{11}	19/04	22/07	95	20/05	03/09	106
T_{12}	19/04	22/07	95	20/05	05/09	107
T_{13}	19/04	20/07	93	20/05	01/09	104
T_{14}	19/04	20/07	93	20/05	02/09	105
T_{15}	19/04	22/07	95	20/05	03/09	106
T_{16}	19/04	22/07	95	20/05	05/09	107

An increase in the crop cycle duration in 2011 may have been related to climatic factors, such as low air temperature, relative humidity, wind speed, and solar radiation during the development of the bean crop. Figure 2 shows the maximum and minimum values of air temperatures along the phonological cycle of the bean crop, for the first and second agricultural seasons (2010 and 2011). In the first year, the ambient temperature did not drop below 15°C in both Phases I and II. In general, the ambient temperature range was within the recommended range according to Silva and Ribeiro (2009), i.e., the optimal minimum, average, and maximum air temperatures as 12ºC, 21ºC, and 29ºC, respectively.

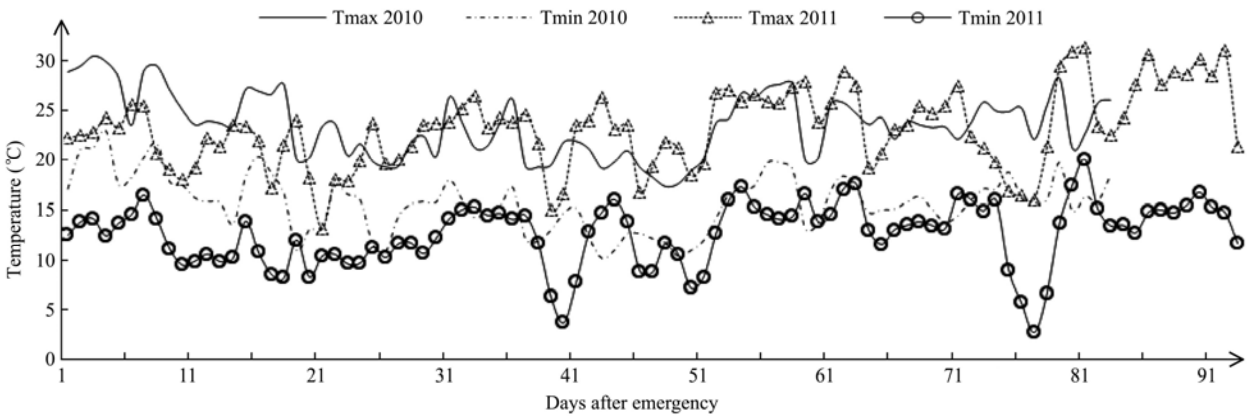

Figure 2 Temperature variation of maximum (Tmax) and minimum (Tmin) during the bean crop cycle measured at a weather station

However, in the second year, the minimum ambient temperature dropped below 15°C during the flowering and grain filling stages, which interfered with the crop cycle. As a result of the low temperatures, the treatments with reduced depths of 40%, 60%, and 80% in Phase II exhibited lower cycles compared to those of T_{16} (i.e., 100% ETc and no hydric restriction).

These results corroborate the findings of Rosales-Serna et al. (2004), who confirmed that under hydric deficiency, tolerant cultivars exhibit a reduction in the number of days until maturation. However, this differs from the results obtained by Guimarães et al. (2011), who found no effect of hydric deficiency on the precocity of common bean genotypes during two harvest years in Porangatu-GO.

The pluvial precipitation in the first experiment occurred during the late vegetative and flowering stage. In the second experiment, the pluvial precipitation was concentrated mainly at the beginning of the third trifoliate and at the end of the vegetative and grain filling stages (Figure 1). The values of the global incident radiation during the experimental period (Table 4) fell within the ranges observed by Escobedo et al. (2011). According to the authors, the decrease in atmospheric transmissivity in winter was due to the cold fronts in the region.

