SÃO PAULO STATE UNIVERSITY – UNESP
JABOTICABAL CAMPUS

AGRONOMIC PERFORMANCE OF COMMON BEAN CULTIVARS UNDER IRRIGATION LEVELS ASSESSED BY SPECTRAL INDICES AND MODELING

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ANDERSON PRATES COELHO – Son of Juliana Prates Baião Coelho and Alecxandro Aparecido Braghini Coelho, he was born in the São Sebastião do Paraiso city, Minas Gerais state, on July 6, 1994. In March 2012 he joined the graduate course in Agronomy at São Paulo State University (Unesp), School of Agricultural and Veterinarian Sciences, Jaboticabal Campus, with completion in January 2017. During his graduation, he received a scientific initiation scholarship from the São Paulo Research Foundation (FAPESP), developing the project “Supplementary irrigation in sugarcane planted through pre-sprouted seedlings”. In March 2017, he joined the master’s degree in Agronomy (Plant Production) at the São Paulo State University (Unesp), School of Agricultural and Veterinarian Sciences, Jaboticabal Campus, with a scholarship from the Brazilian National Council for Scientific and Technological Development (CNPq), with completion in February 2019. Since January 2015 he has been part of the Irrigation and Environment Research Group (GpIMA) at Unesp, Jaboticabal. In March 2019, he entered the Ph.D. in Agronomy (Plant Production) at the São Paulo State University (Unesp), School of Agricultural and Veterinarian Sciences, Jaboticabal Campus, with completion in February 2022. In his PhD, he developed the project “Agronomic performance of common bean cultivars under irrigation levels assessed by spectral indices and modeling” financed with a scholarship by The São Paulo Research Foundation (FAPESP – 2018/17363-2).

“We are insignificant. No matter how much you plan your life, at any time everything can change.” (Ayrton Senna)

“Science can purify religion from error and superstition. Religion can purify science from idolatry and false absolutes.” (São João Paulo II)

DEDICATED

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SUMMARY

AGRONOMIC PERFORMANCE OF COMMON BEAN CULTIVARS UNDER IRRIGATION LEVELS ASSESSED BY SPECTRAL INDICES AND MODELING

ABSTRACT

In tropical and subtropical regions of Brazil, the cultivation of common bean can be carried out throughout the year, but it is subject to high variability in climatic conditions. Associated with this are factors such as irrigation, fertilization, and type of cultivars and the technological degree of the farms which also contribute to increasing the variability in crop yield. Studies on these factors and techniques to explain these variations are required to generate specific recommendations in this context. A two-year field experiment was conducted in the winter season in the Southeastern part of Brazil to evaluate, explain, and model the effect of irrigation levels on grain yield, technological and nutritional quality of grains, extraction and export of macronutrients, and define the level of irrigation and the sowing time that provide the best agronomic performance, using the CSM-CROPGRO-Dry bean model, in common bean cultivars with contrasting growth habits. Additionally, the potential application of spectral indices (NDVI and chlorophyll index - LCI) to forecast the yield of common bean cultivars was evaluated. The cultivars IAC Imperador (determinate growth and early cycle) and IPR Campos Gerais (indeterminate growth and normal cycle) were used in this study. These cultivars were subjected to five irrigation levels (54%, 70%, 77%, 100%, and 132% of crop evapotranspiration). Water deficit reduced the common bean agronomic performance, regardless of the cultivar. Furthermore, the water deficit reduced the technological and nutritional quality of the grains and the accumulation of macronutrients and anticipated the maximum daily demand for most macronutrients. IPR Campos Gerais showed better agronomic performance, efficiency, and response to water use than IAC Imperador, in addition to higher technological and nutritional quality and greater accumulation of biomass and macronutrients. Moreover, the maximum daily nutrient demand of cultivar IAC was anticipated compared with that of IPR. The CSM-CROPGRO-dry bean model showed high accuracy in estimating the growth and yield of the evaluated cultivars. Based on the long-term analysis in the model, it was observed that it is possible to manage irrigation with a controlled water deficit without significantly reducing the common bean yield if sowing is anticipated (March-April) within the winter crop. The meteorological element that most interfered with common bean yield was the global solar radiation (GSR) after the flowering of the crop, in which each unit increment in the GSR generated increments in the grain yield (GY) of the cultivars IAC and IPR by 55 and 50 kg ha^{-1}, respectively. It was possible to forecast the GY of common bean cultivars ($R^2 = 0.64$; RMSE= 370 kg ha^{-1}; MBE= -140 kg ha^{-1}) from the NDVI, both in individual models by cultivar and in the general model, whereas for the LCI, the accuracy was lower ($R^2 < 0.40$; RMSE > 650 kg ha^{-1}; MBE > 450 kg ha^{-1}). These results demonstrate that the definition of more specific management is essential to increase sustainability in areas cultivated with common bean, helping to optimize the use of water and nutrients, sowing dates, and the application of remote sensing in cultivars with contrasting growth habits.

Keywords: *Phaseolus vulgaris* L., DSSAT, grain yield, remote sensing, technological and nutritional quality, water use efficiency

DESEMPENHO AGRONÔMICO DE CULTIVARES DE FEIJÃO-COMUM SOB NÍVEIS DE IRRIGAÇÃO, AVALIADO POR ÍNDICES ESPECTRAIS E MODELAGEM

RESUMO

Em regiões tropicais e subtropicais, como no Brasil, o cultivo do feijão-comum pode ser realizado durante todo o ano, sendo submetido a elevadas variabilidades de condições climáticas. Associado a isso, fatores como, o manejo de irrigação e adubação, a cultivar utilizada e o nível tecnológico dos produtores também contribuem para aumentar a variabilidade de cultivo. Nesse contexto, estudos que envolvam esses fatores e técnicas para explicar essas variações são necessários para gerar recomendações mais específicas. Através de um experimento de dois anos agrícolas na safra de inverno no Sudeste do Brasil, esse estudo objetivou avaliar, explicar e modelar o efeito de níveis de irrigação sobre a produtividade de grãos, qualidade tecnológica e nutricional dos grãos, extração e exportação de macronutrientes e definir o nível de irrigação e a época de semeadura que proporcione o melhor desempenho agronômico, utilizando o modelo CSM-CROPGRO-Dry Bean, em cultivares de feijão-comum com hábitos de crescimento contrastantes, além de avaliar a aplicação de índices espectrais (NDVI e índice de clorofila) para a previsão da produtividade do feijão-comum. Foram utilizadas as cultivares IAC Imperador (crescimento determinado e ciclo precoce) e IPR Campos Gerais (crescimento indeterminado e ciclo normal). Essas cultivares foram submetidas a cinco níveis de irrigação (54, 70, 77, 100 e 132% da evapotranspiração da cultura). O déficit hídrico reduziu o desempenho agronômico do feijão-comum, independentemente da cultivar. Além disso, o déficit hídrico reduziu a qualidade tecnológica e nutricional dos grãos, o acúmulo de macronutrientes e antecipou a máxima demanda diária para a maioria dos macronutrientes. Entre cultivares, a IPR apresentou desempenho agronômico e eficiência e resposta ao uso da água superiores a cultivar IAC, além de maior qualidade tecnológica e nutricional e maior acúmulo de biomassa e macronutrientes. Além disso, a máxima demanda diária de nutrientes da cultivar IAC foi antecipada em relação a IPR. O modelo CSM-CROPGRO-Dry bean apresentou elevada acurácia na estimativa do crescimento e produtividade das cultivares avaliadas. A partir da análise de longo período no modelo, observou-se que é possível manejar a irrigação com déficit hídrico controlado sem reduzir significativamente a produtividade do feijão-comum, desde que a semeadura seja antecipada (mar/abr) dentro da safra de inverno. O elemento meteorológico que mais interferiu na produtividade do feijão foi a radiação solar global (RSG) após o florescimento da cultura, em que cada incremento unitário na RSG gerou incrementos na PG das cultivares IAC e IPR aumentam em 55 e 50 kg ha^{-1}, respectivamente. Foi possível prever a PG das cultivares de feijão-comum (R^2= 0,64; RMSE= 370 kg ha^{-1}; MBE= -140 kg ha^{-1}) a partir do NDVI, tanto em modelos individuais por cultivar quanto pelo modelo geral, enquanto para o ICF a acurácia foi menor (R^2< 0,40; RMSE> 650 kg ha^{-1}; MBE> 450 kg ha^{-1}). Esses resultados demonstram que a definição de manejos mais específicos é fundamental para aumentar a sustentabilidade no cultivo de feijão-comum, auxiliando na otimização de uso da água, nutrientes, datas de semeadura e aplicação de sensoriamento remoto em cultivares contrastantes.

Palavras-chave: *Phaseolus vulgaris* L., DSSAT, produtividade de grãos, eficiência de uso da água, qualidade tecnológica e nutricional, sensoriamento remoto

CHAPTER 1 – General considerations

1.1 Introduction

The common bean (*Phaseolus vulgaris* L.) is one of the main responsible for world food security, being considered one of the cheapest sources of protein for the poorest population in Latin America, Africa and Asia countries. Due to its socioeconomic importance, common bean is cultivated all over the world, being part of the population's food and culture. Along with rice, common bean is part of the Brazilian population's diet and form a dish of high nutritional quality.

In tropical and subtropical regions, such as in Brazil, the common bean can be cultivated in up to three crops per year, being the wet (summer) season, with sowing from October to December, the dry season, with sowing from January to March, and the winter season, with sowing from April to June. It is a consensus that, due to the need for irrigation in a large part of the Brazilian territory, the winter season is the one with the greatest participation of farmers with a high technological level. However, even in this season, the average Brazilian yield still does not reach the 4 Mg ha^{-1} considered as attainable by farmers in field conditions (Melo et al., 2010; Oliveira et al., 2011; Conab, 2021).

Among the factors that contribute for the average yield in the winter season to be below what is considered attainable are the irrigation management and the choice of cultivar. Although this season is considered the one with the highest technological level, the adequate management of irrigation is often neglected, without criteria for water application. Both the irrigation management and the choice of cultivar are essential agricultural managements to obtain high yields in the common bean crop. When these two factors are associated in a production system, these managements must be carried out with even greater discretion, because the region, water availability, season, succession crops and the operationality of the area must be considered.

When the region has low availability of water for irrigation during the dry season of the year, irrigation management with application of a smaller amount of water, i.e., deficit irrigation management, should be prioritized. In irrigated areas, up to 3 grain crops per year are usually grown, mainly the soybean/common bean/maize and maize/common bean/wheat successions. In this type of production system, early cultivars should be prioritized, as they allow the cultivation of different species within a more favorable climatic period and better crop adequacy within succession and crop rotation systems.

Regardless the cultivar, the study of contrasting genotypes in terms of cycle and growth habit can have very different results that will help to define management depending on the cultivar group. Thus, comparing cultivars with an early cycle and determinate growth habit with cultivars with a normal cycle and indeterminate growth habit can promote this variability and generate information for more specific recommendations for common bean.

These specificities mentioned above within an intensive and technological production system, such as irrigated ones, must be studied to ensure the maximum agronomic performance and economic return of crops. Thus, evaluations of the effect of different irrigation levels on the yield of common bean cultivars with contrasting cycles and growth habits are necessary to generate relevant information for farmers and fill gaps in scientific knowledge in the area. Through this type of study, the definition of the best irrigation management depending on the cultivar can help a more conservationist agriculture, generating information to optimize the use of water and establish the best management depending on the genotype.

In addition to yield, irrigation management and the cultivar used can interfere with technological and nutritional quality and nutrient uptake by common bean. As a food directly consumed by the population, the grain quality affects the common bean price, the nutritional quality of the food and the acceptability of the product by the consumer market; therefore, technological and nutritional quality assessments are as important as grain yield (Lemos et al. al., 2015). Irrigation and cultivars can generate different nutrient demands to obtain high yields. Thus, multidisciplinary studies that include this information are needed to generate more assertive recommendations in agriculture, contributing to global food security and the sustainability of the system.

Due to this high variability in the cultivation of common bean mentioned above and due to the complexity of the factors of the soil-plant-atmosphere system, crop growth models are efficient tools to evaluate the effect of managements, such as the application of irrigation depths and fertilization, on the growth and yield of the crops. The use and application of models in the common bean crop can help to understand

and explain the crop variability in Brazil, whether it is climatic, technological or in the choice of cultivar. After calibrated, it is possible to use the model to simulate the growth of each cultivar as a function of the climate and soil factors to which they will be subjected, through historical data of climate and soil, helping to define the sowing date, fertilization management, irrigation management, and others. This information is essential to help technicians and farmers to increase yield and reduce factors that interfere with plant growth. Among the existing models in the DSSAT software, the CSM-CROPGRO-Dry bean is used to simulate the growth of leguminous plants, such as common bean.

The use of remote sensing can help define specific managements and simulate crop yields. Within this context, spectral indices, such as vegetation indices, in which the normalized difference vegetation index (NDVI) is found, and chlorophyll indices are the most used and easily acquired. Indirectly, these indices measure the vigor, physiological state and productive potential of plants as a function of reflectance and light absorption at wavelengths in the red and near infrared range. From these indices, it is possible to build yield maps that will help to define specific management zones, since yield accurately indicates the conditions to which the plants were submitted during the cycle. Moreover, the forecast of yield and productive potential can help farmers, technicians and government agencies in tasks such as managing the production, the need for agricultural management and crop predictions.

Assessing the applicability of these indices in forecasting the yield of common bean is essential for the success of this practice in agriculture, and it can help various sectors of the production chain. However, for this, studies that encompass many factors that can influence the accuracy of the results and that will guide the application of this technique in the common bean crop are needed. Among these factors, the index used, the phenological stage of evaluation, the year, the cultivar and the type of model to calibrate and validate the data stand out.

Given the above, the hypotheses for this work are: (i) Irrigation management and cultivars with determinate and indeterminate growth habits promote differences in agronomic performance, the technological and nutritional quality of grains, and macronutrient uptake, helping to define specific practices; (ii) The CSM-CROPGRO-Dry bean model can be used with high accuracy for long-term simulations in common bean cultivars and will allow the definition of the best sowing times and irrigation management in the winter crop; (iii) it is possible to establish models with satisfactory accuracy for predicting the yield of common bean cultivars with contrasting growth habits based on spectral indices.

Therefore, the aim was to evaluate, explain and model the effect of different irrigation levels on grain yield, technological and nutritional quality of grains, extraction and export of macronutrients and to define the irrigation level and sowing time that provides the best performance agronomic, using the CSM-CROPGRO-Dry bean model, in common bean cultivars with contrasting growth habits, in addition to evaluating the potential application of spectral indices (NDVI and chlorophyll index) to forecast the yield of common bean cultivars.

1.2 Literature review

1.2.1 The common bean crop

Common bean is an agricultural crop belonging to the Fabaceae family, genus *Phaseolus* and species *Phaseolus vulgaris* L., cultivated in several countries. The crop has two centers of origin and primary diversity, one in Central America and the other in the Andes (Debouck and Tohme, 1989; Bitocchi et al., 2012). Wild species of *P. vulgaris* in Central America are characterized by small seeds, while in the Andes they have large seeds (Debouck and Tohme, 1989; Toro et al., 1990). Burle et al. (2010) evaluated the genetic diversity of native bean varieties and observed that Brazil, due to intensive cultivation of this legume for several years, can be considered a secondary center of diversity of common bean.

In Brazil, common bean was cultivated by native populations before the arrival of Europeans. In the book “Botany and agriculture in Brazil in the 16th century”, Hoehne (1937) describes letters and books on the description of crops found by Europeans on their arrival in Brazil, including common bean. Freitas (2006), evaluating an archeological sample found in the municipality of Januária/MG, observed that the results indicated a variety of common bean from the North of South America and Mexico. Although this sample is dated from 1660 to 1738, that is, after the arrival of the Europeans in Brazil, the colonizers were not present in the region until the beginning of the 18th century, being probably originated from the cultivation of common bean by the Indians.

Within the species *P. vulgaris* there are several cultivars available to farmers. In Brazil, there are currently more than 130 registered cultivars (RNC, 2021), demonstrating the high availability and variability of genotypes. Within this context, cultivars can be classified according to the growth habit and commercial group of the grain. Cultivars with determinate growth habits are classified as Type I (erect) and are characterized by having terminal inflorescences and branch growth and leaf emission until flowering. Indeterminate growth cultivars are classified as Type II (bush), Type III (prostrate) and Type IV (climbing) and are characterized by the stem ending with a vegetative or floral and vegetative bud and growth of branches and leaves throughout the cycle (Binotti, 2015).

As a function of grain characteristics such as color, brightness, shape, size and culinary quality (technological), common bean cultivars are classified into more than 10 commercial groups (Lemos et al., 2015). The best known and most cultivated are Carioca, Preto, Manteiga, Roxinho and Mulatinho, among which Carioca is the one with the largest cultivated area and commercial interest in Brazil, representing approximately 70% of the Brazilian production (Lemos et al., 2015). The grains of the Carioca commercial group are characterized by a light cream-colored tegument with brown streaks or stripes (Carbonell et al., 2010).

1.2.2 Common bean cultivation and irrigation management

The cultivation of common bean in the world extends to more than 100 countries, and an area exceeding 30 million hectares (FAO, 2019), demonstrating the socioeconomic importance of the crop. Among the bean intended for the consumption of grains (dry bean), which include other species besides *P. vulgaris*, Brazil is the third country with the largest planted area, only behind India and Myanmar. As for the cultivation of *P. vulgaris*, Brazil has an annual cultivated area of approximately 1.6 million hectares, total production of 2.4 million Mg and average yield close to 1.5 Mg ha^{-1} (Conab, 2021). However, the average yield of common bean in Brazil is considered low, as the yield can reach more than 4 Mg ha^{-1} (Melo et al., 2010; Oliveira et al., 2011; Pereira et al., 2012).

It is a consensus that, due to the need for irrigation, the winter crop is the one that requires a higher technological level from the farmer, since the higher costs for this season (Richetti & Melo, 2012; Richetti & Melo, 2015) require higher yields for the minimum economic return. Besides the need for irrigation, winter season common bean cultivation is an excellent alternative for the farmer due to the lower incidence of diseases at that time for the Southeast and Midwest of Brazil, with low relative humidity and precipitation (Lemos et al., 2015). Due to these factors, common bean yield in the winter season (2.59 Mg ha^{-1}) is 51% higher for these regions when compared to the rainy season (1.72 kg ha^{-1}) and 67% higher when compared to the dry season (1.55 Mg ha^{-1}) (Conab, 2021). However, the average yield of winter season common bean in the Center-South region of Brazil is 35% lower than the 4 Mg ha^{-1} considered commercially achievable by farmers.

In much of the mid-southern region of Brazil, rainfall from April onwards is scarce and returns with an increased intensity only in early spring (October). The need for irrigation in common beans grown in the winter is justified, as evapotranspiration at this time of year is much higher than rainfall, making it fundamental management for obtaining economically viable yields. Although the temperatures and photoperiod in autumn/winter are lower than those in spring/summer, the insolation throughout the day is proportionally higher and the air relative humidity is lower, helping to explain the reference evapotranspiration values obtained between 4 and 5 mm per day (Allen et al., 1998). This loss of water over 90 days of the common bean cycle generates reference evapotranspiration (ETo) of the order of 360–450 mm. As the common bean has crop coefficient values (Kc) that vary from 0.35 to 1.15 (Allen et al., 1998) throughout the cycle, its water demand tends to be slightly different from the values mentioned earlier.

At the beginning of the cycle, when the common bean has a low leaf area index, the crop evapotranspiration is lower than the ETo because the Kc values are lower than 1.0. However, the common bean evapotranspiration at its maximum growth is higher than ETo because Kc values are greater than 1.0 (Klar & Fernandes, 1997). Fener et al. (2016) found that the evapotranspiration of the common bean cultivated in the winter was 478 mm, whereas Mantovani et al. (2012) verified an accumulated value of 380 mm. Teixeira et al. (2017) observed that the irrigation depth of common beans grown in the winter is on average greater than 250 mm, and this value depends on the common bean cultivar used and the sowing date. Based on these values shown, it was observed that the need for irrigation to obtain satisfactory yields in common beans cultivated in the winter is on average greater than 250 mm, corresponding to 2,500 m^3 ha^{-1}.

As there is a need to optimize water use in irrigated agriculture, several agricultural practices can be used as a strategy, highlighting sowing time, cultivar choice, and irrigation management. Teixeira et al. (2017) observed that sowing time can be reduced by providing more than 100 mm (more than 30%) the need for irrigation in common beans cultivated in the winter. According to the authors, sowing common beans earlier (March-April) within the winter season allows greater participation of rainfall in crop growth, mitigating the use of irrigation water and increasing water-use efficiency or irrigation water productivity by more than 50%. Furthermore, the authors found that the use of early cultivars could reduce the accumulated irrigation depth by up to 50 mm (20%). Water-use efficiency may fluctuate by more than 100% between common bean cultivars (Builes et al., 2011), demonstrating the significance of genotype choice for sustainable irrigated agriculture.

Regulated deficit irrigation management is also one of the factors contributing to the optimization of irrigation water use (Kang et al., 2000; Chai et al., 2016). This management consists of irrigating crops with less than the maximum amount of water, without drastically affecting the yield. In this management, the yield per unit of water applied is higher than that of the irrigation that supplies 100% of the water needs, helping to increase water-use efficiency (Chai et al., 2016). This management allows for an increase in irrigated areas, with the same amount of water available for full irrigation. In maize, Kang et al. (2000) observed that regulated deficit irrigation strategies may increase water-use efficiency by 20% and reduce irrigation depth by 24%, without influencing the grain yield. However, the sensitivity of the cultivar to water deficit can affect the results, that is deficit irrigation can significantly reduce the grain yield.

Studies are needed to determine the best strategies to increase water-use efficiency in common bean crops in this context. Therefore, a combination of the aforementioned strategies must be evaluated to generate more specific recommendations, such as irrigation management and common bean sowing date and cultivar. From the results obtained, more conservative management may be recommended, helping to optimize irrigation water use and agricultural sustainability.

1.2.3 Common bean yield response to irrigation and cultivars

Proper irrigation management in winter-grown common bean can increase crop yield by more than 90% (Santana et al., 2008; Monteiro et al., 2010; Torres et al., 2013), demonstrating the importance of this practice for the economic and environmental sustainability of the crop. Santana et al. (2008) evaluated the effect of different irrigation levels on the yield of cultivar BRSMG Talismã and observed that the maximum yield (3.19 Mg ha^{-1}), obtained with a 112% irrigation replacement level, was 97% higher than the yield obtained (1.62 Mg ha^{-1}) in the smallest depth (40% replacement). Monteiro et al. (2010) observed increases of more than 200% in the yield of the Pérola cultivar because of adequate irrigation management. Studying the effect of different irrigation levels on the yield of the common bean cultivar Pérola, Torres et al. (2013) observed increases of up to 1.4 Mg ha^{-1} in 100% replacement compared to 40% replacement management, a value corresponding to more than 100% increase in yield.

As for the cultivar, studies show that the correct choice of the genotype promotes more than 50% higher yields compared to less productive materials. Alves et al. (2020) evaluated the agronomic performance of five common bean cultivars from the Carioca commercial group and observed that the difference in yield between the most productive (BRSMG Majestoso) and the least productive (BRS Cometa) genotype was 1.94 Mg ha^{-1} (more than 100% variation). Comparing the agronomic performance of 16 common bean cultivars from the commercial group Carioca, Nunes et al. (2020) observed that the yield among cultivars varied by more than 100%, with an absolute variation of 1.44 Mg ha^{-1}. These results demonstrate the importance of choosing the right cultivar, a factor that directly affects the yield and profitability.

In the context of optimizing water use in agriculture, defining the terms efficiency and response is essential. Efficiency refers to the ability of the genotype to produce satisfactorily well under conditions of low availability of the studied resource, while the response is the ability of the genotype to significantly increase its yield with increasing availability of the resource (Fageria et al., 2013; Leal et al.., 2019; Nunes et al., 2020). Thus, efficient and responsive genotypes should always be prioritized, because, regardless of the production system and technological level of the farmer, these will be the most productive materials. These two terms are well defined for common bean in relation to fertilization, especially nitrogen (Fageria et al., 2013; Leal et al., 2019; Nunes et al., 2020), however, little is known about efficiency and response of common bean cultivars to water application.

It is verified in the literature that, due to the shorter cycle, early common bean cultivars have lower productive potential compared to cultivars with normal or late cycle. Filla et al. (2020) evaluating the yield of the cultivar IAC Imperador (Type I, early) and IPR Campos Gerais (Type II, normal) submitted to nitrogen fertilization managements, verified that, on average, the indeterminate growth cultivar (IPR Campos Gerais) presented yield 38% higher than the cultivar with determinate growth (IAC Imperador). Studying the efficiency and response of 16 common bean cultivars, Nunes et al. (2020) verified that, on average, the yield of cultivars with normal and late cycle was 40% higher than the yield found in early and semi-early cultivars. The lower productive potential of early cultivars is related to the shorter period that these genotypes remain in the reproductive stages compared to normal and late cycle cultivars. According to Guilherme et al. (2021) a possible strategy to increase the productive potential of early cycle common bean cultivars is to obtain genotypes with early flowering and a long period of grain filling, as these are factors related to higher crop yields.

It is also noteworthy that early cultivars need less water during the cycle. Thus, even with less productive potential, these genotypes can produce more per amount of water applied, featuring high efficiency in water use. In this sense, evaluations of water use efficiency depending on the applied irrigation depth are essential to recommend the best irrigation management depending on the cultivar used.

1.2.4 Technological quality of common bean as a function of irrigation and cultivars

According to the World Food Summit (1996), the definition of food security is “when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life”. Within this context, there are foods considered the most important for global food security, among which common bean stand out (Nassary et al., 2020; Nadeem et al., 2021). Common bean is a source of carbohydrates, vitamins, nutrients and, above all, proteins for humans (Bressani, 1993; Celmeli et al., 2018). It is considered the main source of low-cost protein for the poorest population in American, Asian and African countries (Fageria et al., 2013; Fageria et al., 2014). Along with rice, which provides amino acids, it is a typical dish consumed by the Brazilian population and a combination of foods considered almost perfect, being a source of high quality protein (Rodrigues et al., 2013).

In this sense, as common bean is one of the few foods consumed by the population without transformation processes, their quality is essential for the acceptability of the consumer market and for setting the price of the product. According to Bressani (1993), common bean grain quality can be separated into nutritional value and consumer acceptance. The consumer acceptance attributes are grain appearance, color, size, cooking time, texture, broth color and grain integrity after cooking, while from a nutritional point of view the main attributes are protein and nutrient content, antinutritional factors and protein digestibility. “Carioca” common bean, for example, the most consumed by the Brazilian population, are light cream grain, halo with the same color as the tegument, matte, coarse grain (mass of 100 grains between 25 and 30 g), oblong shape, average cooking time less than 30 minutes, sieves yield greater than or equal to 12 greater than 70% and relative grain production on sieves (RGPS) greater than 7.0 (Ramalho et al., 2004; Ramalho and Abreu, 2006; Carbonell et al., 2010; Lemos et al., 2015).

The attributes listed above, together with the nutritional quality of the common bean, define the acceptance by the consumer market and the price paid for the product. According to Carbonell et al. (2010), batches of common bean with sieves yield greater than or equal to 12 greater than 70% and RGPS greater than 7.0 can receive financial gratification by the packers, increasing the income of farmers. In addition, grains with a high content of protein and nutrients, especially Zn and Fe, help, even if in small scale and proportion, in increasing food security, especially in places where the population suffers from malnutrition and hunger. Within this context, agricultural management can, in addition to altering grain yield, interfere with the quality of common bean grains.

Evaluating the effect of nitrogen fertilization on the technological quality of 16 common bean cultivars, Leal et al. (2021) observed that high doses of N increase the protein content of grains. In addition, the authors observed differences of up to 24% in the protein content, 13% in sieve yield, 16% in RGPS and 62% in cooking time between cultivars. Bettiol et al. (2020), evaluating the effect of N supply management for early common bean cultivars, observed that the association of seed inoculation with *Rhizobium tropici* + foliar spraying of *Azospirillum brasilense* + application of 90 kg ha^{-1} of N in topdressing promoted RGPS above 7.0 in the evaluated cultivars, with possible financial gratification by the packers. Evaluating the technological quality of 25 common bean genotypes in the winter crop, Perina et al. (2014) observed a variation of more than 40% in cooking time between genotypes.

As for the nutritional quality of grains, Sica et al. (2021) verified differences for Ca and Zn between common bean cultivars, with variations greater than 25%. In the same line of research, Hummel et al. (2018) observed relevant differences in the contents of all nutrients between common bean cultivars under water deficit conditions. These results demonstrate the importance of choosing the common bean cultivar, especially in regions where there are nutrient deficiencies (hidden hunger) in the population, especially Zn and Fe. In these regions, the proper choice of cultivar and agricultural management is essential to ensure grains with greater nutritional quality and promote greater food security for the population, even if these managements promote proportionally small gains.

Associated with the choice of cultivar, irrigation management can promote changes in the nutritional and technological quality of common bean, directly affecting the food biological value, acceptability by the consumer and the price paid for the product. This is because water is essential for plant growth and development and directly affects nutrient uptake and translocation to grains (Taiz et al., 2017). Under water deficit conditions, for example, plants tend to have lower photosynthetic rate and growth (Lizana et al., 2006), factors that can directly affect grain filling and nutrient translocation. However, according to Lizana et al. (2006) the impact of water deficit on the photosynthetic rate depends on the common bean cultivar, which may be more or less tolerant to drought.

Water deficit can also affect the translocation of nutrients to grains, interfering with the nutritional quality of the food. Etienne et al. (2018) observed that nutrients present different patterns of remobilization for grains as a function of water deficit, this effect being dependent on the species evaluated. Overall, the authors found that water deficit has little effect on the remobilization of N, Ca, Mn and B to grains, while for K, S, P, Mg, Cu, Fe and Zn the remobilization rate for grains depends on the degree of water deficit and on the crop. These differences can alter the composition of the grains, a fact that can interfere with both nutritional and technological quality, especially in terms of cooking time. For the latter, it is verified that the concentration of a certain nutrient or substance in the grains can change the cooking time of the grains. Less pronounced, Leal et al. (2021) observed that increased protein content can reduce the cooking time of common bean.

In addition to the water deficit, excess water can also change the composition of common bean. Excess water can negatively interfere with plant growth, impacting root and shoot growth and photosynthetic rate (García et al., 2008; Ashraf, 2012; Silveira et al., 2014). These changes can impact the translocation of nutrients to the grains, as well as the water deficit. Furthermore, there may be a dilution effect of nutrients in the plant and grains, affecting the nutritional and technological quality of common bean. However, the effects of both water deficit and excess on common bean grain quality depend on the cultivar used, as there are genotypes that are more morphologically and physiologically tolerant to these water stresses than others.

1.2.5 Extraction and export of macronutrients

Similar to what was observed for most crops, the standard fertilization recommendations for common bean do not include specific factors, such as the cultivar used, the year and the degree of water deficit in which the crop will be cultivated. Obviously, the inclusion of these factors would make the recommendation bulletins very specific and could not easily and practically serve the region's farmers and technicians. Therefore, standard fertilization recommendations include the main factors that can affect nutrient extraction and crop yield, among which are the season, the production destination, the production and rotation systems used and the technological level of the farmer (Raij et al., 1997; Chagas et al., 1999). Therefore, it is the role of scientific research to generate more detailed information regarding different crops through scientific articles, theses and books, so that technicians and professionals in the field have access to this information and can make it available more easily to farmers.

As previously described during this literature review, the cultivation of common bean in Brazil has high variability, whether as a function of climate (year-round production), available cultivars, technological level of farms or even irrigation management adopted. For the State of São Paulo, part of these factors that generate variability in the cultivation of common bean are met in the fertilization recommendations (Ambrosano et al., 1997). In this recommendation, Ambrosano et al. (1997) consider the cropping season (wet, dry and winter crop), expected yield and predecessor crop (response class) and soil nutrient content (when necessary). For the state of Minas Gerais, the fertilization recommendation considers the technological level of production (Chagas et al., 1999), which indirectly refers to the cropping seasons in Bulletin 100, and the nutrient content in the soil. In the Cerrado, fertilization recommendations for common bean consider only the expected yield and the nutrient content in the soil, with no reservations regarding the cropping season and/or technological level of the farm (Sousa and Lobato, 2004). However, factors such as the cultivar used, interannual climatic variations within the same season and the water deficit are not met in these recommendations. Therefore, studies that assess nutrient extraction and export as a function of these factors are essential to generate more specific and assertive fertilization recommendations.

This information is even more important for high technological level farmers, especially in irrigated crops and in the winter season. Through this information, farmers who already reach high yields can further increase their yields through small adjustments in fertilization management. In addition, studies with cultivars released more recently help and guide technicians and farmers in the more correct management of fertilization in the crop, since most fertilizer recommendation bulletins date from the late 1990s and early 2000s and the recommendations were prepared depending on the cultivars available at the time (Raij et al., 1997; Ribeiro et al., 1999).

Assessing the dynamics of macronutrient uptake by two common bean cultivars as a function of fertilization management, Soratto et al. (2013) did not observe relevant differences between cultivars in the total amount extracted, in the daily uptake rate and in the period of greatest demand for N, P, K, Ca, Mg and S nutrients. However, it is noteworthy that the two cultivars evaluated by the authors (Pérola and IAC Alvorada) are similar, with indeterminate growth and normal cycle (85-90 days). In this sense, the evaluation of cultivars with contrasting growth habits and different cycles can generate differences in nutrient demand and uptake dynamics. In the average of cultivars and for the management with 100% of the recommended fertilization, the accumulation of nutrients in the study by Soratto et al. (2013) was 150 kg ha^{-1} of N, 16 kg ha^{-1} of P, 120 kg ha^{-1} of K, 70 kg ha^{-1} of Ca, 18 kg ha^{-1} of Mg and 16 kg ha^{-1} of S.

Assessing the nutrient accumulation of super-early common bean genotypes (IPR Colibri and CNFC 15874 lineage), Nascente and Carvalho (2018) observed that for the phenological stage V4 of the cultivars, the recommended period for topdressing common bean fertilization, occurred between 14 and 21 days after emergence (DAE) and the genotype cycles were of 70 days. In the standard fertilization recommendation for the state of São Paulo, topdressing fertilization is recommended at 25 DAE (Ambrosano et al., 1997), in Minas Gerais between 25 and 30 DAE (Chagas et al., 1999) and in the Cerrado at 30 DAE (Sousa and Lobato, 2004). Thus, the use of standard fertilization recommendations for super-early common bean cultivars can delay the supply of nutrients to the crop and directly interfere with crop yield. Overall, nutrient accumulation for the super-early cultivars evaluated by Nascente and Carvalho (2018) was 110 kg ha^{-1} of N, 13 kg ha^{-1} of P, 68 kg ha^{-1} of K, 50 kg ha^{-1} of Ca, 20 kg ha^{-1} of Mg and 4 kg ha^{-1} of S.

In addition to anticipating the need for topdressing in super-early cycle cultivars compared to normal cycle cultivars, the nutrient accumulation in super-early cycle cultivars is lower than the accumulation in normal cycle cultivars, as highlighted above. Comparing the accumulation of macronutrients among cultivars with normal cycle in the study by Soratto et al. (2013) and the super-early cycle genotypes in the study by Nascente and Carvalho (2018), there is a smaller amount extracted for the super-early cultivars. It is noteworthy that the studies were not conducted in the same year and location, factors that may interfere in the dynamics of nutrient accumulation in the common bean crop, but there is evidence that in early cultivars the management of topdressing must be differentiated.

As well as the cultivars, another factor that can interfere with the nutrient uptake in the common bean and the water deficit. As water is the medium that allows ion-root contact and is responsible for the uptake of nutrients by plants, its lack or scarcity reduces the growth and accumulation of nutrients by crops (Prado, 2008; Taiz et al., 2017). Because common bean is cultivated throughout the year, deficit events are commonly observed in the crop, especially in the dry season and in places with poor irrigation management. In irrigated crops, the management of deficit irrigation is common in places with low availability of water for irrigation, for farmers who do not have criteria to manage the application of water or even to increase the efficiency of water use and profit of the farmer (Chai et al., 2016). In addition to affecting plant growth, water deficit can interfere with nutrient uptake, which may interact with the cultivar used. In this sense, information about the effect of water deficit on the dynamics of nutrient uptake in common bean cultivars is important to generate more specific fertilization recommendations and understand the impact of this abiotic stress on the crop.

In the cultivation of white oat (*Avena sativa* L.), Coelho et al. (2020a) evaluated the effect of water deficit severity on N uptake by the crop. The authors observed that the severe water deficit reduced the accumulation of biomass and the total amount of N extracted by more than 70% compared to management without deficit, while for the moderate deficit the reduction was greater than 30%. In addition, the authors also verified that the severe water deficit anticipated the maximum N demand by white oat in relation to managements under moderate deficit and without deficit. In wheat (*Triticum aestivum* L.), Yan et al. (2020) observed that the extraction of N, P and K by the grains was 22, 20 and 22% lower, respectively, for irrigation management under more severe water deficit. In Conilon coffee (*Coffea canephora* Pierre), Covre et al. (2018) observed that non-irrigated crops presented 25, 19, 22, 34, 19 and 14% lower accumulation of N, P, K, Ca, Mg and S in the grains, respectively.

Nutrient accumulation can also be influenced by weather conditions. Within the same season (wet, drought or winter), interannual climatic variations can interfere with the growth of common bean and, consequently, with the accumulation of nutrients. In wheat, for example, the interannual variation in the export of N, P and K for grains reaches 18, 53 and 38%, respectively (Yan et al., 2020).

1.2.6 CSM-CROPGRO-Dry bean Model

Among the various models available in the literature, the CSM-CROPGRO-Dry bean model, included in the DSSAT software (Hoogenboom et al., 2019), can be applied to aid the interpretation of experimental results and in long-term simulations, to estimate the inter-annual variability of yield and thus recommend management practices based on research results. After calibrated, the model allows simulations of water application at specific crop stages without negatively affecting final yield, which can help to increase water use efficiency. The CSM-CROPGRO-Dry bean model (Hoogenboom et al., 1994; Boote et al., 2008) is a mechanistic model that simulates the growth and development of legumes such as soybean, common bean and peanut using climate, soil and crop management data.

There are several studies on the use of the CSM-CROPGRO-Dry bean model in simulating the growth and yield of common bean (Oliveira et al., 2012; Heinemann et al., 2016; Santos et al., 2016; Teixeira et al., 2016; Teixeira et al., 2016; al., 2017). Oliveira et al. (2012) evaluating the performance of the CROPGRO model in estimating the grain yield of the cultivars Pérola, Ouro Negro and Ouro Vermelho observed high accuracy in the estimate, with a maximum error of 12.63%. Assessing the accuracy of the same model in estimating growth and yield parameters of the common bean cultivar IAC Carioca, Santos et al. (2016) observed a precision of up to 96% in the estimation of the leaf area index in the model validation data, 94% in the accumulation of biomass throughout the cycle and an error of only 56 kg ha^{-1} in yield.

Heinemann et al. (2016), evaluating the accuracy of the CSM-CROPGRO model in estimating the yield of the Pérola (normal cycle) and BRS Radiante (early cycle) common bean cultivars, observed a small estimation error (350 kg ha^{-1}), indicating the model for simulations of these cultivars. Evaluating the effect of sowing dates on the yield of these same two common bean cultivars in the winter season, Teixeira et al. (2017) observed that early sowing (March) increases water use efficiency in irrigated crops and cultivar yield, especially for the early cycle cultivar (BRS Radiante). According to the authors, the increase in the efficiency of water applied via irrigation in early sowing is due to the greater contribution of rainfall at this time of year to the initial growth of plants. The authors also observed that for each day before the sowing date (May 1st) there was a water saving of 1.70 mm for the Pérola cultivar and 1.52 mm for the BRS Radiante.

From the results described above, it is observed that the CSM-CROPGRO-Dry bean model can present high accuracy in estimating crop growth and yield. However, in the studies described above, the authors did not verify the effect of different irrigation levels, either due to a deficit or excess of water, on the growth and yield of common bean. In addition, they did not specifically assess the effects of climate on the growth and yield of cultivars with contrasting growth habits and the commercial group “Carioca”. Thus, the use of the CSM-CROPGRO-Dry bean model to evaluate the effect of different irrigation levels on the yield of cultivars with contrasting growth habits of the “Carioca” commercial group, the most cultivated in Brazil, in long-term simulations, are necessary to evaluate the effect of climate on the growth and yield of cultivars and to help recommend the sowing date depending on the irrigation management.

Simulating the yield of white oat cultivated under five irrigation levels (11, 31, 60, 87 and 100% of crop evapotranspiration) over a long period (16 years) using the CSM-CERES-Barley model, Coelho et al. (2021) observed that the proper choice of sowing date can increase yield by more than 100% for irrigation levels without deficit or with a small deficit (87 and 100%). In addition, the authors found that for irrigation levels with greater water deficit (11 and 31%), sowing in March provides higher yield values, because at that time there is still rain in significant amounts that ensure good development for the crop, while for irrigation levels without deficit or with small water deficit, sowing in May/June guarantees the highest yields due to lower average temperatures. In the case of white oat, the sowing date is essential, because for each 1°C increase in the average temperature before flowering, yield is reduced by 661 kg ha^{-1}.

The CSM-CROPGRO-Dry bean model can also help estimate the irrigation depth demand of common beans and evaluate the effect of water deficit on crop yield. Heinemann & Stone (2015) observed that a water deficit may reduce the yield potential of common beans cultivated in the dry season by up to 48%. Additionally, to obtain maximum yields, the authors found that irrigation depths of 70–157 mm are required depending on the climatic conditions of the year.

Another application of the DSSAT model is the impact of climate change simulations on crop yield. For common beans, the increase in temperature and, consequently, in the CO_2 atmosphere concentration may positively impact and increase the average grain yield in Brazil throughout the year by up to 9% (Antolin et al., 2021). However, this can cause a reduction of up to 7% in the average annual rainfall in common bean-producing regions in Brazil, increasing the production risks in rainfed production systems.

The use of models that simulate crop growth and yield is essential to promote a more sustainable agriculture, with less climate risk and to ensure satisfactory yield and economic returns. This application in crops such as common bean is essential to understand the effect of factors that limit and promote variability in crop yield, especially in tropical and subtropical regions, such as Brazil, and to generate more accurate management recommendations.

1.2.7 Common bean yield estimation based on spectral indices

In addition to mechanistic models, such as the CSM-CROPGRO-Dry bean, the use of indirect measures in agriculture, associated with modeling, can be a good indicator of crop yield and help to distinguish specific management zones (Coelho et al., 2018a; Zhao et al., 2018; Coelho et al., 2020b). Forecast crop yield before harvesting can help several chains in the agricultural sector, from farmers to government agencies. For farmers, knowing the yield of a particular crop helps to define its management and crop practices. In addition, through yield maps, they can identify management zones that can be managed specifically within the same crop or in future crops, since the final yield indicates the conditions under which the plant was maintained throughout the cycle, helping to identify factors that generate variability (Canata et al., 2021). For government agencies, crop yield forecasting can help in predicting crops and in public policies, factors that can directly affect the food price.

Several sensors and indices can be used to identify the vigor and crops production potential, with low cost and high viability. There are structural, chlorophyll, photochemical and thermal indicators (Zarco-Tejada et al., 2013). Among the best-known indices are the structural ones, in which the Normalized Difference Vegetation Index (NDVI) vegetation (Rouse et al., 1974) and the chlorophyll indices are inserted. The evaluation of these indices indirectly allows the identification of the nutritional status of plants (Santos et al., 2017; Coelho et al., 2018b; Zhao et al., 2018), the forecast of yield, biomass accumulation and protein content, in addition to assist in nitrogen fertilization management and weed control (Yao et al., 2012; Kapp Júnior et al., 2016; Pantazi et al., 2016; Maia et al., 2017).

However, the accuracy of predicting crop growth and yield attributes using vegetation and chlorophyll indices varies depending on several factors, especially the region's climate, the crop, the phenological stage of evaluation and even the index used (Bredemeier et al., 2013; Bolton and Friedl, 2013; Coelho et al., 2019). Among these factors, the most easily controlled by researchers, technicians and farmers are the phenological stage of evaluation and the choice of the index. In this context, it is essential to define the best stage of the crop for evaluation using indirect measures, indicating the most appropriate index that provides the greatest accuracy.

Coelho et al. (2019) found that the highest accuracies were obtained from the NDVI when comparing the accuracy of forecasting white oat yield from the NDVI vegetation index and the leaf chlorophyll index. In addition, the authors found that the highest forecast accuracy were obtained in evaluations performed at reproductive phenological stages. Still in the cultivation of white oat, Coelho et al. (2018a) evaluated the performance of models to forecast crop yield from the NDVI and IRVI with one-year data. The authors observed high forecast accuracy, especially in evaluations carried out at the reproductive stages of the crop, with an R^2 of up to 0.91 and an error (RMSE) of 345 kg ha^{-1}. Assessing the generalizability of the models calibrated by Coelho et al. (2018a) with data from another year, Coelho et al. (2020b) observed that the models generated at the phenological stages close to the flowering of white oat showed satisfactory accuracy.

The difference between spectral indices to forecast crop growth and yield attributes may occur due to the sensitivity of each one in identifying morphological and physiological variations in plants, factors associated with vigor. The vegetation index NDVI, for example, is calculated by the ratio of the difference in the light reflectance in the near infrared band (740 ~ 1000 nm) less the light reflectance in the red band (625

~ 740 nm) divided by the sum of the reflectances in the two bands (Rouse et al., 1974). It is known that photosynthetic pigments (chlorophylls) absorb a high amount of light between wavelengths of 650 to 700 nm, within the red range. Thus, the greater the amount of chlorophyll per area, the greater the absorption of light in the red range, the lower the reflectance in that same range and, consequently, the higher the NDVI values. Thus, NDVI is interfered by both the chlorophyll content in the leaves and the leaf area index (LAI).

As for the leaf chlorophyll index (LCI), determined by the Falker® equipment, it is calculated based on the absorption of light at 3 wavelengths, two being close to the chlorophyll a absorption peaks (660 nm) and chlorophyll b (635 nm) and another in the near infrared (880 nm) (Falker, 2008; Bacelar et al., 2015). As individual leaves are used to determine this index, the values are only affected by the chlorophyll content in the leaves and not by the LAI (leaf area index), as occurs in the NDVI. These differences can make the chlorophyll index more sensitive and less accurate than the NDVI due to factors such as the dilution effect, climate, agricultural management and interannual variations. Due to these differences in calculation, measurement and sensitivity, the NDVI and LCI indices can promote different accuracy in forecasting crop yields. Furthermore, the association of the two indices in a single model can promote greater accuracy in forecasting the biophysical parameters and crop yields, as each index can show greater correlation with different morphological and physiological aspects of the plants.

The use of models is necessary for the forecast of yield and biophysical parameters of crops from spectral indices. Due to the easiness of calibration and understanding by researchers and technicians, linear and polynomial models are widely used to forecast, as verified in the studies by Coelho et al. (2018a), Coelho et al. (2019) and Coelho et al. (2020b). However, in addition to linear and polynomial models, other types of models such as artificial neural networks (ANNs) can be applied and present greater accuracy than linear and non-linear regressions (Yilmaz & Kaynar, 2011; Castro et al., 2017; Fernandes et al., 2020). Fernandes et al. (2020) evaluated the accuracy of models in estimating soil resistance to penetration and observed that modeling by ANNs promoted higher accuracies than linear and second-degree models.

ANNs are computational techniques that present mathematical models inspired by the neural structure of a human brain (Haykin, 2001). ANNs acquire knowledge through experience, being able to recognize patterns and make inferences. As they can recognize patterns in the distribution of data, this type of model allows giving less weight to less significant samples in the data set, which cannot be done in linear and non-linear regressions. Thus, the application of models by ANNs can increase the precision in forecasting crop yields and reduce error, enabling more accurate simulations.

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CHAPTER 2 – Irrigation levels effects on common bean cultivars with contrasting growth habits[1]

ABSTRACT- In order to demonstrate that there are differences in water use by common bean cultivars and generate more specific recommendations to optimize water use in agriculture, this study aimed to explain and compare the agronomic performance and water use efficiency and response of common bean cultivars with determinate and indeterminate growth habits submitted to irrigation levels. The experiment was carried out in the winter growing season for two years in the Southeast of Brazil. Two common bean cultivars, one with a determinate growth habit and early cycle (IAC Imperador) and the other with an indeterminate growth habit and intermediate cycle (IPR Campos Gerais), were subjected to five irrigation levels (54, 70, 77, 100, and 132% of the crop evapotranspiration). Water deficit affected the agronomic performance, reducing plant height (up to 29%), leaf area index (up to 40%), soil cover fraction (up to 28%), and grain yield (GY - up to 31%), regardless of the cultivar, while excess water was more detrimental to the cultivar IAC Imperador. The indeterminate growth habit cultivar showed higher agronomic performance (GY up to 18% higher) and water use efficiency and response than the determinate growth habit. The variable soil cover fraction by plant canopy was the most correlated with the grain yield of the common bean cultivars in the two years. Thus, the cultivar choice directly affects the water use efficiency in agriculture, indicating that it is a needful management for the conservation and sustainability of irrigated areas.

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

2.1 Introduction

Agriculture has expanded to areas and climate and soil conditions marginal to cultivation due to the growing world demand for food and climate change, especially regarding water availability, which can drastically affect crop yield and make cultivation economically unfeasible (FAO, 2017). In this sense, irrigation has become a strategy for obtaining high yields and ensuring that yield remains at satisfactory levels. The concern with the optimization of water use has become an increasingly essential factor for the sustainability of this resource with the increased irrigated area in the world over the years (UNESCO, 2021).

Factors such as irrigation system, type of management, soil cover, crop succession, and tillage system are often considered to optimize water use for irrigation

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(Rahil and Qanadillo, 2015; Silva et al., 2019). However, the cultivar is commonly neglected as a factor to optimize water use in agriculture. Studies have shown that the correct choice of the cultivar for an irrigated production system can increase yield by more than 50% (Acosta-Díaz et al., 2009) and water use efficiency by more than 15% (Santos et al., 2020).

The optimization of water use in agriculture does not always refer only to reducing its consumption but to producing more using the least amount possible. In this context, knowledge of the concepts of efficiency and responsiveness is essential to optimize water use in agriculture. Efficiency refers to the genotype capacity to produce satisfactorily well under the low availability of a given resource, while responsiveness refers to the genotype capacity to increase its production due to an increase in the resource (Fageria et al., 2013). Thus, efficient and responsive cultivars should always be recommended because these materials can optimize resource use, regardless of the adopted technology level and climate and soil conditions.

Common bean is widely grown during the winter in tropical regions due to the lower temperature and precipitation conditions at this time of year, reducing the risk of rain in the harvest, as well as diseases and pests throughout the cycle (Lemos et al., 2015). Approximately 600 thousand ha of common bean are estimated to be grown in the winter in Brazil (Conab, 2021). However, due to the low amount of rain at that season, irrigation and proper management are essential to obtain satisfactory yield.

The difference regarding growth habit and cycle of cultivars can interfere with the response and efficiency of the genotype to water use and common bean grain yield (Emam et al., 2012). Early cultivars require less water over the cycle as they have a shorter cycle and may be more efficient in using water. In addition, the use of cultivars with an early cycle has been recommended in intensive production systems, such as the irrigated production system, as it allows for better cultivation adequacy for crop rotation and succession. However, it is commonly observed that early cycle cultivars (determinate growth habit) have a lower yield than intermediate-or late-cycle cultivars (indeterminate growth habit) (Filla et al., 2020; Nunes et al., 2020). In this sense, studies with common bean cultivars with contrasting growth habits and cycles under irrigation levels are necessary to optimize water use in agriculture.

Much is known about the efficiency and response of common bean cultivars to nitrogen use (Leal et al., 2019; Nunes et al., 2020), but little is known about their efficiency and response to water use. In this sense, studies with common bean cultivars with contrasting growth habits cultivated under irrigation levels are necessary to recommend genotypes with higher efficiency and response to irrigation, optimizing water management in agriculture.

This study hypothesized that (i) there are differences in the efficiency and response of common bean cultivars with determinate and indeterminate growth habits due to irrigation levels; and (ii) the indeterminate growth habit cultivar has a higher agronomic performance than the determinate growth habit. Therefore, this study aimed to explain and compare the agronomic performance and efficiency and response of common common bean cultivars with determinate (early cycle) and indeterminate (intermediate cycle) growth habits submitted to irrigation levels.

2.2 Material and methods

The experiment was carried out in the winter growing season of 2019 and 2020 at the São Paulo State University (Unesp), School of Agricultural and Veterinarian Sciences, Jaboticabal, São Paulo, Brazil, close to the geographical coordinates 21°14′44″ S and 48°17′00″ W, with an altitude of 545 m. The regional climate, according to the Köppen classification, is Aw, that is, a tropical climate with a dry winter, summer rains, an average annual temperature of 22 °C, and average annual precipitation of 1,425 mm.

The soil in the experimental area is classified as an Oxisol (Soil Survey Staff, 2014). Three undisturbed and disturbed soil samples were collected for the physical characterization of the experimental area before sowing the experiment in 2019 (Table 1). Fifteen simple soil samples were collected 30 days before sowing the experiment in each year, forming a composite sample for fertility analysis (Table 2).

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

Layer (m)	Ds g cm^{-3}	Moisture FC m^3 m^{-3}	Moisture PWP m^3 m^{-3}	Clay g kg^{-1}	Silt g kg^{-1}	Sand g kg^{-1}
0.00–0.20	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) of the experimental area in 2019 and 2020.

Year	pH	H+Al	Al	K	Ca	Mg	SB	CEC	V
	$CaCl_2$	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.

Common bean was sown on May 7, 2019, and May 18, 2020. Two common bean cultivars from the 'Carioca' commercial group, with contrasting growth habits, were used: the cultivar IAC Imperador, with a determinate growth habit, and the cultivar IPR Campos Gerais, with an indeterminate growth habit. The cultivar IAC Imperador has a determinate growth habit (Type I), erect architecture, and an early cycle of 75 days (Chiorato et al., 2012). The cultivar IPR Campos Gerais has an indeterminate growth habit (Type II), erect architecture, and a normal cycle of 90 days (Moda-Cirino et al., 2012). The cultivars were mechanically sown to obtain a density of 240,000 plants ha^{-1}, with an inter-row spacing of 0.45 m. The seeds were treated before sowing with pyraclostrobin (5 g ai ha^{-1}) + thiophanate-methyl (45 g ai ha^{-1}) + fipronil (50 g ai ha^{-1}), using the commercial product Standak® Top, and inoculated with *Rhizobium tropici* (StarFix® Feijão – Semia 4088) for biological nitrogen fixation, using the dose recommended (250 mL ha^{-1}). The inoculant has a concentration of viable cells of 1.0 x 10^{9} ml^{-1}.

Common bean was sown in an area previously cultivated with corn, using a seed-cum-fertilizer drill intended for no-tillage. The corn hybrid P4285VYHR was sown in October in the two years, with an inter-row spacing of 0.90 m and 75,000 plants ha^{-1}. Limestone with a total neutralizing power of 95 was applied 30 days before corn sowing in the two years at a dose of 1.5 Mg ha^{-1}. The limestone was incorporated into the soil with a plowing harrow operation (0.00–0.20 m) and two leveling harrow operations. The amount of corn straw (dry matter) on the soil was estimated at common bean sowing and reached 7,622 ± 272 kg ha^{-1} in 2019 and 9,052 ± 367 kg ha^{-1} in 2020, while the average grain yield reached 11,200 ± 134 kg ha^{-1} in 2019 and 11,800 ± 210 kg ha^{-1} in 2020.

The sowing fertilization of the common bean crop was carried out according to the soil analysis (Table 2) and recommendation of Ambrosano et al. (1997) by applying a dose of 200 kg ha^{-1} of the formulation 04–20–20 in the two years, supplying 8 kg ha^{-1} of N, 40 kg ha^{-1} of P_2O_5, and 40 kg ha^{-1} of K_2O. Topdressing fertilization was carried out at the V_{4-3} stage, characterized by the third trifoliate leaf fully expanded (Fernández et al., 1985), and consisted of the application of a dose of 100 kg ha^{-1} of N in both years, with urea as source (Ambrosano et al., 1997). The topdressing fertilization was carried out at 19 and 21 days after emergence (DAE) of the common bean crop in 2019 and 2020, respectively, in a continuous strip at 0.10 m from the sowing row. A 10-mm irrigation depth was applied to all treatments in the two years after topdressing fertilization to avoid the effect of different volatilization rates between the different irrigation levels. This 10-mm irrigation depth was used because it is a minimum value that does not promote losses of urea by volatilization (Espindula et al., 2021), not significantly interfering with the applied treatments. The control of weeds, pests, and diseases was carried out when necessary, using products registered for the crop.

The experimental design used was strip-plot (Figure 1). The study factors were five irrigation levels and two common bean cultivars, with four replications. Each subplot had 15 rows of common bean, with a dimension of 6.75 m long and 2.4 m wide. The first row of common bean at each end and the initial 50 cm of the central rows were considered as borders. Six out of the remaining 13 cultivation rows were used to estimate yield and the other seven for destructive analysis.

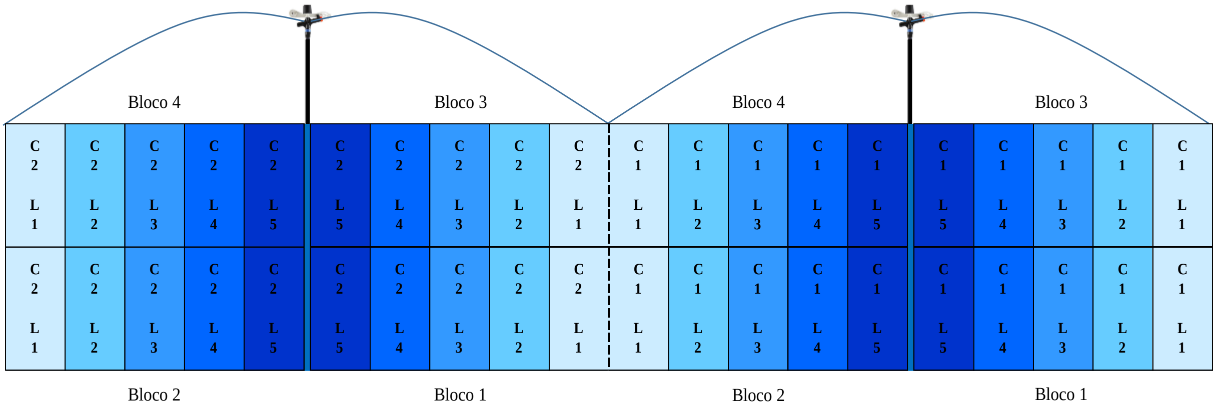
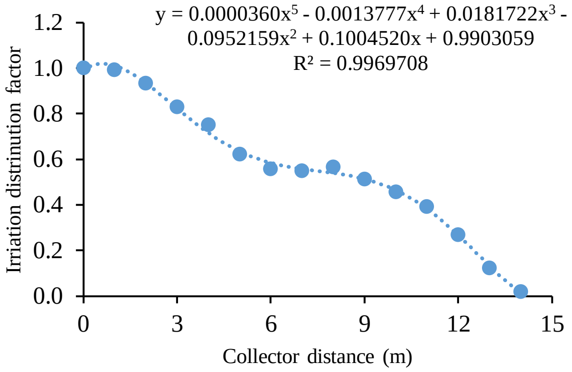


Figure 1. Sketch of the experimental area with the arrangement of treatments. C1: IAC

Imperador; C2: IPR Campos Gerais; L1: 54% ETc; L2: 70% ETc; L3: 77% ETc; L4: 100% ETc; L5: 132% ETc

The line-source sprinkler system was used, allowing the distribution of the irrigation water with variable application depths as the treatment moves away from the central sprinkler line (Hanks et al., 1976). A field test enabled the definition of the distribution fractions of the sprinkler precipitation (Figure 2). In model fit, the regression that generated the highest precision (R^2) was used, aiming to estimate the most accurate irrigation distribution factor possible in each treatment. Senninger 4023-2 sprinklers and ¾″ M 08Qx05 nozzles were used spaced every 6 m on the central line. The water application intensity of the sprinklers was measured in the field in tests with collectors placed at 1 m from each other up to the limit distance of water application by the sprinklers in a line perpendicular to the irrigation line, with four replications.



Distance (m)	Treatment	Irrigation distribution factor
0.00–2.40	L5	1.002 (132%)
2.40–4.80	L4	0.754 (100%)
4.80–7.20	L3	0.584 (77%)
7.20–9.60	L2	0.532 (70%)
9.60–12.00	L1	0.407 (54%)

Figure 2. Sprinkler irrigation distribution factor as a function of the distance from the irrigation line, with sprinklers spaced at 6 m from the line, obtained in field tests. Service pressure: 250 kPa

For study purposes, the treatments consisted of five irrigation levels (L1, L2, L3, L4, and L5), which were set up after the establishment of the water application regression by the sprinkler line (Figure 2). The L4 level was used as a standard, receiving 100% of the water required by the common bean crop. The L5 level received excess water, with 132% of the water requirement by the common bean, while the L3, L2, and L1 levels provided 77, 70, and 54% of the water requirement, respectively.

The irrigation management was carried out based on the crop water demand, according to the FAO 56 method, using climate data obtained daily from an automated agrometeorological station located 1,500 m from the experiment. The reference evapotranspiration (ETo) was estimated daily using the FAO 56 method (Allen et al., 1998). The evapotranspiration of the common bean crop (ETc) was calculated using the product of ETo by the crop coefficients (Kc) (Allen et al., 1998). The used Kc values 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 from 1.15 to 0.35 (maturation). For the Kc range between 0.40 and 1.15, the values were interpolated daily up to the maximum value (1.15). The daily increment was calculated as the ratio of the difference between the Kc range (1.15 – 0.40) and the number of days between the initial Kc (0.40) and maximum Kc (1.15).

Irrigation was carried out when the water deficit in the area was equal to 18 mm. This water depth was calculated according to the soil physical attributes (Table 1) and the common bean crop. The calculation considered an effective root depth of 0.25 m and a water availability factor of 0.40 (Allen et al., 1998). Two water depths of 15 mm were applied for the plant emergence considering a uniform initial stand in all treatments.

Average maximum and minimum temperatures during 2019 were 27.8 and 13.9 °C, respectively, with accumulated precipitation of 48.7 mm (Figure 3a and b). Low temperatures were observed in 2019, especially between July 5 and 8 and July 16 and 18.

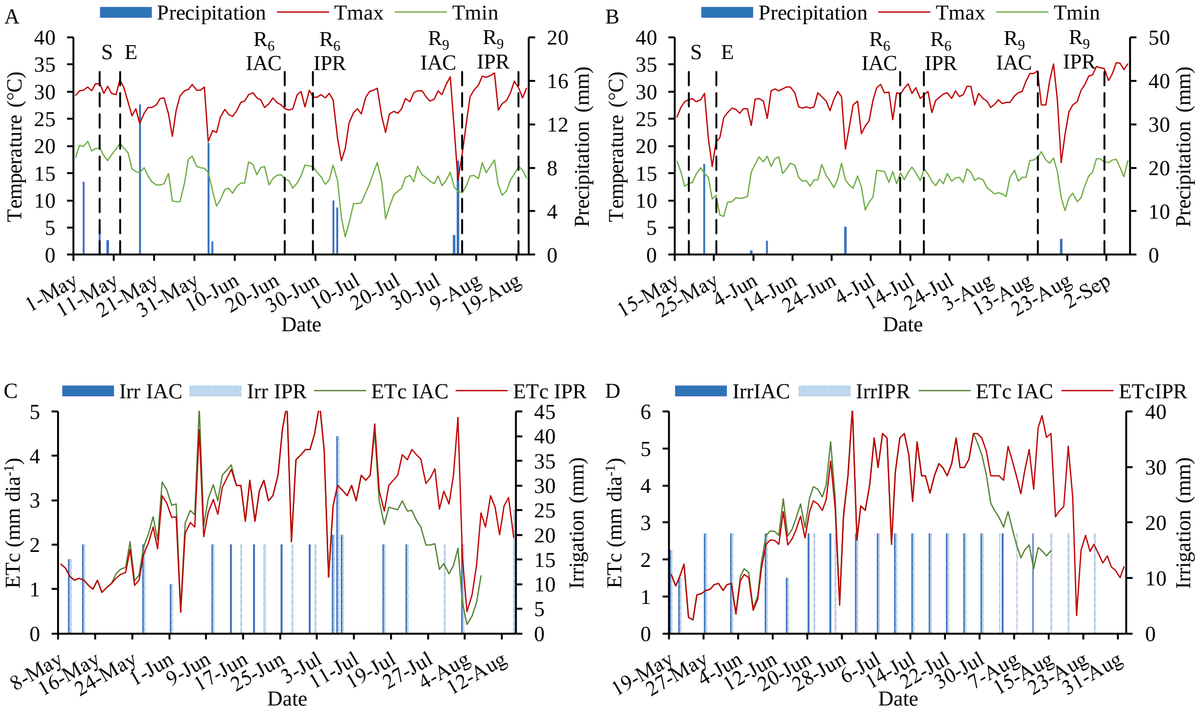


Figure 3. Daily maximum temperature, minimum temperature, precipitation (A and B), crop evapotranspiration, and irrigation (C and D) of bean cultivars during the experimental period from May 7, 2019, to August 19, 2019 (A and C) and May 18 to September 1 (B and D). S: sowing; E: emergence; R_6: full bloom; R_9: physiological maturity; Irr: irrigation; ETc: crop evapotranspiration.

The minimum temperature was 3.3 °C on July 7, which caused frost in the experimental area. The number of trifoliate leaves reached after the frost in each cultivar was counted, with an average of 10% in the cultivar IAC Imperador and 12% in the cultivar IPR Campos Gerais. In 2020, the average maximum and minimum temperatures during the experimental period were 28.4 and 13.9 °C, respectively, with accumulated precipitation of 35 mm (Figure 3c and d). Minimum temperatures below 5 °C were not observed in 2020.

The mean and standard deviation of the average of the fortnightly values of temperature and global solar radiation for the 2019 and 2020 experimental periods are shown in Table 3. Irrigation was used as an attempt to control the deleterious effects of frost during the early hours of July 6, 7, and 8. Thus, the water depth was constant for all treatments on these days and 20, 40, and 20 mm were applied, respectively. For calculation purposes, an accumulated irrigation depth of 30 mm was considered on these days for all treatments.

Table 3. Mean and standard deviation of the mean of the 10-day period values of maximum temperature (T Max), minimum temperature (T Min), average temperature (T Avg), and global solar radiation (GSR, MJ m^{-2} day^{-1}) during the experimental period from 2019 and 2020.

DAE	2019 T Max	2020 T Max	2019 T Min	2020 T Min	2019 T Avg	2020 T Avg	2019 GSR	2020 GSR
0–15	28.5 ±2.3	25.4 ±3.8	16.9 ±2.4	11.5 ±2.7	21.9 ±2.1	18.1 ±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	19.9 ±3.0	21.6 ±1.5	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	20.1 ±1.5	19.8 ±1.7	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	20.9 ±1.3	20.9 ±2.1	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	17.4 ±3.4	21.4 ±1.1	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	20.3 ±2.6	21.4 ±2.1	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	21.4 ±2.9	20.6 ±3.7	16.5 ±4.3	17.9 ±5.5

DAE: days after emergence.

Three days after the frost, 3 kg ha^{-1} of purified MAP fertilizer (12% N and 61% P_2O_5) and 0.5 kg ha^{-1} of N (urea) were sprayed to provide conditions for crop recovery. This management was also carried out in the second year at the same time frame as the application in the first year.

Soil moisture was determined weekly at three points per subplot in the 0.00–0.20 m depth layer, using the time domain reflectometry (TDR) technique (Fellner Feldegg, 1969). The calibration of the equipment was carried out before the experiment was set up in the soil of the experimental area. For this, 25 points were randomly chosen in the area for the determinations with the equipment and an undisturbed soil sample was collected at these points for determining the actual soil moisture (m^3 m^{-3}), generating a regression of the observed values as a function of the values measured on the equipment. This regression was used to correct the soil moisture during the experiment.

The leaf area index (LAI) was determined throughout the cycle of the common bean cultivars. For this, three plants were collected from each subplot. The areas of all leaves of three plants per plot were determined on an LI-3100C area meter, generating the average leaf area per plant. After that, the LAI was calculated by dividing the average area per plant by the area occupied in the soil, considering the plant population of each subplot. Collections for the cultivar IAC Imperador were carried out at 14, 29, 44, 68, and 85 DAE in 2019 and 21, 37, 57, and 79 DAE in 2020, while the collections for the cultivar IPR Campos Gerais were performed at 14, 29, 44, 68, 85, and 103 DAE in 2019 and 21, 37, 57, 79, and 93 DAE in 2020. The polynomial regression analysis of LAI was performed as a function of time for each treatment and year. The soil cover fraction by the canopy of common bean treatments was determined on the same days of the LAI evaluation using a software application Canopeo, which provides the percentage of soil covered by the crop canopy through images. Three photos were taken from each subplot to determine the cover fraction (CF), always between 9:00 am and 12:00 pm. The polynomial regression analysis of LAI and CF was performed as a function of time for each treatment and year.

Fifteen trifoliate leaves with petiole were collected per subplot at the R_6 (full bloom) stage for nitrogen leaf diagnosis, following a recommendation by Ambrosano et al. (1997). The collections were carried out in the seven rows of each plot destined for destructive analysis. The leaves were washed with running water, aqueous detergent solution, and deionized water. Subsequently, the leaves were taken to a forced-air circulation oven at a temperature of 65 °C until constant weight. After drying, the samples were ground in a Wiley mill and taken to digestion to determine the N content, according to the methodology described by Bataglia et al. (1983). Plant height was determined still at the R_6 stage in 10 plants per subplot.

The evaluations at harvest consisted of the final plant population (plants ha^{-1}), number of pods per plant, number of grains per pod, 100-grain weight (g), protein content of grains (%), and grain yield (kg ha^{-1}). The final population was estimated using three useful rows of each subplot. Seven consecutive plants were collected from each subplot 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 the grain moisture content to 0.13 kg kg^{-1}. Grain yield was estimated by harvesting six useful common bean rows, standardizing grain moisture content to 0.13 kg kg^{-1}. The harvest index was determined by the ratio between grain yield and total dry mass, multiplied by 100. The water use efficiency (WUE) of treatments was calculated by the ratio between grain yield and irrigation depth for each treatment (kg ha^{-1} mm^{-1}) (Singh et al., 2007).

The degree-day accumulation was calculated according to the equation (Eq. 1) proposed by Arnolds (1959). A base temperature (Tb) of 10°C was used (Wutke et al., 2000).

$$\sum DD = \left(\frac{Tmax + Tmin}{2}\right) - Tb \qquad (1)$$

Where:

DD = degree-day accumulation, Tmax = maximum temperature, Tmin= minimum temperature, Tb = common bean base temperature (10°C).

As in this study the variation sources were levels (quantitative factor), all the analyzed variables were subjected to the polynomial regression analysis as a function of the irrigation depths applied to each cultivar. Analyses were performed using the software SigmaPlot. Pearson’s correlation analysis was performed for each cultivar and year between all growth variables and production components evaluated with grain yield. For variables with non-significant regressions in the two cultivars, the F-test ($p < 0.05$) was used for mean comparison.

2.3 Results and discussion

The cycle of the cultivar IAC Imperador reached 85 and 82 days, with a total sum of degree-day (SDD) of 877 and 914 DD in 2019 and 2020, respectively, while the cycle of the cultivar IPR Campos Gerais reached 99 days for both years, with SDD of 1049 and 1116 DD, respectively (Table 4). On average, the cycle of the cultivar IAC Imperador was 15 days and 187 DD less than that of the cultivar IPR Campos Gerais. The comparison of the cycle between irrigation levels showed differences in the L4 management only for L1 and L2 levels in the two cultivars, with a cycle 5 and 3 days lower than that of the L4 management for the two cultivars, respectively.

Table 4. Sum of degree-days and cycle of common bean cultivars in the years 2019 and 2020 for water management with no water stress (L4).

Stage	IAC Imperador				IPR Campos Gerais			
	2019		2020		2019		2020	
	SDD	Days	SDD	Days	SDD	Days	SDD	Days
V_1–V_4	198.5	0–18	202.2	0–19	198.5	0–18	202.2	0–19
V_4–R_5	139.4	18–32	146.4	19–32	176.7	18–35	171.0	19–35
R_5–R_6	103.5	32–41	150.5	32–47	147.4	35–48	201.1	35–53
R_6–R_8	150.0	41–55	143.2	47–59	186.0	48–69	184.8	53–69
R_8–R_9	285.8	55–85	271.6	59–82	340.5	69–99	357.2	69–99
Total	877.1		913.8		1048.9		1116.2	

In 2019, every 10 days of the common bean cycle, there was an increase in the thermal sum of 103 DD, while in 2020, this increase was 114 DD (Figure 4).

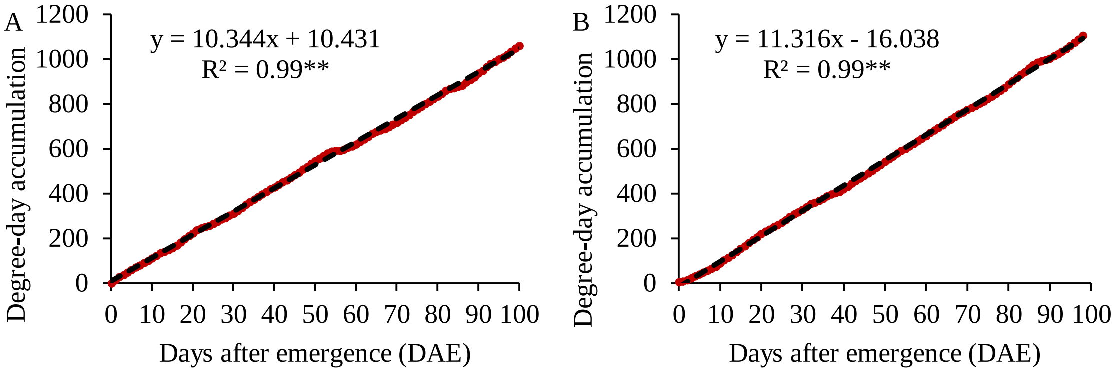


Figure 4. Degree-day accumulation throughout the common bean cycle in the years 2019 (A) and 2020 (B). **($p < 0.01$)

The total irrigation depth applied in the second year was higher than the first year, with an average of approximately 30% higher in the management with no water stress (L4) for both cultivars (Table 5). Overall, water depth applied to the cultivar IPR Campos Gerais was 17% higher than that of the IAC Imperador.

Table 5. Irrigation depth for the irrigation management systems of the cultivars IAC Imperador and IPR Campos Gerais in two years.

Water management	Irrigation depth (2019)	Irrigation depth (2020)	Irrigation depth (2019)	Irrigation depth (2020)
	------------IAC Imperador-----------		---------IPR Campos Gerais-------	
	--------------------------------------- mm		---------------------------------------	
L1	151.9	188.7	175.1	217.7
L2	181.8	230.6	212.1	268.6
L3	194.2	247.9	227.5	289.7
L4	235.0	305.0	278.0	359.0
L5	293.6	387.1	350.6	458.6

Each 10 mm of water applied by irrigation corresponded to 5.6 and 4.5% in the irrigation level for the IAC Imperador and IPR Campos Gerais in the first year, respectively, and 4.0 and 3.2% of the irrigation level in the second year, respectively (Figure 5a and b). Plant height (PH) increased quadratically, with the IPR Campos Gerais presenting the highest values for this attribute (Figure 5c and d). The maximum PH for the IAC Imperador (0.59 m) and IPR Campos Gerais (0.69 m) in 2019 was obtained with irrigation depths of 279 and 340 mm, respectively. In 2020, maximum

PH was 0.54 m (IAC Imperador) and 0.65 m (IPR Campos Gerais) with irrigation depths of 333 and 382 mm, respectively.

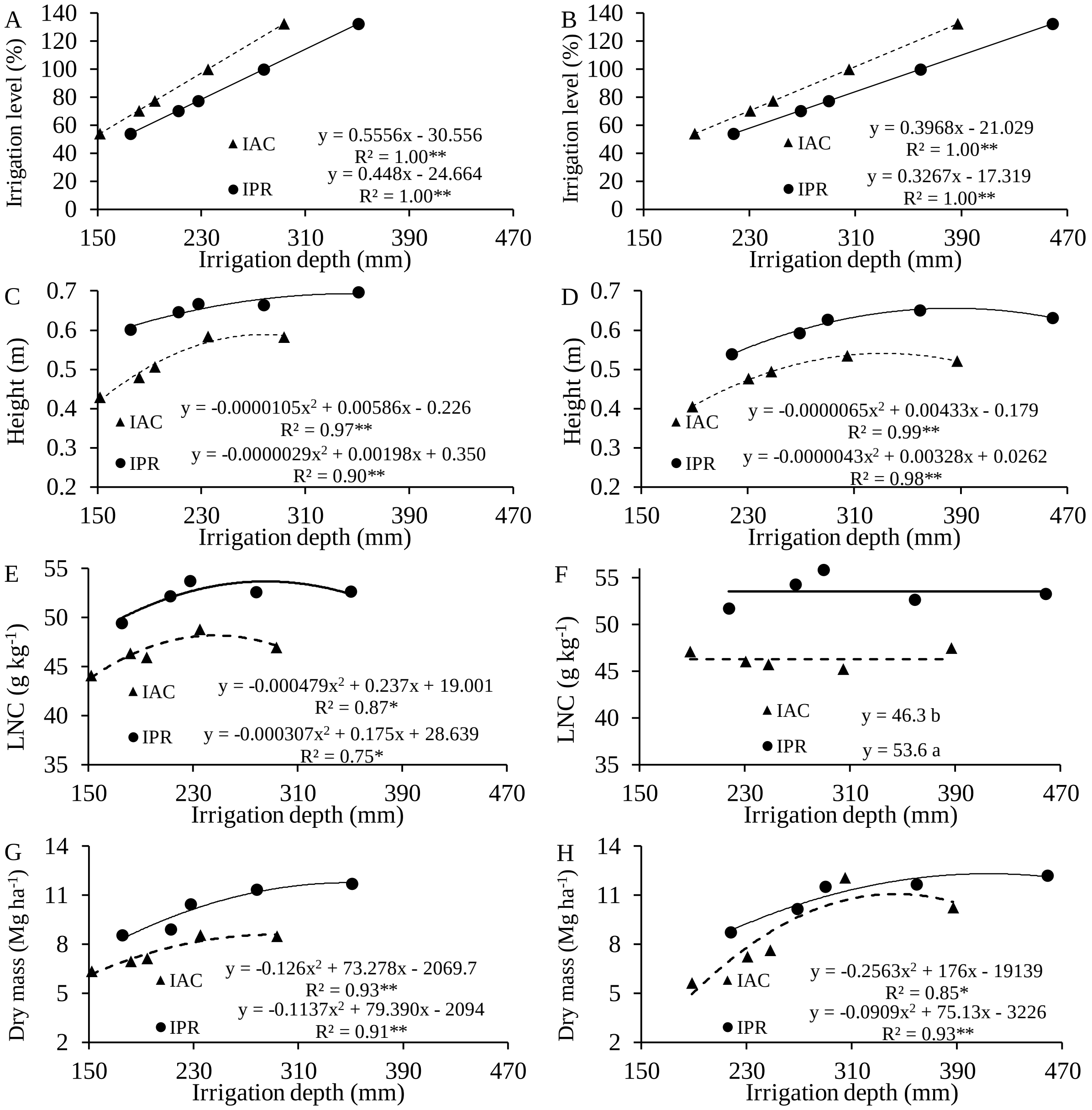


Figure 5. Variation in irrigation level (A and B), plant height at R_6 (C and D), leaf nitrogen content (LNC, E and F), and dry mass of plants (G and H) as a function of irrigation depths for two common bean cultivars evaluated in two years (2019 and 2020). *($p<0.05$); **($p<0.01$)

The leaf N content (LNC) had a quadratic increase for the first year, regardless of the cultivar (Figure 5e). The maximum LNC for the IAC Imperador (48.2 g kg^{-1}) and IPR Campos Gerais (53.7 g kg^{-1}) were obtained with depths of 247 and 286 mm, respectively. The second year showed no differences in LNC as a function of the irrigation depths. The IPR Campos Gerais presented the highest LNC in the two years, regardless of the irrigation management, and both cultivars presented LNC above the minimum considered ideal for common bean (30 g kg^{-1}), regardless of the irrigation depth (Ambrosano et al., 1997).

The total dry mass at harvest showed a quadratic increase to both cultivars (Figure 5g and h). The maximum dry mass for the IAC Imperador (8.6 Mg ha^{-1}) and IPR Campos Gerais (11.8 Mg ha^{-1}) in 2019 were obtained with irrigation depths of 291 and 349 mm, respectively. For 2020, maximum dry mass was of 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, the mean was the parameter that best explained the variation of the final plant population (FP) as a function of the irrigation depths for the two cultivars in 2019 and the IPR Campos Gerais in 2020 (Figure 6a and b). The 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 influenced by irrigation depths and cultivars in 2019 (Figure 6c). Increases in NGP were found in 2020, with a quadratic variation for the cultivar IAC Imperador and linear variation for the cultivar IPR Campos Gerais (Figure 6d). The maximum NGP for the IAC Imperador (4.6) was obtained with 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 applied.

The number of pods per plant (NPP) showed quadratic increments for both cultivars in 2019 and the IAC Imperador in 2020 (Figure 6e and f). No NPP variation was observed in 2020 to the IPR Campos Gerais. The maximum NPP values for the cultivars IAC Imperador (17.6) and IPR Campos Gerais (21.7) in 2019 were obtained with irrigation depths of 220 and 298 mm, respectively. On the other hand, the maximum NPP value for the IAC Imperador (26.5) in 2020 was obtained with an irrigation depth of 427 mm.

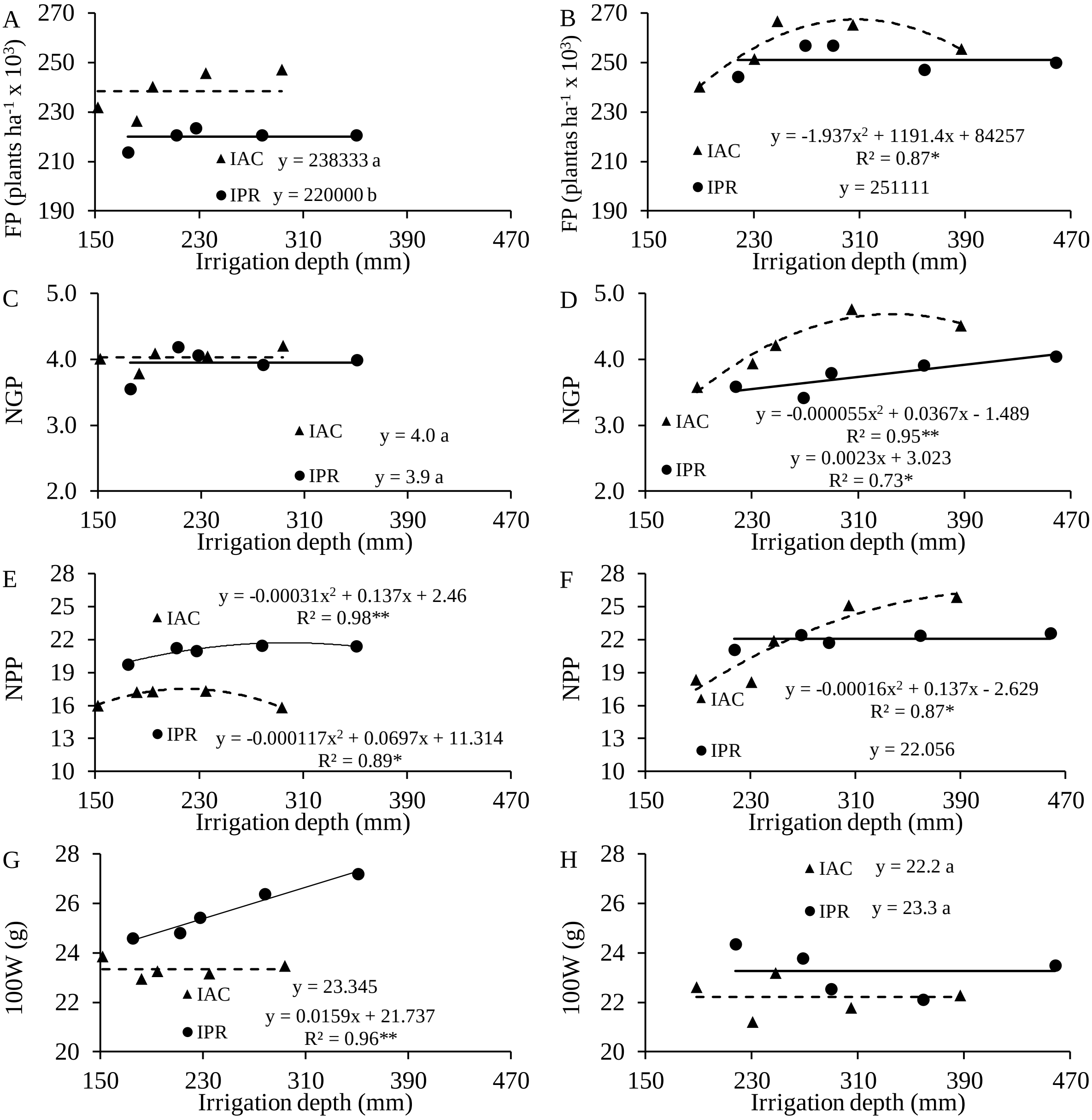


Figure 6. Variation in the final plant population (FP, A and B), number of grains per pod (NGP, C and D), number of pods per plant (NPP, E and F), and 100-grain weight (100W, G and H) as a function of irrigation depths for two common bean cultivars evaluated in two years (2019 and 2020). *($p<0.05$); **($p<0.01$)

Regarding the 100-grain weight (100W), only the IPR Campos Gerais showed variation in 2019 (Figure 6g and h), with a linear increase of 1.59 g for each 100 mm of water applied by irrigation. The mean was the parameter that best represented 100W variation as a function of irrigation depths for the other treatments.

The IAC Imperador showed quadratic increases regarding grain yield (GY) in both years, with maximum values in 2019 (3,961 kg ha^{-1}) and 2020 (3,802 kg ha^{-1}) obtained with irrigation depths of 281 and 378 mm, respectively (Figure 7a and b). The 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 compared to IAC Imperador. Grain yield in 2020 was lower than in 2019, especially for the management with a lower irrigation level.

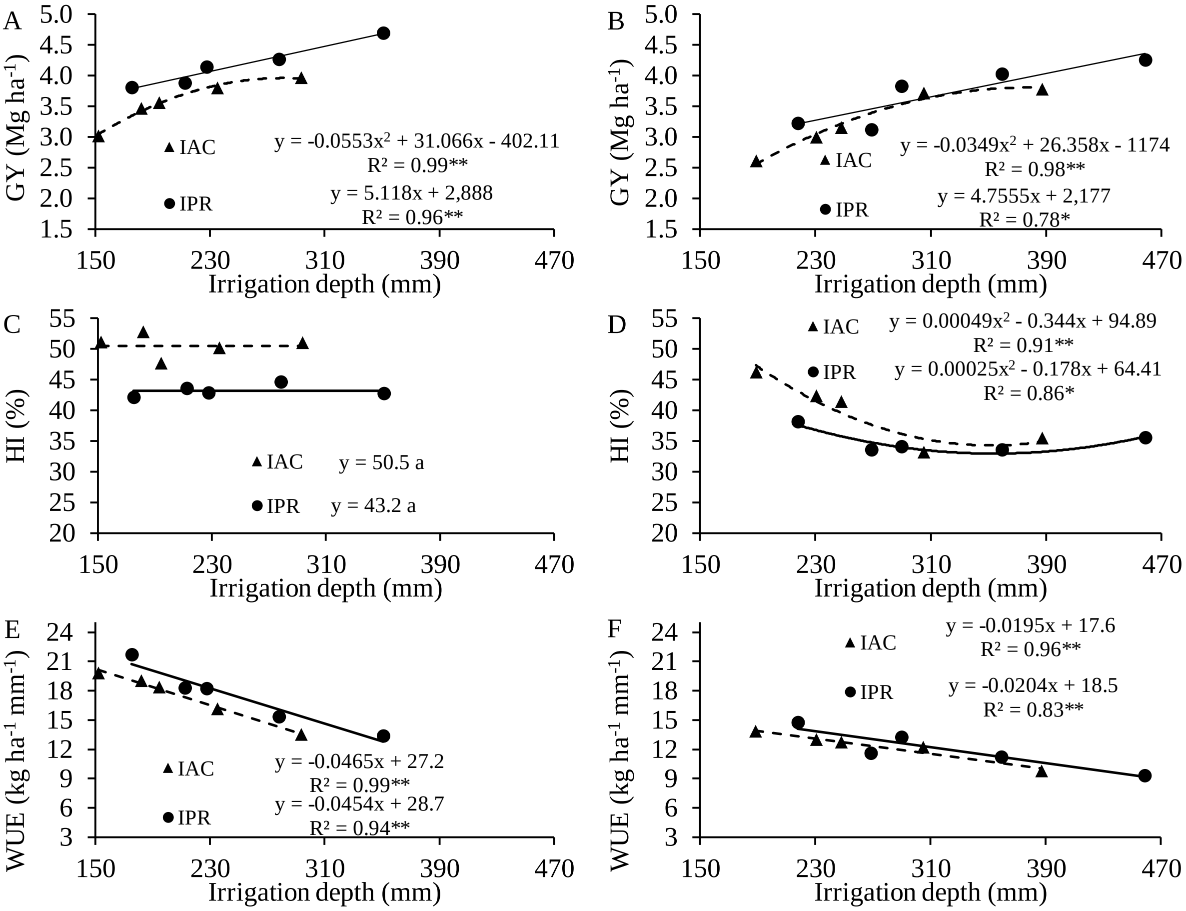


Figure 7. Variation in grain yield (GY, A and B), harvest index (HI, C and D), and water use efficiency (WUE, E and F) as a function of irrigation depths for two common bean cultivars evaluated in two years (2019 and 2020). *($p<0.05$); **($p<0.01$)

The harvest index (HI) showed no variation in 2019 as a function of the irrigation depths (Figure 7c). Quadratic decreases in HI were observed in 2020, with minimum values of the IAC Imperador (34%) and IPR Campos Gerais (32%) obtained with irrigation depths of 351 and 356 mm, respectively.

Water use efficiency (WUE) decreased linearly for both cultivars in two years

(Figure 7e and f). In 2019, WUE reduced 4.65 and 4.54 kg ha^{-1} mm^{-1} for every 100 mm of irrigation depth to the IAC Imperador and IPR Campos Gerais, respectively, but this reduction reached 1.95 and 2.05 kg ha^{-1} mm^{-1} for the IAC Imperador and IPR Campos Gerais, respectively, in 2020.

The maximum leaf area index (LAI) between irrigation levels for the cultivar IAC Imperador varied from 2.39 to 4.05 in 2019 and 1.47 to 2.44 in 2020 (Figure 8). The management with deficit irrigation reduced the LAI of the common bean crop throughout the cycle, especially after 30 DAE. The maximum LAI of treatments of the cultivar IAC Imperador were obtained between 60 and 67 DAE for both years.

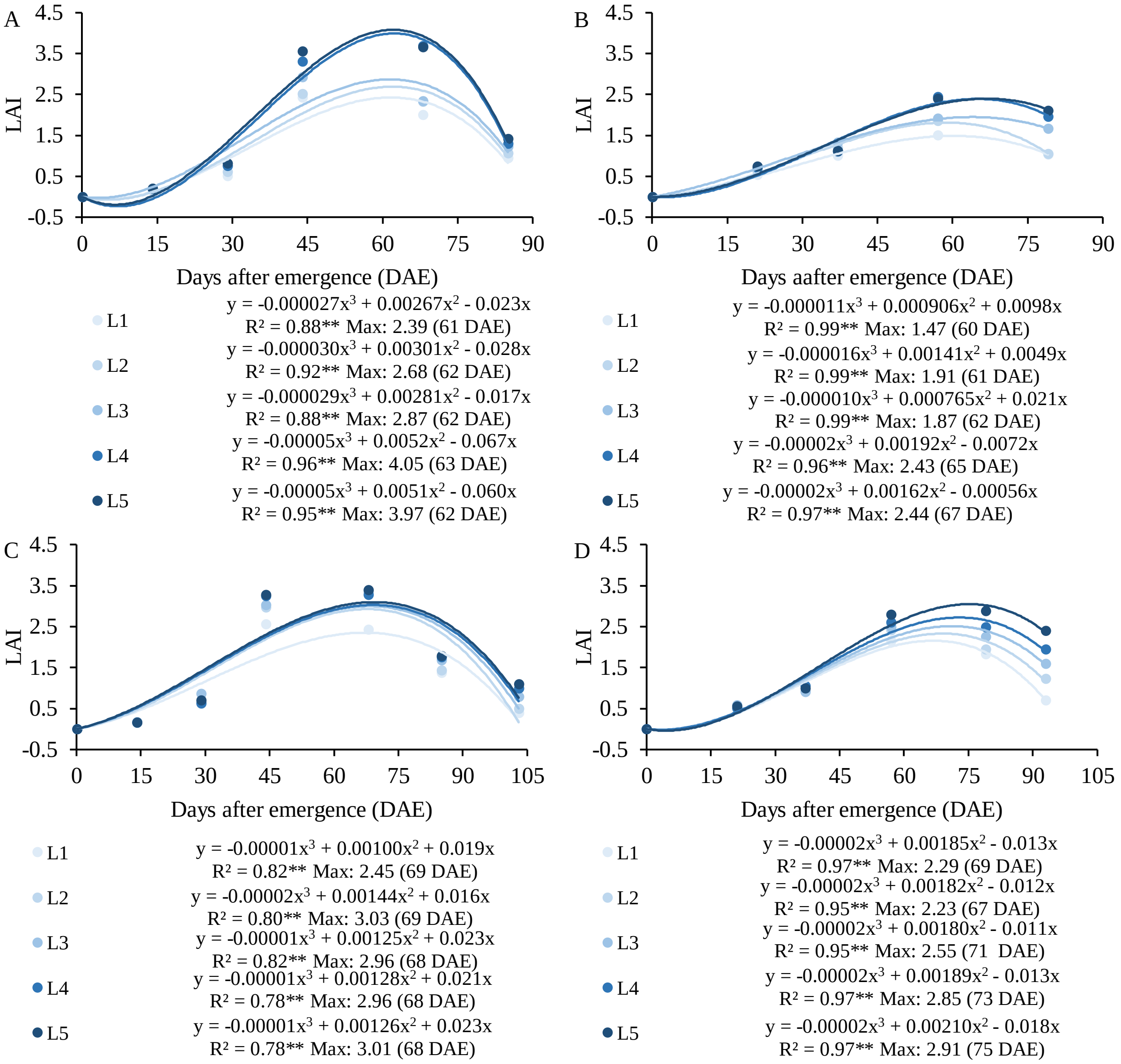


Figure 8. Variation in the leaf area index as a function of time for the cultivars IAC Imperador (A and B) and IPR Campos Gerais (C and D) for five irrigation management systems in two years (2019 and 2020). **($p<0.01$)

The maximum LAI of treatments for the cultivar IPR Campos Gerais ranged from 2.45 to 3.01 in 2019 and 2.23 to 2.91 in 2020 (Figure 8). Irrigation levels under water deficit reduced LAI of the cultivar IPR Campos Gerais, especially after 45 DAE. The maximum LAI values for the cultivar IPR Campos Gerais were obtained between 69 and 75 DAE.