Table 4 Degree days (DD), monthly average temperature (MAT, ºC), wind speed (WS, m s^{-1}), relative humidity (RH, %) and global radiation (GR, MJ m^{-2} d^{-1}) in the first and second experimental years, Botucatu-SP

Year/Month	DD	MAT	WS	RH	GR
2010					
April	13.31	23.31	0.72	69.13	16.22
May	8.74	18.74	0.84	72.62	13.62
June	9.01	19.01	0.86	61.17	13.22
July	9.65	19.89	0.65	62.12	13.79
2011					
May	6.79	16.78	0.83	71.69	14.42
June	5.89	15.89	0.83	71.55	13.01
July	8.39	18.39	0.77	66.68	12.65
August	8.48	18.94	0.71	61.76	14.81
September	3.57	13.57	1.09	62.86	12.50

Table 5 is a summary analysis of the variance of PG, NVP, MG, NGV and NVC, referring to the first- and second-year experiments. The treatment × irrigation depth variable indicated a significance difference in the NGV in the first and second experiments. The interaction between treatment × irrigation depths showed no significance difference in PG, NVP, MG, and NVC.

Water stress in Phases I and II reduced the NGV in comparison to the treatment without hydric deficiency. The means obtained in the NGV by *cv.* IAC-Alvorada were subjected to hydric deficiency during Phases I and II. The first and second experiments were lower when compared to the treatment without hydric deficiency (Table 6). In the second experiment, the effect of hydric deficiency in Phase I was more severe, due to the greater reduction in the applied depth. These results corroborate those obtained by Oliveira et al. (2009), who found significant differences in the NGV (4.5, 4.2, and 3.7) for the different irrigation depths (16.5, 27.5, and 30.5 mm) plus the pluvial precipitation, which resulted in 50%, 30%, and 27% water reserves in the soil, respectively. Our findings differ from those of Sousa and Lima (2010), who found that withholding irrigation during the vegetative stage, the most sensitive period, resulted the largest reductions in NGV. The values of NGV were 3.0, 5.56, 6.12, 6.56, and 6.75 from the suppression of irrigation in the vegetative, pre-flowering, full-flowering, grain-filling, maturation, or witness stages, respectively. Miorini et al. (2011) verified that the suppression of water in the vegetative and flowering stages most affected the NGV. They also noted that the emergence and maturation phases were less affected by the suppression of irrigation. Binotti et al. (2007) observed that the NGV was more related to the utilized cultivar than with the cultivation practices of the bean crop, such as irrigation and nitrogen fertilization, which had little influence. NGV values are normally 4 to 5.

Table 5 Values of F and level of significance in the analysis of variance in culture of the common bean, under different combinations in depth of applied water

Source of Variation/Year	A[(a)]	B[(b)]	A×B	Treat/test	Year	CV (%)
PG year						
2010	1.395^{ns}	1.512^{ns}	0.474^{ns}	1.986^{ns}	3.01^{*}	14.28
2011	0.987^{ns}	17.062^{*}	1.078^{ns}	7.772^{*}		10.93
NVP						
2010	3.429^{*}	6.800^{*}	0.807^{ns}	2.674^{ns}	1.97^{ns}	16.18
2011	1.361^{ns}	9.170^{*}	0.587^{ns}	3.118^{ns}		18.72
MG						
2010	0.043^{ns}	16.223^{*}	0.781^{ns}	3.045^{ns}	2.28^{ns}	3.73
2011	1.351^{ns}	2.069^{ns}	1.547^{ns}	1.185^{*}		3.41
NGV						
2010	8.576^{*}	6.668^{*}	4.758^{*}	6.934^{ns}	4.19^{*}	5.34
2011	7.886^{*}	7.230^{*}	4.458^{*}	16.519^{*}		7.32
NVC						
2010	5.870^{ns}	10.319^{ns}	1.263^{ns}	4.755^{ns}	1.50^{ns}	21.44
2011	4.388^{*}	3.005^{*}	1.118^{ns}	2.333^{ns}		34.65

Note: [(a)] Phase I – vegetative; [(b)] Phase II – reproductive; * Significant at 5% level of probability for the test of F; [ns] not significant at 5% level of probability for the test of F.