The water deficit of the cultivar IAC Imperador decreased the soil cover fraction (CF) by the crop canopy in both years (Figure 9). The maximum values for the management ranged from 81.9 to 94.1% (58 to 61 DAE) in 2019 and 79.4 and 97.4% (63 to 76 DAE) in 2020.

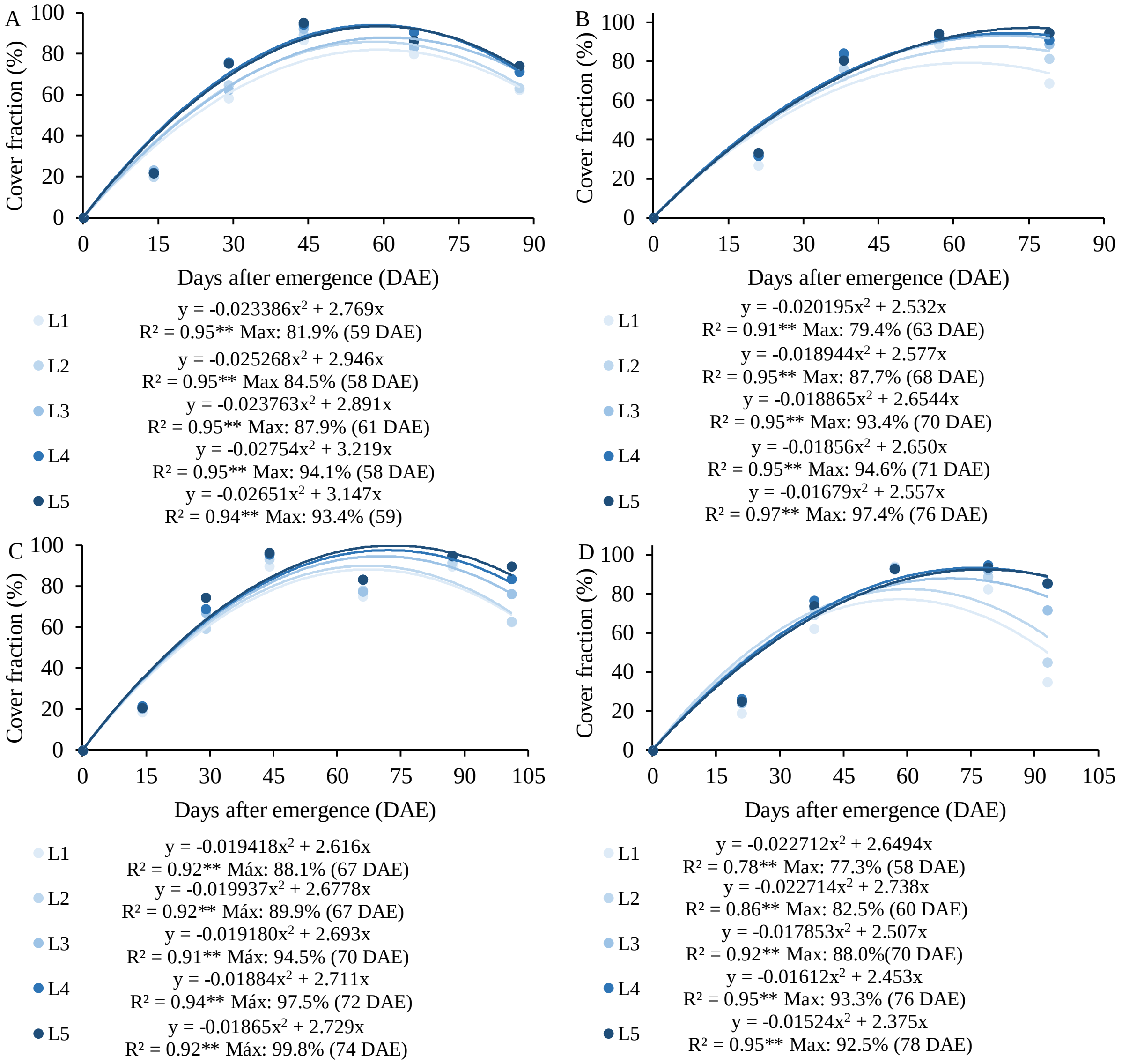


Figure 9. Variation in soil cover fraction by bean canopy as a function of time for the cultivars IAC Imperador (A and B) and IPR Campos Gerais (C and D) for five

irrigation management systems in two years (2019 and 2020). **(p<0.01)

Moreover, the water deficit of the cultivar IPR Campos Gerais also reduced the soil CF by the crop canopy in the two years (Figure 9). The maximum CF values varied from 88.1 to 99.8% (67 to 74 DAE) in 2019 and 77.3 to 93.3% (58 to 78 DAE) in 2020.

The variables that significantly correlated with GY for the cultivar IAC Imperador were plant height (PH), maximum LAI, maximum CF, DM, and 100W in 2019 and PH, maximum LAI, maximum CF, DM, NPP, and NGP in 2020 (Table 6). Also, the variables that significantly correlated with GY for the cultivar IPR Campos Gerais were maximum CF, NPP, and 100W in 2019 and PH, maximum CF, DM, and NGP in 2020.

Table 6. Pearson correlation between growth and yield variables of common bean cultivars and grain yield in the years 2019 and 2020.

Year	IAC Imperador								
	PH	LNC	LAI	CF	FP	DM	NPP	NGP	100W
2019	0.568*	0.045^{ns}	0.498*	0.606**	-0.066^{ns}	0.542*	-0.346^{ns}	0.193^{ns}	0.531*
2020	0.764**	0.228^{ns}	0.681**	0.748**	0.277^{ns}	0.735**	0.696**	0.692**	-0.163^{ns}
Year	IPR Campos Gerais								
	PH	LNC	LAI	CF	FP	DM	NPP	NGP	100W
2019	-0.101^{ns}	-0.010^{ns}	0.296^{ns}	0.649**	-0.316^{ns}	0.249^{ns}	0.599**	0.051^{ns}	0.808**
2020	0.566*	0.008^{ns}	0.441^{ns}	0.731**	0.208^{ns}	0.551*	0.088^{ns}	0.562*	-0.306^{ns}

PH: plant height; LNC: leaf nitrogen content; 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

Soil moisture was affected by the water deficit of levels L1, L2, and L3 in both cultivars (Figure 10). These management systems presented less soil moisture than the others throughout the cycle, especially after 25 DAE. The effect of water deficit was more severe from the common bean flowering (R_6) and in 2020 when irrigation levels under deficit showed a higher difference in soil moisture than the L4 and L5 levels. Moreover, the irrigation management throughout the experiment in 2019 during the night to avoid damage to the common bean crop due to the frost on July 7 promoted similar soil moisture between treatments in the period from 60 to 68 DAE (Figure 10a and 8c).

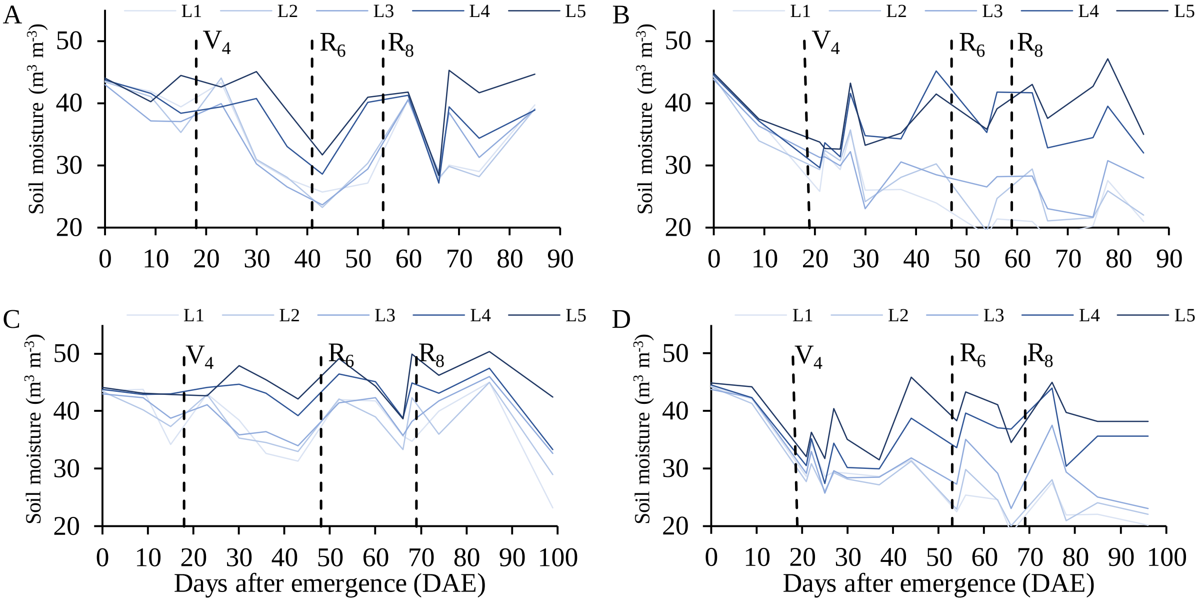


Figure 10. Variation in soil moisture as a function of time for the cultivars IAC Imperador (A and B) and IPR Campos Gerais (C and D) for five irrigation management systems in the two years (2019 and 2020).

Overall, the IPR Campos Gerais (indeterminate growth habit and intermediate cycle) agronomic performance was better compared to the IAC Imperador (determinate growth habit and early cycle), showing a maximum GY until 18% higher. It occurred because the cultivar IPR Campos Gerais has a longer cycle (15 days). This difference occurred at the reproductive stages, as the cultivars cycle was similar until the phenological stage R_5 (appearance of flower buds). Thus, cultivars with an intermediate cycle have a longer time for the formation of reproductive structures, such as pods, and grain filling, directly affecting GY. On average, it is justified by the higher values of plant height, total dry mass, and 100-grain weight in the IPR Campos Gerais, explaining its higher GY.

The GY of early cultivars tends to be lower than cultivars with intermediate cycle. Filla et al. (2020) evaluated the GY of the cultivars IAC Imperador and IPR Campos Gerais and observed an average GY 38% higher for the cultivar IPR Campos Gerais. Nunes et al. (2020) evaluated sixteen common bean cultivars and found that cultivars with an intermediate and late cycle presented, on average, GY 40% higher compared to cultivars with a early cycle.

According to the literature, IAC Imperador is considered a standard genotype to evaluate the water deficit tolerance due to its high stomatal conductance (Gonçalves et al., 2019), production of biochemical substances tolerant to water deficit (Andrade et al., 2016), and high development of the root system (Dipp et al., 2017). However, this cultivar had less efficiency and response to irrigation in the present study compared to the IPR Campos Gerais. This is because IPR Campos Gerais presented a higher GY than the IAC Imperador at the lowest irrigation levels, characterizing the efficiency of producing satisfactorily well under conditions of low water availability (Fageria et al., 2013). Moreover, the IPR Campos Gerais presented linear GY increments, while the cultivar 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 lower compared to 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). This demonstrates the high productive potential of this genotype, which can be recommended for more intensive production systems due to its shorter cycle, being better suited for crop rotation and succession.

It is verified in the literature that IPR Campos Gerais presents high efficiency and response to several factors, especially water and nitrogen. Arruda et al. (2019) recommended the cultivar IPR Campos Gerais to breeding programs to obtain cultivars tolerant to water deficit more productive due to its high agronomic performance. Zanella et al. (2019) evaluated yield of common bean cultivars and observed that the cultivar IPR Campos Gerais was one of the genotypes with higher stability and agronomic performance. Nunes et al. (2020) evaluated the efficiency and response of common bean cultivars to N use and found that IPR Campos Gerais was more efficient and responsive than the IAC Imperador. Thus, IPR Campos Gerais presents high yield, being responsive to management practices such as fertilization and irrigation.

Regarding the irrigation levels, the water deficit reduced the cultivars agronomic performance, given the lower values of growth and yield variables relative to irrigation levels without deficit (Figures 5 to 9). Water deficit reduced plant height by up to 29%, LAI by up to 40%, CF by up to 28% and GY by up to 31%. Even affecting the cultivars agronomic performance, IPR Campos Gerais presented higher agronomic performance compared to IAC Imperador under irrigation levels with water deficit. In addition, this cultivar increased its agronomic performance under excess irrigation levels, a fact confirmed by the increasing linear variation of the values of GY in both years, while the IAC Imperador showed no significant increase in the agronomic performance from irrigation levels above 100%. The IAC Imperador is tolerant of water deficit (Dipp et al., 2017; Gonçalves et al., 2019), and the morphological and physiological mechanisms that promote this tolerance, such as stomatal opening control and a well-developed root system, may reduce the response of this genotype as a function of irrigation depths higher than the replacement of 100%.

Water deficit was more severe and affected the yield of common bean cultivars mainly in 2020. It is justified by the lower soil moisture values throughout the cycle for management under water deficit in 2020 (Figure 10) and the highest difference between the minimum and maximum yields of each cultivar in 2020. Moreover, irrigations to control frost in 2019 mitigated the effect of water deficit at the cycle end.

The comparison between years shows that initial growth of cultivars in 2020 was lower than that observed in 2019, given the lower values of PH obtained at the phenological stage R_6. These differences are due to climate, as 2020 presented an average temperature 3.8 °C lower than that registered in 2019 (Table 3) during the first 15 days after emergence (DAE), affecting the initial plant growth. Moreover, even though the average temperature between years in the period from 15 to 45 DAE was similar, the radiation during this period in 2020 was, on average, 2 MJ m^{-2} day^{-1} lower than that registered in 2019, affecting plant growth.

The IPR Campos Gerais total dry mass at harvest was similar between years, regardless of the irrigation level. It is related to the higher plant population and the high temperature between 61 and 75 DAE in 2020, which was 4.0 °C higher than that registered in 2019, creating conditions for the growth of plants of this cultivar. Therefore, the slow initial growth of this cultivar due to the lower temperature and global solar radiation in 2020 was offset by the higher temperatures after flowering that same year. However, the total dry mass of the IAC Imperador at lower irrigation levels was lower in 2020, but higher irrigation levels provided a higher total dry mass in 2020. The cultivar IAC Imperador has a determinate growth habit, that is, it does not present emission of leaves and branches after flowering (R_6). Thus, plants from treatments with the lowest irrigation level did not recover from the lowest initial growth and the highest total dry mass at higher irrigation levels was due to the higher final plant population in these management systems in 2020. The lowest GY of cultivars in 2020 can be explained by the lower NGP and 100W for the cultivar IPR Campos Gerais in 2020 compared to 2019 and the lower 100W for the cultivar IAC Imperador.

Low and high temperatures at the reproductive stages of common bean can affect the NPP, NGP, and 100W, with the ideal temperature for common bean development ranging from 15 to 30 °C (Omae et al., 2012). Average maximum temperatures above 30 °C were not observed at the reproductive stages of common bean in both years (Table 3), but 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. The cultivar IAC Imperador was at the beginning of grain filling (R_8) and the cultivar IPR Campos Gerais was at pod formation (R_7) during that period (Table 4), a fact that may have contributed to the lower NGP for the cultivar IAC Imperador in 2019 and NPP for the cultivar IPR Campos Gerais.

The high temperatures between 61 to 75 DAE and 76 to 90 DAE in 2020, with an average value 4.0 and 1.7 °C higher compared to 2019, respectively, contributed to the lower 100W in 2020. According to Silva et al. (2020), high temperatures at the grain filling drastically affect 100W. These high temperatures in 2020 also acted to make soil moisture at the cycle end that year below the moisture found at the same period in 2019 (Figure 10), affecting grain filling. In addition, the lower 100W of common bean in 2020 can be explained by the source-drain balance for photoassimilates, as the plants had a higher number of grains per plant in the second year, considering the higher NPP and NGP values compared to 2019. Thus, the drains number increase (grains) reduces photoassimilates distribution for each grain (Fageria et al., 2013).

Only the maximum CF was observed in both cultivars and years among the variables correlated with GY (Table 6). Also, the maximum CF was one of the variables with the highest correlation value, regardless of the year and cultivar, with values and significance higher than the maximum LAI. CF indirectly indicates the plant vigor, accumulated biomass, and percentage of solar radiation intercepted by leaves, which are directly associated with GY (Patrignani and Ochsner, 2015). In this context, the maximum CF can be considered more efficient to verify the solar radiation interception by leaves than the maximum LAI. It occurs because the maximum LAI considers all leaves, including those closest to the soil, which are overlapped by the uppermost leaves, contributing little to net photosynthesis (Joggi et al., 1983). In addition, the saturation of the maximum amount of solar radiation that plants can absorb occurs from a specific LAI, that is, LAI increases from that value, but 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 with a determined soil cover rate.

Another important difference to be highlighted is the correlation between PH at R_6 and GY. PH was directly correlated with GY of the IAC Imperador in both years, but the IPR Campos Gerais showed correlation only in 2020. It is due to differences in the type of cultivars growth habits. The IAC Imperador, with a determinate growth habit, does not present emission of leaves and branches after flowering (R_6) and, therefore, plant growth up to this stage influences more its vigor and final yield compared to cultivars with an indeterminate growth habit, such as IPR Campos Gerais, which grow after R_6 and can recover from stresses at early stages. A high interannual variation was observed in the correlation of yield components with GY, not being possible to select just one of them to verify the crop yield.

2.4 Conclusions

The water deficit reduces common bean agronomic performance, regardless of cultivar, decreasing PH, LAI, CF and GY by up to 29%, 40%, 28% and 31%, respectively. The cultivar with an indeterminate growth habit and intermediate cycle (IPR Campos Gerais) has a higher agronomic performance compared to cultivar with a determinate growth habit and early cycle (IAC Imperador), showing maximum GY up to 18% higher. Even with an average irrigation depth (mm) 17% higher compared to that applied to the IAC Imperador, the IPR Campos Gerais was, on average, more efficient and responsive to irrigation. However, the two cultivars showed similar irrigation water-use efficiency (irrigation water productivity), with values ranging from 9 to 22 kg ha^{-1} mm^{-1}. On average, IPR Campos Gerais grain yield increased linearly by 494 kg ha^{-1} for every 100 mm irrigation depth, while the cultivar IAC Imperador presented the highest yields close to the irrigation level that provides 100% of the ETc.

Therefore, irrigation management and cultivar choice are essential for an irrigated production system, helping farmers to increase production and income.

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CHAPTER 3 - Does water stress change technological and nutritional quality of common bean cultivars with contrasting growth habits?[2]

ABSTRACT: In addition to yield, agricultural management practices such as the cultivar choice and irrigation can change the technological and nutritional common bean quality, affecting the product price and the food biological value. This study aimed to explain and compare the technological and nutritional quality of grains of common bean cultivars with contrasting growth habits submitted to irrigation levels. The study was carried out for two years in the Southeast of Brazil. Treatments consisted of two common bean cultivars and five irrigation levels. The cultivars were IAC Imperador, with a determinate growth habit, and IPR Campos Gerais, with an indeterminate growth habit, both subjected to five irrigation levels (54, 70, 77, 100, and 132% of the crop evapotranspiration). All in all, the IPR Campos Gerais have better technological and nutritional quality than the IAC Imperador, showing grain size up to 119% larger, cooking time up to 36% lower, and higher contents of the most important nutrients for human consumption, such as P (up to 37% higher), Mg (14%), Fe (27%), and Cu (18%). Water deficit reduces P, Ca, Mg, Cu, Mn, and Fe contents in the grains up to 22, 35, 6, 11, 5 and 5%, respectively, with this effect depending on the year and cultivar. Moreover, water deficit promotes grains with up to 22% more protein and 11% more Zn. These results demonstrate the importance of proper irrigation management and cultivar choice with a view to common bean quality, generating higher acceptance by the market and food biological value.

Keywords: *Phaseolus vulgaris* L.; food security; protein content; cooking time; zinc.

3.1 Introduction

Common bean is one of the main foods responsible for world food security (Hummel et al., 2018; Nassary et al., 2020). It presents a high availability, easy access by the population, and adequate nutritional quality for humans (Miano et al., 2018). In addition, it is considered the main source of low-cost protein for the poorest population (Fageria et al., 2014). Worldwide, the common bean crop is grown in more than 100 countries, occupying an area of more than 33 million ha, showing its economic and social importance (FAOSTAT, 2019).

Human malnutrition is considered a serious global problem, and the nutrients that most affect and promote deficiencies in the world population are Fe, Zn, I, and Se (White and Broadley, 2009). Common bean has significant amounts of Fe and Zn,

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helping to mitigate these deficiencies. World food security depends on the nutritional quality of the food, and agricultural management practices and conditions that reduce the nutritional quality of common bean can affect world food security, causing deficiencies to the population (Hummel et al., 2018). In this sense, common bean consumption by the population has been decreasing to the detriment of other foods with lower nutritional quality, which may promote nutrient deficiencies in humans. In Brazil, for example, consumption per capita of common bean decreased by 52% between 2003 and 2018, that is, from 12.4 kg inhabitant^{-1} year^{-1} to 5.9 kg inhabitant^{-1} year^{-1} (IBGE, 2020). Thus, the search for common bean cultivars richer in nutrients and vitamins is essential to minimize the impact of this reduced consumption on human nutrition.

Factors such as nitrogen fertilization (Nunes et al., 2020), soil tillage system (Farinelli and Lemos, 2010), cultivars (Smith et al., 2019; Nunes et al., 2020), and climate conditions (Hummel et al., 2018) can promote differences in the technological and nutritional attributes of common bean. The proper choice of cultivar, for instance, may increase crude protein content by more than 15% (Nunes et al., 2020). Considering the nutritional quality, common bean has Fe and Zn, which are limiting to a large part of the world population. Regarding technological quality, variables that directly affect the price of the product are the most important, such as grain size and cooking time. Thus, the evaluation of management practices that promote higher nutritional and technological quality of common bean are necessary to increase the producer income and the food biological value.

Water is a limiting factor for crop growth and yield. The water deficit of the common bean crop can reduce its yield by more than 40% (Mathobo et al., 2017). However, little is known about the effects of irrigation depths on the technological and nutritional quality of common bean. Water deficit and excess can affect the technological and nutritional quality of common bean as water is the main means for translocating nutrients in plants, which may be a genotype-dependent effect, as there are genotypes more tolerant to water deficit and excess than others (Ribeiro et al., 2019). Thus, studies on the effect of irrigation depths on the grain quality of common bean cultivars are essential to indicate management practices that promote the best attributes of grains.

This study hypothesized that stress due to water deficit reduces the technological and nutritional quality of grains of common bean cultivars with contrasting growth habits. Thus, this study aimed to explain and compare the grain technological and nutritional quality of common bean cultivars with contrasting growth habits subjected to irrigation levels.

3.2 Material and methods

The experiment was carried out in the winter growing season of 2019 and 2020 at the São Paulo State University (Unesp), School of Agricultural and Veterinarian Sciences, Jaboticabal, São Paulo, Brazil, close to the geographical coordinates 21°14′44″ S and 48°17′00″ W, with an altitude of 545 m. The regional climate, according to the Köppen classification, is Aw, that is, a tropical climate with a dry winter, summer rains, an average annual temperature of 22 °C, and average annual precipitation of 1,425 mm.

The soil in the experimental area is classified as an Oxisol (Soil Survey Staff, 2014). Three undisturbed and disturbed soil samples were collected for the physical characterization of the experimental area before sowing the experiment in 2019 (Table 1). Fifteen simple soil samples were collected 30 days before sowing the experiment in each year, forming a composite sample for fertility analysis (Table 2).

Common bean was sown on May 7, 2019, and May 18, 2020. Two common bean cultivars from the ‘Carioca’ commercial group, with contrasting growth habits, were used. The cultivar IAC Imperador has a determinate growth habit (Type I), erect architecture, and an early cycle of 75 days (Chiorato et al., 2012). The cultivar IPR Campos Gerais has an indeterminate growth habit (Type II), erect architecture, and a normal cycle of 90 days (Moda-Cirino et al., 2012). The cultivars were mechanically sown to obtain a density of 240,000 plants ha^{-1}, with an inter-row spacing of 0.45 m. The seeds were treated before sowing with pyraclostrobin (5 g ai ha^{-1}) + thiophanate-methyl (45 g ai ha^{-1}) + fipronil (50 g ai ha^{-1}), using the commercial product Standak® Top, and inoculated with *Rhizobium tropici* (StarFix® Feijão) for biological nitrogen fixation, using the dose recommended.

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

Layer (m)	Ds g cm^{-3}	Moisture FC m^3 m^{-3}	Moisture PWP m^3 m^{-3}	Clay g kg^{-1}	Silt g kg^{-1}	Sand g kg^{-1}
0.00–0.20	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) of the experimental area in 2019 and 2020.

Year	pH	H+Al	Al	K	Ca	Mg	SB	CEC	V
	$CaCl_2$	-------------------------------- 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	

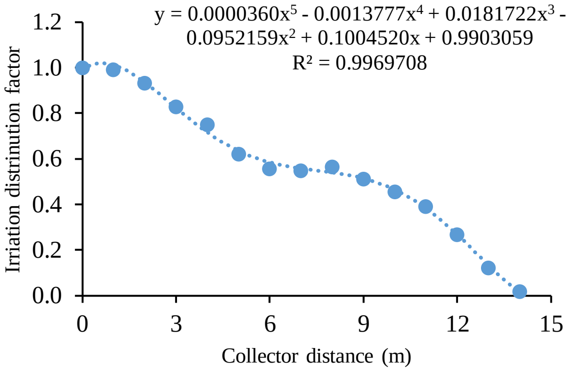
OM: organic matter; SB: sum of bases; CEC: cation exchange capacity; V: base saturation.

Common bean was sown in an area previously cultivated with corn, using a seed-cum-fertilizer drill intended for no-tillage. The corn hybrid P4285VYHR was sown in October in the two years, with an inter-row spacing of 0.90 m and 75,000 plants ha^{-1}. Limestone with a total neutralizing power of 95 was applied 30 days before corn sowing in the two years at a dose of 1.5 Mg ha^{-1}. The limestone was incorporated into the soil with a plowing harrow operation (0.00–0.20 m) and two leveling harrow operations. The amount of corn straw (dry matter) on the soil was estimated at common bean sowing and reached 7,622 ± 272 kg ha^{-1} in 2019 and 9,052 ± 367 kg ha^{-1} in 2020, while the average grain yield reached 11,200 ± 134 kg ha^{-1} in 2019 and 11,800 ± 210 kg ha^{-1} in 2020.

The sowing fertilization of the common bean crop was carried out according to the soil analysis (Table 2) and recommendation of Ambrosano et al. (1997) by applying a dose of 200 kg ha^{-1} of the formulation 04–20–20 in the two years, supplying 8 kg ha^{-1} of N, 40 kg ha^{-1} of P_2O_5, and 40 kg ha^{-1} of K_2O. Topdressing fertilization was carried out at the $V_{4\text{–}3}$ stage, characterized by the third trifoliate leaf fully expanded (Fernández et al., 1985), and consisted of the application of a dose of 100 kg ha^{-1} of N in both years, with urea as source (Ambrosano et al., 1997). The topdressing fertilization was carried out at 19 and 21 days after emergence (DAE) of the common bean crop in 2019 and 2020, respectively, in a continuous strip at 0.10 m from the sowing row. A 10-mm irrigation depth was applied to all treatments in the two years after topdressing fertilization to avoid the effect of different volatilization rates between the different irrigation levels. This 10-mm irrigation depth was used because it is a minimum value that does not promote losses of urea by volatilization (Espindula et al., 2021), not significantly interfering with the applied treatments. The control of weeds, pests, and diseases was carried out when necessary, using products registered for the crop.

The experimental design used was strip-plot. The study factors were five irrigation levels and two common bean cultivars, with four replications. Each subplot had 15 rows of common bean, with a dimension of 6.75 m long and 2.4 m wide. The first row of common bean at each end and the initial 50 cm of the central rows were considered as borders. Six out of the remaining 13 cultivation rows were used to estimate yield and the other seven for destructive analysis.

The line-source sprinkler system was used, allowing the distribution of the irrigation water with variable application depths as the treatment moves away from the central sprinkler line (Hanks et al., 1976). A field test enabled the definition of the distribution fractions of the sprinkler precipitation (Figure 1). In model fit, the regression that generated the highest precision (R^2) was used, aiming to estimate the most accurate irrigation distribution factor possible in each treatment. Senninger 4023-2 sprinklers and ¾″ M 08Qx05 nozzles were used spaced every 6 m on the central line. The water application intensity of the sprinklers was measured in the field in tests with collectors placed at 1 m from each other up to the limit distance of water application by the sprinklers in a line perpendicular to the irrigation line, with four replications.



Distance (m)	Treatment	Irrigation distribution factor
0.00–2.40	L5	1.002 (132%)
2.40–4.80	L4	0.754 (100%)
4.80–7.20	L3	0.584 (77%)
7.20–9.60	L2	0.532 (70%)
9.60–12.00	L1	0.407 (54%)

Figure 1. Sprinkler irrigation distribution factor as a function of the distance from the irrigation line, with sprinklers spaced at 6 m from the line, obtained in field tests. Service pressure: 250 kPa

For study purposes, the treatments consisted of five irrigation levels (L1, L2, L3, L4, and L5), which were set up after the establishment of the water application regression by the sprinkler line (Figure 1). The L4 level was used as a standard, receiving 100% of the water required by the common bean crop. The L5 level received excess water, with 132% of the water requirement by the common bean, while the L3, L2, and L1 levels provided 77, 70, and 54% of the water requirement, respectively.

The irrigation management was carried out based on the crop water demand, according to the FAO 56 method, using climate data obtained daily from an automated agrometeorological station located 1,500 m from the experiment. The reference evapotranspiration (ETo) was estimated daily using the FAO 56 method (Allen et al., 1998). The evapotranspiration of the common bean crop (ETc) was calculated using the product of ETo by the crop coefficients (Kc) (Allen et al., 1998). The used Kc values 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 from 1.15 to 0.35 (maturation). For the Kc range between 0.40 and 1.15, the values were interpolated daily up to the maximum value (1.15). The daily increment was calculated as the ratio of the difference between the Kc range (1.15 – 0.40) and the number of days between the initial Kc (0.40) and maximum Kc (1.15).

Irrigation was carried out when the water deficit in the area was equal to 18 mm. This water depth was calculated according to the soil physical attributes (Table 1) and the common bean crop. The calculation considered an effective root depth of 0.25 m and a water availability factor of 0.40 (Allen et al., 1998). Two water depths of 15 mm were applied for the plant emergence considering a uniform initial stand in all treatments in two years.

The average maximum and minimum temperatures during the 2019 experimental period were 27.8 and 13.9 °C, respectively, with accumulated precipitation of 48.7 mm. The minimum temperature on July 7 was 3.3 °C, which caused frost in the experimental area. The number of trifoliate leaves hit by the frost was counted in each cultivar, with an average of 10% in the cultivar IAC Imperador and

12% in the cultivar IPR Campos Gerais. In 2020, the average maximum and minimum temperatures during the experimental period were 28.4 and 13.9 °C, respectively, with accumulated precipitation of 35 mm. Minimum temperatures below 5 °C were not observed in 2020. The mean and standard deviation of the mean of the fortnightly values of global solar radiation and temperature for the 2019 and 2020 experimental periods are shown in Table 3.

Table 3. Mean and standard deviation of the mean of the fortnightly values of maximum temperature (T Max), minimum temperature (T Min), average temperature (T Avg), and global solar radiation (GSR, MJ m^{-2} day^{-1}) during the experimental period (2019 and 2020).

DAE	2019 T Max	2020 T Max	2019 T Min	2020 T Min	2019 T Avg	2020 T Avg
0-15	28.5 ±2.3	25.4 ±3.8	16.9 ±2.4	11.5 ±2.7	21.9 ±2.1	18.1 ±2.7
16-30	27.4 ±3.6	28.6 ±2.2	13.6 ±3.0	15.9 ±2.0	19.9 ±3.0	21.6 ±1.5
31-45	27.6 ±1.4	26.9 ±2.9	13.8 ±2.0	13.8 ±1.3	20.1 ±1.5	19.8 ±1.7
45-60	28.1 ±2.2	28.9 ±2.5	14.5 ±1.3	13.7 ±2.4	20.9 ±1.3	20.9 ±2.1
61-75	25.7 ±3.7	29.3 ±1.2	10.2 ±3.6	14.2 ±0.9	17.4 ±3.4	21.4 ±1.1
75-90	28.0 ±4.5	29.7 ±2.3	13.8 ±1.2	13.8 ±2.4	20.3 ±2.6	21.4 ±2.1
90-105	29.4 ±3.9	28.9 ±4.8	14.2 ±2.0	13.8 ±3.5	21.4 ±2.9	20.6 ±3.7

DAE: days after emergence.

The irrigation was triggered as an attempt to control the frost during the dawns of July 6, 7, and 8. Thus, the water depth on these days was constant for all treatments, and 20, 40, and 20 mm were applied for days 6, 7, and 8, respectively. The calculation considered 30 mm of irrigation water on those days for all treatments.

Soil moisture was determined weekly at three points per subplot in the 0.00–0.20 m depth layer, using the time domain reflectometry (TDR) technique (Fellner Feldegg, 1969). The calibration of the equipment was carried out before the experiment was set up in the soil of the experimental area. For this, 25 points were randomly chosen in the area for the determinations with the equipment and an undisturbed soil sample was collected at these points for determining the actual soil moisture (m^3 m^{-3}), generating a regression of the observed values as a function of the values measured on the equipment. This regression was used to correct the soil moisture during the experiment.

The subplots were harvested, and the grains were packed in paper bags at temperature 25 ±2.0 °C and relative humidity of 60 ±5.0% for 30 days in the two years to determine the variables related to the grain nutritional and technological quality. The grains of each subplot were separated by size using a set of sieves with oblong openings, that is, P10 = 10/64″ × 3/4 (3.97 × 19.05 mm), P11 = 11/64″ × 3/4 (4.37 × 19.05 mm), P12 = 12/64″ × 3/4 (4.76 × 19.05 mm), P13 = 13/64″ × 3/4 (5.16 × 19.05 mm), P14 = 14/64″ × 3/4 (5.56 × 19.05 mm), and P15 = 15/64″ × 3/4 (5.96 × 19.05 mm), under stirring for one minute. The grain mass retained on each sieve was determined and the sieve yield higher than or equal to 12 ($SY \geq 12$) and the relative grain production on sieves (RGPS) were calculated according to the methodology proposed by Carbonell et al. (2010). The 100-grain weight (100W) was determined using samples from the previous evaluation to count four subsamples of 100 grains per subplot, standardizing the grain moisture content to 0.13 kg kg^{-1}.

Grains retained on sieve 12 were used to determine N, P, K, Ca, Mg, S, B, Zn, Cu, Fe, and Mn contents. For this, the grains were washed in running water, water with neutral detergent (0.1%), and deionized water, placed in a forced-air circulation oven at 65 °C until constant weight, and ground using a Willey mill. The crude protein content of grains (CPC) was determined using the equation (AOAC, 1995) CPC = total N × 6.25, where CP is the crude protein content in the grains (%) and total N is the nitrogen content in the grains, according to the methodology proposed by Bataglia et al. (1983). The other nutrients were determined according to the methodology proposed by Malavolta et al. (1997).

Grains retained on sieve 13 were used to determine cooking time. The cooking time of grains was determined using the Mattson cooker, which consists of 25 vertical stylets with 1/16″ tips and a weight of 90 g at the other end. The bottom end is supported by the common bean grain during cooking and the tip penetrates the grain when it is cooked, displacing the stylet. The final cooking time of the sample was obtained when 50% + 1, that is, 13 stylets, were displaced. For this determination, 25 g of grains were hydrated in 100 mL of deionized water for 12 hours. The water temperature was maintained at 96 °C. The scale of Proctor and Watts (1987) was used to check the resistance level of grains to cooking.

As in this study the variation sources were levels (quantitative factor), all the analyzed variables were subjected to the polynomial regression analysis as a function of the irrigation depths applied to each cultivar. Analyses were performed using the software SigmaPlot. For variables with non-significant regressions in the two cultivars, the F-test ($p < 0.05$) was used for mean comparison.

3.3 Results and discussion

Each 10 mm of water applied by irrigation corresponded to 5.6 and 4.5% in the irrigation level in the first year and 4.0 and 3.2% of the irrigation level in the second year for the cultivars IAC Imperador and IPR Campos Gerais, respectively (Figure 2A and B). The cultivars had no variation in sieve yield higher than or equal to 12 (SY≥12) as a function of the applied irrigation depths (Figure 2C and D). The cultivar IPR Campos Gerais presented a SY≥12 higher compared to IAC Imperador in both years, with an average 40% higher in 2019 and 118% higher in 2020. Only the cultivar IPR Campos Gerais presented an SY≥12 higher than or close to 70% in the two years.

The relative grain production on sieves (RGPS) showed no variations as a function of irrigation depths for both cultivars in 2019 and the cultivar IAC Imperador in 2020 (Figure 2E and F). Only the cultivar IPR Campos Gerais presented a linear increase for RGPS, with an increase of 0.4 units for every 100 mm of water applied. Similar to SY≥12, IPR Campos Gerais presented RGPS higher compared to IAC Imperador, with an average value higher than 7.0 in 2019, regardless of the irrigation depth, and an average value higher than 7.0 in 2020 from the irrigation depth of 350 mm, a value corresponding to the management under 97% of the irrigation level (Figure 2B).

The IAC Imperador showed a reduction in cooking time (CT) in the two years as a function of irrigation depths, but this variable was not affected by irrigation levels for the cultivar IPR Campos Gerais. On average, every 100 mm of water applied reduced 3.4 minutes in CT for the IAC Imperador. The overall average showed that the CT of the IPR Campos Gerais was lower than that of IAC Imperador.

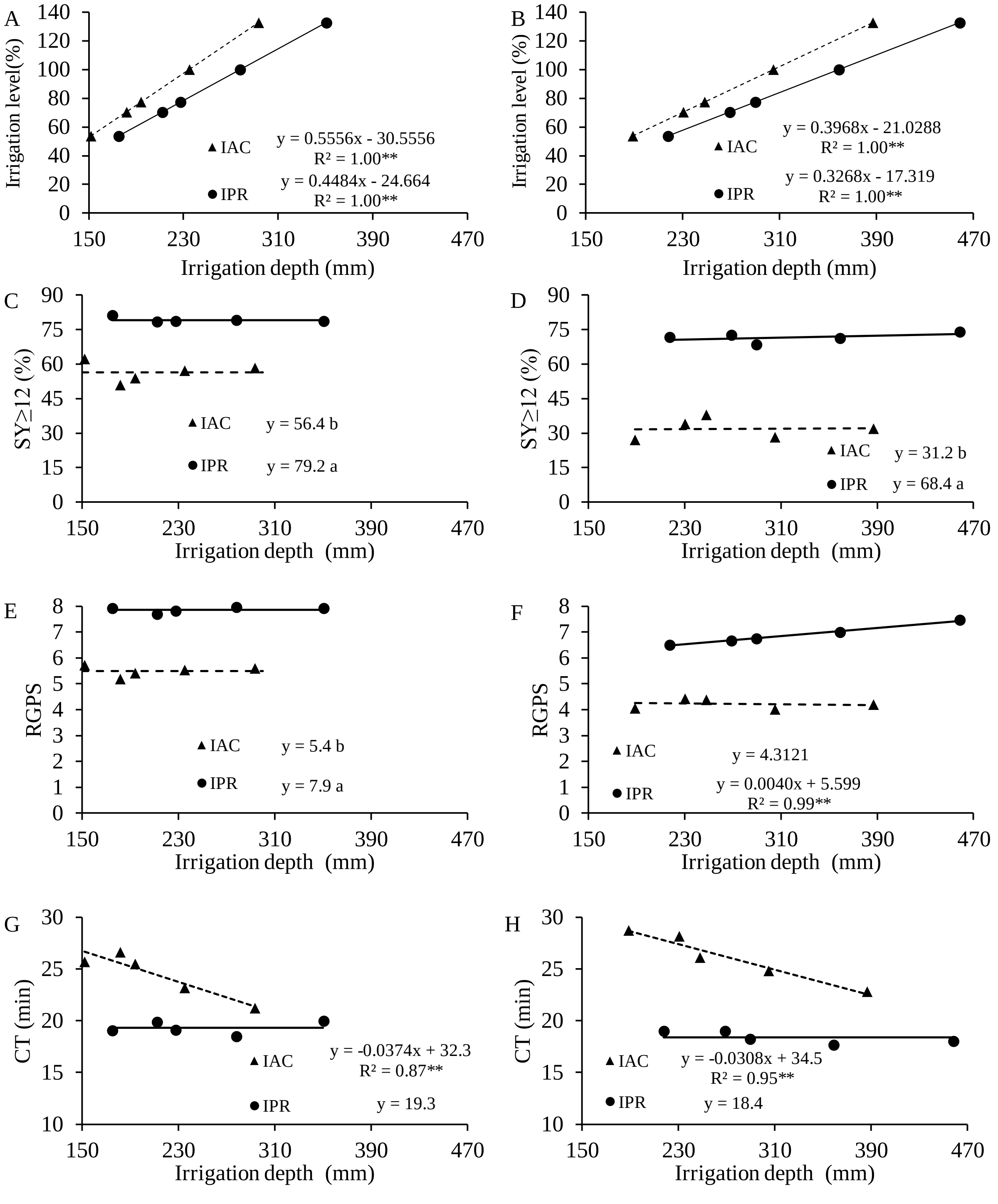


Figure 2. Irrigation levels (A and B), sieve yield higher than or equal to 12 (SY≥12, C and D), relative grain production on sieves (RGPS, E and F), and cooking time (CT, G and H) of the common bean cultivars IAC Imperador (A and C) and IPR Campos Gerais (B and D) as a function of irrigation levels in the years 2019 and 2020. **($p<0.01$)

The crude protein content of grains (CPC) showed a quadratic increase in 2019, with the maximum values for the IAC Imperador (23.1%) and IPR Campos Gerais (23.0%) obtained with irrigation depths of 180 and 216 mm, respectively (Figure 3A and B).

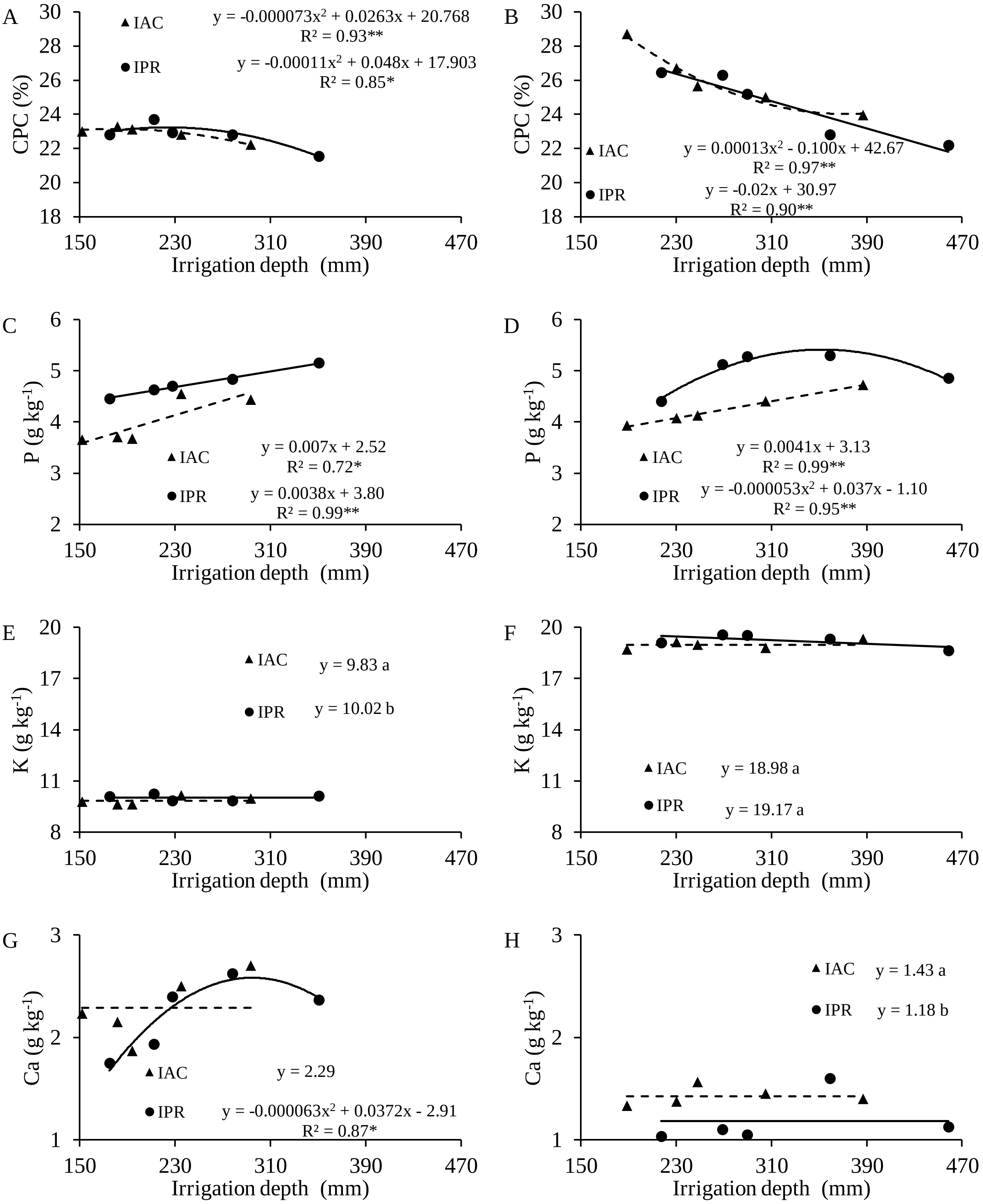


Figure 3. Crude protein content (CPC, A and B), phosphorus (C and D), potassium (E

and F), and calcium (G and H) of grains of the common bean cultivars IAC Imperador (A and C) and IPR Campos Gerais (B and D) as a function of irrigation depths in the years 2019 and 2020. *($p<0.05$); **($p<0.01$)

A decrease in CPC was observed in 2020 for both cultivars, with a quadratic variation for IAC Imperador and a linear variation for IPR Campos Gerais. The lowest CPC for the IAC Imperador (23.4%) was obtained with an irrigation depth of 385 mm, while the IPR Campos Gerais showed a 2% reduction in CPC for every 100 mm of water applied.