Table 6 Grains/pods in the different combinations of irrigation depth applied at two phases during the bean crop cycle: Phase I – vegetative, and Phase II - reproductive

Phase I (%)	Phase II (%)			
	40	60	80	100
	2010			
40	3.63 Aa[(a)]	3.51 Ab	3.44 Ab	3.79 Aa
60	3.55 Aa	3.52 Ab	3.49 Aab	3.34 Ab
80	3.43 Ba	3.85 Ab	3.37 Bb	3.39 Bb
100	3.56 Ba	4.23 Aa	3.85 Ba	3.52 Bab
	Average Witness = 3.030		d'[(b)] = 0.419	
	2011			
40	3.59 Bb	4.29 Aa	3.78 ABb	4.27 Aab
60	3.61 Bb	4.35 Aa	4.62 Aa	4.45 Aab
80	4.25 Ba	4.32 ABa	4.91 Aa	3.93 Bb
100	4.43 Aa	4.40 Aa	4.51 Aa	4.68 Aa
	Average Witness = 2.16		d'[(b)] = 0.647	

Note: [(a)] The means followed by the same letter capital in the horizontal and lowercase in the vertical does not differ at 5% level of probability according to Tukey's test; [(b)] least difference by Dunnett's test.

The combined results of hydric deficiency in Phases I and II impacted the PG in the second experiment, but not in the first experiment. With reduced depths in both Phases, lower PGs were produced compared to treatments without restrictions in any phase (Table 7).

In the second experiment (2011), the means productivity there was a significant difference in the treatments in Phase II (Table 7). When 40% of the ETc was applied, an average of 2,475.86 kg ha^{-1} was produced. A result that was significantly less than the PG from 100% ETc in Phase II, which was 3,247.00 kg ha^{-1}.

These results are similar to those obtained by Oliveira et al. (2009), who found a significant difference in the values (3,134; 2,915; and 2,722 kg ha^{-1}) at different irrigation depths (16.5, 27.5, and 30.5 mm) and pluvial precipitation levels, which resulted in 50%, 30%, and 27% water reserves in the soil, respectively. The authors mention that the values of PG revealed a downward tendency as the depletion of soil water increased.

Miorini et al. (2011) obtained a 10.7% decrease in PG with the withholding of irrigation only during maturation. However, with greater effects observed from withholding irrigation during the flowering phase, a decrease of 72.8% was observed compared with the irrigated treatment during all phases. The same authors found that results from irrigation at all stages did not differ from treatments with water stress in emergency, the grain filling, and maturation. Furthermore, there was decreased productivity of 10.1%, 35.8%, and 5.4% in treatments withholding irrigation during emergence, filling, and maturation, respectively.

Table 7 Average productivity (kg ha^{-1}), number of pods per plant, weight of 100 grains and empty pods in different combinations of irrigation during the bean crop cycle for the years 2010 and 2011, Botucatu-SP

Phase/Year	Crop evapotranspiration (%)			
	40	60	80	100
PG				
Phase I - vegetative				
2010	2,424.60 a	2,431.26 a	2,388.98 a	2,619.54 a
2011	2,814.85 a	2,951.70 a	2,973.43 a	2,988.21 a
Phase II - reproductive				
2010	2,340.30 a	2,445.51 a	2,475.01 a	2,603.57 a
2011	2,475.86 c[(a)]	2,928.44 b	3,076.89 ab	3,247.00 a
NVP				
Phase I - vegetative				
2010	12.66 a	13.95 a	14.59 a	15.10 a
2011	12.99 a	13.45 a	12.06 a	12.07 a
Phase II - reproductive				
2010	12.79 b	13.46 b	13.85 b	16.20 a
2011	10.81 b	11.77 b	13.02 ab	14.96 a
MG				
Phase I - vegetative				
2010	24.32 a	24.25 a	24.37 a	24.34 a
2011	27.96 a	28.36 a	28.03 a	27.68 a
Phase II - reproductive				
2010	23.84 b	24.01 b	23.75 b	24.68 a
2011	27.77 a	28.00 a	27.76 a	28.50 a
Weight of 100 grains				
Phase I - vegetative				
2010	24.32 a	24.25 a	24.37 a	24.34 a
2011	27.96 a	28.36 a	28.03 a	27.68 a
Phase II - reproductive				
2010	23.84 b	24.01 b	23.75 b	24.68 a
2011	27.77 a	28.00 a	27.76 a	28.50 a

Note: [(a)] Means followed by the same letter in horizontal do not differ at the level of 5% of probability according to Tukey's test.

These results differed from those found by Sousa and Lima (2010) who evaluated the effect of water stress during different development stages of the common bean. They showed a reduction in productivity in the order of 80.49%, 69.14%, 68.61%, and 27.29% during phases of vegetative development, pre-flowering, full-flowering, and grain-filling, respectively.

The combined results of water stress during Phases I and II are reflected in the NVP during the first and second experiments (Table 7). In general, it was found that the reduction in applied water in Phase I and II, resulted in lower NVP compared to the treatment without water restriction at any stage during the bean crop cycle. The major hydric deficiencies in Phase II resulted in lower NVP. These results corroborate the values obtained by Sousa and Lima (2010), who found average values of 14.98 NVP under conditions of irrigation, withholding during the vegetative, pre-flowering, full-flowering, grain-filling, and maturation stages, respectively. However, this differs from the results found by Sousa and Lima (2010), who presented NVP values of 6.83, 14.00, 13.56, 19.62, and 20.87 during the vegetative, pre-flowering, full-flowering, grain-filling, and maturation stages, respectively, when irrigation was suppressed.

The results obtained by Aguiar et al. (2008) in a study with and without hydric stress during flowering and the early stages of development, over 20 d, resulted in a reduction of the NVP, with values of 58.5% to 11.1%, respectively, in the "carioca" group.

These results contradict those observed by Oliveira et al. (2009), who found no significant difference in the NVP. Values of 15.4; 15.6 and 15.1 NVP at different irrigation depths (16.5, 27.5, and 30.5 mm) plus pluvial precipitation that resulted in 50%, 30%, and 27% of water reserves in the soil, respectively.

Moraes et al. (2010), during a study conducted in a greenhouse in the region of Alegre-ES, observed a difference in the NVP, with average values of 1.77 and 0.60, with and without water stress, respectively. Under conditions of water stress after 30 DAE, a period of pre-flowering and the formation of floral buds stage, irrigation was ceased for 15 d.

Altogether, Torres et al. (2013) found that the PG of the bean crop, NVP, and NGV, were greater when water replenishment to the soil was performed with 100% evapotranspiration in relation to a deficit of 70% and 40% of the applied water depth.

The combinations of water stress during Phases I and II resulted in MG values that were similar in the first and second experiment (Table 7). In general, it was observed that a reduction of applied water in Phase II, combined with Phase I, had a lower MG of beans, compared with the treatment without restriction in both phases.

The highest levels of water stress in Phase II, combined with Phase I, resulted in lower MG during the year of 2010. These results were similar to those gathered by Oliveira et al. (2009), who found a significant difference in the MG. The values of 28.96, 28.85, and 30.35 grams at different irrigation depths (16.5, 27.5, and 30.5 mm) plus pluvial precipitation responded to 50%, 30%, and 27% of water reserves in the soil, respectively.