Linear increments were observed in the P content for both cultivars in 2019 and the cultivar IAC Imperador in 2020 (Figure 3C and D). The P content in the IAC Imperador increased by 0.7 and 0.4 g kg^{-1} for each 100 mm of water applied in 2019 and 2020, respectively, and 0.38 g kg^{-1} in the IPR Campos Gerais. The maximum P content in the grains for the IPR Campos Gerais in 2020 (5.35 g kg^{-1}) was obtained with an irrigation depth of 349 mm. Overall, the IPR Campos Gerais presented a higher P content in the grains compared to the IAC Imperador. The K content showed no variation as a function of irrigation depths (Figure 3E and F). The K contents in the grains were similar between cultivars. Only the IPR Campos Gerais showed variation in the Ca content as a function of irrigation depths, with the maximum value (2.6 g kg^{-1}) obtained with irrigation depth of 296 mm in 2019. Ca levels in grains were similar between cultivars.

The common bean cultivars showed increments in Mg contents as a function of irrigation depths (Figure 4A and B). In 2019, a linear increase was observed for the IAC Imperador, with increases of 0.05 g kg^{-1} for each 100 mm of applied water, while the IPR Campos Gerais presented a quadratic increase, with the maximum content (1.68 g kg^{-1}) observed for an irrigation depth of 300 mm. In 2020, both cultivars showed quadratic increments, with maximum values found for the IAC Imperador (1.77 g kg^{-1}) and IPR Campos Gerais (1.94 g kg^{-1}), with irrigation depths of 312 and 369 mm, respectively.

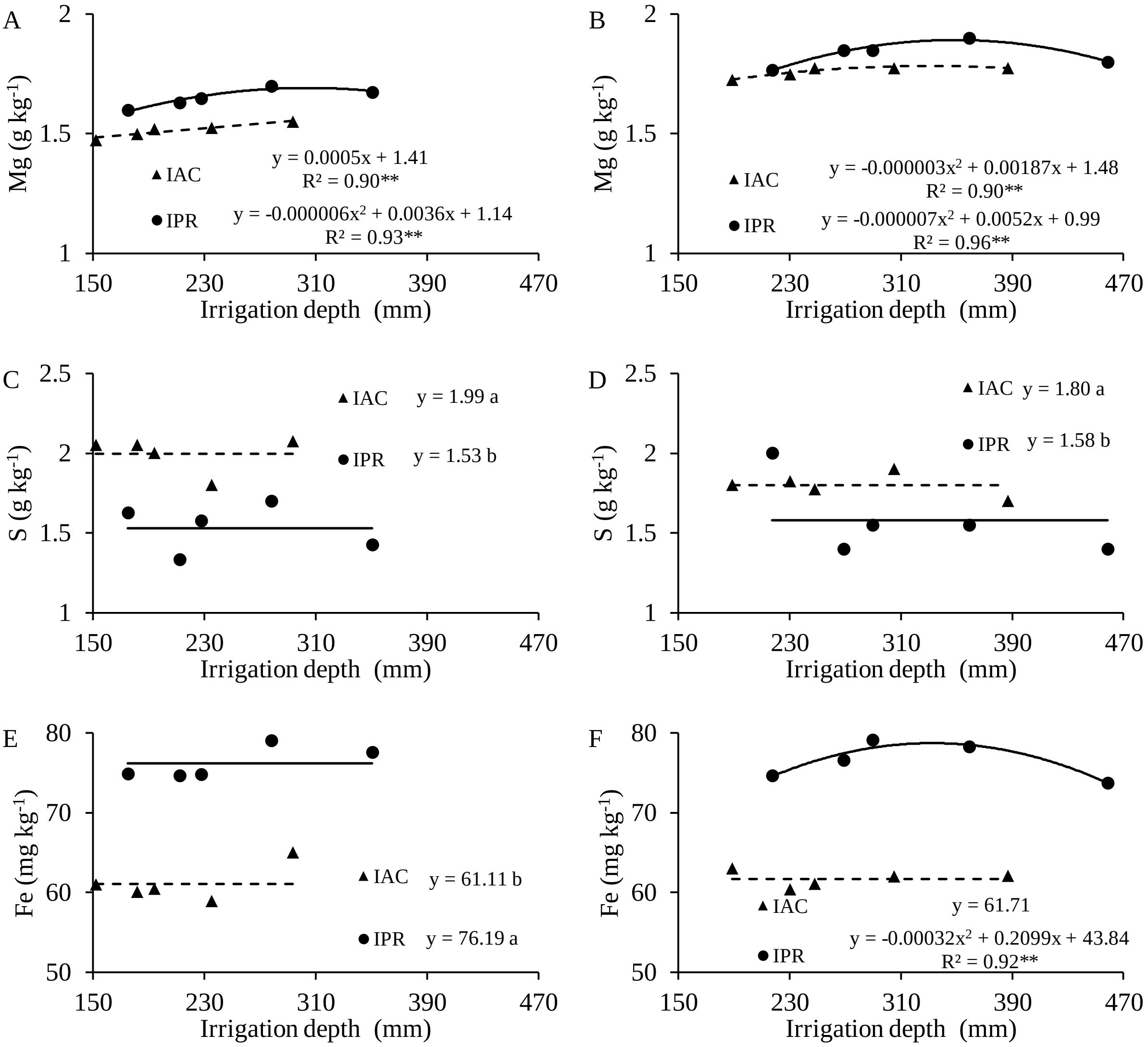


Figure 4. Contents of magnesium (A and B), sulfur (C and D), and iron (E and F) of grains of the common bean cultivars IAC Imperador (A and C) and IPR Campos Gerais (B and D) as a function of irrigation depths in the years 2019 and 2020. **(p<0.01)

The S content in the grains was not affected by irrigation depths in the two years (Figure 4C and D). The S content was higher for the cultivar IAC Imperador. Only the IPR Campos Gerais showed variation in the Fe content, with a quadratic increase (Figure 4E and F) in 2020. In addition, the IPR Campos Gerais presented higher Fe grain content in both years, with up to 60% superiority.

The B content did not vary as a function of the irrigation depths (Figure 5A and B). The cultivars showed a similarity in the B contents of grains in both years. The Cu contents showed variation only in 2019, with increments of 1.15 and 1.19 g kg^{-1} for every 100 mm of water applied for the IAC Imperador and IPR Campos Gerais, respectively (Figure 5C and D). The cultivar IPR Campos Gerais presented the highest Cu contents in both years.

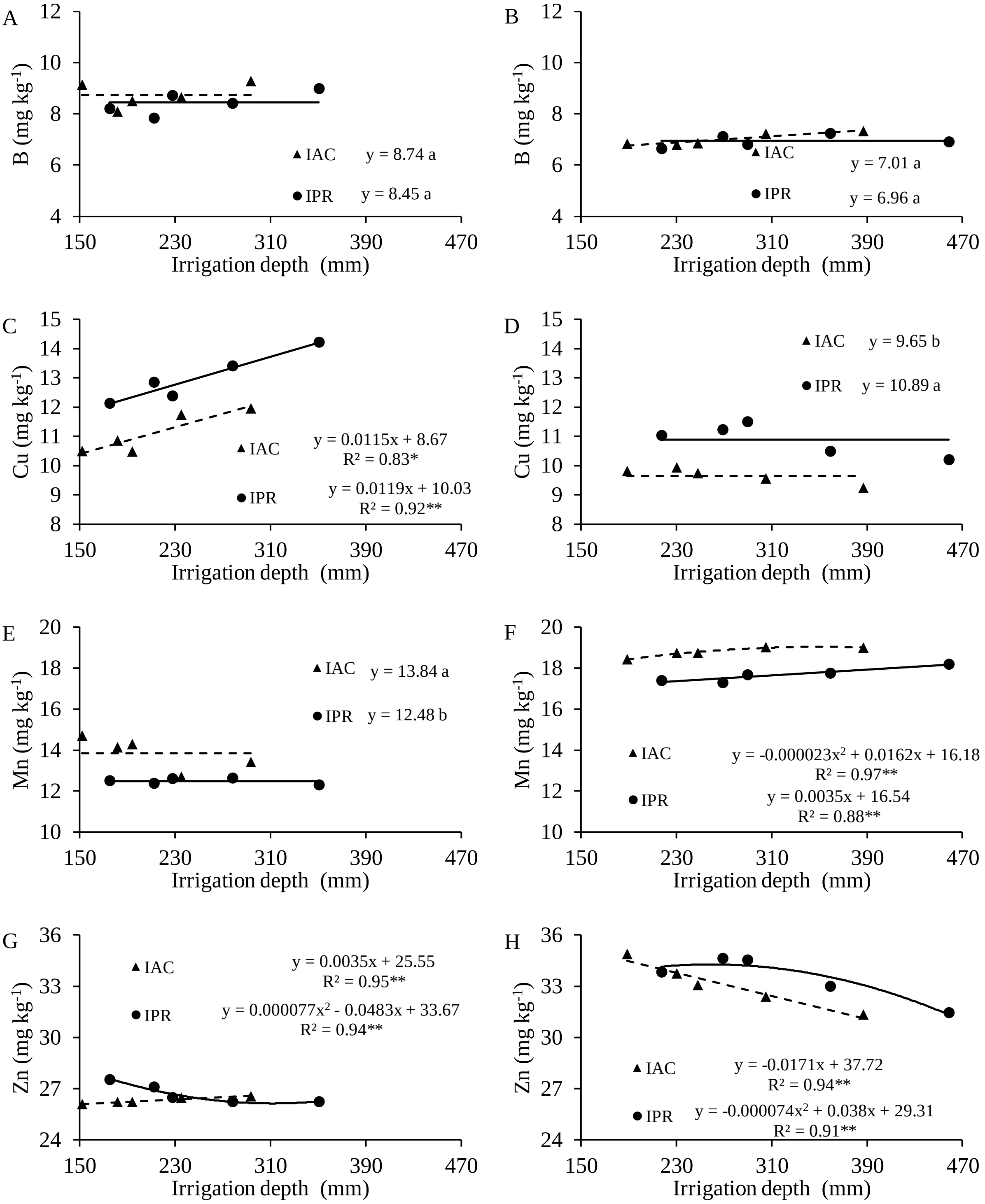


Figure 5. Contents of boron (A and B), copper (C and D), manganese (E and F), and

zinc (G and H) of grains of the common bean cultivars IAC Imperador (A and C) and IPR Campos Gerais (B and D) as a function of irrigation levels in the years 2019 and 2020. *($p<0.05$); **($p<0.01$)

The grains Mn content was only affected by irrigation depths in 2020, with a quadratic increment for the IAC Imperador and a linear increment of 0.35 g kg^{-1} for every 100 mm of water applied to the IPR Campos Gerais (Figure 5E and F). The maximum Mn value for the IAC Imperador in 2020 (19.0 g kg^{-1}) was obtained with an irrigation depth of 353 mm. In addition, the IAC Imperador had a higher Mn content.

The Zn content showed differences regarding the responses of the cultivars (Figure 5G and H). In 2019, the IAC Imperador showed a linear increase of 0.35 g kg^{-1} for every 100 mm of applied water, while in the IPR Campos Gerais decreased quadratically, with the minimum value (26.1 g kg^{-1}) reached with a water depth of 314 mm. In 2020, the IAC Imperador showed a linear reduction of 1.7 g kg^{-1} the Zn content of grains for every 100 mm of applied water, while the cultivar IPR Campos Gerais increased the Zn content (34.3 g kg^{-1}) up to the irrigation depth of 259 mm, from which the content also decreased.

Additionally, only the IPR Campos Gerais showed variation regarding the 100-grain weight (100W), with linear increments of 1.59 g in 100W for each 100 mm of applied water (Figure 6) in 2019. The highest 100W was found for the IPR Campos Gerais in 2019, while in 2020 no differences were observed.

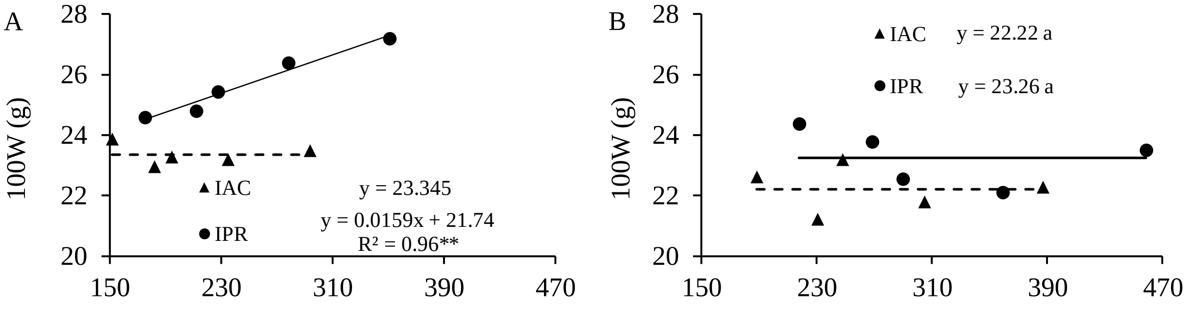


Figure 6. Variation in the 100-grain weight (100W) as a function of irrigation depths for two common bean cultivars evaluated in years 2019 (A) and 2020 (B). **($p<0.01$)

Soil moisture during the two years was lower for the management under water deficit (L1 to L3) and higher for the management under water excess (L5) compared to the management L4, which provided 100%, confirming the effect of water deficit and excess in the study (Figure 7). Water deficit was more severe from the flowering stage (R_6) and in 2020. In 2019, the similar soil moisture between irrigation management practices from 60 to 68 DAE was due to the adopted management, with a constant water depth for all treatments to avoid frost damage to the plants.

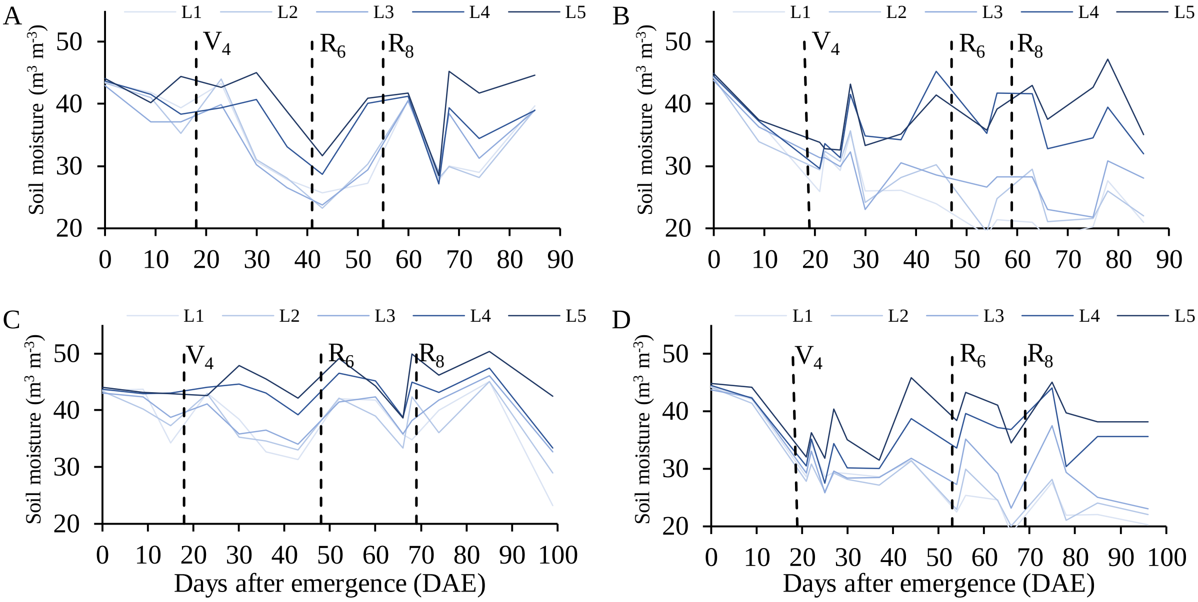


Figure 7. Soil moisture variation as a function of time for the cultivars IAC Imperador (A and B) and IPR Campos Gerais (C and D) in two years (2019 and 2020) for five irrigation management practices.

Irrigation depths had little effect on the variables SY≥12 and RGPS, related to the grain size of common bean. Common bean lots must have SY≥12 and RGPS above 70% and 7.0, respectively, to be characterized as coarse grains, with financial compensation (agility) in the sale and commercially more accepted grains (Carbonell et al., 2010). In this context, only the IPR Campos Gerais showed SY≥12 and PRGP values above or close to those recommended, characterizing a genotype with higher acceptance by the market and the possibility of generating a higher selling price compared to the IAC Imperador.

Filla (2019) evaluated the technological quality of the common bean cultivars IAC Imperador and IPR Campos Gerais and also found a higher SY≥12 for the cultivar

IPR Campos Gerais (86%). In addition, the author observed that the SY≥12 of the IAC Imperador was within the minimum limit of 70% to be classified as ideal for common bean. Aires et al. (2019) also observed that the IPR Campos Gerais presented SY≥12 and RGPS higher than the IAC Imperador. It demonstrates that the IPR Campos Gerais presents bigger grains than the IAC Imperador, regardless of the environment. Here, it was found that the IPR Campos Gerais presented SY≥12 up to 119% higher than the IAC Imperador.

The IPR Campos Gerais presented lower values for cooking time than the IAC Imperador, regardless of the irrigation depth and year. The CT of IPR Campos Gerais was up to 36% lower compared to IAC Imperador. Also, the CT of the IAC Imperador was dependent on the applied irrigation depth, with a reduction as a function of the applied water depth, while the irrigation depth used in the IPR Campos Gerais showed no changes for this variable. It shows that the water deficit increases the CT of the IAC Imperador (up to 27%), which is not desirable from the point of view of grain quality. The CT of the IAC Imperador varied from 21.3 to 26.6 minutes in 2019 and 22.5 to 28.7 minutes in 2020. Thus, in addition to increasing the CT of the IAC Imperador, the water deficit with an irrigation depth lower than 210 mm in 2020 changes the cooking time classification from “Normal cooking resistance” (21 to 28 minutes) to “Average cooking resistance” (28 to 32 minutes), while the IPR Campos Gerais is classified as “Average susceptibility to cooking” (16 to 21 minutes) (Proctor and Watts, 1987).

Overall, the highest CPC values were obtained in deficit irrigation depths for both cultivars. The water deficit promoted CPC values up to 22% higher compared to values of the irrigation depths without deficit. Silva et al. (2020) evaluated the effect of water deficit on the CPC of common bean and observed that higher CPC values were found under conditions of less water availability due to the dilution effect related to the higher grain production in the irrigation management without water deficit or with moderate water deficit. Foster et al. (1995) observed that the water deficit in the field did not affect N remobilization from the shoot to the grains of common bean subjected to deficit levels. Water deficit does not affect N remobilization for common bean grains but reduces the number of grains produced per plant, which leads to a higher CPC in grains under this condition (Palta et al., 1994). Aires et al. (2019) observed similar CPC values between IAC Imperador and IPR Campos Gerais, with an average of 25%.

Irrigation depths hardly changed the contents of K, Ca, S, Fe, and B. Ghanbari et al. (2015) observed that water deficit reduced the Fe content of common bean cultivars, regardless of the cultivar. However, the deficit evaluated by the authors was more severe than that observed in the present study. Similarly, Smith et al. (2019) observed that a reduction in the Fe content due to water deficit was genotype-dependent, as observed in 2020 in the present study. K has no structural function in plants, with enzymatic activation being its main action (Prado, 2021). This characteristic allows for the high mobility of K throughout the plant. As this nutrient is not part of the structure of any molecule, irrigation has a small effect on its content in grains, justifying the similarities in its content between treatments. Ca and B are the two nutrients with the lowest mobility in plants. Therefore, the water status of the plant did not impede their translocation to the grains, justifying the similarity between the treatments for the contents of these two nutrients. Although S has a structural role in some molecules in plants, especially sulfur amino acids, the similarity in common bean grain content as a function of irrigation depth is justified by the low sulfur amino acid content in the common bean (Flores-Sosa et al., 2020; Prado, 2021).

Water deficit reduced the P (up to 22%), Mg (up to 6%), Cu (up to 11%), and Mn (up to 5%) contents in the grains, regardless of the cultivar. Hummel et al. (2018) observed that the P, Mg, Cu, and Mn contents also decreased for most of the studied genotypes under water deficit conditions, as the lack of water reduces the absorption and translocation of these nutrients to the grains. Jin et al. (2006) observed that the water deficit reduced the amount of P translocated to the grains in soybean genotypes, reducing the P content in the grains, as observed for common bean in the present study.

In addition to CPC, Zn was the only nutrient that had higher contents under water deficit conditions (up to 11% higher). Almost all situations showed a decrease in the Zn content of grains with an increase in the irrigation depth. This fact was similar to that observed by Hummel et al. (2018), in which water deficit increased the Zn contents in the grains in most of the evaluated cultivars. According to the authors, water deficit changes little the translocation of this nutrient to the grains and the Zn content in the grains is higher under these conditions due to the dilution effect caused by the lower number of grains in plants with water deficit. In this sense, Sica et al. (2021)

observed that the Zn content in common bean grains is higher under water deficit conditions depending on the cultivar.

Etienne et al. (2018) conducted a bibliographic review on the remobilization of macro-and micronutrients in different crops as a function of water deficit observed that N is always remobilized for grains in all plant species, while the degree of water deficit and the crop can affect the remobilization of K, S, P, Mg, Cu, Fe, and Zn. Moreover, the authors also found little evidence that water deficit affects Ca, Mn, and B remobilization, as these nutrients already show little remobilization without water deficit conditions.

The comparison between cultivars showed general similarities in the contents of K, Ca, B, and Zn. The IPR Campos Gerais presented the highest contents for P (up to 37% higher), Mg (up to 14% higher), Fe (up to 27% higher), and Cu (up to 18% higher), while the cultivar IAC Imperador had the highest values for S and Mn, regardless of the year and irrigation levels. Therefore, the IPR Campos Gerais can be considered a genotype with a higher grain nutritional quality, as it has a higher number and contents of nutrients compared to IAC Imperador among those most important for human consumption, such as Fe. This cultivar has a higher Fe content and Zn content similar to the cultivar IAC Imperador.

Sica et al. (2021) observed differences of 16% in CPC, 26% in the Ca content, and 37% in the Zn content of grains between five common bean cultivars. Nunes et al. (2020) found differences of 35% in CT and 44% in SY≥12 between 16 cultivars. In addition, early cultivars have a lower SY≥12 than cultivars of normal and late cycles, especially grain size (Aires et al., 2019; Nunes et al., 2020). These differences show that the correct choice of a common bean cultivar directly affects the product price and food biological value. Cultivars with higher nutritional quality should be prioritized in regions where nutrient deficiencies predominate in the population, especially Fe and Zn, while cultivars with higher technological quality, especially with a high SY≥12, should be chosen in regions where the so-called hidden hunger does not occur, as they are an alternative to increase the price paid for the product and, consequently, the producer income.

3.4 Conclusions

Overall, water deficit reduces the technological and nutritional quality of common bean. Water deficit reduces relative grain production on sieves in the IPR Campos Gerais up to 13% and increases the cooking time of grains in the cultivar IAC Imperador up to 27%, affecting the acceptability and the price of the product. Regarding the nutritional quality, water deficit reduces P, Ca, Mg, Cu, Mn, and Fe contents in the grains up to 22, 35, 6, 11, 5 and 5%, respectively. Moreover, water deficit not changing K, S, and B contents, and increasing crude protein and Zn content in the grains by more than 10%. The IPR Campos Gerais, with an indeterminate growth habit, has the best technological and nutritional quality of grains. This cultivar presents grain size up to 119% larger, cooking time up to 36% lower, and higher contents of the most important nutrients for human consumption, such as P (up to 37% higher), Mg (14%), Fe (27%), and Cu (18%), compared to the IAC Imperador. These results demonstrate the importance of proper irrigation management and cultivar choice with a view to common bean quality, generating higher acceptance by the market, price paid for the product, and food biological value.

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CHAPTER 4 - What are the impacts of water deficit, cultivars, and years on the dynamics of nutrient absorption by common bean? Part I: N, P, and K[3]

ABSTRACT: Knowing the effect of water deficit intensity on the nutrient absorption dynamics by common bean cultivars with contrasting growth habits in different years is necessary to appraise and recommend more specific fertilization management practices. A field study was carried out in the Southeast of Brazil for two years aiming to explain and compare the accumulation and extraction of the macronutrients N, P, and K from two common bean cultivars with contrasting growth habits as a function of water deficit severity. The common bean cultivars IAC Imperador and IPR Campos Gerais, with determinate and indeterminate growth habits, respectively, were evaluated. Both cultivars were submitted to three irrigation management practices: severe water deficit (54% of the crop evapotranspiration – ETc), moderate water deficit (77% ETc), and no water deficit (100% ETc). Overall, the severe water deficit reduced N, P, and K accumulation in the common bean cultivars by 26, 37, and 23%, respectively. The cultivar IPR Campos Gerais showed, on average, higher accumulation of biomass (+30%), N (+47%) and P (+28%), and higher interannual variability in the accumulation of nutrients for management with no water deficit. In no water deficit treatment, the maximum daily demand for nutrients N and K in the IAC Imperador was anticipated in 9 and 11 days, respectively, compared to the IPR Campos Gerais. Therefore, the adopted irrigation management, cultivar, and climate of the year are important factors in decision-making for the most adequate establishment of fertilization with N, P, and K in common bean.

Keywords: *Phaseolus vulgaris* L., absorption march, deficit irrigation, fertilization

4.1 Introduction

The knowledge of the nutrient absorption march by crops allows the fertilization management to maximize the use of nutrients in agriculture. Knowing the demand and the time of highest demand generate relevant information to schedule the best management, increasing nutrient use efficiency (Fageria and Melo, 2014). However, several factors can affect the dynamics of nutrient absorption by crops, standing out the cultivar and year (Araújo and Teixeira, 2008; Nascente and Carvalho, 2018). Thus, the recognition of patterns, such as the climate conditions of cultivation and the cultivar,

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[3] This chapter was submitted to the Journal of Plant Nutrition and is under peer review process for publication

allows more assertive fertilization management practices, besides optimizing resources relative to recommended standard management practices (Fageria and Melo, 2014).

Common bean is among the crops with the highest variability in cultivation during the year. This variability encompasses climate conditions, as the crop can be cultivated in tropical regions throughout the year, from summer to winter (Conab, 2021), and cultivars, which show determinate (Type I) and indeterminate growth habits (Types II and III). In Brazil for example, common bean (*Phaseolus vulgaris* L.) is cultivated on 526 thousand hectares (ha) in the spring/summer, 567 thousand ha in the summer/autumn, and 525 thousand ha in the autumn/winter (Conab, 2021). Moreover, more than 100 cultivars are available to farmers (RNC, 2021), demonstrating the variability of genotypes with different efficiencies and responses to nutrients (Fageria and Melo, 2014; Silva et al., 2014; Leal et al., 2019).

Among all plant nutrients, N and K are the most absorbed by common bean (Soratto et al., 2013). Although a legume, the common bean crop is insufficient in biological nitrogen fixation (BNF), that is, high common bean yields require the application of up to 90 kg ha^{-1} of N utilizing mineral fertilizers (Ambrosano et al., 1997). In addition, P must be supplied in high amounts, often at levels higher than N and K, due to its dynamics in tropical soils and low fertilization efficiency, although this nutrient is not accumulated in plants in high amounts (Ambrosano et al., 1997). Early cycle common bean cultivars with a determinate growth habit generally have lower growth, accumulated biomass, and yield than cultivars with an indeterminate growth habit, with differences higher than 30% (Filla et al., 2020). In this sense, knowledge of the absorption dynamics of these nutrients by different common bean cultivars is essential to support more specific recommendations, such as rate and ideal fertilization time for each genotype, always considering the mobility of the nutrient in the soil and plant (Soratto et al., 2013).

Another factor that directly interferes with the growth and, consequently, nutrient absorption by plants is water availability (Taiz et al., 2017). Water is the main medium responsible for the ion-root contact in the soil and nutrient absorption. Coelho et al. (2020) found that moderate and severe water deficits reduced the maximum N absorption by white oat by approximately 35 and 80%, respectively. Thus, evaluations of the effect of water deficit severity on the N, P, and K absorption by common bean are necessary to guarantee better fertilization recommendations. This fact is even more important for common bean because the autumn/winter growing season must be irrigated in tropical regions given the scarcity of rainfall at this time of year. Therefore, evaluations of the impact of different irrigation management practices on the dynamics of N, P, and K absorption are essential to generate more accurate information on nutrient management.

This study hypothesized that (i) water deficit, especially the severe level, reduces the absorption of nutrients N, P, and K in common bean cultivars; and (ii) there are differences in the dynamics of N, P, and K absorption between cultivars with contrasting growth habits and years. Therefore, this study aimed to explain and compare the accumulation and extraction of the macronutrients N, P, and K from two common bean cultivars with contrasting growth habits as a function of water deficit severity in two years.

4.2 Material and methods

The experiment was carried out in the winter growing season of 2019 and 2020 at the São Paulo State University (Unesp), School of Agricultural and Veterinarian Sciences, Jaboticabal, São Paulo, Brazil, close to the geographical coordinates 21°14′44″ S and 48°17′00″ W, with an altitude of 545 m. The regional climate, according to the Köppen classification, is Aw, that is, a tropical climate with a dry winter, summer rains, an average annual temperature of 22 °C, and average annual precipitation of 1,425 mm.

The soil in the experimental area is classified as an Oxisol (Soil Survey Staff, 2014). Three undisturbed and disturbed soil samples were collected for the physical characterization of the experimental area before sowing the experiment in 2019 (Table 1). Fifteen simple soil samples were collected 30 days before sowing the experiment in each year, forming a composite sample for fertility analysis (Table 2).

Table 1. Soil physical attributes of the experimental area.

Layer (m)	Ds g cm^{-3}	Moisture FC m^3 m^{-3}	Moisture PWP m^3 m^{-3}	Clay g kg^{-1}	Silt g kg^{-1}	Sand g kg^{-1}
0.00–0.20	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 of the experimental area in the 2019 and 2020.

Layer	pH	H+Al	Al	K	Ca	Mg	SB	CEC	V
(m)	$CaCl_2$	mmol$_c$ dm^{-3}							%
					2019				
0.00–0.20	5.7	26	0	5.7	47	12	64.7	91	71
0.20–0.40	5.7	26	0	5.7	39	10	53.7	80	67
Layer	OM	Presin	S	B	Cu	Fe	Mn	Zn	
(m)	g dm^{-3}	mg dm^{-3}							
0.00–0.20	25	59	8	0.77	6.6	31	47.3	3.5	
0.20–0.40	21	32	13	0.56	6.2	24	34.4	2.0	
					2020				
Layer	pH	H+Al	Al	K	Ca	Mg	SB	CTC	V
(m)	$CaCl_2$	mmol$_c$ dm^{-3}							%
0.00–0.20	5.9	25	0	5.1	50	14	69.1	94	74
0.20–0.40	5.5	28	0	5.2	33	10	48.2	76	63
Layer	OM	Presin	S	B	Cu	Fe	Mn	Zn	
(m)	g dm^{-3}	mg dm^{-3}							
0.00–0.20	24	66	5	0.46	4.5	16	25.8	3.2	
0.20–0.40	19	49	7	0.39	4.4	11	24.5	1.6	

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

Common bean was sown on May 7, 2019, and May 18, 2020. Two common bean cultivars from the ‘Carioca’ commercial group, with contrasting growth habits, were used. The cultivar IAC Imperador has a determinate growth habit (Type I), erect architecture, and an early cycle of 75 days (Chiorato et al., 2012). The cultivar IPR Campos Gerais has an indeterminate growth habit (Type II), erect architecture, and a normal cycle of 90 days (Moda-Cirino et al., 2012). The cultivars were mechanically sown to obtain a density of 240,000 plants ha^{-1}, with an inter-row spacing of 0.45 m. The seeds were treated before sowing with pyraclostrobin (5 g ai ha^{-1}) + thiophanate-methyl (45 g ai ha^{-1}) + fipronil (50 g ai ha^{-1}), using the commercial product Standak®

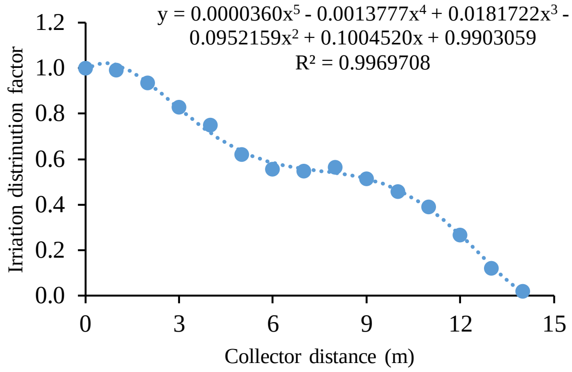
Top, and inoculated with *Rhizobium tropici* (StarFix® Feijão) for biological nitrogen fixation, using the dose recommended.

Common bean was sown in an area previously cultivated with corn, using a seed-cum-fertilizer drill intended for no-tillage. The corn hybrid P4285VYHR was sown in October in the two years, with an inter-row spacing of 0.90 m and 75,000 plants ha^{-1}. Limestone with a total neutralizing power of 95 was applied 30 days before corn sowing in the two years at a dose of 1.5 Mg ha^{-1}. The limestone was incorporated into the soil with a plowing harrow operation (0.00–0.20 m) and two leveling harrow operations. The amount of corn straw (dry matter) on the soil was estimated at common bean sowing and reached 7,622 ± 272 kg ha^{-1} in 2019 and 9,052 ± 367 kg ha^{-1} in 2020, while the average grain yield reached 11,200 ± 134 kg ha^{-1} in 2019 and 11,800 ± 210 kg ha^{-1} in 2020.

The sowing fertilization of the common bean crop was carried out according to the soil analysis (Table 2) and recommendation of Ambrosano et al. (1997) by applying a dose of 200 kg ha^{-1} of the formulation 04–20–20 in the two years, supplying 8 kg ha^{-1} of N, 40 kg ha^{-1} of P_2O_5, and 40 kg ha^{-1} of K_2O. Topdressing fertilization was carried out at the V_{4-3} stage, characterized by the third trifoliate leaf fully expanded (Fernández et al., 1985), and consisted of the application of a dose of 100 kg ha^{-1} of N in both years, with urea as source (Ambrosano et al., 1997). The topdressing fertilization was carried out at 19 and 21 days after emergence (DAE) of the common bean crop in 2019 and 2020, respectively, in a continuous strip at 0.10 m from the sowing row. A 10-mm irrigation depth was applied to all treatments in the two years after topdressing fertilization to avoid the effect of different volatilization rates between the different irrigation levels. This 10-mm irrigation depth was used because it is a minimum value that does not promote losses of urea by volatilization (Espindula et al., 2021), not significantly interfering with the applied treatments. The control of weeds, pests, and diseases was carried out when necessary, using products registered for the crop.

The experimental design used was strip-plot. The study factors were five irrigation levels and two common bean cultivars, with four replications. Each subplot had 15 rows of common bean, with a dimension of 6.75 m long and 2.4 m wide. The first row of common bean at each end and the initial 50 cm of the central rows were considered as borders. Six out of the remaining 13 cultivation rows were used to estimate yield and the other seven for destructive analysis.

The line-source sprinkler system was used, allowing the distribution of the irrigation water with variable application depths as the treatment moves away from the central sprinkler line (Hanks et al., 1976). A field test enabled the definition of the distribution fractions of the sprinkler precipitation (Figure 1). In model fit, the regression that generated the highest precision (R^2) was used, aiming to estimate the most accurate irrigation distribution factor possible in each treatment. Senninger 4023-2 sprinklers and ¾″ M 08Qx05 nozzles were used spaced every 6 m on the central line. The water application intensity of the sprinklers was measured in the field in tests with collectors placed at 1 m from each other up to the limit distance of water application by the sprinklers in a line perpendicular to the irrigation line, with four replications.



Distance (m)	Treatment	Irrigation distribution factor
0.00–2.40	L5	1.002 (132%)
2.40–4.80	L4	0.754 (100%)
4.80–7.20	L3	0.584 (77%)
7.20–9.60	L2	0.532 (70%)
9.60–12.00	L1	0.407 (54%)

Figure 1. Sprinkler irrigation distribution factor as a function of the distance from the irrigation line, with sprinklers spaced at 6 m from the line, obtained in field tests. Service pressure: 250 kPa

For study purposes, the treatments consisted of five irrigation levels (L1, L2, L3, L4, and L5), which were established after the establishment of the regression of water application by the sprinkler line (Figure 1). The L4 water level was used as a standard, receiving 100% of the water requirement of the common bean crop. The L5 water level applied excess water, with 132% of the water requirement of the common bean crop, while the L3, L2, and L1 water levels provided 77, 70, and 54% of the water requirement, respectively. The irrigation levels L1, L3, and L4 and two common bean cultivars were used in the present study to evaluate the effect of water deficit on the absorption and extraction of macronutrients N, P, and K in the common bean crop.

Management L4 was used as a standard, providing 100% of the water requirement for the common bean crop, while management L3 was considered a moderate water deficit, providing 77% of the water requirement, and management L1 was considered a severe water deficit, providing 54% of the water requirement.

The irrigation management was carried out based on the crop water demand, according to the FAO 56 method, using climate data obtained daily from an automated agrometeorological station located 1,500 m from the experiment. The reference evapotranspiration (ETo) was estimated daily using the FAO 56 method (Allen et al., 1998). The evapotranspiration of the common bean crop (ETc) was calculated using the product of ETo by the crop coefficients (Kc) (Allen et al., 1998). The used Kc values 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 from 1.15 to 0.35 (maturation). For the Kc range between 0.40 and 1.15, the values were interpolated daily up to the maximum value (1.15). The daily increment was calculated as the ratio of the difference between the Kc range (1.15 – 0.40) and the number of days between the initial Kc (0.40) and maximum Kc (1.15).

Irrigation was carried out when the water deficit in the area was equal to 18 mm. This water depth was calculated according to the soil physical attributes (Table 1) and the common bean crop. The calculation considered an effective root depth of 0.25 m and a water availability factor of 0.40 (Allen et al., 1998). Two water depths of 15 mm were applied for the plant emergence considering a uniform initial stand in all treatments.

The average maximum and minimum temperatures during the 2019 experimental period were 27.8 and 13.9 °C, respectively, with accumulated precipitation of 48.7 mm (Figure 2A). Low temperatures were observed in 2019, especially from July 5 to 8 and July 16 and 18. The minimum temperature reached 3.3 °C on July 7, 2019, which caused frost in the experimental area. The number of trifoliate leaves reached by the frost in each cultivar was counted, with an average of 10% in the cultivar IAC Imperador and 12% in the cultivar IPR Campos Gerais. The average maximum and minimum temperatures during the experimental period in 2020 were 28.4 and 13.9 °C, respectively, with accumulated precipitation of 35 mm (Figure 2C). Minimum temperatures below 5 °C were not observed in 2020.

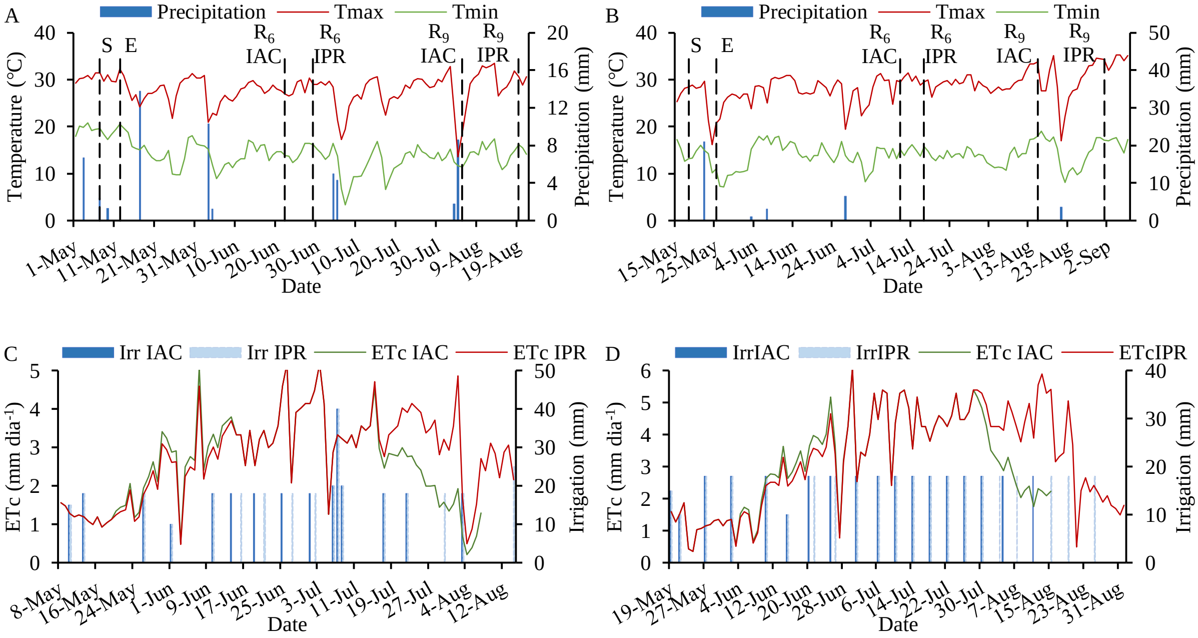


Figure 2. Daily maximum temperature, minimum temperature, precipitation (A and B), crop evapotranspiration, and irrigation (C and D) of common bean cultivars during the experimental period from May 7, 2019, to August 19, 2019 (A and C) and May 18 to September 1 (B and D). S: sowing; E: emergence; R_6: full bloom; R_9: physiological maturity; Irr: irrigation; ETc: crop evapotranspiration.

Irrigation was activated during the dawns of July 6, 7, and 8 as an attempt to control the frost. The water depth was constant for all treatments and 20, 40, and 20 mm were applied on July 6, 7, and 8, respectively. For calculation purposes, 30 mm of irrigation were considered on these days for all treatments.

Soil moisture was determined weekly at three points per subplot of the irrigation levels L1, L3, and L4 in the 0.00–0.20 m layer using the time domain reflectometry (TDR) technique (Fellner-Feldegg, 1969). The equipment calibration was carried out before the experiment was set up in the soil of the experimental area. For this, 25 points were randomly chosen in the area for the determinations using the equipment, and one undisturbed soil sample was collected at these sites for determining the actual soil moisture ($m^3\ m^{-3}$), generating a regression between the observed values and the values measured on the equipment. This regression was used to correct the soil moisture during the experiment.

The water deficit effect on the accumulation and extraction of nutrients from common bean cultivars was evaluated through the absorption march for the primary macronutrients N, P, and K. For this, 16 plants (four plants per replicate) were collected in treatments L1, L3, and L4 (54, 77, and 100% of the water requirement, respectively) for the two cultivars. Collections in the early cycle cultivar (IAC Imperador) were carried out at 12, 24, 35, 46, 59, 66, and 85 days after emergence (DAE) in 2019 and 14, 28, 37, 50, 61, 71, and 80 DAE in 2020. Moreover, collections in the normal cycle cultivar (IPR Campos Gerais) were performed at 14, 30, 42, 51, 63, 83, and 99 DAE in 2019 and 14, 28, 43, 59, 74, 83, and 96 DAE in 2020. The collected material was separated into leaves, stem, and reproductive structures, as performed by Soratto et al. (2013). The amount of nutrients extracted per hectare was estimated in each evaluation using the average population of the plots at the collection time and dry matter of each partition of samples. In addition, the N, P, and K contents of grains of each treatment were analyzed at the harvest time. The export of macronutrients by grains (kg ha^{-1}) was estimated by the product between the nutrient content and the grain yield of each treatment.

All plant materials were washed with running water, deionized water, 1% aqueous detergent solution, and deionized water again. Subsequently, the plant materials were dried in a forced-air circulation oven at 65 °C until constant mass. After drying, the samples were ground in a Willey mill and taken to digestion to determine the N content, according to the methodology described by Bataglia et al. (1983). P and K were determined using the methodology proposed by Malavolta et al. (1997). Each ground sample was divided into triplicates for analysis of N, P, and K contents.

Polynomial regressions ($p<0.05$) were tested to model the total accumulation of biomass and macronutrients of common bean cultivars grown under severe (L1), moderate (L3), and no water deficits (L4) as a function of time. The daily rate of total accumulation of macronutrients absorbed by common bean cultivars was obtained by the first derivative of equations adjusted for the accumulation of each treatment. The percentage of the amount of macronutrients accumulated in the leaves, stems, and reproductive structures was calculated for each evaluation period and treatment. The macronutrient harvest index (%) was calculated by the ratio between the amount of nutrient accumulated in the grains (kg ha^{-1}) and the amount of nutrient accumulated in the entire shoot (kg ha^{-1}), multiplied by 100.

4.3 Results and discussion

Water deficit, especially the severe level, reduced biomass accumulation in the different parts of the cultivar IAC Imperador in the two years (Figure 3). The total biomass accumulation was 11% lower under moderate deficit (L3) and 26% lower under severe deficit (L1) compared to no water deficit (L4) in 2019, while the moderate and severe deficits reduced by 25 and 33% the total biomass accumulation in 2020, respectively. The total biomass accumulation was similar for L1 and L3 between the years, while a higher biomass accumulation was observed for the L4 management in 2020 (19% higher). The highest biomass for the L4 irrigation management of the cultivar IAC Imperador in 2020 was mainly due to the highest biomass accumulation in stems and leaves.

As observed for biomass, water deficit reduced the total N accumulation for the IAC Imperador in both years (Figures 4A and 4B). Regarding the management with no deficit, N accumulation reached 17 and 6% lower for L1 and L3 in 2019 and 29 and 15% in 2020, respectively. A similarity in the total N accumulation was observed for irrigation management practices between years. Only the severe water deficit promoted significant reductions (25%) for P in 2019 compared to the management with no water deficit, while both moderate (21%) and severe water deficits (37%) reduced the total accumulation of this nutrient in 2020. The total P accumulation between years was similar for the irrigation management practices.

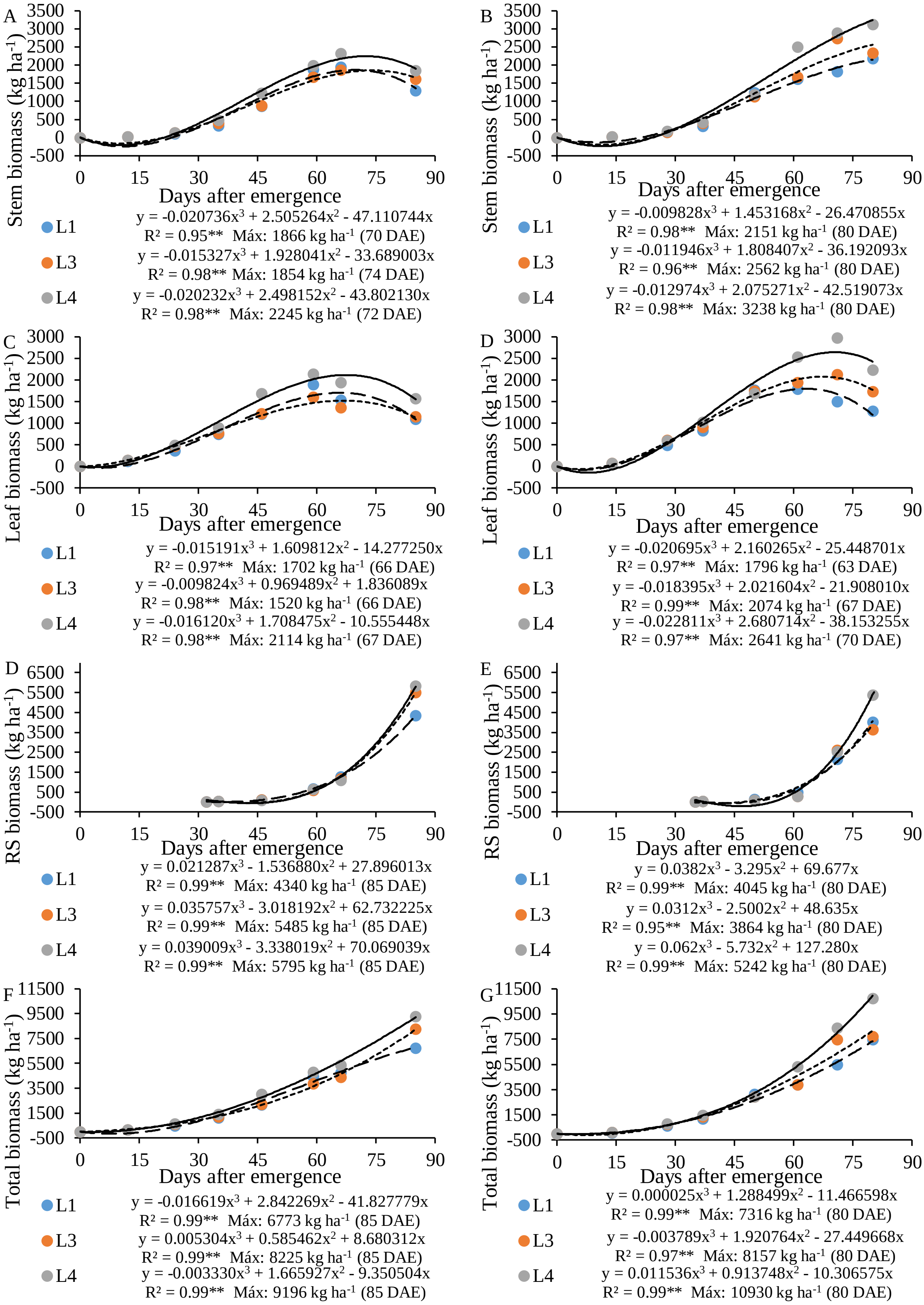


Figure 3. Stem (A and B), leaf (C and D), reproductive structure (RS) (E and F), and total biomass accumulation (G and H) of the common bean cultivar IAC

Imperador under three irrigation levels (L1: 54%, L3: 77%, and L4: 100% ETc) in 2019 and 2020. **(p<0.01).

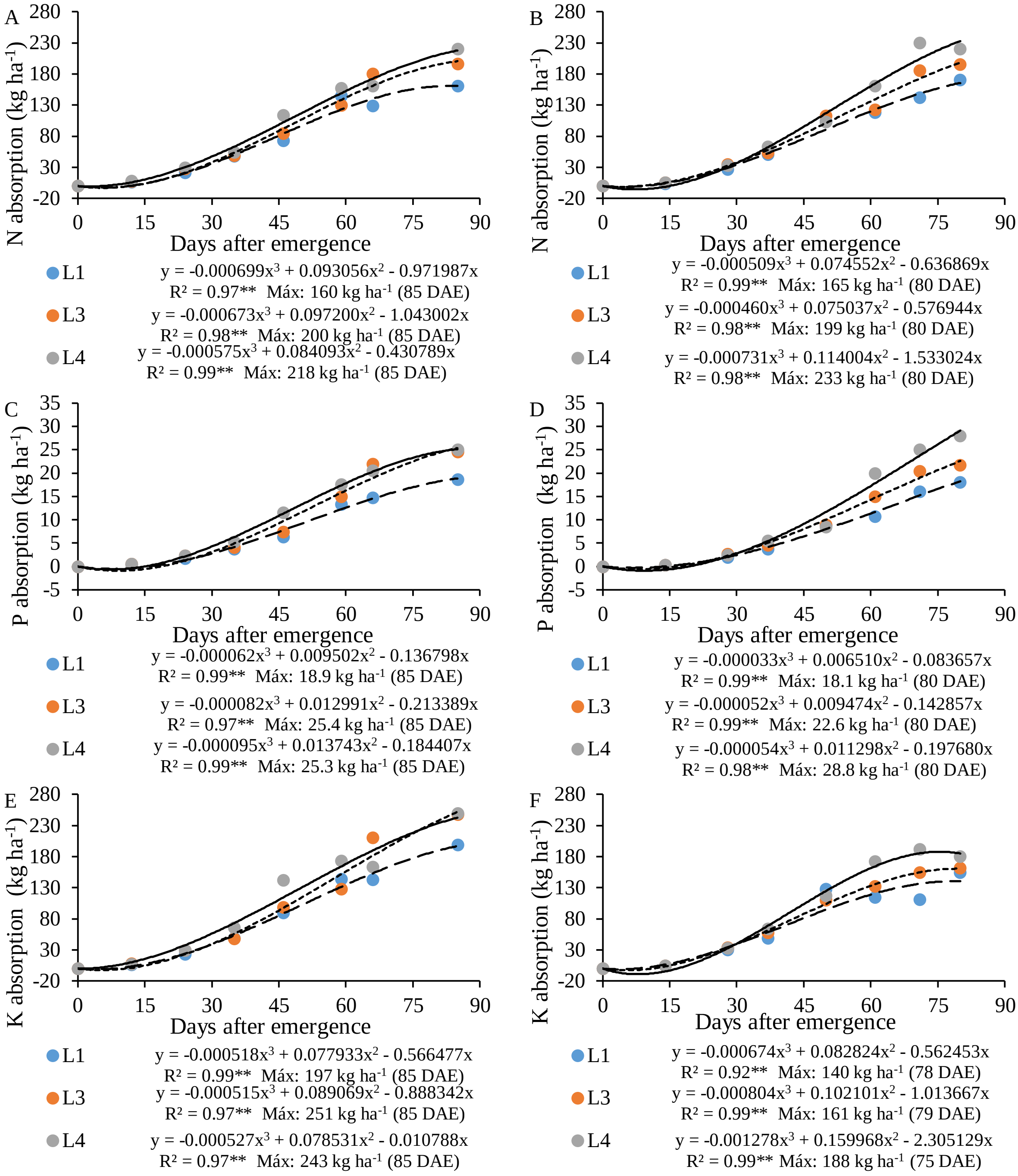


Figure 4. Nitrogen (A and B), phosphorus (C and D), and potassium accumulation (E and F) in the common bean cultivar IAC Imperador under three irrigation levels (L1: 54%, L3: 77%, and L4: 100% ETc) in 2019 and 2020. **(p<0.01).

In 2019, only the severe water deficit (19%) significantly reduced the total K accumulation for the IAC Imperador compared to no water deficit, but reductions were observed in the accumulation for both moderate (14%) and severe water deficits (26%) in 2020 (Figure 4). The comparison between years showed higher K accumulations in 2019, regardless of the water management. The maximum accumulations were 41, 56, and 29% higher in 2019 for L1, L3, and L4, respectively, compared to 2020.

The water deficit, especially the severe level, reduced the maximum daily rate of N, P, and K absorption of the IAC Imperador (Figure 5). The maximum N absorption rate in both years occurred between 42 and 54 DAE, with a trend to be anticipated, on average, by 5 days in the severe water deficit management. The peak of the P and K absorption rates in the two years occurred from 46 to 80 and 39 to 59 DAE, respectively. The nutrients P and K showed no trends in anticipating the peak of the absorption rate due to water deficit.

All in all, leaf nutrient contents in the cultivar IAC Imperador were higher for the management with no water deficit, followed by moderate and severe water deficits (Figure 6). An exception was observed for K in both years, in which similarities in the leaf content were found between irrigation management practices. In some periods, the L1 management showed higher levels. Between years, the highest differences occurred only for K, with 2020 tending to have contents lower than those observed in 2019, especially at the end of the crop cycle.

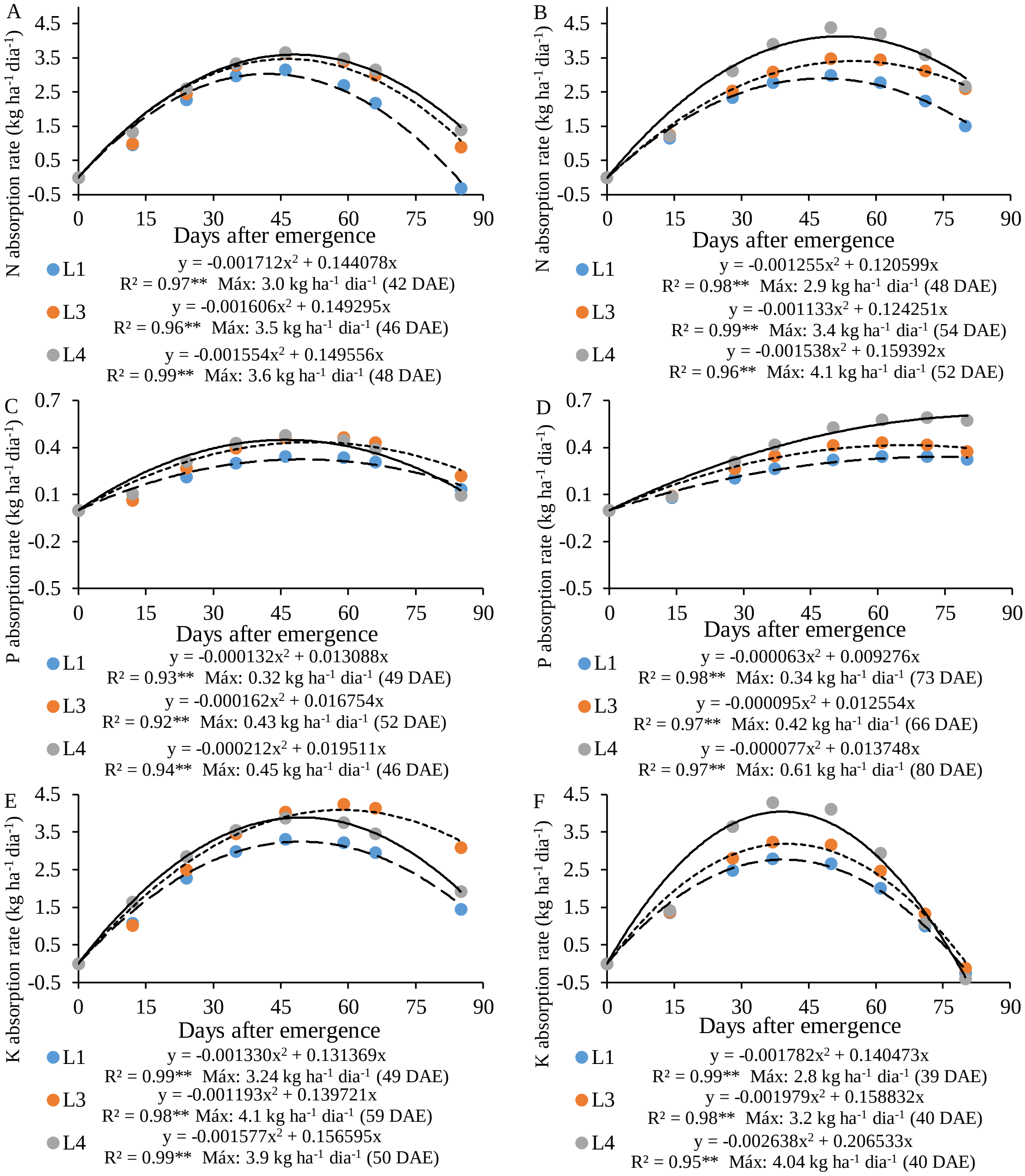


Figure 5. Daily nitrogen (A and B), phosphorus (C and D), and potassium absorption rate (E and F) in the common bean cultivar IAC Imperador under three irrigation levels (L1: 54%, L3: 77%, and L4: 100% ETc) in 2019 and 2020. **($p<0.01$).

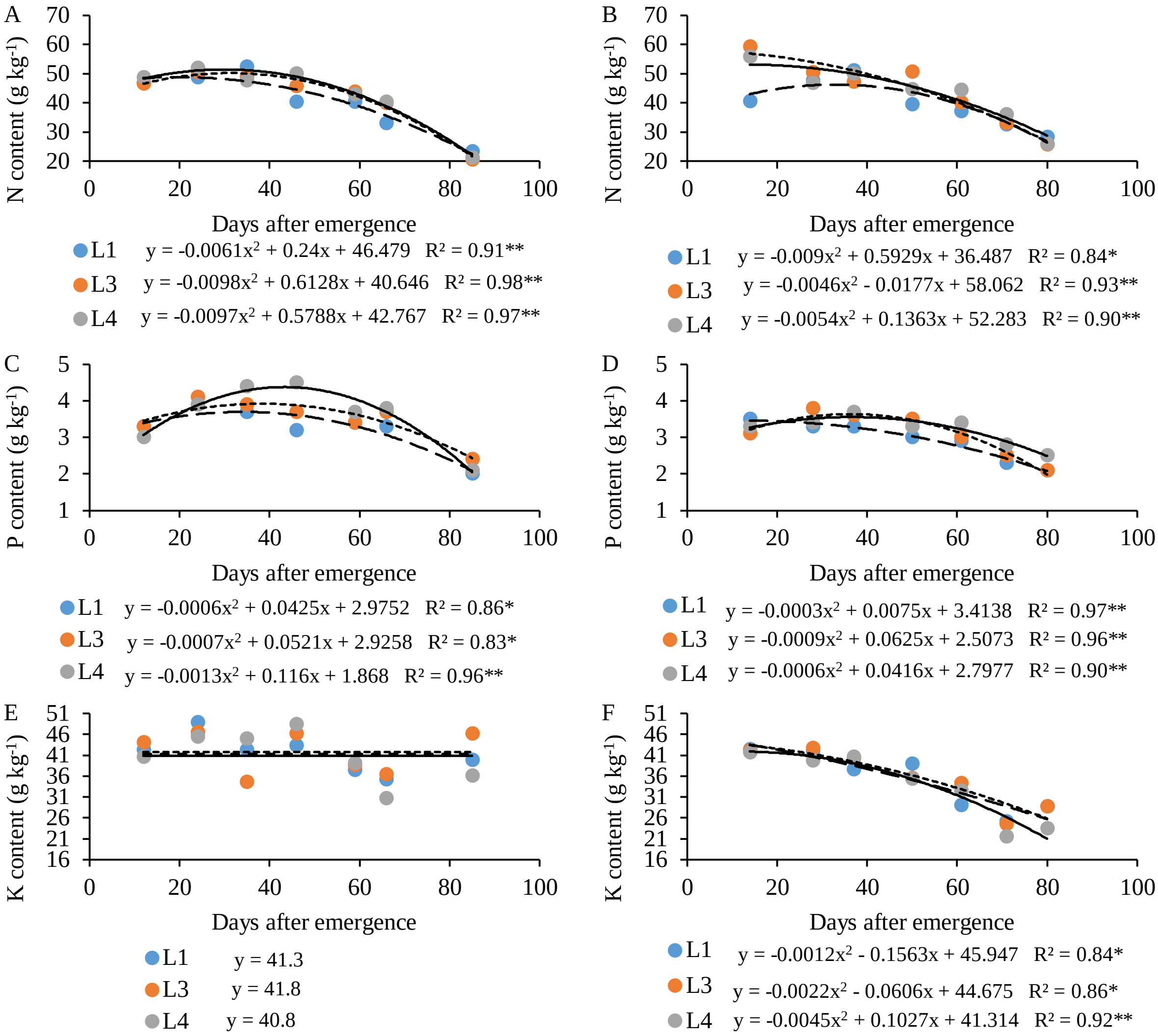


Figure 6. Leaf nitrogen (A and B), phosphorus (C and D), and potassium contents (E and F) in the common bean cultivar IAC Imperador under three three irrigation levels (L1: 54%, L3: 77%, and L4: 100% ETc) in 2019 and 2020. *($p<0.05$); **($p<0.01$).

The penultimate evaluation of the two years showed that the severe water deficit management tended to show a higher proportion of reproductive structures in the total nutrient accumulation, followed by L3 and L4 (Figure 7). However, this fact was not observed for the last evaluation of each year, with similarities between the management practices in the proportion of each plant structure in the total accumulation. Between 60 and 80% of the total N and P accumulations were observed in the reproductive structures of the plant, while K had an accumulation between 30 and 55%.

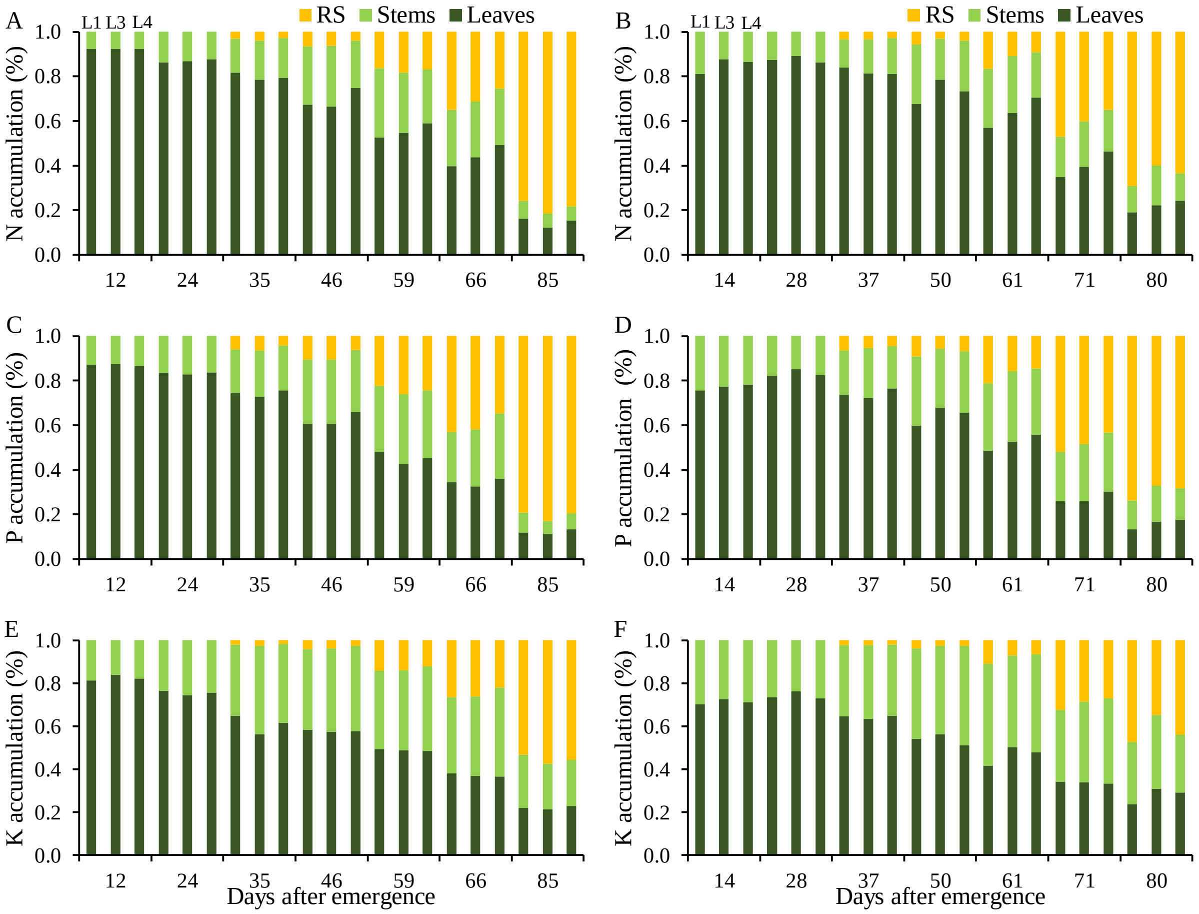


Figure 7. Proportion of nitrogen (A, B), phosphorus (C, D), and potassium accumulation (E, F) in stems, leaves, and reproductive structures (RS) of the common bean, IAC Imperador, under three irrigation levels (L1: 54%, L3: 77%, and L4: 100% ETc) in 2019 and 2020.

The L1 management reduced the total biomass accumulation of the IPR Campos Gerais by 21% compared to the L4 management in 2019, with a 17% reduction in the L3 management (Figure 8). In 2020, the reductions in the total biomass accumulation for L1 and L3 were 35 and 18%, respectively. Biomass accumulation in all irrigation management practices and plant parts was higher in 2020, with increases in total biomass of 8, 32, and 32% for L1, L3, and L4, respectively, compared to 2019.

The cultivar IPR Campos Gerais showed similarities regarding the total N accumulation between irrigation management practices for 2019, with superiority of only 13% for L4 relative to the average maximum accumulation for L1 and L3 (Figure 9A and 9B). In 2020, the differences between water management were higher, as the moderate and severe water deficits reduced the total N accumulation by 15 and 33%, respectively. Higher N accumulations occurred in 2020, with a 17, 48, and 54%

superiority for L1, L3, and L4, respectively, regardless of the irrigation management.

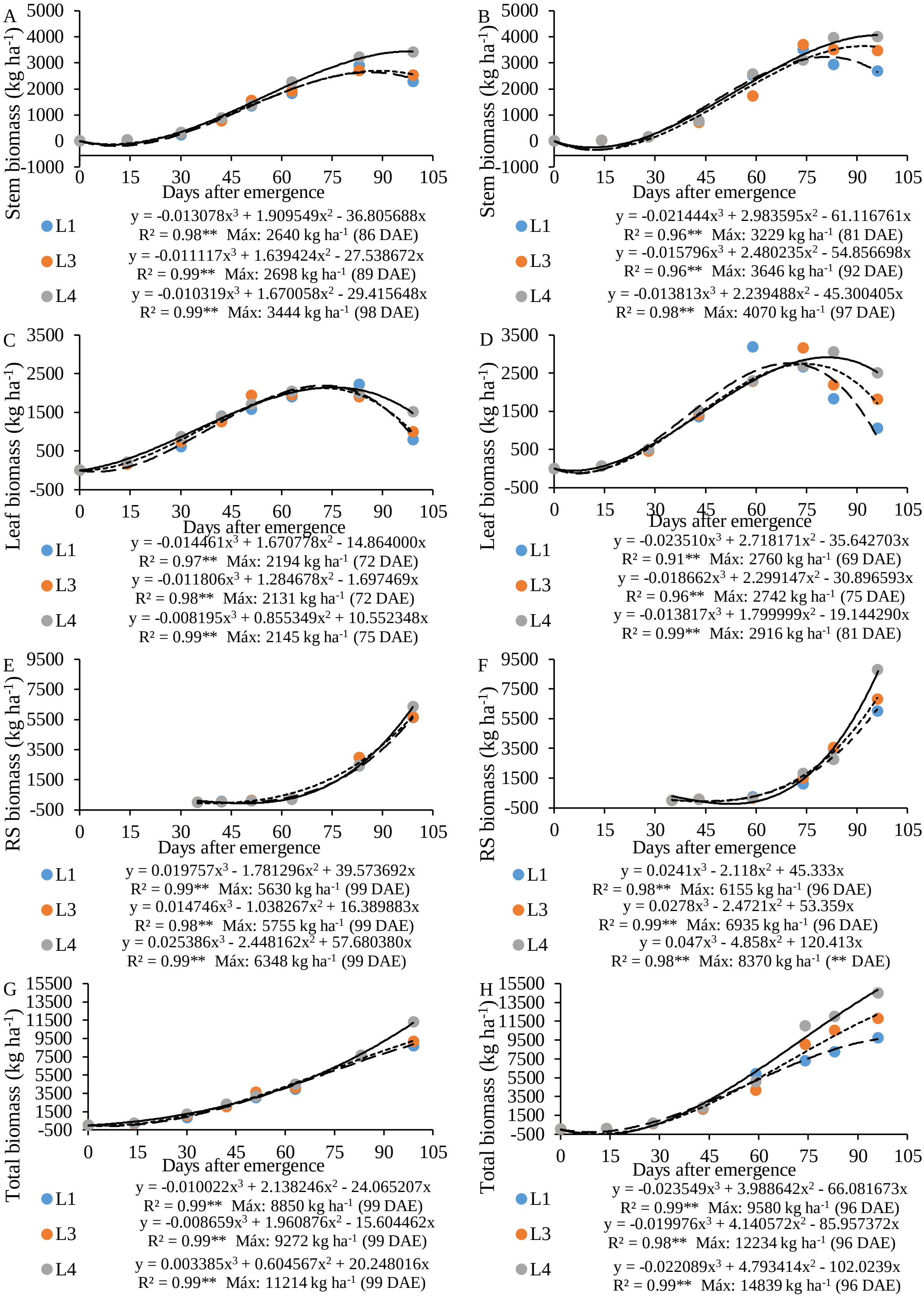


Figure 8. Stem (A and B), leaf (C and D), reproductive structure (RS) (E and F), and

total biomass accumulation (G and H) in the common bean cultivar IPR Campos Gerais under three irrigation levels (L1: 54%, L3: 77%, and L4: 100% ETc) in 2019 and 2020. **(p<0.01).

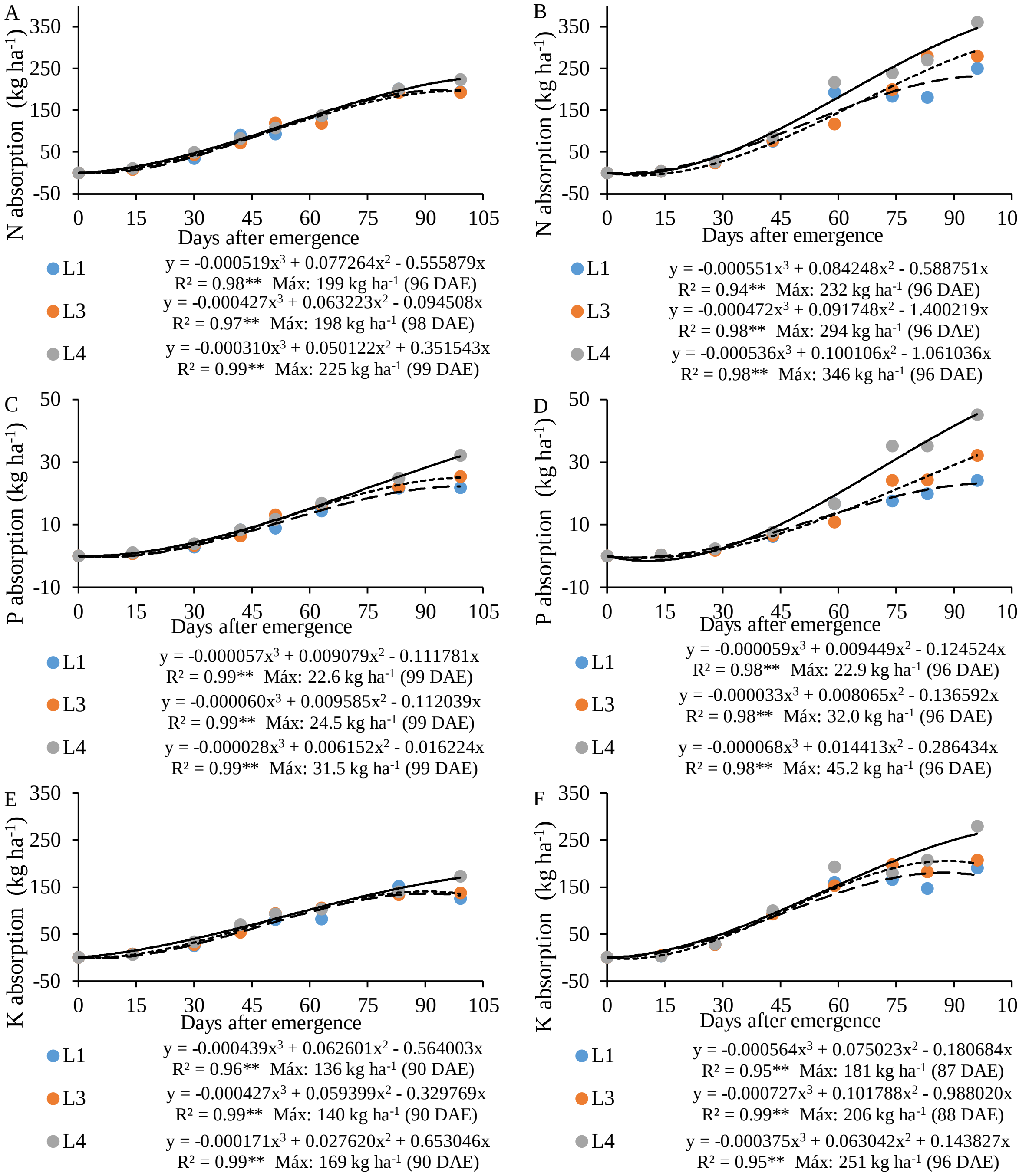


Figure 9. Nitrogen (A and B), phosphorus (C and D), and potassium accumulation (E and F) in the common bean cultivar IPR Campos Gerais under three irrigation levels (L1: 54%, L3: 77%, and L4: 100% ETc) in 2019 and 2020. **(p<0.01).

Similarly, P and K accumulation in 2019 for the IPR Campos Gerais was similar between both water deficit management practices (L1 and L3). On average, P and K accumulation in L1 and L3 were 25 and 18% lower than the accumulation in the management with no water deficit, respectively. In 2020, the differences between irrigation management practices were higher for P and K. The L1 and L3 management practices presented a total accumulation 49 and 29% lower than L4 for P and 28 and 18% for K, respectively. Almost all treatments showed higher accumulation in 2020, except for P in L1.

The N absorption rate peak of the IPR Campos Gerais was between 48 and 62 DAE in both years (Figure 10). The severe water deficit reached the peak of absorption, on average, 10 days before the management with no water deficit in both years, while this factor was dependent on the year in the management with moderate water deficit. Moreover, 2020 showed the highest N absorption peak. The maximum absorption rate for P between years ranged from 50 to 78 DAE, with the severe water deficit management showing a peak before the management with no water deficit, with an average of 26 days. Almost all management practices showed a higher P absorption peak in 2020, except for L1. The maximum K absorption rate occurred between 45 and 55 DAE in both years. The two irrigation management practices under water deficit showed peak absorption, on average, 12 days before the peak of the management with no water deficit. As observed for N and P, 2020 generated higher nutrient absorption rates than 2019.

In general, leaf nutrient contents in the IPR Campos Gerais were higher for the management with no water deficit, followed by moderate and severe water deficits (Figure 11). An exception was found for N in 2019, in which similarities in the leaf content were observed between irrigation management practices. In fact, the L1 management showed the highest values in some periods. The highest differences between years occurred only for P, with 2020 tending to have lower contents than 2019, especially at the end of the crop cycle.

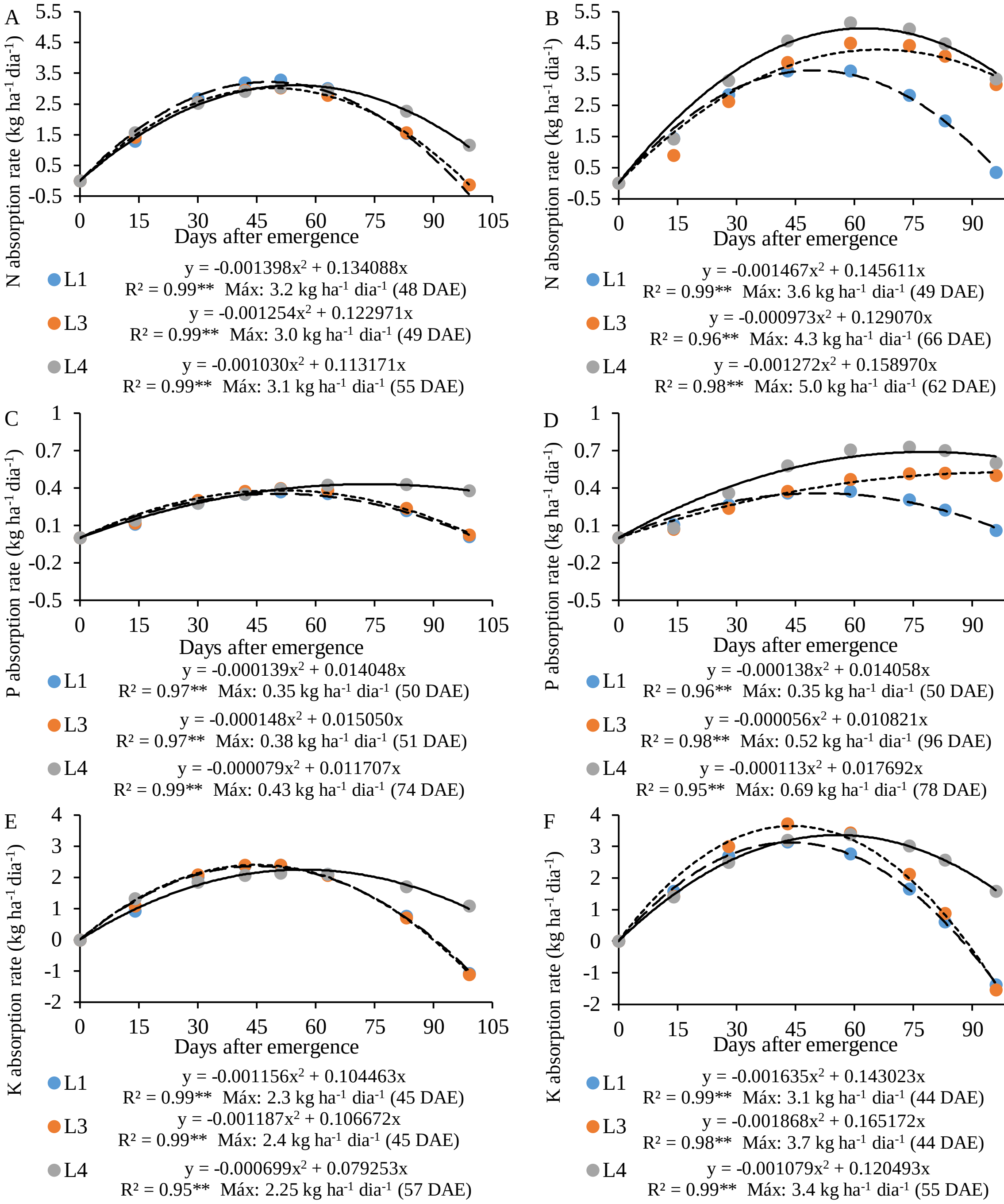


Figure 10. Daily nitrogen (A and B), phosphorus (C and D), and potassium absorption rate (E and F) in the common bean cultivar IPR Campos Gerais under three irrigation levels (L1: 54%, L3: 77%, and L4: 100% ETc) in 2019 and 2020. **(p<0.01).

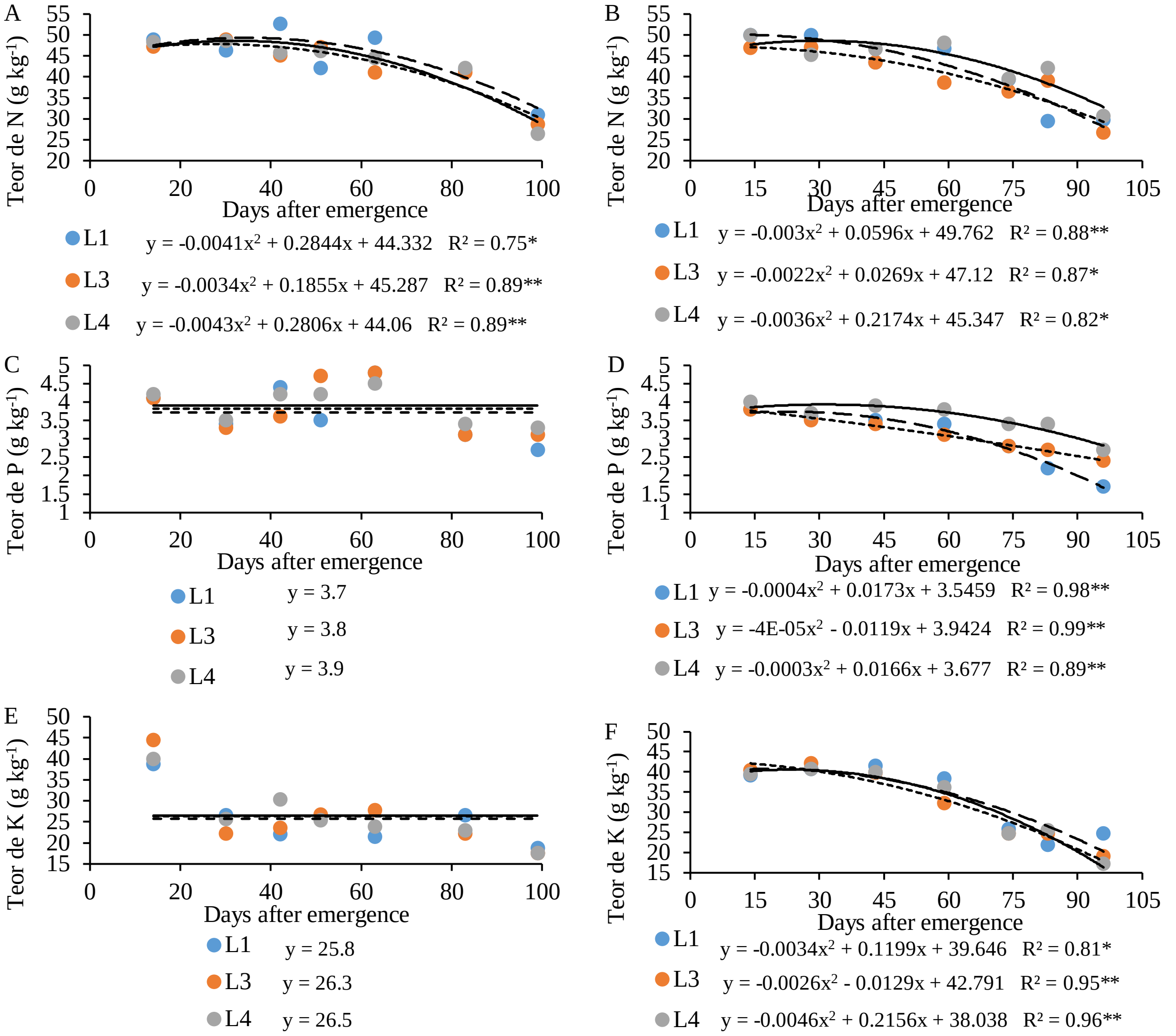


Figure 11. Leaf nitrogen (A and B), phosphorus (C and D), and potassium contents (E and F) in the common bean cultivar IPR Campos Gerais under three irrigation levels (L1: 54%, L3: 77%, and L4: 100% ETc) in 2019 and 2020. *($p<0.05$); **($p<0.01$).

The proportion of each plant part in the total N, P, and K accumulation showed a trend, in the last evaluation carried out each year, of a higher percentage of accumulation in the reproductive structures in the severe water deficit management, followed by moderate water deficit and no water deficit (Figure 12). Between 60 and 80% of the total N and P were accumulated in the reproductive structures, regardless of the water management; this proportion reached between 50 and 65% for K.

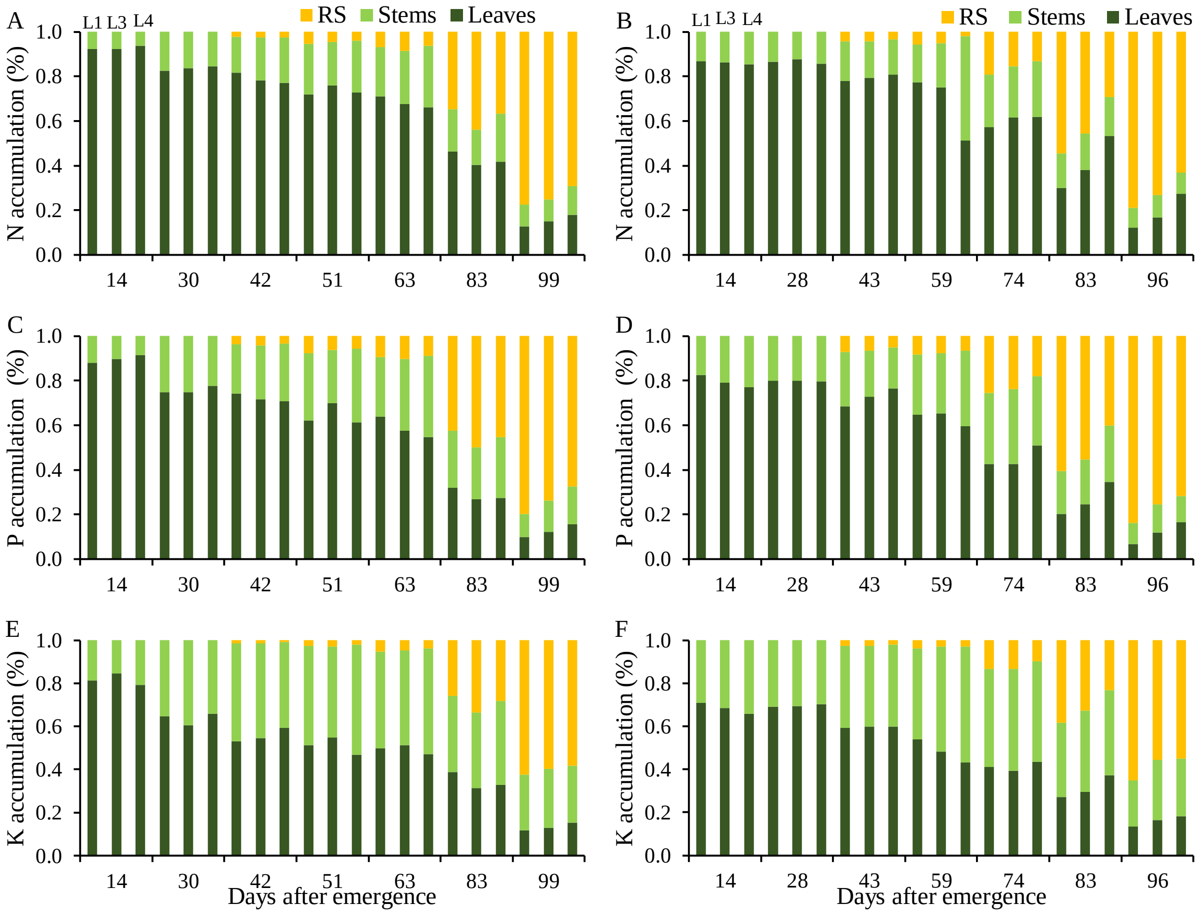


Figure 12. Proportion of nitrogen (A, B), phosphorus (C, D), and potassium accumulation (E, F) in stems, leaves, and reproductive structures (RS) of the common bean, IAC Imperador, under three irrigation levels (L1: 54%, L3: 77%, and L4: 100% ETc) in 2019 and 2020.

The IPR Campos Gerais showed a higher grain yield and, therefore, presented a higher export of primary macronutrients than the IAC Imperador (Table 3). The average yield for L1, L3, and L4 of the IPR Campos Gerais was 3.81, 4.14, and 4.70 Mg ha^{-1} in 2019 and 3.22, 3.83, and 4.03 Mg ha^{-1} in 2020, respectively. The average yield of the cultivar IAC Imperador in the L1, L3, and L4 management practices reached 3.01, 3.56, and 3.96 Mg ha^{-1} in 2019 and 2.61, 3.15, and 3.71 Mg ha^{-1} in 2020, respectively. The N, P, and K requirements to produce 1 Mg ha^{-1} of grains ranged from 53 to 86, 5.9 and 11.2, and 34 to 62 kg ha^{-1}, respectively, in both years. High differences were observed for the relative export between irrigation management practices, as observed between cultivars.

Table 3. Export, relative extraction, and macronutrients harvest index of the common bean cultivars IAC Imperador (IAC) and IPR Campos Gerais (IPR) in two years.

Irrigation management	---------------------2019---------------------						---------------------2020---------------------					
	N		P		K		N		P		K	
	IAC	IPR	IAC	IPR	IAC	IPR	IAC	IPR	IAC	IPR	IAC	IPR
Export (kg ha^{-1})												
L1	135.7	148.4	13.7	18.2	36.4	41.1	119.5	156.9	10.3	16.4	48.8	71.6
L3	121.2	145.4	12.4	17.5	32.5	38.9	129.5	154.1	13.0	20.2	59.7	74.8
L4	141.0	169.7	17.0	24.5	39.6	48.4	148.8	147.6	16.4	20.3	69.8	76.9
Relative extraction (kg Mg^{-1})												
L1	53.1	52.3	6.3	5.9	65.4	35.7	63.3	72.0	6.9	7.1	53.7	56.2
L3	56.1	47.8	7.1	5.9	70.4	33.8	63.2	76.8	7.2	8.4	51.1	53.8
L4	55.0	47.9	6.4	6.7	61.3	36.0	62.7	85.8	7.7	11.2	50.6	62.3
Nutrients harvest index (%)												
L1	84.8	74.6	72.4	80.5	18.5	30.2	72.4	67.6	56.9	71.6	34.8	39.6
L3	60.6	73.4	48.9	71.3	13.0	27.8	65.1	52.4	57.5	63.1	37.1	36.3
L4	64.7	75.4	67.1	77.9	16.3	28.6	63.9	42.7	56.9	44.9	37.1	30.6

Great differences in the harvest index of primary macronutrients were observed between cultivars and irrigation management practices, with no patterns between treatments. The only observed patterns, which were repeated in the two years, were the highest N harvest index for the IAC Imperador and the highest P and K harvest index for the IPR Campos Gerais in the severe water deficit management. The highest harvest indices were found for N and P, with minimum values above 45%, while the highest harvest index for K was 40%.

Overall, the cultivar IPR Campos Gerais showed higher total uptake of N and P than IAC Imperador, with similar values for K (Table 4). Severe water deficit reduced the uptake of N, P, and K by more than 20%. IPR Campos Gerais presented greater interannual variation in nutrient accumulation. On average, the nutrient uptake peak of IAC Imperador was anticipated by 11 days compared with the uptake peak of IPR Campos Gerais.

Table 4. Variation in the total uptake of nutrients N, P, and K as a function of cultivars, irrigation levels, and years and in the uptake peak between cultivars.

	------------------------ Amount (%)	------------------------			Uptake peak (days)
Nutrients	Cultivars	Irrigation levels	Years - L4 (Highest/Lowest)		Cultivars
	IPR / IAC	L1 / L4	IAC	IPR	IAC - IPR
N	47%	-26%	6.9%	54%	-9
P	28%	-37%	14%	43%	-13
K	-3%	-23%	29%	49%	-11

The results presented are the average of the two years and for irrigation management without a water deficit (L4).