The obtained results diverge from those found by Oliveira et al. (2009), who found no significant effect in the irrigation depth (272.04, 407.39, and 341.63 mm); this was estimated using handling methods (TS, TCA, and PM), respectively on the MG. These authors obtained an average of 30.15 g MG. The higher values obtained in this study are probably due to the cultivars and regions of study.

The combined results of water stress during Phases I and II are reflected in the NVP per plant for the first and second experiments. In general, the reduction in applied water in Phase I, combined with a reduction of water in Phase II, was found to have a significant impact, reflecting an increased NVP per plant, compared to the treatment without restriction during any phase of the bean crop cycle (Table 7). The major water deficiencies in Phases I and II resulted in lower NVP, as shown in Table 7.

The average NVP between the experiments were significant in the T_{05}, T_{09}, T_{11}, T_{16} treatments. One of the reasons for this increase in the NVP in the first experiment, compared to the second, was due to the lower final plant stand numbers per hectare (Table 8).

In the first experiment, it was found that a MG in all treatments differed from the second experiment, with lower average values. The average NGV values between the first and the second year were significant in the T_{04}, T_{05}, T_{06}, T_{07}, T_{08}, T_{09}, T_{11}, T_{12}, T_{13}, T_{15}, T_{16}, and T_0 treatments. The NGV was found to be superior in the second year under irrigated conditions and was inferior in the witness. One of the reasons for these larger-sized grains per pod correlates to the lower final plant stand numbers per hectare (Table 8).

Pereira et al. (2011) obtained lower averages in the macronutrient and micronutrient levels between the two years, attributing these variations to different climatic conditions during the periods of flowering and pod formation. In the second year of study, during the initial pod formation, a high precipitation and temperature average (close to 20°C) were observed, whereas in the first experiment, the flowering phase coincided with water stress and higher temperature fluctuations. In other cases, it is known that both water stress and high temperature during grain filling may provide an explanation for the variations in the concentration of proteins, both between sites and between years at the same place (Rangel et al., 2007).

Table 8 Comparison of pods/plant, weight of 100 grains (g), and grains/pods in two experimental years, Botucatu-SP

Treatment	NVP		MG		NGV	
	2010	2011	2010	2011	2010	2011
T_0	09.6 a[(a)]	06.5 a	23.3 b	29.4 a	3.1 a	2.1 b
T_{01}	10.1 a	11.6 a	23.9 b	27.1 a	3.6 a	3.6 a
T_{02}	13.2 a	11.2 a	24.2 b	28.3 a	3.5 a	4.0 a
T_{03}	13.3 a	12.8 a	23.9 b	27.0 a	3.4 a	3.8 a
T_{04}	14.0 a	16.3 a	25.1 b	29.3 a	3.6 b	4.3 a
T_{05}	14.0 a	10.3 b	23.9 b	28.8 a	3.4 a	3.2 a
T_{06}	12.7 a	13.5 a	24.2 b	28.1 a	3.5 b	4.1 a
T_{07}	12.8 a	14.0 a	23.6 b	28.2 a	3.7 b	4.4 a
T_{08}	16.2 a	15.9 a	25.2 b	28.3 a	3.5 b	4.4 a
T_{09}	13.0 a	10.0 b	23.6 b	28.1 a	3.4 b	4.2 a
T_{10}	13.9 a	11.4 a	24.1 b	28.0 a	3.6 a	4.2 a
T_{11}	13.7 a	12.6 b	23.7 b	27.7 a	3.5 b	5.2 a
T_{12}	17.6 a	14.2 a	26.1 b	28.3 a	3.2 b	3.9 a
T_{13}	14.0 a	11.2 a	23.9 b	27.1 a	3.7 b	4.4 a
T_{14}	14.0 a	10.9 a	23.5 b	27.6 a	4.0 a	3.9 a
T_{15}	15.5 a	12.7 a	23.7 b	28.0 a	3.6 b	4.5 a
T_{16}	16.9 a	13.4 b	26.2 b	28.0 a	3.5 b	4.7 a

Note: [(a)] Means followed by the same letter in horizontal do not differ at the level of 5% of probability according to Tukey's test.