Soil moisture was affected by water deficit in the L1 and L3 management practices in both cultivars (Figure 13). These management practices presented lower soil moisture over the cycle, especially after 25 DAE. Moreover, the effect of water deficit was more severe from the flowering stage (R_6) of the common bean crop and in 2020, in which water deficit management practices showed higher differences regarding soil moisture than the L4 management. However, the irrigation management carried out in the entire experiment during the frost night on July 7, 2019, to avoid damage to the common bean crop promoted similar soil moisture between treatments in the period from 60 to 68 DAE (Figures 13A and 13C).

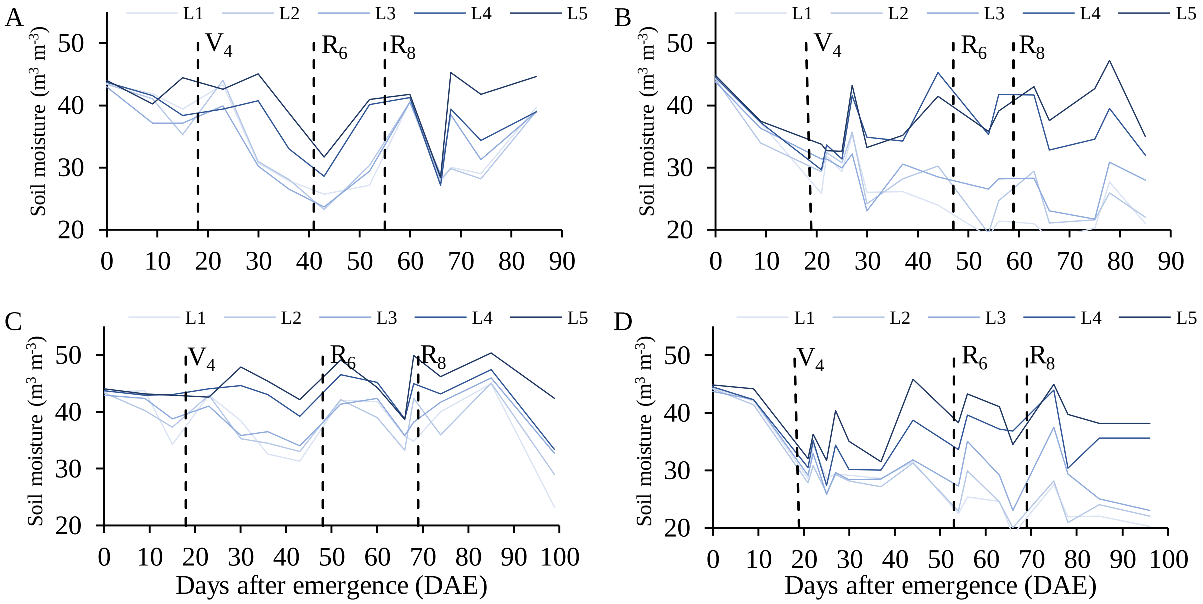


Figure 13. Variation in soil moisture as a function of time for the cultivars IAC Imperador (A and B) and IPR Campos Gerais (C and D) for five irrigation management systems in the two years (2019 and 2020). L1: 54%, L3: 77%; L4: 100% ETc

Water deficit reduced accumulations and nutrient absorption rates. This effect was more observed for the irrigation management with severe water deficit than the moderate deficit management, as the amount of nutrients extracted by the moderate water deficit and no water deficit management practices were similar in some situations. It occurred because the available water during the cultivar cycle was lower for the severe water deficit, considering the soil moisture (Figure 13). Coelho et al. (2020) observed that the severe water deficit reduced the amount of N absorbed by white oat by 80%, while the moderate water deficit led to a 35% reduction. It occurred because water is limiting plant growth, affecting the ion-root contact in the soil (Taiz et al., 2017), factors that reduce growth and absorption of nutrients by plants.

Water deficit also promoted the anticipation of nutrient absorption peak by common bean cultivars, which was dependent on the nutrient and cultivar. The water deficit in the IAC Imperador anticipated N absorption only, with an average of 5 days. Moreover, the water deficit in the IPR Campos Gerais anticipated the absorption of the three nutrients, with averages of 10 days for N, 26 for P, and 12 for K. Thus, topdressing N fertilization in the common bean crop should be anticipated for both cultivars when grown under water deficit, while topdressing K fertilization, when necessary, should be anticipated only for the IPR Campos Gerais. The reduction in the plant cycle is common when grown under some stress, such as water deficit, as observed by Coelho et al. (2020). It occurs from physiological and morphological mechanisms that try to mitigate the water deficit effect and guarantee satisfactory production for the species propagation (Jaleel et al., 2009).

Irrigation management practices have little effect on phosphate fertilization under common field conditions, as the topdressing P application is not recommended in tropical soils due to its complex dynamics and low mobility. However, knowledge of this information is essential for management under research conditions and for farmers who use fertigation as a function of the crop absorption march and more soluble phosphate sources. Furthermore, as P is a macronutrient, but has a low amount absorbed relative to the others, with values varying from 18 to 45 kg ha^{-1} in the present study, the knowledge of the P absorption peak by common bean cultivars as a function of water deficit can be useful for leaf fertilization. P supply by leaf fertilization can supply up to 10% of the crop demand and increase crop yield, as observed by Gonçalves et al. (2017), unlike nutrients such as N and K, which have a high absorbed amount and leaf fertilizations are not very useful.

In the average of the two years, the IAC Imperador absorbed 39, 46, and 28% more N, P, and K, respectively, in the management with no water deficit (L4) than the management under severe deficit (L1), while the cultivar IPR Campos Gerais showed a difference of 31, 68, and 31%, respectively. Moreover, the highest differences between L4 and L1 regarding the absorption of the three primary macronutrients occurred in the second year, regardless of the cultivar. Water deficit was more intense in the second year than in the first year, as shown by the soil moisture values between treatments (Figure 13), which led to a higher restriction on growth and accumulation of nutrients in the common bean crop due to the irrigation management practices with water deficit. Thus, N, P, and K fertilization in the common bean crop can be reduced under water deficit due to lower demand for these nutrients in this condition.

The cultivar IPR Campos Gerais, with an indeterminate growth habit, presented higher total biomass accumulation than the cultivar IAC Imperador, with a determinate growth habit, in the two years, regardless of the irrigation management. On average, the biomass accumulation at IPR Campos Gerais was 30% higher than the accumulation at IAC Imperador. It is justified by the longer cycle and the fact that the IPR Campos Gerais presents the emission of new leaves and branches after flowering, while the IAC Imperador does not present emission of vegetative structures after flowering. Filla et al. (2020) compared the biomass per plant of the cultivars IAC Imperador and IPR Campos Gerais and also observed higher values for the cultivar IPR Campos Gerais, with an average 60% higher.

The IAC Imperador showed a higher similarity in biomass accumulation between years and the cultivar IPR Campos Gerais showed higher accumulation in 2020, regardless of the irrigation management. High vegetative growth of the IPR Campos Gerais was observed in 2020 due to average temperatures up to 4 °C higher 45 days after plant emergence compared to 2019 (Figure 2). It was not observed in the IAC Imperador, which was at the full flowering stage (R_6) at 45 DAE, and higher temperatures in 2020 after flowering did not promote its biomass growth in leaves and branches, as this genotype presents a determinate growth habit.

Overall, the highest mass of plants of the IPR Campos Gerais promoted higher extraction of the macronutrients N, P, and K compared to the IAC Imperador. The IPR Campos Gerais showed higher extraction of the nutrients N, P, and K in almost all irrigation management practices, except for K in 2019. The IPR Campos Gerais extracted 27 and 42% more N and P compared to the IAC Imperador, respectively, considering the average years for the irrigation management with no water deficit (L4), whereas the average extraction for K was similar between cultivars. The interannual variation in the total N, P, and K extraction for the IAC Imperador was 7, 14, and 29% for the L4 management, respectively, while the IPR Campos Gerais showed variations of 54, 43, and 49%, respectively. It indicates that specific fertilization management practices for each cultivar are necessary, especially for K in the IAC Imperador and between years for the IPR Campos Gerais. Climate acts more in the interannual growth variation for the cultivar IPR Campos Gerais, which has an indeterminate growth habit, that is, it emits new leaves and branches throughout the cycle. In this sense, the biomass and hence the extraction of nutrients of the IPR Campos Gerais will be higher in years climatically more favorable for vegetative growth. Thus, a higher amount of nutrients is needed in the fertilization to supply the demand for this cultivar or not to reduce the availability of nutrients in the soil.

In the first year, the amount of primary macronutrients extracted by the cultivars IAC Imperador and IPR Campos Gerais followed the decreasing order: K>N>P and N>K>P, respectively, regardless of the irrigation management. In the second year, the decreasing order of extraction for the cultivars IAC Imperador and IPR Campos Gerais was N>K>P, regardless of the irrigation management. It shows the need for specific potassium fertilization management in the IAC Imperador depending on the year, as this nutrient was the most extracted by this cultivar in 2019.

The K absorption rates in the IAC Imperador were higher, although similar to those observed in the IPR Campos Gerais, which can be attributed to the early cycle of the former. Thus, the topdressing K fertilization in soils with lower available contents of this nutrient is more essential in the IAC Imperador relative to the IPR Campos Gerais, either to meet the plant demand or increase the available K content in the soil at the time of highest absorption aiming not to harm the crop development and yield. It allows specific management systems for this cultivar that are not included in standard fertilization recommendations (Ambrosano et al., 1997), enabling a more rational use of this nutrient.

The periods with the maximum nutrient absorption rates for water deficit management practices, especially the severe level (L1), were similar between cultivars, while the cultivar IPR Campos Gerais always showed absorption peaks after the cultivar IAC Imperador for L3 and L4. Absorption peaks, mainly for N and K, coincided with the two cultivars between the pre-flowering (R_5) and full flowering (R_6) stages of the common bean crop. The K absorption peak occurred, on average, 2 days before the N absorption peak for the cultivar IAC Imperador and 7 days before for the cultivar IPR Campos Gerais.

The N absorption peaks between cultivars varied from 7 to 10 days, depending on the year; for K, this variation ranged between 7 and 15 days. It demonstrates another specific management that must be carried out between cultivars, depending on their type of growth habit. Determinate growth habit cultivars, such as IAC Imperador, present an early cycle, and the maximum N and K absorption rates occurred, on average, between 7 and 14 days before the absorption peak of the cultivar IPR Campos Gerais. Thus, N and K fertilization management in early cultivars should be carried out before this management in normal cycle cultivars, when necessary, especially under conditions with no water deficit or moderate water deficit.

The N and K absorption peaks were high in the present study, with values of up to 5 kg ha^{-1} day^{-1} for N and 4.0 kg ha^{-1} day^{-1} for K. Soratto et al. (2013) evaluated the macronutrient extraction by common bean plants in soil with fertility similar to that of the present study and observed maximum N and K absorption rates of 3 kg ha^{-1} day^{-1}, a value lower than that observed here.

The maximum N and K export in the two years reached 346 and 251 kg ha^{-1}, respectively. The amount of N applied at sowing and topdressing in the common bean crop totaled 108 kg ha^{-1}, that is, considering a fertilization efficiency of 100%, the remaining 238 kg ha^{-1} were supplied by BNF and the soil. K was supplied during the cycle through mineral fertilization at a dose of 40 kg K_2O ha^{-1} (33 kg K ha^{-1}). Thus, soil provided 218 kg ha^{-1} considering 100% efficiency of potassium fertilization. Coelho et al. (2020) evaluated N absorption by white oat in the soil close to our experimental area and observed that this soil provided at least 126 kg N ha^{-1}. It demonstrates the high soil fertility in the experimental area, with the capacity to provide high amounts of nutrients to the common bean, a fact that justifies the high growth and absorption of nutrients by the crop (Table 2).

Leal et al. (2019) evaluated the nitrogen use efficiency in common bean cultivars and observed an average need for extraction of 28 kg N ha^{-1} to produce 1 Mg ha^{-1} of grains. Perez et al. (2013) evaluated nutrient extraction by the common bean crop under no-till and observed that the plant extracted approximately 30 kg ha^{-1} of N to produce 1 Mg ha^{-1} of grains. These values were 40% lower than the minimum observed in the present study, that is, 47.8 kg ha^{-1} of N to produce 1 Mg ha^{-1} of grains. The values observed in the present study in 2020 were even higher, with a minimum of 62.7 kg ha^{-1} of N to produce 1 Mg ha^{-1} of grains. It confirms the high soil fertility of the experimental area, characterizing a luxury N consumption by common bean.

The harvest index showed high variations between treatments. Overall, the harvest indices of N, P, and K were 66, 64, and 29%, respectively. Soratto et al. (2013) evaluated the harvest index of N, P, and K of common bean cultivars (Pérola and IAC Alvorada) and did not observe relevant differences between genotypes, with average values of 65, 80, and 44%, respectively. Similarly, Fageria et al. (2007) observed harvest indices for N, P, and K of 88, 90, and 61%, respectively. It indicates that the highest amount of K is left on the soil after harvesting relative to N and P, contributing to the maintenance of K contents in the soil at adequate levels for the common bean.

4.4 Conclusions

Water deficit, cultivar, and year promoted differences in the absorption dynamics of the nutrients N, P, and K by common bean plants, indicating the need for specific fertilization management practices to optimize nutrient use. On average, severe water deficit reduces uptake of N, P, and K in 26, 37 and 23%, respectively, and anticipated the N absorption peak for the IAC Imperador in 5 days and N, P, and K in 10, 26 and 12 days, respectively, for the IPR Campos Gerais. The cultivar IPR Campos Gerais, with an indeterminate growth habit and normal cycle, had a higher accumulation of biomass (+30%) and nutrients N (+47%) and P (+28%) compared to the IAC Imperador. The amount of K absorbed between cultivars was similar, but the IAC Imperador presented the highest daily K absorption rate (43% higher in no deficit irrigation management) due to its early cycle, making the practice of topdressing fertilization with this nutrient more important in this cultivar. Moreover, the K absorption peak was earlier in the IAC Imperador (-11 days in no deficit irrigation), indicating the anticipation of possible fertilization in this cultivar. Years with temperatures more favorable to the vegetative growth of common bean promoted higher N, P, and K absorption, and this effect was more pronounced in indeterminate growth habit cultivars, such as IPR Campos Gerais. Thus, monitoring the weather forecast for each growing season is important in decision-making, even in real-time, for the most appropriate establishment of the amount of nutrients required and the application time.

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CHAPTER 5 - What are the impacts of water deficit, cultivars, and years on the dynamics of nutrient absorption by common bean? Part II: Ca, Mg, and S[4]

ABSTRACT: Ca, Mg, and S supply to crops is commonly neglected in fertilization management, reducing their soil availability, and affecting yield. We aimed to explain and compare Ca, Mg, and S absorption dynamics by two common bean cultivars with contrasting growth habits as a function of water deficit severity in two years to generate more specific information for their fertilization management. A field study was set up in Southeastern Brazil, using the cultivars IAC Imperador, with a determinate growth habit and early cycle, and IPR Campos Gerais, with an indeterminate growth habit and normal cycle. These cultivars were maintained under three irrigation management systems, that is, severe (54% ETc), moderate (77% ETc), and no water deficit (100% ETc). The absorption order was Ca>Mg>S, regardless of the treatment. Overall, the severe water deficit reduced Ca, Mg, and S absorption by more than 25% compared to the management with no water deficit. The IPR Campos Gerais presents, on average, 64% higher S accumulation compared to the IAC Imperador, while the highest Ca and Mg accumulation depends on the year. Moreover, this cultivar showed a later S absorption peak (up to +23 days), and higher interannual variability in the growth and nutrient absorption due to its indeterminate growth habit compared to the IAC Imperador. These differences in the dynamics of absorption of these nutrients as a function of water deficit, cultivar, and year are essential for specific fertilizer management practices in common bean, assisting in optimizing nutrient use.

Keywords: *Phaseolus vulgaris* L.; nutrient accumulation; secondary macronutrients; water regime.

5.1 Introduction

Common bean (*Phaseolus vulgaris* L.) is one of the main foods responsible for global food security related to its easy access by the population, low cost, and high nutritional value (Nassary et al., 2020), besides generating income for many farmers. However, the average crop yield is low in tropical regions due to the climate or technological cultivation variability, with a value close to 1,000 kg ha^{-1} in Brazil, for example (Conab, 2021). Therefore, the evaluation and recommendation of agricultural management systems to increase common bean yield in tropical regions are essential to increase the food supply and income of farmers.

One of the main management practices to increase common bean yield is

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[4] This chapter was submitted to the Journal of Plant Nutrition and is under peer review process for publication

fertilization, regardless of the technological level and climate conditions (Wang et al., 2020). Studies have shown that adequate fertilization increases common bean yield by more than 20% (Domingues et al., 2014; Canizella et al., 2017; Nascente et al., 2017). N, P, and K are the three most required plant macronutrients for common bean fertilization in tropical regions, with total amounts during the common bean cycle reaching up to 110 kg N ha^{-1}, 90 kg P_2O_5 ha^{-1}, and 100 kg K_2O ha^{-1} (Ambrosano et al., 1997). Fertilization programs adopted by producers often include only these three macronutrients due to their higher demand, and the application of the macronutrients Ca, Mg, and S are neglected, which can lead to a deficiency of these nutrients and reduce common bean yield.

Ca, Mg, and S fertilization in different crops is often neglected because these nutrients are provided by soil amendments, such as lime and gypsum, and fertilizers that have these nutrients as secondary sources (Cakmak and Yazici, 2010; Wang et al., 2020). However, farmers often use more concentrated sources of NPK fertilizers that do not have Ca, Mg, and S in their composition to reduce costs. Also, the frequency of application of soil amendments may not be sufficient to supply these nutrients in adequate amounts. Thus, these nutrients may reach low availability in the soil over the growing seasons, especially in more technified fields that have higher yields and export. Satisfactory yields are reached by common bean from the application of 30 kg S ha^{-1} for values above 2.0 Mg ha^{-1}, with a soil Mg content above 5 mmol$_c$ dm^{-3} (Ambrosano et al., 1997). In this sense, studies on the absorption dynamics of these nutrients in the common bean are necessary to establish more specific fertilization recommendations, determining the best doses and times of application.

Factors such as water deficit, cultivar, and year can affect the amounts of absorbed nutrients and interfere with Ca, Mg, and S absorption and export rates (Soratto et al., 2013). The water deficit in growing seasons with irregular rainfall and under deficient irrigation conditions can affect common bean growth and yield and, consequently, nutrient absorption and export, given that water limits plant growth and is the means for the ion-root contact (Taiz et al., 2017). Common bean is also grown during the winter in tropical regions such as Brazil due to more favorable climate conditions and to avoid rainfalls at harvest (Lemos et al., 2015). Irrigation is essential for growing common bean during that season, as most areas in tropical regions have a dry winter. In this sense, farmers have managed irrigation considering a water deficit due to water scarcity in many regions and as an attempt to reduce production costs, which can affect the nutrient absorption dynamics in the common bean.

Moreover, there is a high number of common bean cultivars available for farmers. The cultivars present a determinate growth habit and early cycle (Type I) or an indeterminate growth habit and normal or late cycle (Types II and III) (Lemos et al., 2015). These differences may promote variations in nutrient demand, accumulation rate, and export. Furthermore, these cultivars may show variations in growth and nutrient demand in different years, which may be a genotype-dependent effect. Therefore, the evaluation of the effect of water deficit on common bean cultivars with contrasting growth habits in more than one year is essential to establish more specific fertilization recommendations with Ca, Mg, and S for common bean.

This study hypothesized that (i) water deficit reduces Ca, Mg, and S absorption in common bean cultivars; and (ii) cultivars with contrasting growth habits and years promote differences in Ca, Mg, and S absorption dynamics. Thus, the aim was to explain and compare the accumulation dynamics of macronutrients Ca, Mg, and S of two common bean cultivars with contrasting growth habits as a function of water deficit in two years.

5.2 Material and methods

The experiment was carried out in the winter growing season of 2019 and 2020 at the São Paulo State University (Unesp), School of Agricultural and Veterinarian Sciences, Jaboticabal, São Paulo, Brazil, close to the geographical coordinates 21°14′44″ S and 48°17′00″ W, with an altitude of 545 m. The regional climate, according to the Köppen classification, is Aw, that is, a tropical climate with a dry winter, summer rains, an average annual temperature of 22 °C, and average annual precipitation of 1,425 mm.

The soil in the experimental area is classified as an Oxisol (Soil Survey Staff, 2014). Three undisturbed and disturbed soil samples were collected for the physical characterization of the experimental area before sowing the experiment in 2019 (Table

1). Fifteen simple soil samples were collected 30 days before sowing the experiment in each year, forming a composite sample for fertility analysis (Table 2).

Table 1. Soil physical attributes of the experimental area.

Layer (m)	Ds $g\ cm^{-3}$	Moisture FC $m^3\ m^{-3}$	Moisture PWP $m^3\ m^{-3}$	Clay $g\ kg^{-1}$	Silt $g\ kg^{-1}$	Sand $g\ kg^{-1}$
0.00–0.20	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 of the experimental area in the 2019 and 2020.

Layer	pH	H+Al	Al	K	Ca	Mg	SB	CEC	V
(m)	$CaCl_2$	---------------------------------			mmol$_c$ dm^{-3}			---------------------------------	%
					2019				
0.00–0.20	5.7	26	0	5.7	47	12	64.7	91	71
0.20–0.40	5.7	26	0	5.7	39	10	53.7	80	67
Layer	OM	Presin	S	B	Cu	Fe	Mn	Zn	
(m)	g dm^{-3}	---------------------------------			mg dm^{-3}			---------------------------------	
0.00–0.20	25	59	8	0.77	6.6	31	47.3	3.5	
0.20–0.40	21	32	13	0.56	6.2	24	34.4	2.0	
					2020				
Layer	pH	H+Al	Al	K	Ca	Mg	SB	CEC	V
(m)	$CaCl_2$	---------------------------------			mmol$_c$ dm^{-3}			---------------------------------	%
0.00–0.20	5.9	25	0	5.1	50	14	69.1	94	74
0.20–0.40	5.5	28	0	5.2	33	10	48.2	76	63
Layer	OM	Presin	S	B	Cu	Fe	Mn	Zn	
(m)	g dm^{-3}	---------------------------------			mg dm^{-3}			---------------------------------	
0.00–0.20	24	66	5	0.46	4.5	16	25.8	3.2	
0.20–0.40	19	49	7	0.39	4.4	11	24.5	1.6	

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

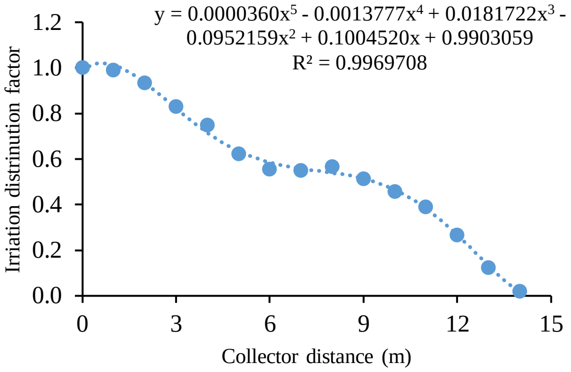
Common bean was sown on May 7, 2019, and May 18, 2020. Two common bean cultivars from the ‘Carioca’ commercial group, with contrasting growth habits, were used. The cultivar IAC Imperador has a determinate growth habit (Type I), erect architecture, and an early cycle of 75 days (Chiorato et al., 2012). The cultivar IPR Campos Gerais has an indeterminate growth habit (Type II), erect architecture, and a normal cycle of 90 days (Moda-Cirino et al., 2012). The cultivars were mechanically sown to obtain a density of 240,000 plants ha^{-1}, with an inter-row spacing of 0.45 m. The seeds were treated before sowing with pyraclostrobin (5 g ai ha^{-1}) + thiophanate-methyl (45 g ai ha^{-1}) + fipronil (50 g ai ha^{-1}), using the commercial product Standak® Top, and inoculated with *Rhizobium tropici* (StarFix® Feijão) for biological nitrogen fixation, using the dose recommended.

Common bean was sown in an area previously cultivated with corn, using a seed-cum-fertilizer drill intended for no-tillage. The corn hybrid P4285VYHR was sown in October in the two years, with an inter-row spacing of 0.90 m and 75,000 plants ha^{-1}. Limestone with a total neutralizing power of 95 was applied 30 days before corn sowing in the two years at a dose of 1.5 Mg ha^{-1}. The limestone was incorporated into the soil with a plowing harrow operation (0.00–0.20 m) and two leveling harrow operations. The amount of corn straw (dry matter) on the soil was estimated at common bean sowing and reached 7,622 ± 272 kg ha^{-1} in 2019 and 9,052 ± 367 kg ha^{-1} in 2020, while the average grain yield reached 11,200 ± 134 kg ha^{-1} in 2019 and 11,800 ± 210 kg ha^{-1} in 2020.

The sowing fertilization of the common bean crop was carried out according to the soil analysis (Table 2) and recommendation of Ambrosano et al. (1997) by applying a dose of 200 kg ha^{-1} of the formulation 04–20–20 in the two years, supplying 8 kg ha^{-1} of N, 40 kg ha^{-1} of P_2O_5, and 40 kg ha^{-1} of K_2O. Topdressing fertilization was carried out at the $V_{4\text{–}3}$ stage, characterized by the third trifoliate leaf fully expanded (Fernández et al., 1985), and consisted of the application of a dose of 100 kg ha^{-1} of N in both years, with urea as source (Ambrosano et al., 1997). The topdressing fertilization was carried out at 19 and 21 days after emergence (DAE) of the common bean crop in 2019 and 2020, respectively, in a continuous strip at 0.10 m from the sowing row. A 10-mm irrigation depth was applied to all treatments in the two years after topdressing fertilization to avoid the effect of different volatilization rates between the irrigation levels. This 10-mm irrigation depth was used because it is a minimum value that does not promote losses of urea by volatilization (Espindula et al., 2021), not significantly interfering with the applied treatments. The control of weeds, pests, and diseases was carried out when necessary, using products registered for the crop.

The experimental design used was strip-plot. The study factors were five irrigation levels and two common bean cultivars, with four replications. Each subplot had 15 rows of common bean, with a dimension of 6.75 m long and 2.4 m wide. The first row of common bean at each end and the initial 50 cm of the central rows were considered as borders. Six out of the remaining 13 cultivation rows were used to estimate yield and the other seven for destructive analysis.

The line-source sprinkler system was used, allowing the distribution of the irrigation water with variable application depths as the treatment moves away from the central sprinkler line (Hanks et al., 1976). A field test enabled the definition of the distribution fractions of the sprinkler precipitation (Figure 1). In model fit, the regression that generated the highest precision (R^2) was used, aiming to estimate the most accurate irrigation distribution factor possible in each treatment. Senninger 4023-2 sprinklers and ¾″ M 08Qx05 nozzles were used spaced every 6 m on the central line. The water application intensity of the sprinklers was measured in the field in tests with collectors placed at 1 m from each other up to the limit distance of water application by the sprinklers in a line perpendicular to the irrigation line, with four replications.



Distance (m)	Treatment	Irrigation distribution factor
0.00–2.40	L5	1.002 (132%)
2.40–4.80	L4	0.754 (100%)
4.80–7.20	L3	0.584 (77%)
7.20–9.60	L2	0.532 (70%)
9.60–12.00	L1	0.407 (54%)

Figure 1. Sprinkler irrigation distribution factor as a function of the distance from the irrigation line, with sprinklers spaced at 6 m from the line, obtained in field tests. Service pressure: 250 kPa

For study purposes, the treatments consisted of five irrigation levels (L1, L2, L3, L4, and L5) determined after establishing the water application regression by the sprinkler line (Figure 1). Irrigation level L4 was used as a standard, receiving 100% of the common bean water requirement. Irrigation level L5 applied excess water, with 132% of the common bean water requirement, while L3, L2, and L1 provided 77, 70, and 54% of the water requirement, respectively. Irrigation levels L1, L3, and L4 and two common bean cultivars were used to evaluate the water deficit effect on Ca, Mg, and S absorption and extraction in the common bean. Irrigation level L4 was used as a standard, providing 100% of the common bean water requirement, while L3 and L1 were considered as the moderate and severe water deficits, providing 77 and 54% of the water requirement, respectively.

The irrigation management was carried out based on the crop water demand, according to the FAO 56 method, using climate data obtained daily from an automated agrometeorological station located 1,500 m from the experiment. The reference evapotranspiration (ETo) was estimated daily using the FAO 56 method (Allen et al., 1998). The evapotranspiration of the common bean crop (ETc) was calculated using the product of ETo by the crop coefficients (Kc) (Allen et al., 1998). The used Kc values 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 from 1.15 to 0.35 (maturation). For the Kc range between 0.40 and 1.15, the values were interpolated daily up to the maximum value (1.15). The daily increment was calculated as the ratio of the difference between the Kc range (1.15 – 0.40) and the number of days between the initial Kc (0.40) and maximum Kc (1.15).

Irrigation was carried out when the water deficit in the area was equal to 18 mm. This water depth was calculated according to the soil physical attributes (Table 1) and the common bean crop. The calculation considered an effective root depth of 0.25 m and a water availability factor of 0.40 (Allen et al., 1998). Two water depths of 15 mm were applied for the plant emergence considering a uniform initial stand in all treatments.

The average maximum and minimum temperatures during the 2019 experimental period were 27.8 and 13.9 °C, respectively, with accumulated precipitation of 48.7 mm (Figure 2A). Low temperatures were observed in 2019, especially from July 5 to 8 and July 16 and 18. The minimum temperature reached 3.3 °C on July 7, 2019, which caused frost in the experimental area. The number of trifoliate leaves reached by the frost in each cultivar was counted, with an average of 10% in the cultivar IAC Imperador and 12% in the cultivar IPR Campos Gerais. The average maximum and minimum temperatures during the experimental period in 2020 were 28.4 and 13.9 °C, respectively, with accumulated precipitation of 35 mm (Figure 2C). Minimum temperatures below 5 °C were not observed in 2020.

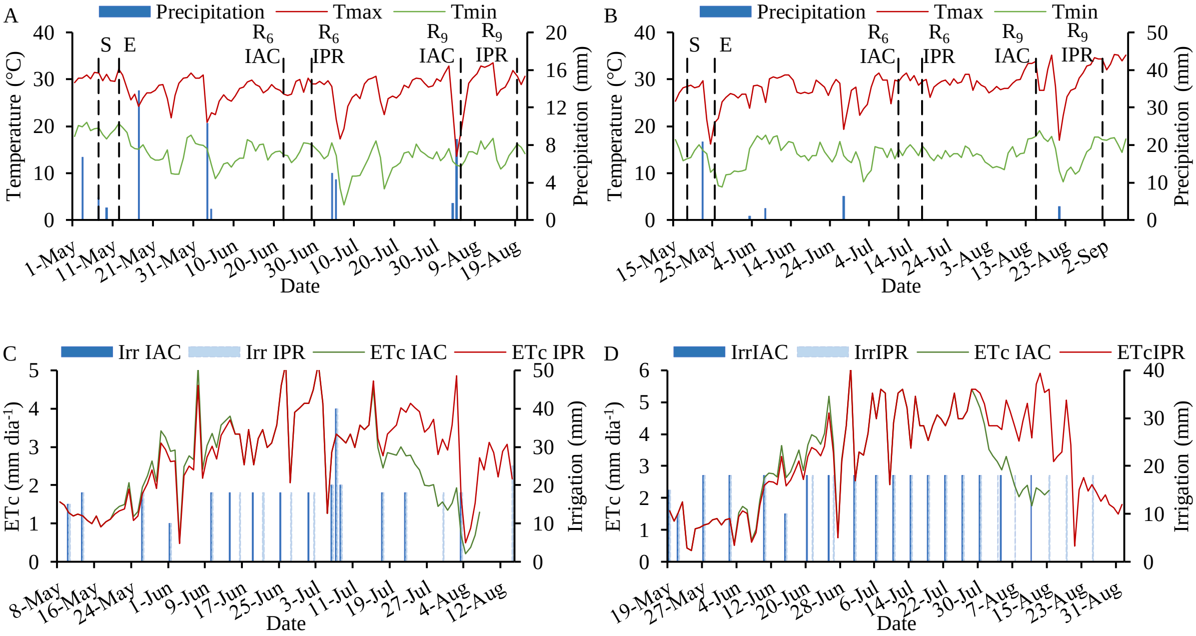


Figure 2. Daily maximum temperature, minimum temperature, precipitation (A and B), crop evapotranspiration, and irrigation (C and D) of common bean cultivars during the experimental period from May 7, 2019, to August 19, 2019 (A and C) and May 18 to September 1 (B and D). S: sowing; E: emergence; R_6: full bloom; R_9: physiological maturity; Irr: irrigation; ETc: crop evapotranspiration.

Irrigation was activated during the dawns of July 6, 7, and 8 as an attempt to control the frost. The water depth was constant for all treatments and 20, 40, and 20 mm were applied on July 6, 7, and 8, respectively. For calculation purposes, 30 mm of irrigation were considered on these days for all treatments.

Soil moisture was determined weekly at three points per subplot of the irrigation levels L1, L3, and L4 in the 0.00–0.20 m layer using the time domain reflectometry (TDR) technique (Fellner-Feldegg, 1969). The equipment calibration was carried out before the experiment was set up in the soil of the experimental area. For this, 25 points were randomly chosen in the area for the determinations using the equipment, and one undisturbed soil sample was collected at these sites for determining the actual soil moisture (m^3 m^{-3}), generating a regression between the observed values and the values measured on the equipment. This regression was used to correct the soil moisture during the experiment.

The absorption march of the secondary macronutrients Ca, Mg, and S was performed to evaluate the water deficit effect on the nutrient accumulation and extraction from bean cultivars. For this, 16 plants (four per replication) were collected from irrigation levels L1, L3, and L4 (54, 77, and 100% of the water requirement, respectively) for both cultivars. The collections of the early-cycle cultivar IAC Imperador were carried out at 12, 24, 35, 46, 59, 66, and 85 days after emergence (DAE) in 2019 and 14, 28, 37, 50, 61, 71, and 80 DAE in 2020. Additionally, the collections of the normal-cycle cultivar IPR Campos Gerais were carried out at 14, 30, 42, 51, 63, 83, and 99 DAE in 2019 and 14, 28, 43, 59, 74, 83, and 96 DAE in 2020. The collected material was separated into leaves, stems, and reproductive structures, as performed by Soratto et al. (2013). Each evaluation estimated the amount of nutrients extracted per hectare using the average population of the plots at the collection time and the dry matter of each sample partition. Also, Ca, Mg, and S contents in the grains of each treatment were analyzed at harvest time. The export of macronutrients by grains (kg ha^{-1}) was estimated by the product between the nutrient content and the grain yield of each treatment.

All plant materials were washed with running water, deionized water, 1% aqueous detergent solution, and deionized water again. Subsequently, the plant materials were dried in a forced-air circulation oven at 65 °C until constant weight. The samples were ground in a Willey mill and Ca, Mg, and S contents were determined following the methodology proposed by Malavolta et al. (1997). Each ground sample was divided into triplicates to analyze Ca, Mg, and S contents.

Polynomial regressions ($p<0.05$) were tested to model the total biomass and macronutrient accumulation of common bean cultivars grown under severe (L1), moderate (L3), and no water deficit (L4) as a function of time. The daily rate of total accumulation of macronutrients absorbed by common bean cultivars was obtained by the first derivative of the equations adjusted for the accumulation of each treatment. The percentage of macronutrients accumulated in the leaves, stems, and reproductive structures was calculated for each period of evaluation and treatment. The macronutrient harvest index (%) was calculated by the ratio between the amount of nutrient accumulated in the grains (kg ha^{-1}) and the amount of nutrient accumulated in the entire shoot (kg ha^{-1}), multiplied by 100.

5.3 Results and discussion

Water deficit, especially the severe, reduced biomass accumulation in different plant parts of the cultivar IAC Imperador in both years (Figure 3). The total biomass accumulation was 11 and 26% lower under the moderate (L3) and severe (L1) water deficits than the management with no water deficit (L4) in 2019 and 25 and 33% lower under the moderate and severe water deficits in 2020, respectively. The total biomass accumulation was similar for L1 and L3 between years, with a higher value for L4 in 2020 (19% higher). The highest biomass for L4 irrigation level of the IAC Imperador in 2020 was mainly due to the highest biomass accumulations in stems and leaves.

Water deficit reduced Ca absorption of the IAC Imperador in both years (Figure 4). The severe and moderate water deficits reduced the total Ca accumulation by 24 and 13% in 2019 and 28 and 10% in 2020, respectively. The highest Ca accumulation was observed in 2019, with an average of 22% higher considering all irrigation levels. Only the severe water deficit significantly reduced the total Mg accumulation in 2019, with a value 29% lower than the average of L3 and L4; in 2020, both water deficits reduced, on average, 23% of the total Mg accumulation. A higher Mg accumulation was observed in 2019 for all treatments, with an average 75% higher than 2020.

S accumulation was also influenced by water deficit, with a reduction of 33 and 13% in the accumulated total for L1 and L3 irrigation levels, respectively, relative to L4 in 2019 (Figure 4). Reductions in S accumulation for L1 and L3 were 49 and 37% compared to L4 in 2020, respectively. L1 and L3 irrigation levels showed higher S accumulations in 2019, with a similarity in the accumulated total between years.

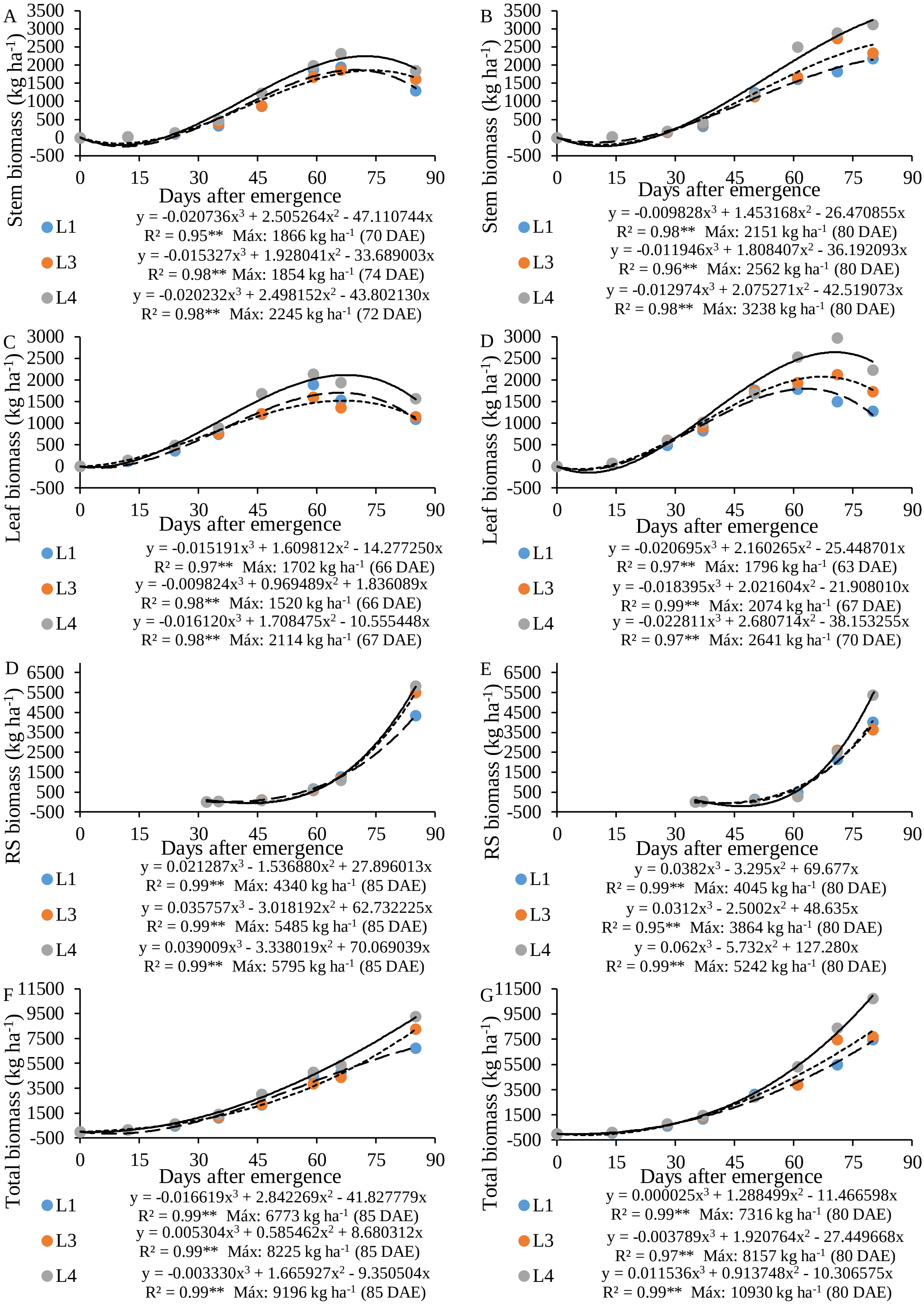


Figure 3. Stem (A, B), leaf (C, D), reproductive structure (RS) (E, F), and total biomass accumulation (G and H) of the common bean cultivar IAC Imperador under

three irrigation levels (L1: 54% ETc, L3: 77% ETc, and L4: 100% ETc) in 2019 and 2020. **(p<0.01).

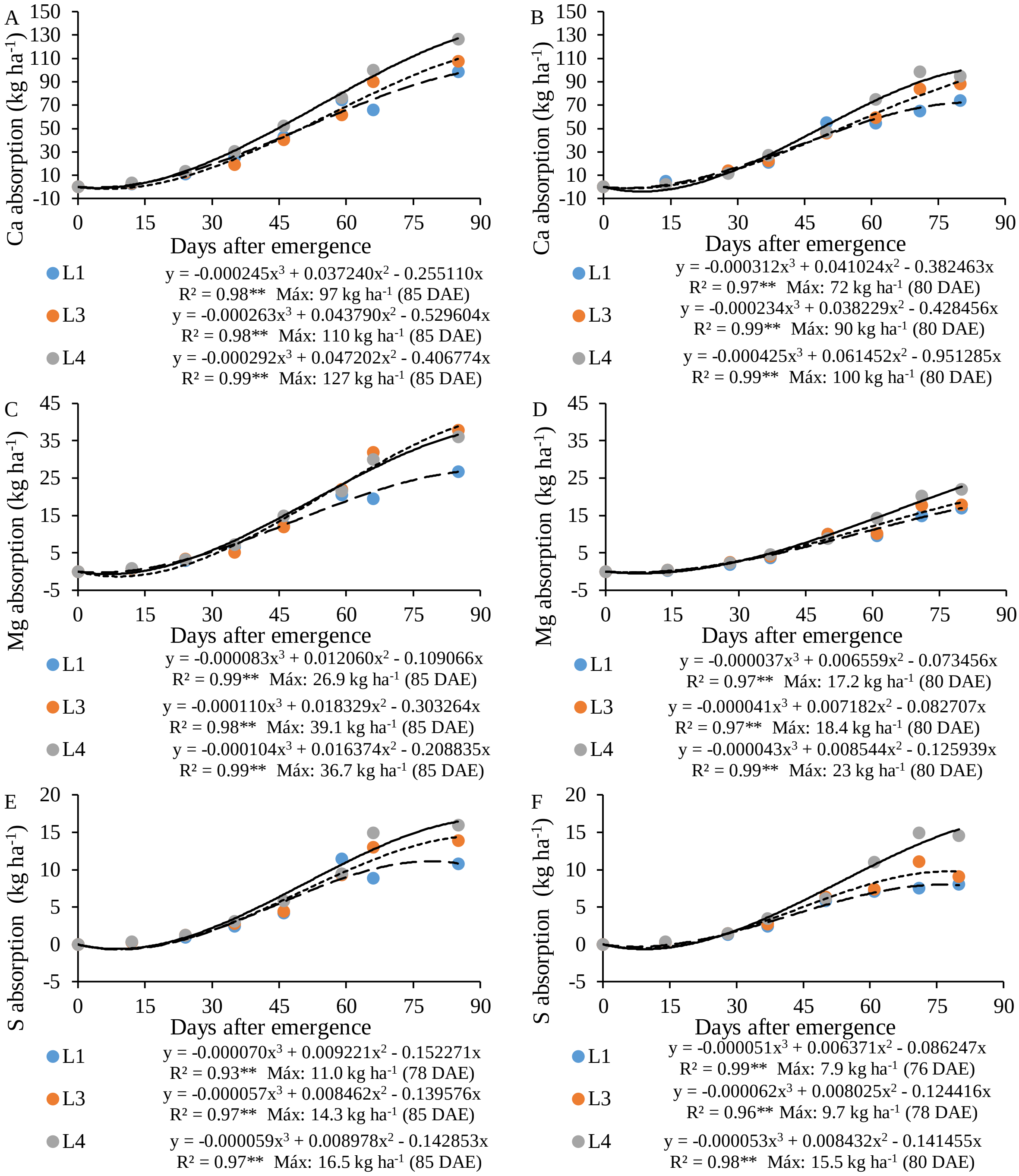


Figure 4. Calcium (A, B), magnesium (C, D), and sulfur accumulation (E, F) in the common bean cultivar IAC Imperador under three irrigation levels (L1: 54% ETc, L3: 77% ETc, and L4: 100% ETc) in 2019 and 2020. **(p<0.01).

The maximum Ca absorption rate of the IAC Imperador was between 42 and 56 DAE in both years (Figure 5). Ca absorption peak in the severe water deficit management was anticipated, on average, by 7 days relative to L3 and L4 irrigation levels. Furthermore, the maximum absorption rate was higher in L4 and L3. The peak absorption rate for Mg was between 47 and 76 DAE in both years, with a later peak in 2020 in the three irrigation levels. L1 irrigation level had an absorption peak anticipated by 5 days in 2019 and 15 days in 2020 relative to L4. Moreover, L3 presented a time absorption peak similar to L1 in 2020. The peak of S absorption rate was anticipated, on average, by 12 days for L1 compared to L4 in both years.

Leaf Ca and Mg contents were similar for both years between irrigation levels, except for Mg content in 2019, with higher average values for L1 (Figure 6). In addition, leaf Ca and Mg contents were lower in 2020, especially at the end of the common bean cycle. S presented similar values between irrigation levels and between years.