Thus, it was found that 682.8 and 679.1 L (relation water depth/productivity) of water were required to produce 1 kg of grains utilizing T_{16} in the first and second experiments, respectively, as shown in Table 9. These results differ from those of Santana et al. (2009), who found that the water use efficiency increased until it reached a maximum value 7.26 kg^{-1} mm^{-1}, with a water tension on the soil of 37 kPa.

In direct sowing, with the presence of mulch on the soil surface, water usage is more efficient due to increased water retention and reduced evaporation, thereby resulting in higher productivity yields and smaller quantities of applied water (Stone and Moreira, 2000). Silveira and Moreira (1990) found values of 2,000 L of water were required to produce 1 kg of beans during the period of autumn/winter in the “Cerrado” region, with a PG of 2,325 kg ha^{-1}, using depths of 447 mm of water.

Table 9 Productivity (kg ha^{-1}), water depth (mm), and water use efficiency (kg m^{-3}) under different applied water depths in two experimental years, Botucatu-SP

Treatment	Productivity		Water Depth		Efficiency	
	2010	2011	2010	2011	2010	2011
T_0	1,633.62	968.44	14.38	14.83	11.4	6.5
T_{01}	2,357.91	2,358.54	85.11	96.06	2.8	2.5
T_{02}	2,424.09	2,827.12	107.27	120.71	2.3	2.3
T_{03}	2,418.51	2,751.52	129.43	145.25	1.9	1.9
T_{04}	2,497.89	3,322.27	151.59	169.95	1.6	2.0
T_{05}	2,375.04	2,303.34	98.32	112.15	2.4	2.1
T_{06}	2,216.61	3,092.67	120.48	136.77	1.8	2.3
T_{07}	2,432.15	3,239.53	142.64	161.31	1.7	2.0
T_{08}	2,701.25	3,171.27	164.80	186.01	1.6	1.7
T_{09}	2,202.58	2,639.15	111.53	128.12	2.0	2.1
T_{10}	2,563.64	2,764.37	133.69	152.74	1.9	1.8
T_{11}	2,375.27	3,205.58	155.85	177.28	1.5	1.8
T_{12}	2,414.47	3,284.62	178.01	201.98	1.4	1.6
T_{13}	2,425.69	2,602.43	124.74	144.13	1.9	1.8
T_{14}	2,577.70	3,029.63	146.90	168.75	1.8	1.8
T_{15}	2,674.11	3,110.96	169.06	185.29	1.6	1.7
T_{16}	2,800.69	3,209.85	191.22	217.99	1.5	1.5

In the first experiment (2010), the highest water use efficiencies were found in the combinations of depth of 40% in Phase I and 40% in Phase II. In 2011, there was greater water use efficiency in comparison with 2010, because higher PG were found in the different treatments studied. The highest water use efficiencies in the second experiment (2011) also were observed in the combinations of a depth of 40% in Phase I and 40% in Phase II.

4 Conclusions

The reduction in applied depth in Phase I did not interfere with PG. The highest reductions in water in Phase II had a greater effect on the PG and the NVP. The PG obtained in the irrigated treatments differed from that of the witness in 2011. The highest PG was 3,322.27 kg ha^{-1} and was obtained from the combination of applications of a depth of 40% in Phase I and 100% in Phase II. The required water consumption by the bean crop over its full cycle in treatments with no water stress was 191.22 mm and 217.99 mm in the years 2010 and 2011, respectively.

Acknowledgements

The authors are grateful to Ministry of Science, Technology, Innovation and Communications (MCTIC), the State of Goiás Research Foundation (FAPEG), the National Council for Scientific and Technological Development (CNPq), and Goiano Federal Institute (IF Goiano) for funding of current scientific project.

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