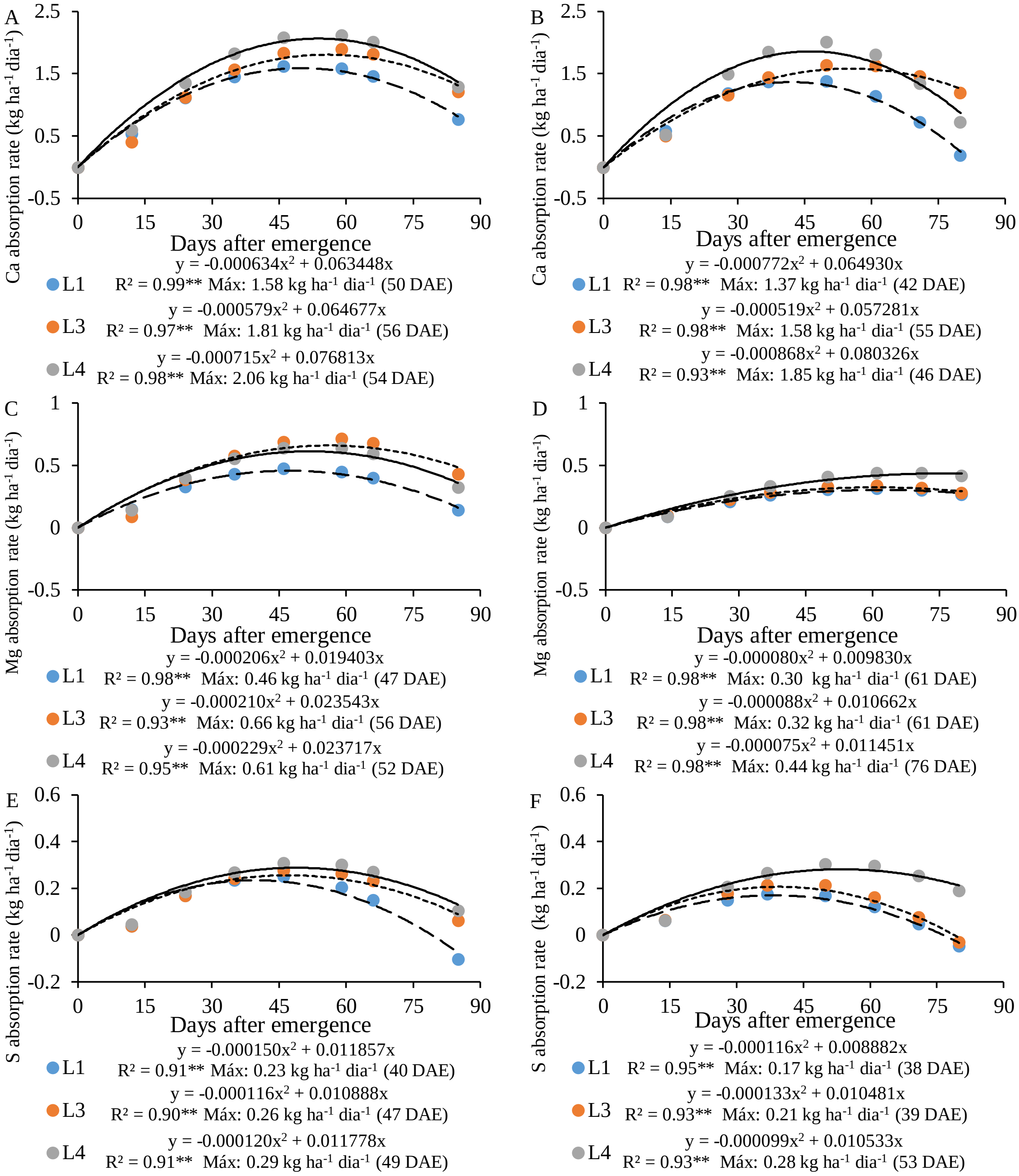


Figure 5. Daily calcium (A, B), magnesium (C, D), and sulfur absorption rate (E, F) in the common bean cultivar IAC Imperador under three irrigation levels (L1: 54% ETc, L3: 77% ETc, and L4: 100% ETc) in 2019 and 2020. **($p<0.01$).

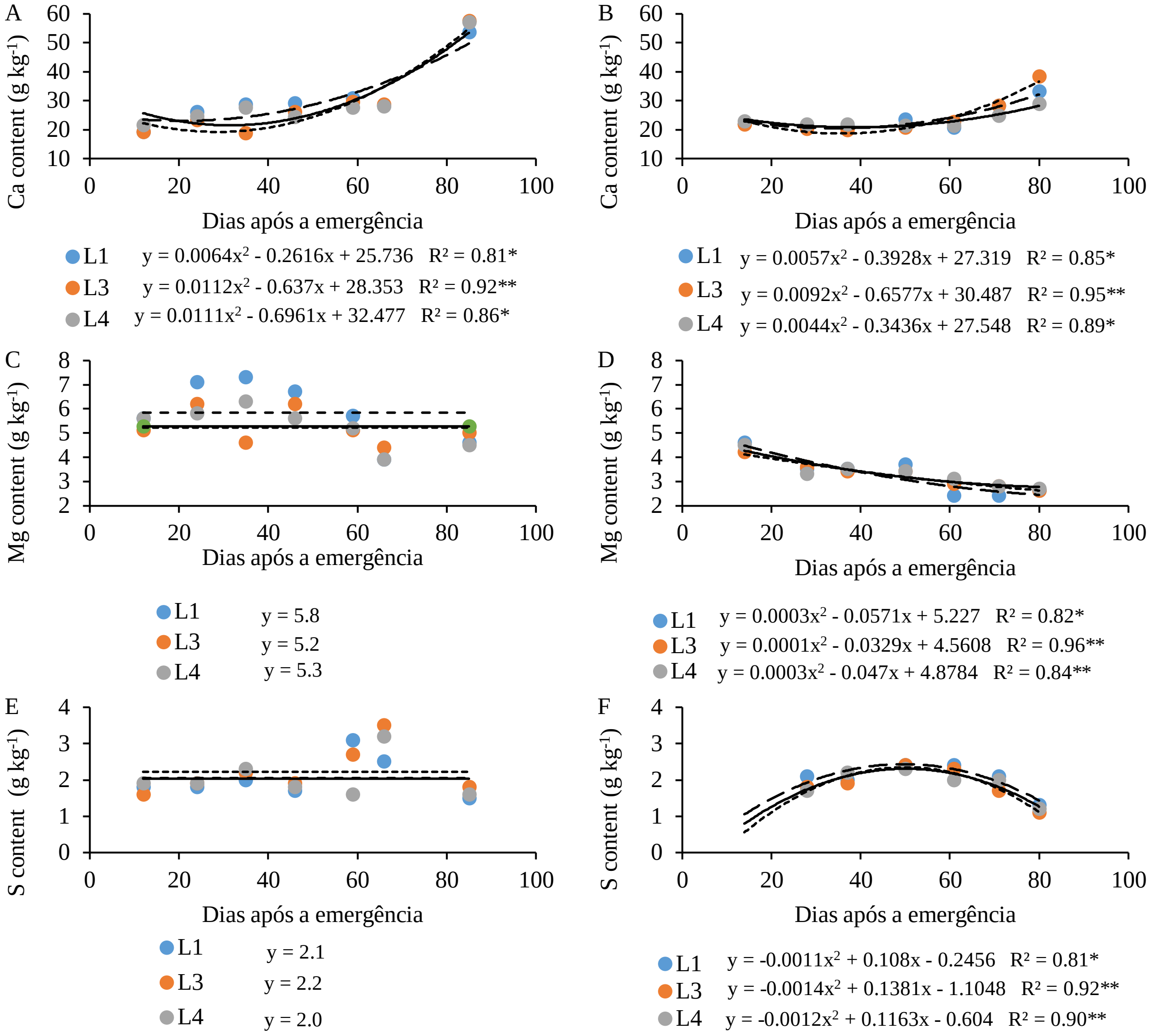


Figure 6. Leaf calcium (A, B), magnesium (C, D), and sulfur contents (E, F) in the common bean cultivar IAC Imperador under three irrigation levels (L1: 54% ETc, L3: 77% ETc, and L4: 100% ETc) in 2019 and 2020. *($p<0.05$); **($p<0.01$).

A similarity was observed between irrigation management systems in the proportion of each plant part regarding the total Ca, Mg, and S accumulation (Figure 7). The last evaluation for the IAC Imperador showed that the highest amount of Ca accumulated in the plant remained in the leaves (60 to 70%) in both years, while only approximately 20% was accumulated in the reproductive structures. A higher variation in the total Mg and S accumulation was observed between years, with the first year showing the highest relative amount of nutrients accumulated in the reproductive structures compared to the second year. About 70 to 80% and 40 to 50% of the Mg was accumulated in the reproductive structures in 2019 and 2020, respectively. Similarly, from 70 to 80% and 40 to 55% of the total accumulated S were found in the reproductive structures in 2019 and 2020, respectively.

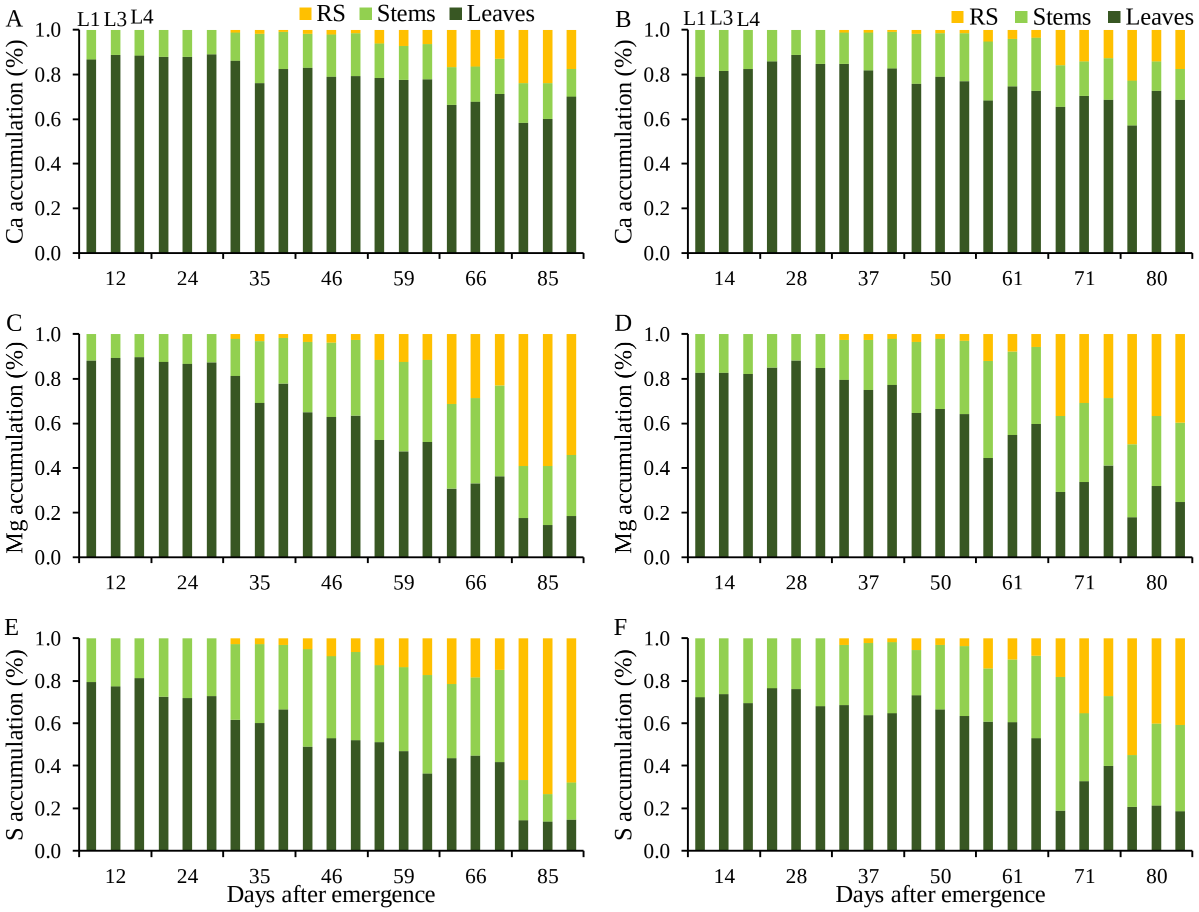


Figure 7. Calcium (A, B), magnesium (C, D), and sulfur accumulation proportion (E, F) in stems, leaves, and reproductive structures (RS) of the common bean cultivar IAC Imperador under three irrigation levels (L1: 54%, L3: 77%, and L4: 100% ETc) in 2019 and 2020.

The L1 irrigation management reduced the total biomass accumulation by 21% in the IPR Campos Gerais compared to the L4 management in 2019, reaching a 17% reduction in L3 (Figure 8). The reductions in total biomass accumulation for L1 and L3 reached 35 and 18% in 2020, respectively. Biomass accumulation in all irrigation levels and plant parts was higher in 2020, with increases in the total biomass of 8, 32, and 32% for L1, L3, and L4, respectively, relative to 2019.

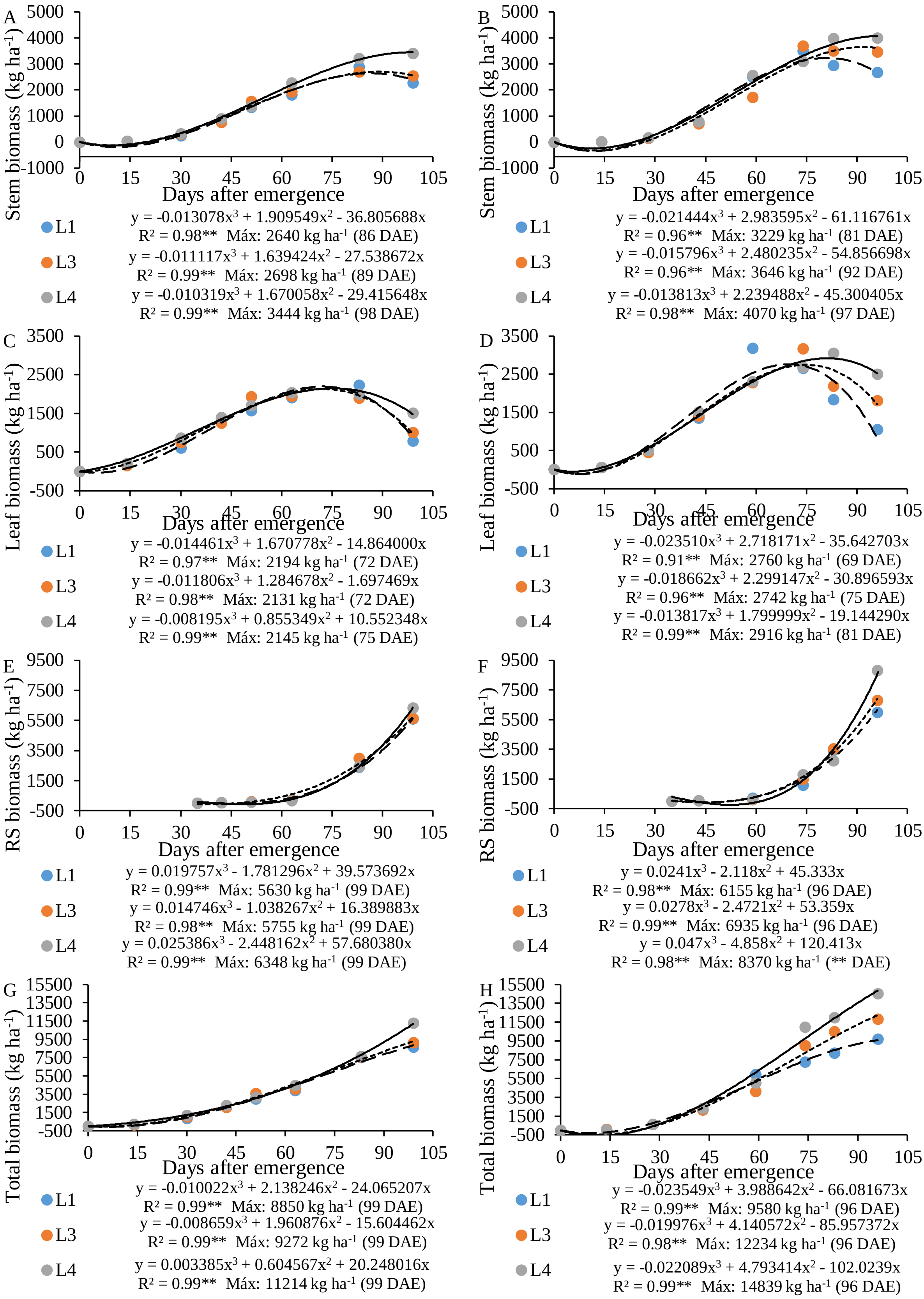


Figure 8. Stem (A, B), leaf (C, D), reproductive structure (RS) (E, F), and total biomass accumulation (G and H) in the common bean cultivar IPR Campos Gerais

under three irrigation levels (L1: 54% ETc, L3: 77% ETc, and L4: 100% ETc) in 2019 and 2020. **($p<0.01$).

Water deficit also affected the Ca absorption of the common bean cultivar IPR Campos Gerais in both years (Figure 9). Overall, the moderate and severe water deficits reduced the total Ca accumulation by 12% in 2019, reaching 41 and 24% for L1 and L3 in 2020, respectively. In 2020, the highest and lowest accumulations were observed in L4 and L1, respectively, with similar accumulated values in L3. Mg presented no relevant differences between irrigation levels in 2019, with an average total accumulation of 22.3 kg ha^{-1}. In 2020, L1 and L3 reduced by 41 and 27% the accumulated total compared to L4, respectively. The highest Mg accumulation was observed in 2020 for L3 and L4, with a similarity between years for L1.

The severe water deficit reduced, on average, 25% of the S accumulation for L3 and L4 irrigation levels in 2019 (Figure 9). In 2020, the reduction in accumulation for L1 and L3 was 57 and 42%, respectively, relative to L4. The comparison between years showed a relevant difference only for L4, with a higher S accumulation in 2020.

The maximum Ca absorption rate was similar between irrigation levels in 2019, with the management systems with the highest irrigation levels showing higher absorption peaks in 2020 (Figure 10). Also, the absorption peak for L1 was anticipated, on average, by 14 days relative to L4. The Mg absorption rate was similar between irrigation levels in 2019, but L4 presented the highest values in 2020. On average, L1 irrigation level anticipated the Mg absorption peak by 26 days in both years. Similarly, anticipation in the S absorption peak was observed in both years relative to L1. Furthermore, higher absorption rates were observed in 2020.

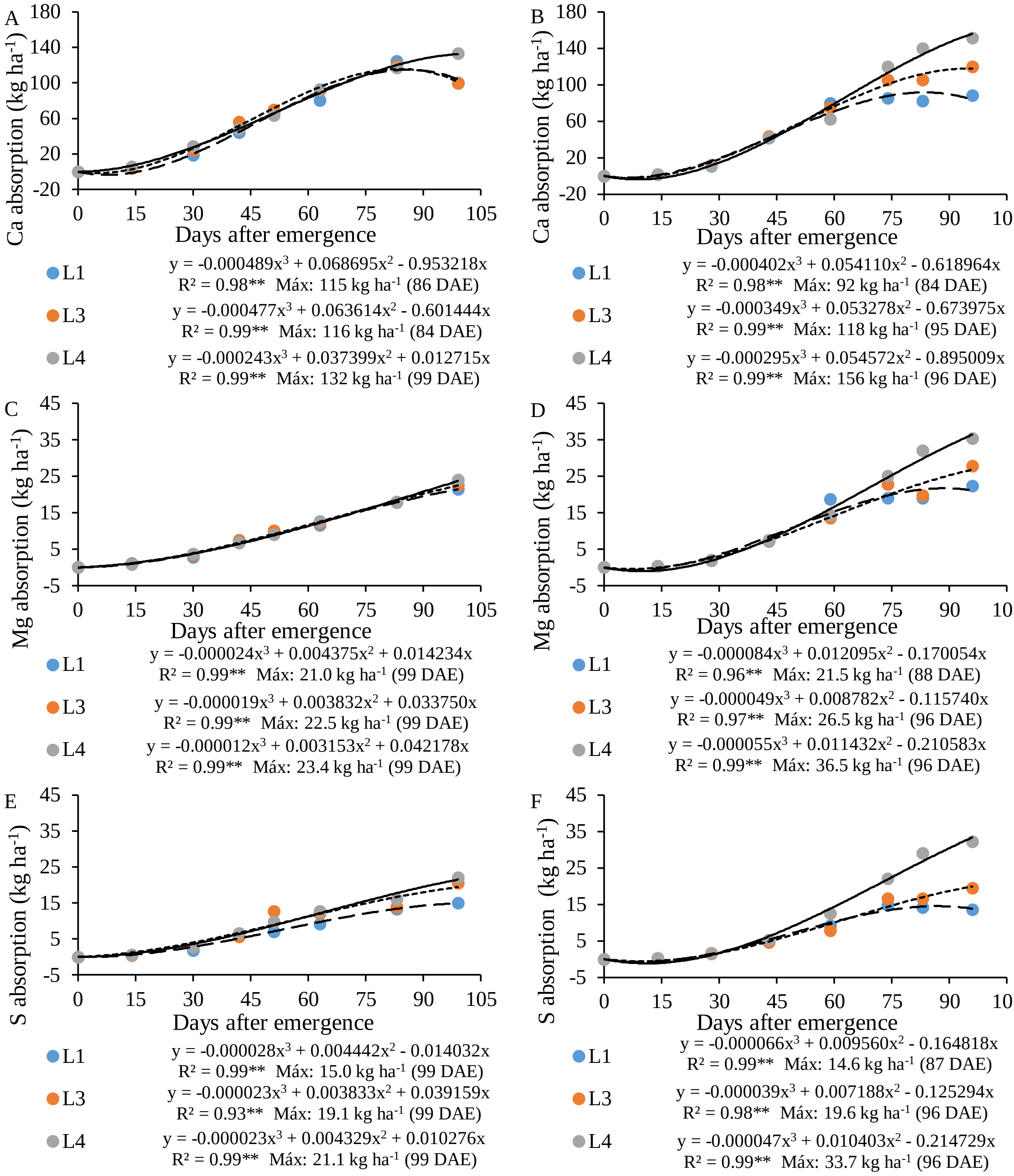


Figure 9. Calcium (A, B), magnesium (C, D), and sulfur accumulation (E, F) in the common bean cultivar IPR Campos Gerais under three irrigation levels (L1: 54% ETc, L3: 77% ETc, and L4: 100% ETc) in 2019 and 2020. **($p<0.01$).

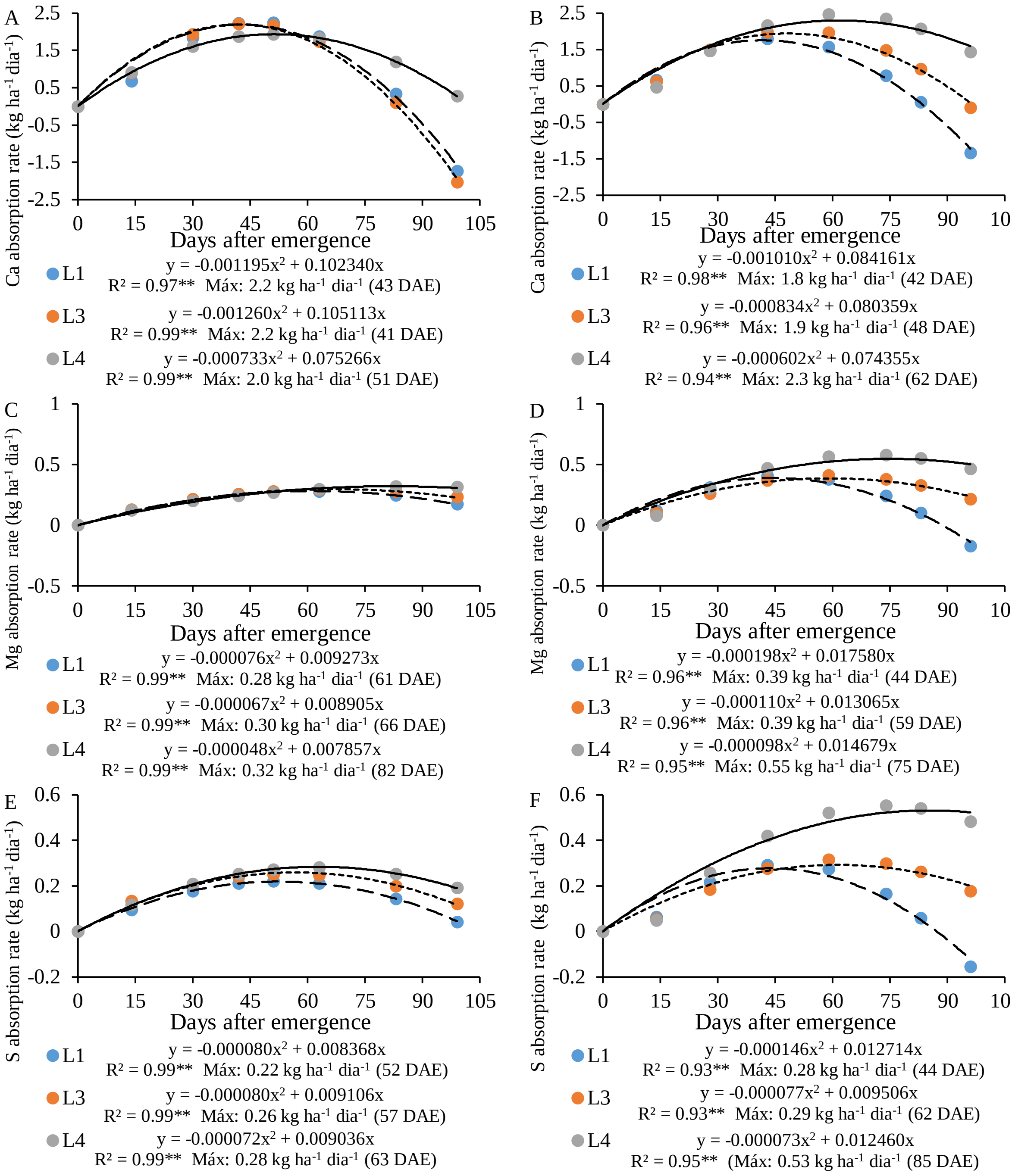


Figure 10. Daily calcium (A, B), magnesium (C, D), and sulfur absorption rate (E, F) in the common bean cultivar IPR Campos Gerais under three irrigation levels (L1: 54% ETc, L3: 77% ETc, and L4: 100% ETc) in 2019 and 2020. **(p<0.01).

Leaf Ca and Mg contents for both years were similar between irrigation levels, except for Ca content in 2020, which presented higher average values for L1 and L3, especially in the last evaluations over the crop cycle (Figure 11). In general, leaf Ca and Mg contents were lower in 2020 for all irrigation levels. Moreover, S showed similar values between irrigation levels in both years. Only L3 showed an average value higher than the other irrigation levels in 2019.

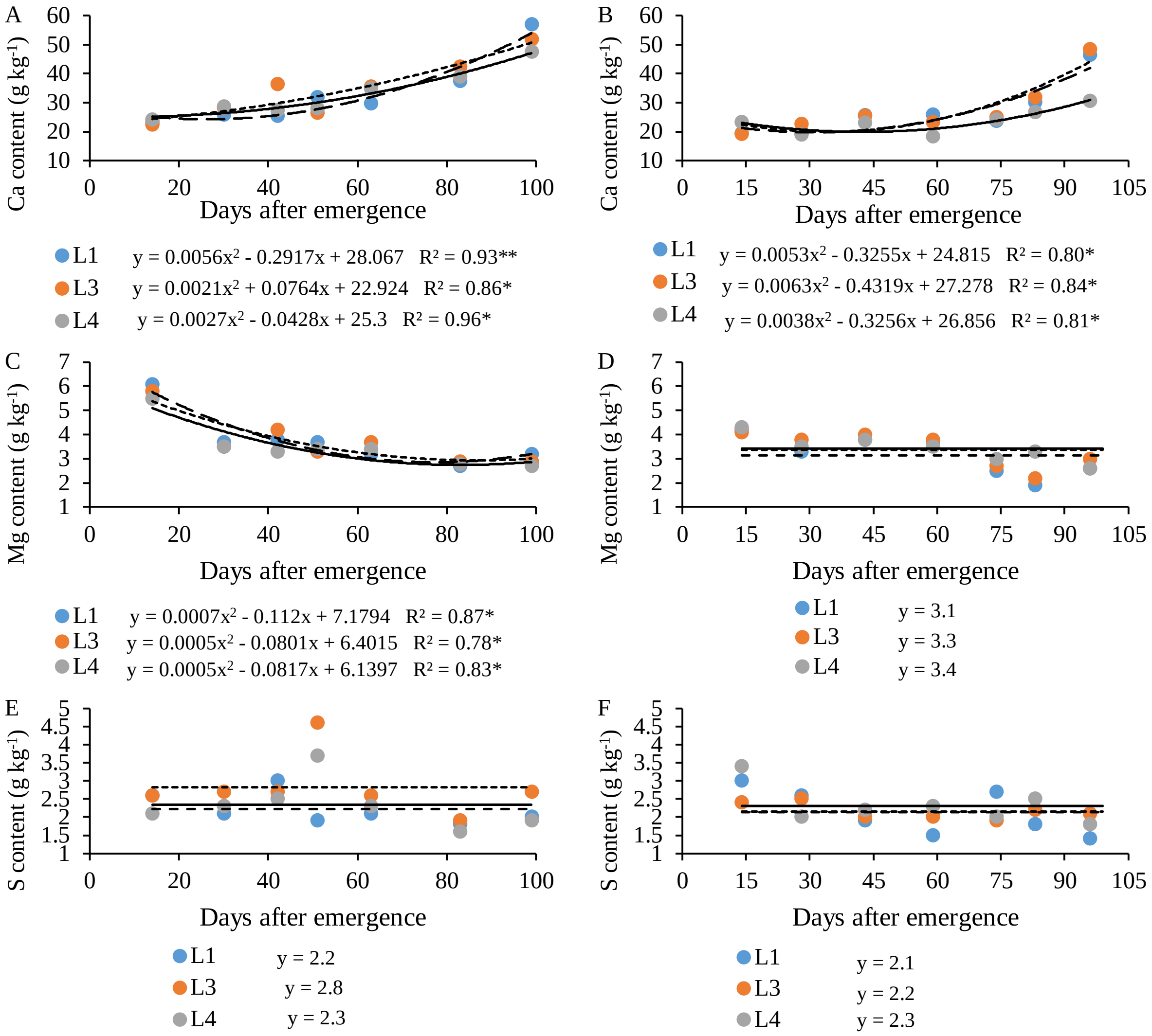


Figure 11. Leaf calcium (A, B), magnesium (C, D), and sulfur contents (E, F) in the common bean cultivar IPR Campos Gerais under three irrigation levels (L1: 54% ETc, L3: 77% ETc, and L4: 100% ETc) in 2019 and 2020. *($p<0.05$); **($p<0.01$).

Management L1 tended to have a higher relative amount of the nutrients Ca, Mg, and S accumulated in reproductive structures compared to L3 and L4 in both years (Figure 12). The last evaluation of both years showed that the highest amount of Ca accumulated in the plants remained in the leaves (50 to 70%) and only 20 to 30% was accumulated in the reproductive structures. Between 50 and 70% of the Mg and S were accumulated in the reproductive structures in both years.

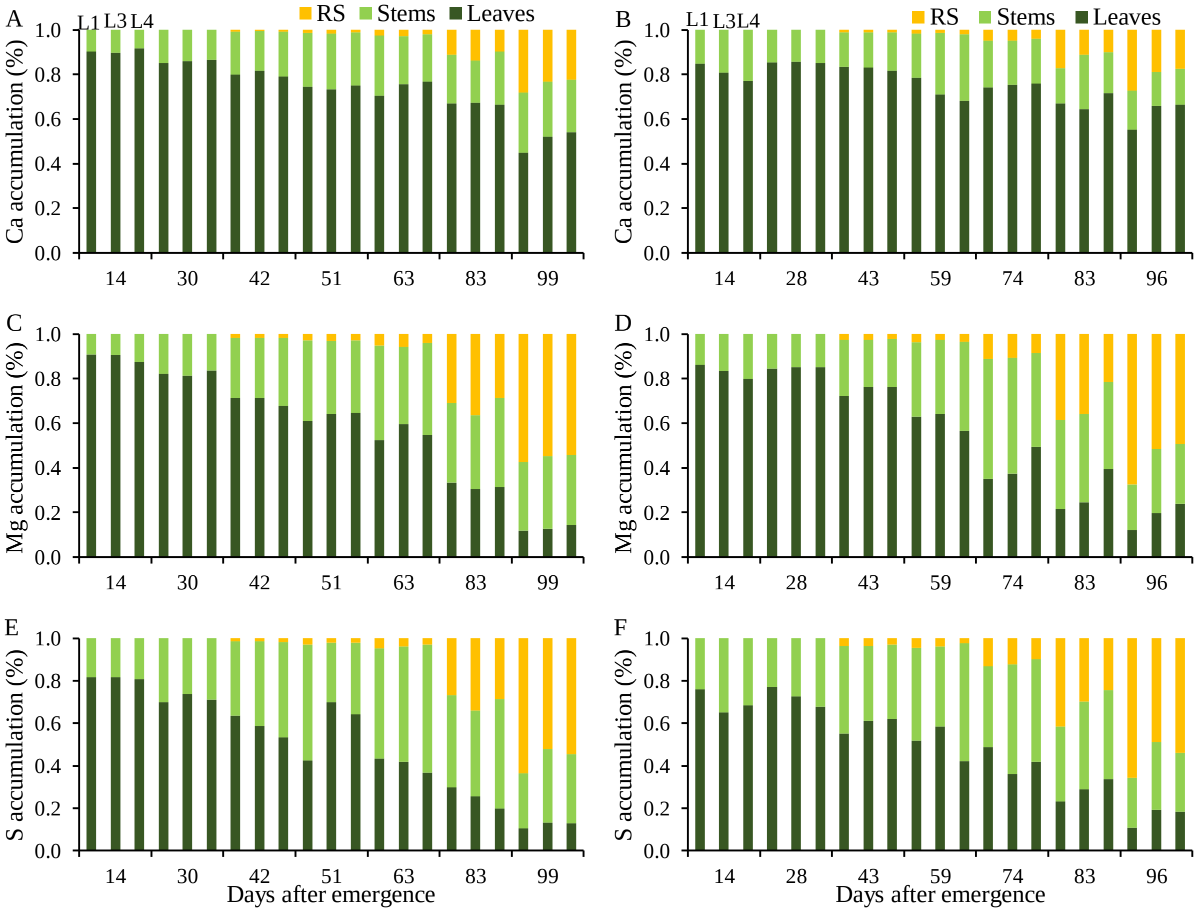


Figure 12. Calcium (A, B), magnesium (C, D), and sulfur accumulation proportion (E, F) in stems, leaves, and reproductive structures (RS) of the common bean cultivar IPR Campos Gerais under three irrigation levels (L1: 54%, L3: 77%, L4: 100% ETc) in 2019 and 2020.

In general, the export of secondary macronutrients was similar between cultivars in the three irrigation levels despite grain yield was higher in the IPR Campos Gerais (Table 3). The average yield of the IPR Campos Gerais reached 3.81, 4.14, and 4.70 Mg ha^{-1} in 2019 and 3.22, 3.83, and 4.03 Mg ha^{-1} in 2020 for L1, L3, and L4, respectively. The average yield of the IAC Imperador reached 3.01, 3.56, and 3.96 Mg ha^{-1} in 2019 and 2.61, 3.15, and 3.71 Mg ha^{-1} in 2020 for L1, L3, and L4, respectively. In both cultivars, Ca, Mg, and S requirements to produce 1 Mg ha^{-1} of grains ranged from 27 to 38, 5.0 to 11.0, and 3.0 to 8.4 kg ha^{-1} in the two years, respectively. High differences for relative export were observed between irrigation levels and between cultivars, with no standards being established.

Table 3. Export, relative extraction, and harvest index of primary macronutrients of the common bean cultivars IAC Imperador (IAC) and IPR Campos Gerais (IPR) in two years.

Irrigation Management	2019						2020					
	Ca		Mg		S		Ca		Mg		S	
	IAC	IPR	IAC	IPR	IAC	IPR	IAC	IPR	IAC	IPR	IAC	IPR
	Export (kg ha^{-1})											
L1	7.5	7.2	5.4	6.6	7.5	6.7	3.9	5.2	4.5	6.9	4.7	7.4
L3	5.8	9.4	4.9	6.6	6.7	6.3	4.4	4.0	5.6	7.1	5.6	5.9
L4	11.5	10.6	6.1	8.0	8.2	6.8	5.4	6.4	6.6	7.6	7.0	6.3
	Relative extraction (kg Mg^{-1})											
L1	32.2	30.2	8.9	5.5	3.7	3.9	27.6	28.6	6.6	6.7	3.0	4.5
L3	30.9	28.0	11.0	5.4	4.0	4.6	28.6	30.8	5.8	6.9	3.1	5.1
L4	32.0	28.1	9.3	5.0	4.2	4.5	26.9	38.7	6.2	9.1	4.2	8.4
	Harvest index of nutrients (%)											
L1	7.7	6.3	20.2	31.2	68.1	44.7	5.4	5.7	26.1	32.2	59.3	50.9
L3	5.3	8.1	12.6	29.1	47.0	32.8	4.9	3.4	30.5	26.7	57.7	30.3
L4	9.0	8.0	16.8	34.2	49.9	32.4	5.4	4.1	28.7	21.0	45.5	18.6

The harvest index showed high differences between cultivars and irrigation levels, with no consistent patterns between the evaluated treatments. The only pattern observed in both years was the highest S harvest index for the IAC Imperador, regardless of the irrigation management. The highest harvest indices were observed for Mg and S, with minimum values above 12%, while the highest harvest index for Ca reached 9%.

Overall, the cultivar IPR Campos Gerais showed higher total uptake of Ca and S than IAC Imperador, with similar values for Mg (Table 4). Severe water deficit reduced the uptake of Ca, Mg, and S by more than 25%. IPR Campos Gerais presented a greater interannual variation in S accumulation, whereas IAC Imperador showed greater interannual variation in Ca accumulation. Both cultivars exhibited similar interannual variations in Mg accumulation. On average, the nutrient uptake peak of IAC Imperador was anticipated by 15 days compared with the uptake peak of IPR Campos Gerais.

Table 4. Variation in the total uptake of nutrients Ca, Mg, and S as a function of cultivars, irrigation levels, and years and in the uptake peak between cultivars.

	------------------------ Amount (%) ------------------------				Uptake peak (days
Nutrients	Cultivars	Irrigation levels	Years - L4 (Highest/Lowest)		Cultivars
	IPR / IAC	L1 / L4	IAC	IPR	IAC - IPR
Ca	27%	-27%	27%	18%	-7
Mg	0%	-28%	59%	56%	-15
S	71%	-44%	6%	60%	-23

The results presented are the average of the two years and for irrigation management without a water deficit (L4).

The irrigation levels under water deficit (L1 and L3) presented lower soil moisture than the management with no water deficit (L4), regardless of the cultivar or year (Figure 13). The lowest soil moisture values in these irrigation levels were found throughout the cycle, especially from 25 DAE. Water deficit was more severe after crop flowering (R_6) and in 2020, with higher differences in soil moisture in L1 and L3 compared to L4. The irrigation management adopted to prevent frost damage to the common bean crop due to an intense cold on July 7, 2019, with constant irrigation depth throughout the experiment, promoted similar soil moisture between treatments in the period from 60 to 68 DAE (Figure 13A and 13C).

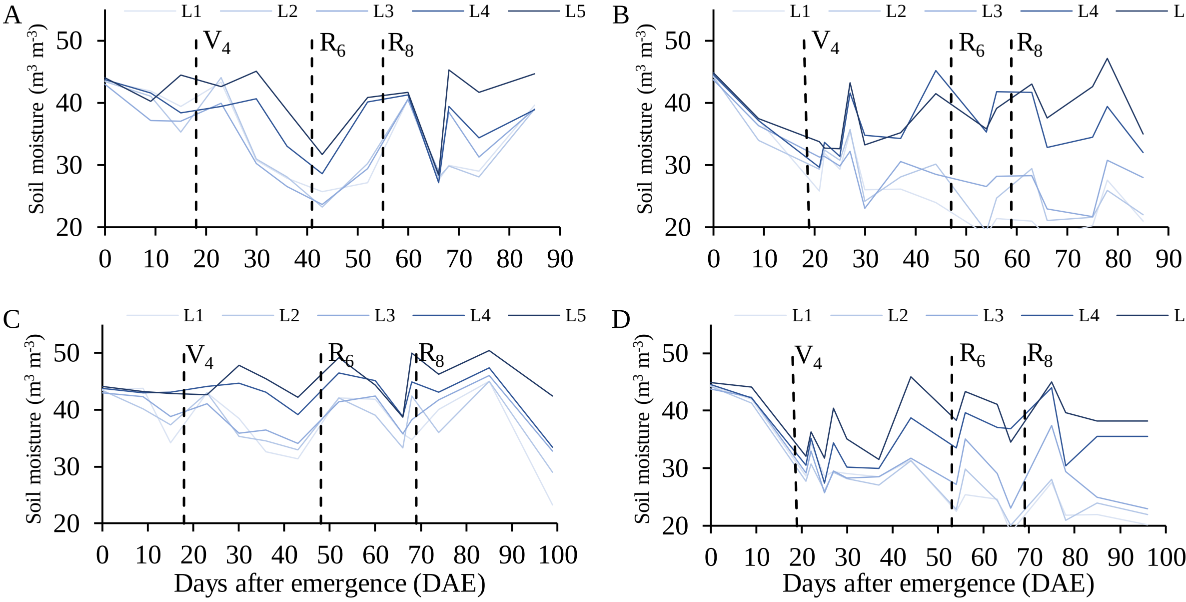


Figure 13. Variation in soil moisture as a function of time for the cultivars IAC Imperador (A, B) and IPR Campos Gerais (C, D) for three irrigation levels in the two

years (2019 and 2020). L1: 54%, L3: 77%; L4: 100% ETc

IPR Campos Gerais showed higher extraction of secondary macronutrients than the IAC Imperador, regardless of the irrigation management, except for Ca and Mg in 2019. The higher extraction for this cultivar is related to the higher biomass production, with a total value 22% higher in 2019 and 36% higher in 2020 compared to the IAC Imperador under the management with no water deficit (L4). The similar values of Ca extraction between cultivars in the first year are due to the higher Ca contents in the cultivar IAC Imperador (Figures 6 and 11), minimizing the higher biomass production of the IPR Campos Gerais. The highest Mg extraction was observed for the IAC Imperador in 2019 in all irrigation levels, which was due to the high Mg contents of the IAC Imperador (Figures 6 and 11), being proportionally higher than the difference in biomass production between cultivars.

The higher biomass production of the IPR Campos Gerais in 2020 compared to the IAC Imperador is due to differences in the type of habit growth between cultivars and climate conditions between years. The IAC Imperador has a determinate growth habit, that is, it does not have growth of leaves and branches after flowering, while the IPR Campos Gerais presents an indeterminate growth habit, with the growth of leaves and branches after flowering. The longer cycle of the IPR Campos Gerais, associated with the type of growth, favors a higher biomass production in this type of cultivar, as also observed by Andraus et al. (2016). Moreover, the year of 2020 had more favorable climate conditions for vegetative growth compared to 2019, with an average temperature up to 4 °C higher than 2019 after 45 days of emergence. In this period, both common bean cultivars were at the flowering stage and the high temperatures of 2020 provided higher growth of the indeterminate growth habit cultivar, justifying the higher relative difference between cultivars in the total biomass in this year.

The highest differences between years for the extraction of secondary macronutrients in the IPR Campos Gerais occurred in the management with no water deficit, with similar extraction values for severe and moderate water deficits in both years. Even though 2020 presented more favorable conditions for the vegetative growth of the cultivar IPR Campos Gerais, the water deficit was more intense for L1 and L3 than in 2019, given the variation in soil moisture (Figure 13).

The total biomass production between years was more similar for the IAC Imperador, but higher for the IPR Campos Gerais in 2020. It occurred due to differences in the type of habit growth between cultivars and differences in climate conditions between years, as explained above. These factors must be considered in the fertilization management of contrasting common bean cultivars regarding the type of growth because the nutrient extraction in years with higher average temperatures and under the irrigation management with no water deficit is higher than in years with milder temperatures for indeterminate growth cultivars, with a trend of a lower variation between years for determinate growth cultivars.

The amount of secondary macronutrients extracted by the cultivars IAC Imperador and IPR Campos Gerais in both years followed the decreasing order Ca>Mg>S, regardless of the irrigation management. Perez et al. (2013) and Soratto et al. (2013) observed the same export sequence, regardless of the evaluated treatment.

The nutrient absorption peak between all treatments ranged from 42 to 62 DAE for Ca, 44 to 82 DAE for Mg, and 38 to 85 DAE for S. A pattern between cultivars was only observed for S, which had the absorption peaks anticipated for the cultivar IAC Imperador. The average of years showed that the maximum S absorption rate for L1, L3, and L4 irrigation levels of the cultivar IAC Imperador occurred 9, 17, and 23 days before the maximum absorption rate for treatments of the cultivar IPR Campos Gerais, respectively. Ca and Mg presented a high variability between treatments. Thus, S fertilization management in the cultivar IAC Imperador must be carried out, when necessary, before the same management in the cultivar IPR Campos Gerais, especially under conditions with no water deficit or moderate deficit.

Lesser problems with fertilization management and deficiency occur for Ca considering the three secondary macronutrients. This nutrient is usually found at high contents in the soil, being supplied through other management practices, such as the application of limestone and fertilizers that have it in their composition. However, there are differences in the efficiency and response of common bean cultivars to the use of Ca (Domingues et al., 2014), that is, some genotypes are more responsive to Ca and can increase their yield through its fertilization management.

Deficiencies are more frequent for Mg even though it is a nutrient that can also be provided by limestone or other fertilizers as a secondary source. Wang et al. (2020)

conducted a literature review and found that the increased crop yield in soils with pH below 6.5 due to Mg fertilization can reach more than 10%, confirming the importance of fertilization management using this nutrient in more acidic soils. Mg contents below 5 $\text{mmol}_c\ \text{dm}^{-3}$ in low-fertility soils may promote deficiencies and generate losses in yield (Ambrosano et al., 1997). Canizella et al. (2017) observed that Mg fertilization conducted in a greenhouse increased grain yield per plant by more than 50% in common bean cultivars.

Between 10 and 15% of the total Mg requirement can be provided by corrective leaf fertilization, if necessary, unlike Ca, for which total extraction is close to or higher than 100 kg ha^{-1}. Leaf Ca fertilization would be ineffective, as it would provide one or two applications between 2 and 5% of the total extracted by common bean. In addition, possible leaf fertilization with Mg should be started before the season with its maximum absorption rate, which is usually between 50 and 60 DAE, considering the time required for the leaves to absorb 50% of the applied amount of each nutrient. In this context, little is known about the effect of leaf S and Mg fertilization on the common bean, and studies that guide this practice are required. Thus, the present study is a source of information for research on leaf Mg and S fertilization to be carried out on common bean. On the other hand, some studies on leaf Ca fertilization have been conducted on common bean and no increases in grain yield have been found (Silva et al., 2006; Paula Júnior et al., 2009).

Applications of 30 kg S ha^{-1} are necessary to obtain yields above 2 Mg ha^{-1} (Ambrosano et al., 1997). Nascente et al. (2017) evaluated the effect of topdressing S fertilization on common bean cultivars and observed that the highest yields were observed with S doses close to 30 kg ha^{-1}. Leaf S fertilization could be carried out and would be effective to supply part of the S demand for common bean due to its small extraction, as discussed for Mg. Considering the S extraction by common bean and two leaf applications, this management could provide from 15 to 20% of the total extracted by the crop, becoming an alternative to correct possible deficiencies of this nutrient and mitigate negligence in soil fertilization management. Possible leaf S fertilization should also be started before the period of its maximum absorption rate, that is, approximately from 40 to 50 DAE for the cultivar IAC Imperador and 50 and 60 DAE for the cultivar IPR Campos Gerais.

Ca, Mg, and S absorption peaks were high, with values of up to 2.3, 0.55, and 0.53 kg ha^{-1} day^{-1}, respectively. Soratto et al. (2013) evaluated the macronutrient extraction by common bean in soil with similar fertility to the soil in the present study and observed Ca, Mg, and S absorption rates close to 2.0, 0.45, and 0.50 kg ha^{-1} day^{-1}, which are lower than the values observed in the present study.

Besides differences between cultivars and years in the extraction of secondary macronutrients by the common bean crop, water deficit reduced the amount of extracted nutrients and their absorption rates. This effect was more observed for the irrigation management with severe water deficit compared to the management with moderate water deficit, as the amount of nutrients in the management systems with moderate and no water deficits were similar in some situations. The cultivar IAC Imperador absorbed, on average, 34, 35, and 69% more Ca, Mg, and S, respectively, relative to the management under severe water deficit (L1), reaching 40, 41, and 85% for the cultivar IPR Campos Gerais, respectively. Moreover, the highest differences between L4 and L1 in the absorption of the three secondary macronutrients occurred in the second year, regardless of the cultivar, except for Mg in the cultivar IAC Imperador, which showed a similar variation between years. The values of soil moisture between treatments (Figure 13) show that water deficit was more intense in the second year than in the first year and, therefore, there was a higher restriction to growth and nutrient accumulation by irrigation management practices with water deficit relative to the first year.

A high variation was found between years, cultivars, and irrigation levels in the average requirement for Ca, Mg, and S to produce 1 Mg ha^{-1} of common bean grains, with no specific patterns. Overall, the extraction of 30, 7.2, and 4.4 kg ha^{-1} of Ca, Mg, and S were necessary to produce 1 Mg ha^{-1} of grains. Perez et al. (2013) observed that 19, 4.5, and 1.5 kg ha^{-1} of Ca, Mg, and S were required to produce 1 Mg ha^{-1} of common bean grains. Pegoraro et al. (2014) evaluated the nutrient extraction of an irrigated winter-grown common bean and observed that 22, 2.2, and 3.5 kg ha^{-1} of Ca, Mg, and S were required to produce 1 Mg ha^{-1} of common bean grains. Thus, the relative extraction of Ca, Mg, and S in the present study was 58, 60, and 98% higher than that found by Perez et al. (2013) and 36, 227, and 26% higher than that observed by Pegoraro et al. (2014), respectively. It demonstrates the high soil fertility in the experimental area, which had high available Ca, Mg, and S contents (Table 2), generating their luxury consumption by common bean cultivars.

No pattern was observed between treatments for the Ca and Mg harvest indices of common bean cultivars. The average harvest index for Ca and Mg was 6.1 and 25.5%, respectively, that is, 6.1% of the total Ca and 25% of the total Mg extracted by the plant goes to the grains. Fageria et al. (2007) observed Ca and Mg harvest indices of 28 and 41%, respectively, values higher than those observed in the present study. Soratto et al. (2013) also observed harvest index values of Ca (13%) and Mg (40%) higher than those found in the present study. The harvest index for Ca was lower than that of Mg, as observed by Fageria et al. (2007) and Soratto et al. (2013). It occurs because Ca is a poorly mobile nutrient in the plant, while Mg is highly mobile (Malavolta et al., 1997). These differences promote a small Ca remobilization and a lower Mg remobilization to the grains.

Higher average values of the S harvest index were found for the IAC Imperador (55%) compared to the IPR Campos Gerais (35%). Soratto et al. (2013) observed no relevant differences in the cultivars Pérola and IAC Alvorada, with an average harvest index of 48% for S. This difference in the S harvest index between cultivars presents benefits and harms. The main benefit is the higher S content in the grains of the IAC Imperador cultivar, increasing the nutritional value of the food, while the main harm is the higher proportional removal of S from the area, which may reduce S availability of S in the soil cultivated with this cultivar over time. Thus, there is a higher need for S replacement via fertilization when using the common bean cultivar IAC Imperador.

5.4 Conclusions

Water deficit, cultivars, and years promote changes in Ca, Mg, and S absorption dynamics by common bean crop. The severe water deficit affects more the nutrient uptake by common bean compared to the moderate water deficit, reducing the total accumulated Ca, Mg, and S by 25, 26, and 41% for the IAC Imperador and 28, 29, and 46% for the IPR Campos Gerais compared to the management with no water deficit, respectively. The severe water deficit also anticipates the maximum demand for Ca (up to 20 days), Mg (up to 31 days), and S (up to 41 days) by common bean. On average, the IPR Campos Gerais presents 64% higher S accumulation compared to the IAC Imperador. The IAC Imperador presents maximum S uptake 23 days before that verified for the IPR Campos Gerais under no water deficit conditions. The indeterminate growth habit IPR Campos Gerais have proportionally higher biomass production in years with more favorable climate conditions for vegetative growth, a factor that promotes higher Ca and Mg accumulation compared to IAC Imperador and increases the interannual variability in the nutrient accumulation dynamics for this genotype. The differences in Ca, Mg, and S absorption dynamics as a function of water deficit, cultivar, and year are essential for specific fertilizer management in the common bean crop, in addition to promoting higher optimization in nutrient use.

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CHAPTER 6 - Application of the CSM-CROPGRO-Dry bean model to optimize irrigation as a function of sowing date in common bean cultivars[5]

ABSTRACT: In tropical and subtropical regions, common bean cultivation is highly variable whether as a function of climate, farmer technological level, or grown cultivar. In this context, simulation models are feasible and promising alternatives for specific recommendations. This study aimed to use the CSM-CROPGRO-Dry bean model as a tool to optimize irrigation management as a function of sowing date and common bean cultivar. An experiment was carried out in southeastern Brazil during two years in the winter season to evaluate the effect of five irrigation levels (54, 70, 77, 100, and 132% of crop evapotranspiration) on the agronomic performance of the common bean cultivars IAC Imperador (determinate growth) and IPR Campos Gerais (indeterminate growth). After model parameterization, a long-term analysis was performed to simulate the effect of the five irrigation levels on the grain yield of common bean cultivars as a function of eight sowing dates. The results showed that irrigation can be managed under a regulated water deficit without significantly reducing common bean yields if sowing is brought forward (Mar/Apr) within the winter season. For full irrigation, sowing dates in which common bean reproductive stages coincide with the period of lower global solar radiation (GSR) should be avoided. The reason is because the unit increase in GSR after flowering leads grain yield of the cultivars IAC and IPR to increase by 55 and 50 kg ha^{-1}, respectively. Therefore, the CSM-CROPGRO-Dry bean model is a powerful tool for defining more specific and sustainable irrigation management for common bean cultivars.

Keywords: *Phaseolus vulgaris* L., DSSAT, growth habits, deficit irrigation

6.1 Introduction

In agriculture, sowing dates for different crops are defined as a function of climatic factors, especially photoperiod, rainfall, temperature, solar radiation, and relative humidity. The association of these factors with crop responses to them allows us to point out sowing dates that guarantee satisfactory yields, thus generating information for agroclimatic zoning. In rainfed agriculture for photoperiod-unresponsive crops, the most yield-influencing factors are rainfall and its distribution over time. As for irrigated crops, yields can be drastically affected by other meteorological factors, especially temperature and solar radiation (Teixeira et al., 2017; Coelho et al., 2021).

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[5] This chapter was submitted to the Field Crops Research and is under peer review process for publication

In this context, pieces of software encompassing different crop models, such as DSSAT (Hoogenboom et al., 2019), are effective tools to generate management recommendations and assess the impacts of different climatic factors on crop yields. For crops with varied cultivation systems, these models are even more essential, whether for defining the best sowing dates or for agricultural management such as fertilization and irrigation. Among these, common bean stand out because, in tropical and subtropical regions, their cultivation can be done throughout the year under diverse conditions that may range from high to low temperatures and rainfalls. Moreover, this crop has a wide range of cultivars available to producers, with cycles varying from 65 to about 100 days (Lemos et al., 2015), in addition to contrasting growth habits (determinate and indeterminate).

In Brazil, common bean is grown during three crop seasons in a year, which are the rainy season, dry season, and winter crop (Tarsitano et al., 2015; Conab, 2021). Given the need for irrigation, researchers and farmers reach a consensus that winter crops require a higher technological level. In this season, common bean sowing lasts from March to June. However, even within this season, another climatic variability may directly interfere with the agronomic performance of common bean, as early sowing contributes more to plant growth given the higher rainfall volumes, while later sowing is done in drier and colder times.

The CSM-CROPGRO-Dry bean model (Hoogenboom et al., 1994; Boote et al., 2018) has been a feasible alternative to simulate common bean growth, in addition to allowing long-term analyzes to verify the effects of climatic factors on the agronomic performance of plants (Boote et al., 2018). Several studies have used this model to simulate growth and yield in different common bean cultivars and have shown high estimation accuracy (Oliveira et al., 2012; Heinemann et al., 2016; Santos et al., 2016; Teixeira et al., 2017). By using the same model, Teixeira et al. (2017) observed that advance in common bean sowing (Mar/Apr) within the winter crop increases irrigation efficiency. However, none of these studies has ascertained which irrigation management is better for a given sowing date within the winter crop for cultivars with contrasting growth habits.

Agriculture is responsible for 70% of water withdrawals worldwide (FAO, 2017). Irrigation management in agriculture is essential to ensure farm sustainability and optimize water use, without drastically reducing crop yields. Controlled water deficit has been used and ensured reductions in the amount of water used, without significantly reducing crop yields (Chai et al., 2016; Memmi et al., 2016). Thus, defining irrigation managements for different common bean cultivars with contrasting growth habits as a function of sowing date within the winter crop can help producers and technicians to increase management sustainability, ensuring lower production costs and optimizing irrigation water use.

The hypothesis raised is that long-term simulations using CSM-CROPGRO-Dry bean model allow us to optimize irrigation management as a function of sowing date and cultivar grown. Therefore, this study aimed to calibrate, validate, and apply the CSM-CROPGRO-Dry bean model to simulate phenology, growth, and yield of common bean cultivars with contrasting growth habits to optimize irrigation management as a function of sowing date and the cultivar used.

6.2 Material and methods

The experiment was conducted in the winter seasons of 2019 and 2020 at the São Paulo State University (Unesp), School of Agricultural and Veterinarian Sciences, Campus of Jaboticabal, São Paulo State, Brazil. The area is near the geographical coordinates of latitude 21º 14’ 44” S, longitude 48º 17’ 00” W, and 545-m altitude. According to Köeppen’s classification, the local climate is Aw type, which stands for tropical with dry winters and rainy summers. Annual averages of temperature and rainfall are 22 ºC and 1,425 mm, respectively (Alvares et al., 2013). The soil in the experimental area is classified as Oxisol (Soil Survey Staff, 2014).

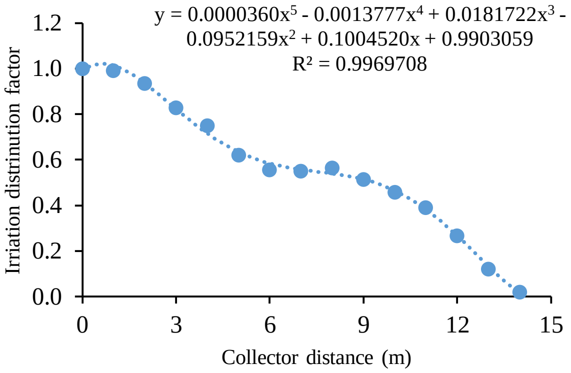
Common bean seeds were sown on May 7 in 2019, and on May 18 in 2020. Two cultivars of the commercial group “Carioca”, with contrasting growth habits, were used, namely IAC Imperador and IPR Campos Gerais. The former has determinate (type I) and erect growth habit and 75-day mean cycle length, while the latter has indeterminate (type II) and erect growth habit and 90-day mean cycle length.

Cultivars were sown mechanically to reach a 240,000-plant-per-hectare density, with a 0.45-m between-row spacing. In both years, seeding was done in an area previously grown with corn, using no-tillage seeder-fertilizer. During the two years, the corn hybrid P4285VYHR was grown in rows with 0.90 m spacing and a density of 75,000 plants ha^{-1}.

Sowing fertilization of common bean was carried out according to soil analysis and the recommendation of Ambrosano et al. (1997), applying 200 kg ha^{-1} of the formula 04-20-20, providing 8 kg N, 40 kg P_2O_5, and 40 kg K_2O ha^{-1}. Topdressing was performed at the V4-3 stage, which is characterized by the third trifoliate leaf being fully expanded (Fernández et al., 1985). For topdressing, a dose of 100 kg N ha^{-1} was used in both years, with urea as N source (Ambrosano et al., 1997), with applications at 19 and 21 days after emergence (DAE) of common bean in 2019 and 2020, respectively, along a continuous line at 0.10 m from the planting row.

The experimental design used was strip-plot. The study factors were five irrigation levels and two common bean cultivars, with four replications. Each plot had 15 common bean rows with 6.75 m in length and 2.4 m in width. The first row from each end, as well as the initial 50 cm of the central rows, were considered as borders.

The line-source sprinkler system was used, allowing the distribution of the irrigation water with variable application depths as the treatment moves away from the central sprinkler line (Hanks et al., 1976). A field test enabled the definition of the distribution fractions of the sprinkler precipitation (Figure 1). In model fit, the regression that generated the highest precision (R^2) was used, aiming to estimate the most accurate irrigation distribution factor possible in each treatment. Senninger 4023-2 sprinklers and ¾″ M 08Qx05 nozzles were used spaced every 6 m on the central line. The water application intensity of the sprinklers was measured in the field in tests with collectors placed at 1 m from each other up to the limit distance of water application by the sprinklers in a line perpendicular to the irrigation line, with four replications.



Distance (m)	Treatment	Irrigation distribution factor
0.00–2.40	L5	1.002 (132%)
2.40–4.80	L4	0.754 (100%)
4.80–7.20	L3	0.584 (77%)
7.20–9.60	L2	0.532 (70%)
9.60–12.00	L1	0.407 (54%)

Figure 1. Sprinkler irrigation distribution factor as a function of the distance from the

irrigation line, with sprinklers spaced at 6 m from the line, obtained in field tests. Service pressure: 250 kPa

For study purposes, the treatments consisted of five irrigation levels (L1, L2, L3, L4, and L5), which were set up after the establishment of the water application regression by the sprinkler line (Figure 1). The L4 level was used as a standard, receiving 100% of the water required by the bean crop. The L5 level received excess water, with 132% of the water requirement by the common bean, while the L3, L2, and L1 levels provided 77, 70, and 54% of the water requirement, respectively.

The irrigation management was carried out based on the crop water demand, according to the FAO 56 method, using climate data obtained daily from an automated agrometeorological station located 1,500 m from the experiment. The reference evapotranspiration (ETo) was estimated daily using the FAO 56 method (Allen et al., 1998). The evapotranspiration of the common bean crop (ETc) was calculated by the product of ETo and crop coefficients (Kc) (Allen et al., 1998). The Kc values 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 from 1.15 to 0.35 (maturation). For the Kc range between 0.40 and 1.15, the values were interpolated daily up to the maximum value (1.15). The daily increment was calculated as the ratio of the difference between the Kc range (1.15 – 0.40) and the number of days between the initial Kc (0.40) and maximum Kc (1.15).

Irrigation was carried out when the water deficit in the area was equal to 18 mm. This water depth was calculated according to the soil physical attributes (Table 1) and the bean crop. The calculation considered 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 were applied at sowing to common bean emergence to promote a uniform initial stand in all treatments.

Table 1. Data used to compose the experimental area soil file required by the DSSAT software

Layer depth	Lower limit	Upper limit drainage	Upper limit saturation	Bulk density	Organic carbon	Clay	Silt	pH water	CEC	N-total
cm	------------- m^3 m^{-3} -------------			g cm^{-3}	------------ % ------------			-	cmolc kg^{-1}	%
10	0.157	0.363	0.508	1.31	2.23	47.90	28.90	6.40	13.89	0.13
20	0.185	0.351	0.492	1.36	2.05	50.50	26.90	7.10	15.83	0.11
40	0.166	0.325	0.478	1.24	1.54	53.60	26.60	6.40	15.34	0.08
60	0.202	0.393	0.484	1.41	1.12	56.20	24.60	6.50	9.25	0.07
100	0.190	0.397	0.482	1.43	0.92	54.00	25.40	6.40	6.78	0.05

CEC: cation exchange capacity

The CSM-CROPGRO-Dry bean model was calibrated and validated considering as state variables the dates of growth stages, plant growth during the cultivar cycle, and grain yield. In each treatment, phenological phases comprised the time, in days, between the sowing and plant emergence (V_1), flowering (R_6), first-pod appearance (R_7), and physiological maturity (R_9). Growth variables consisted of accumulations of total biomass, leaves, and stems, all in dry matter, throughout the crop cycle, besides plant height at flowering (R_6). Yield traits were total biomass accumulation at R_9, grain yield, and N export by grains. Total biomass accumulation at R_9 was estimated by collecting seven plants from each plot and drying them in a forced-air circulation oven at 65 °C until constant weight. Grain yield was estimated by harvesting the six useful rows within each subplot and results expressed in dry mass, using the same output unit of the CSM-CROPGRO-Dry bean model. Grain N export was calculated as the product between grain yield and grain N content, which was estimated according to the method of Bataglia et al. (1983).

The growth and yield of the common bean cultivars were simulated using the CSM-CROPGRO-Dry bean model, available in the DSSAT software (Hoogenboom et al., 2019). Genetic coefficients of the cultivars under study (IAC Imperador and IPR Campos Gerais) were calibrated by at first assuming those of two existing common bean cultivars in the DSSAT database. The genetic coefficients used for the cultivar IAC Imperador were those of the cultivar “Seafarer,” which has determinate growth (MESDET - type I) and Mesoamerican center of origin. As for IPR Campos Gerais, we initially assumed the genetic coefficients of the cultivar “Carioca (G4017),” which has indeterminate growth (MESIND – types II to IV) and Mesoamerican center of origin as well. We could not choose the same cultivar since growth habit was a parameter to be met for each cultivar. Assuming the same cultivar would lead to discrepancies in the growth habits of each genotype (ecotype coefficients).

The genetic coefficients of both cultivars were calibrated using data observed in the field during L4 irrigation management in 2019. From these, phenology related genetic coefficients were first altered until the model-simulated phenological stage dates were similar to those observed in the field. At this phase, the dates of emergence (V_1), full flowering (R_6), first-pod appearance (R_7), and phenological maturity (R_9) were used. After calibrating phenology-related genetic coefficients, we calibrated growth- and yield-related genetic coefficients. To this end, the variables used were leaf and stem biomass accumulations over the entire cycle, total biomass accumulation at physiological maturity (R_9), number of grains per m^2, grain weight (g $unit^{-1}$), plant height at flowering (R_6), N extraction by grains, and grain yield.

The genetic coefficients were calibrated interactively through sensitivity analysis. In other words, a value was assigned to each coefficient and accuracy between model-predicted and field-observed values was observed. For model calibration, only the genetic coefficients had to be changed. Only one ecotype coefficient was calibrated for the two cultivars, as the value in the DSSAT database did not correspond to the one observed in the field. This coefficient was R_7-R_8 (time between physiological and harvest maturity, in days), for which the values in the database were 9 days for the MESIND ecotype (IPR Campos Gerais) and 7 days for MESDET ecotype (IAC Imperador); these values were then adjusted to 14 and 13 days, respectively.

During calibration, the model was input with management specifications for each cultivar (sowing time, spacing, plant density, irrigation, nutrient application, etc.) and soil characteristics (water retention and fertility). The latter, in turn, was defined in an "X-File," wherein simulation conditions are described (Table 1). Daily values of maximum and minimum temperatures, global solar radiation, wind speed, relative humidity, and rainfall were also added as input data. These data were gathered from an agro-climatological station in the São Paulo State University.

After calibration, the model was tested for generalization capacity (validation) to simulate growth and yield attributes for some irrigation managements in 2019 (L1, L2, L3, and L5) and all in 2020 (L1, L2, L3, L4, and L5) in both cultivars. To do so, phenological stage dates (emergence, flowering, first-pod, and physiological maturity), biomass accumulation at maturity (R_9), N export by grains, and grain yield were used. The goodness of fit of the CSM-CROPGRO-Dry bean model in both calibration and validation was evaluated by the following indexes: coefficient of determination (R^2), root mean square error (RMSE), mean bias error (MBE), and Willmott's concordance index (d). (Willmott, 1981).

After validation, long-term simulations for each cultivar and irrigation level were performed for eight sowing dates. These dates encompassed the winter common bean crop in Brazil, which were March 1, March 15, April 1, April 15, May 1, May 15, June 1, and June 15. The long-term simulations were made using the “seasonal” subroutine of the DSSAT 4.7 system (Hoogenboom et al. 2019). This tool enables simulating crop cycles over the different years considered within a historical meteorological data series. These simulations made use of the genetic coefficients of the common bean cultivars previously calibrated in the CSM-CROPGRO-Dry bean model.

Table 2 shows the monthly averages of historical climate data between 2001 and 2020 (20 years) used in simulations. After simulations, averages and cumulative yield probability functions were calculated for the simulated period to recommend the ideal irrigation management for each sowing date and common bean cultivar.

The effects of mean temperature, relative humidity, wind speed, rainfall, and global solar radiation on grain yield of each irrigation management and bean cultivar were evaluated by Pearson's linear correlation (r). To this end, we used average data of climatic factors before and after flowering of common bean. For IAC Imperador flowering was assumed at 45 days after sowing (DAS) and cycle to physiological maturity at 90 DAS, while for IPR Campos Gerais flowering was assumed at 50 DAS and cycle to maturity at 100 DAS. Averages of climatic factors at each sowing date within each irrigation management were correlated to crop yields simulated by the CSM-CROPGRO-Dry bean model.

Table 2. Characterization of monthly averages of climatic factors for the experimental area from 2001 to 2020

Month	Max. Temp.	Min. Temp.	RH	Rainfall	Wind speed	GSR
	-------------- °C --------------		%	mm	km dia^{-1}	MJ m^{-2} dia^{-1}
January	30.54	20.19	78.56	299.76	114.55	19.64
February	30.93	19.89	77.50	198.65	101.04	20.26
March	30.67	19.47	77.01	140.14	98.01	19.06
April	29.85	17.59	71.80	64.55	89.28	17.84
May	27.15	14.43	71.56	58.00	92.70	15.27
June	27.13	13.58	68.86	18.13	94.23	14.28
July	27.36	12.96	62.54	19.58	109.96	15.23
August	29.54	14.18	55.80	27.07	132.88	17.91
September	31.08	16.61	57.15	53.91	151.14	19.12
October	31.96	18.92	62.40	93.09	155.90	20.05
November	31.08	18.61	57.15	53.91	151.14	19.12
December	30.75	19.84	76.12	213.32	134.51	20.12
Mean/Sum	29.84	17.02	68.04	1240.10	118.78	18.16

RH: relative humidity of air; GSR: global solar radiation

6.3 Results and discussion

During calibration of the common bean cultivars, IAC Imperador and IPR Campos Gerais, genetic coefficients related to phenological stage dates (namely, EM-FL, FL-SH; SL-SD, and SD-PM) were increased concerning patterns of cultivars already existing in the DSSAT database (Table 3).

An exception can be made for the SD-PM coefficient in the cultivar IAC Imperador, which remained the same value (19) as in the cultivar Seafarer. This was necessary to adjust the phenological stage dates observed in the field with the model-simulated ones. The calibrated values of most of the growth- and yield-related coefficients were higher than those observed in the DSSAT database. The coefficients remaining unchanged during calibration were SD-PM in the cultivar IAC Imperador, LFMAX and SIZLF in the cultivar IPR Campos Gerais, and CSDL, PPSEN, XFRT, THRSH, SDPRO and SDLIP in both cultivars. These coefficients were related to crop physiological factors.

Table 3. Genetic coefficients of the cultivars in the DSSAT database (Seafarer and Carioca G4017) and of the cultivars calibrated for the experiment (IAC Imperador and IPR Campos Gerais)

Coefficient	Description	Seafarer	IAC Imperador	Carioca G4017	IPR Campos Gerais
CSDL	Critical day length above which reproductive development is unaffected (h)	12.17	12.17	12.17	12.17
PPSEN	Slope of the relative response of development to photoperiod with time (1/hour)	0	0	0	0
EM-FL	Time between plant emergence and appearance of the first flower (R_6) (photothermal days)	28	34	32.5	38
FL-SH	Time between the appearance of the first flower (R_6) and first pod (R_7) (photothermal days)	4	6	3.5	7
FL-SD	Time between the appearance of the first flower (R_6) and beginning of seed formation (R_8) (photothermal days)	11	13	10.8	15
SD-PM	Time between and the beginning of seed formation (R_8) and physiological maturity (R_9) (photothermal days)	19	19	18.2	21
FL-LF	Time between the appearance of the first flower (R_6) and end of leaf expansion (photothermal days)	18	20	18	23
LFMAX	Maximum leaf photosynthesis rate at 30 °C, 350 ppm CO_2, and high light intensity (mg CO_2/m^2-s)	0.95	1	1	1
SLAVR	Specific leaf area under standard growth conditions (cm^2/g)	315	280	300	330
SIZLF	Maximum size of the fully expanded leaf (cm^2)	133	140	140	140
XFRT	Maximum fraction of daily growth that is partitioned to seed and shell	1	1	1	1
WTPSD	Maximum weight per seed (g)	0.22	0.24	0.25	0.26
SFDUR	Length of time of seed filling in pods under standard growing conditions (photothermal days)	17	20	19	20
SDPDV	Average of seeds per pod under standard growing conditions (photothermal days)	5	4.05	5.5	3.92
PODUR	Time for the cultivar to reach ideal pod conditions (photothermal days)	11	13	11.5	16
THRSH	Seed/ (seed + shell) ratio (%)	78	78	78	78
SDPRO	Protein fraction in seeds (g protein g $seed^{-1}$)	0.235	0.235	0.235	0.235
SDLIP	Oil fraction in seeds (g oil g $seed^{-1}$)	0.03	0.03	0.03	0.03

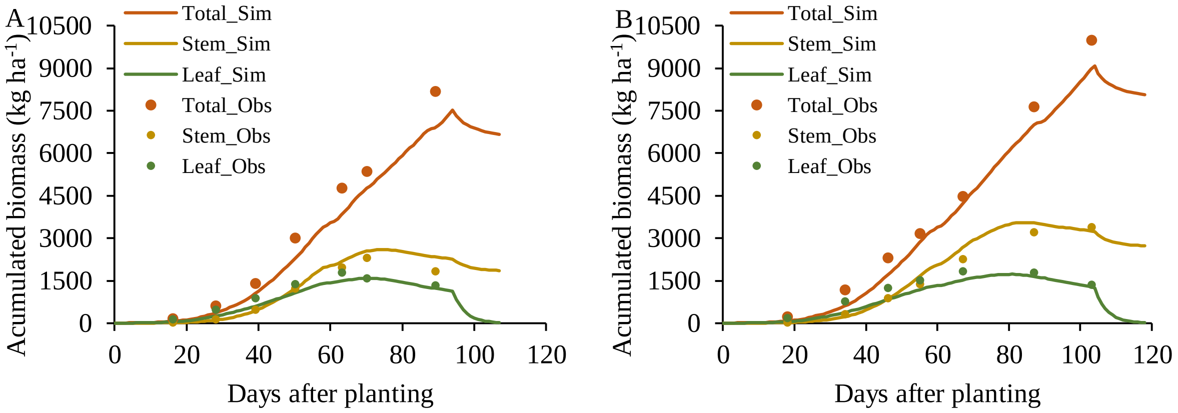
During model calibration, field-observed and model-simulated values were close for both cultivars under L4 irrigation management in 2019, therefore calibration was accurate (Table 4). All yield and growth attributes and phenological stage dates observed in the field were similar to those simulated by the model.

Table 4. Observed and simulated data in the calibration of the CSM-CROPGRO-Dry bean model for the common bean cultivars IAC Imperador (determinate growth) and IPR Campos Gerais (indeterminate growth)

Cultivar	Production data									
	GY		BY		GM		NG		NE	
	kg ha^{-1}		kg ha^{-1}		g unidade^{-1}		n° m^{-2}		kg ha^{-1}	
	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim
IAC Imperador (L4 2019)	3305	3425	8412	7523	0.202	0.192	1728	1788	121	127
IPR Campos Gerais (L4 2019)	3710	3946	10521	9072	0.229	0.220	1855	1798	136	144
Cultivar	**Phenological and growth data**									
	EM		FL		FP		PM		PH	
	--------------------------- days ---------------------------								m	
	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim
IAC Imperador (L4 2019)	5	4	46	48	54	55	90	92	0.58	0.62
IPR Campos Gerais (L4 2019)	5	4	53	53	62	63	104	104	0.66	0.75

Obs: observed data; Sim: simulated data; GY; grain yield; BY: biomass yield; GM: grain mass; NG: number of grains; NE: nitrogen exports; EM: emergence; FL: flowering; FP: first pod: PM: physiological maturity; PH: plant height

In addition to the similarity between observed and simulated point values for phenology and growth and yield attributes, the model showed high accuracy in simulating biomass accumulation over time by common bean cultivars in the calibration phase (Figure 2).



Total
R^2= 0.99 RMSE= 727 kg ha^{-1} MBE= 615 kg ha^{-1} d= 0.98
Stem
R^2= 0.98 RMSE= 219 kg ha^{-1} MBE= -119 kg ha^{-1} d= 0.99
Leaf
R^2= 0.96 RMSE= 233 kg ha^{-1} MBE= 201 kg ha^{-1} d= 0.96

Total
R^2= 0.99 RMSE= 518 kg ha^{-1} MBE= 514 kg ha^{-1} d= 0.99
Stem
R^2= 0.98 RMSE= 233 kg ha^{-1} MBE= -101 kg ha^{-1} d= 0.99
Leaf
R^2= 0.95 RMSE= 289 kg ha^{-1} MBE= 260 kg ha^{-1} d= 0.93

Figure 2. Performance in the calibration of the CSM-CROPGRO-Dry bean model to simulate total, stem, and leaf biomass accumulations over the time for the

common bean cultivars IAC Imperador (A) and IPR Campos Gerais (B) under irrigation level L4 in 2019

Regardless of the cultivar and plant part, the model showed accuracy above 95% for simulating biomass accumulation over time. Furthermore, low error (RMSE) and bias (MBE) were observed in underestimating the field-observed total biomass accumulation. CROPGRO model was highly accurate during its calibration.

During validation, the model was also highly accurate to simulate grain yield, biomass accumulation at physiological maturity, N export by grain, and phenological stage dates for both common bean cultivars (Figure 3). Except for biomass accumulation, all other parameters were simulated with high accuracy by the model, with precision (R^2) above 75%, as well as low errors and bias. Although simulation accuracy was lower for biomass accumulation, the model can be considered satisfactory for both cultivars. It has accuracy close to 70%, an error of about 950 kg ha^{-1}, and underestimate the bias of biomass accumulation by 500 kg ha^{-1} for IAC Imperador and by 800 kg ha^{-1} for IPR Campos Gerais.

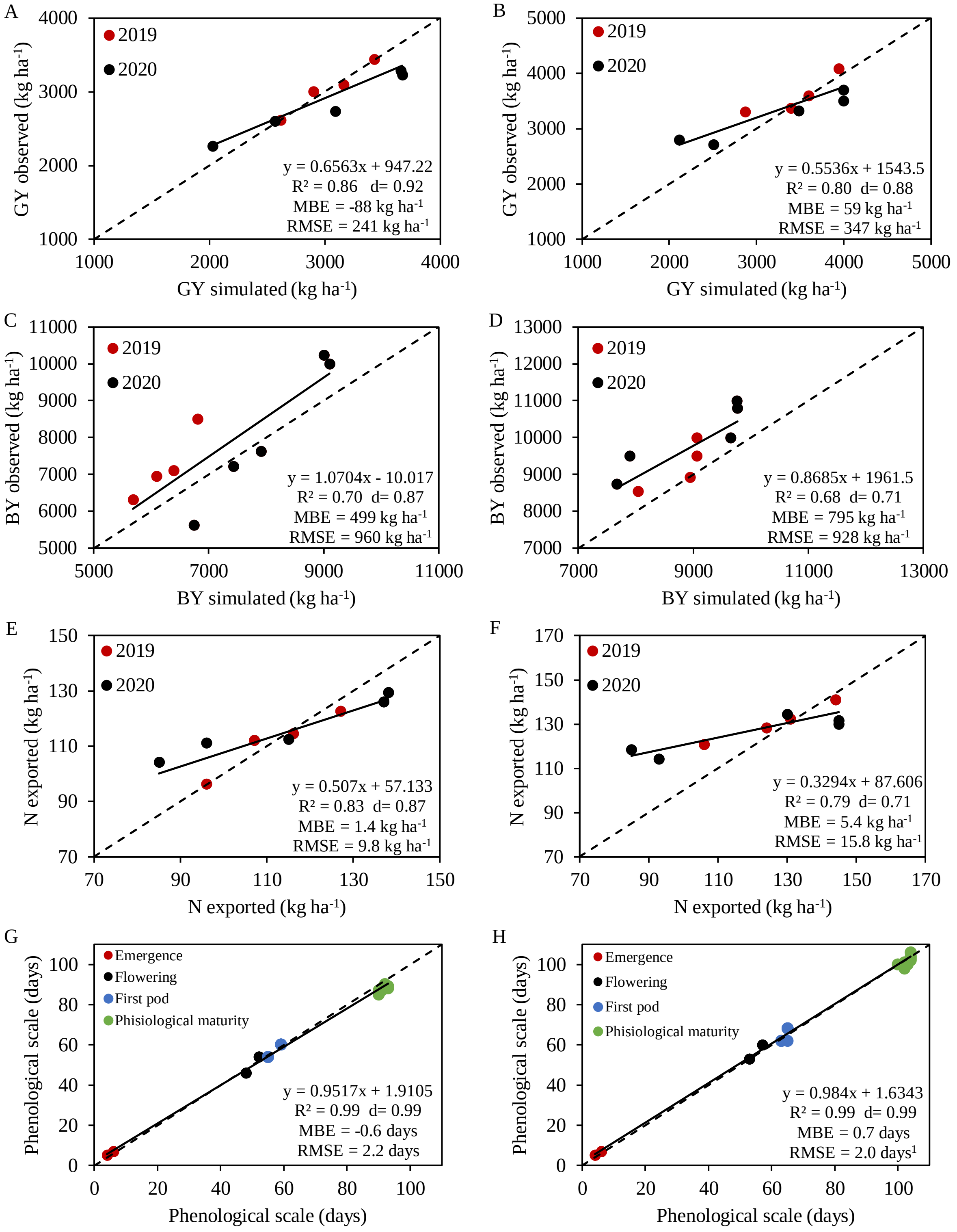


Figure 3. Performance in the validation of the CSM-CROPGRO-Dry bean model to simulate grain yield (GY – A and B), total biomass accumulation (BY – C and D), nitrogen exports (E and F), and phenological stage dates (G and H) in the common bean cultivars IAC Imperador (A, C, E and G) and IPR Campos Gerais (B, D, E and H)

The long-time simulation in treatment L1 (54% ETc) showed that for IAC Imperador sowing from April 15 onwards promotes highly variable GY, while between March 1 and April 1 provides higher and more uniform GY among years (Figure 4A).

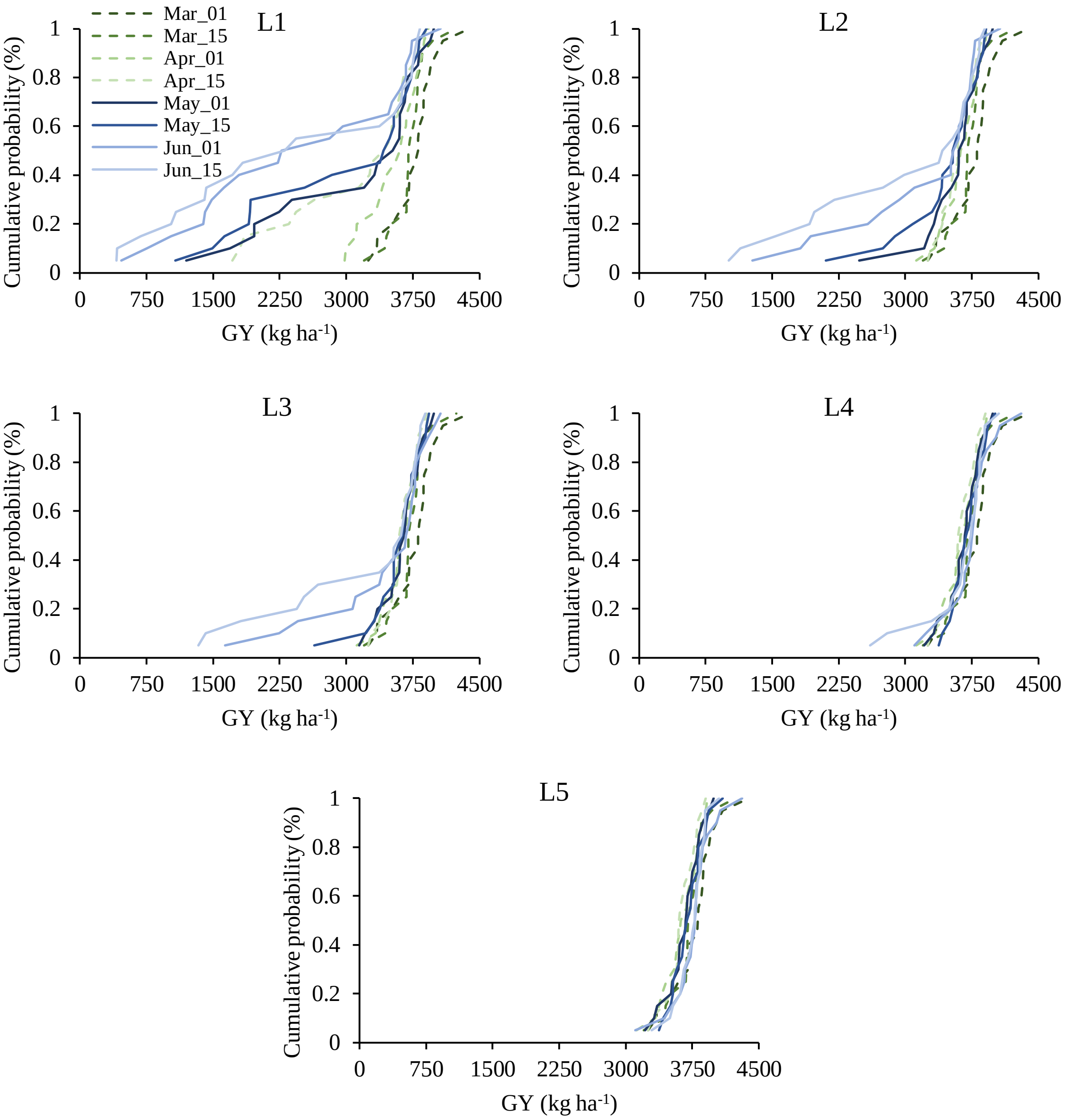


Figure 4. Cumulative probability of common bean grain yield for the cultivar IAC Imperador simulated for a long-term (20 years) as a function of sowing date for each level of irrigation studied. L1: 54%; L2: 71%, L3: 77%; L4: 100%; L5: 132% of crop evapotranspiration (ETc)

GY values were above 3,000 kg ha^{-1} for winter crops under L1 with sowing until April 1 in all simulated years. Something similar occurred in L2 and L3, wherein sowing from May 1 and May 15 onwards, respectively, increased GY variability for the cultivar IAC Imperador. For higher irrigation levels (L4 and L5), GY values were above 3,000 kg ha^{-1} in virtually all years evaluated, regardless of the sowing date. Under these depths, GY values were similar among the sowing dates simulated in the model.

IPR Campos Gerais GY varied widely among the years under deficit irrigation (L1) in sowings from April 1 onwards, which is 15 days before that observed for IAC Imperador (Figure 5A). Under such management, sowing dates promoting less GY variability among the years were March 1 and 15. For these dates, all evaluated years showed GY above 3600 kg ha^{-1}. Under L2 and L3, GY were mostly variable among the years for sowing from May 1 and May 15, respectively. Except for the sowing on June 15 under L4, higher irrigation levels (L4 and L5) promoted low GY variability, regardless of the sowing date, and all years showed GY above 3300 kg ha^{-1}.

From the descriptive analysis of model-simulated maximum, minimum, and average GY in the long-term analysis for the IAC Imperador cultivar (Table 5), GY were similar among all irrigation managements until the sowing date of April 1. From April 15 onwards, L1 showed relevant differences, with minimum and average GY being significantly lower than those observed in L4 and L5 managements. The same reasoning can be attributed to L2 and L3 from sowing on May 15 and June 1, respectively. Between L4 and L5, no relevant GY differences were observed, regardless of the sowing date. Differences between maximum and minimum GY averages among the simulated dates as a function of the irrigation managements L1, L2, L3, L4, and L5 in the 20 years were 58, 27, 18, 4, and 4%, respectively.

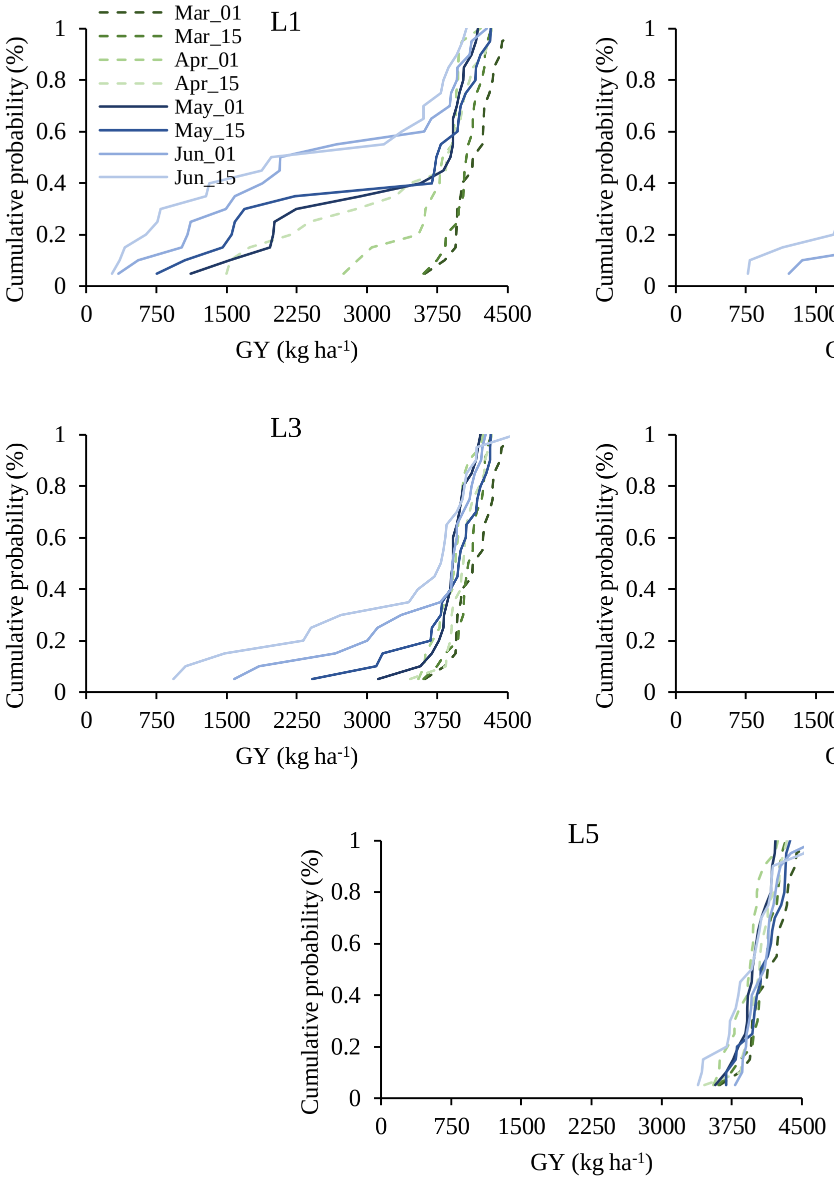


Figure 5. Cumulative probability of common bean grain yield for the cultivar IPR Campos Gerais simulated for a long-term (20 years) as a function of sowing date for each level of irrigation studied. L1: 54%; L2: 71%, L3: 77%; L4: 100%; L5: 132% of crop evapotranspiration (ETc)

Table 5. Maximum, minimum, and average yields simulated for long-term in the CSM-CROPGRO-Dry bean model for different irrigation levels and sowing dates (SD) in the common bean cultivars IAC Imperador (determinate) and IPR Campos Gerais (indeterminate).

SD	IAC Imperador														
	Maximum GY					Minimum GY					Average GY				
	L1	L2	L3	L4	L5	L1	L2	L3	L4	L5	L1	L2	L3	L4	L5
Mar 01	4389	4389	4389	4389	4389	3252	3252	3252	3252	3252	3771	3775	3775	3775	3775
Mar 15	4239	4239	4239	4239	4239	3201	3201	3201	3201	3201	3715	3715	3715	3715	3715
Apr 01	3924	3924	3924	3924	3924	2985	3122	3122	3122	3122	3534	3629	3629	3629	3630
Apr 15	3904	3904	3904	3904	3904	1716	3252	3252	3253	3253	3133	3594	3622	3622	3622
May 01	3987	3987	3987	3987	3987	1198	2478	3145	3216	3216	3112	3564	3625	3658	3658
May 15	3907	3908	3933	4013	4093	1074	2103	2638	3377	3377	2950	3449	3580	3698	3703
Jun 01	4065	4065	4065	4310	4310	465	1277	1633	3105	3105	2484	3217	3424	3727	3764
Jun 15	3833	3894	3894	4052	4052	413	1011	1335	2606	3294	2389	2980	3193	3628	3742
SD	IPR Campos Gerais														
	Maximum GY					Minimum GY					Average GY				
	L1	L2	L3	L4	L5	L1	L2	L3	L4	L5	L1	L2	L3	L4	L5
Mar 01	4636	4636	4636	4636	4636	3619	3619	3619	3619	3619	4151	4156	4156	4156	4156
Mar 15	4327	4327	4326	4327	4327	3606	3606	3606	3606	3606	4058	4078	4078	4078	4078
Apr 01	4211	4243	4242	4243	4243	2750	3551	3551	3551	3551	3720	3908	3908	3908	3908
Apr 15	4338	4338	4338	4338	4338	1496	3394	3458	3459	3459	3386	3978	4027	4037	4037
May 01	4184	4210	4210	4214	4214	1119	2405	3118	3570	3570	3266	3790	3893	3979	3979
May 15	4322	4322	4322	4375	4374	750	1946	2413	3690	3690	3121	3709	3869	4072	4084
Jun 01	4284	4268	4268	4667	4667	344	1209	1578	3372	3784	2570	3365	3602	4041	4090
Jun 15	4062	4570	4594	4594	4594	274	774	932	2396	3389	2348	3063	3296	3812	3936

SD: sowing date; L1: 54%; L2: 71%, L3: 77%; L4: 100%; L5: 132% of crop evapotranspiration (ETc)

As for IPR Campos Gerais, maximum, minimum, and mean GY values were similar among the irrigation managements until sowing on March 15. From April 1 onwards, GY in L1 was lower than those of L4 and L5. The same was verified for L2 and L3 on sowing dates from May 1 and May 15 onwards, respectively. GY values were similar between L4 and L5 on all sowing dates except June 15, when GY values were higher for L5. Differences between maximum and minimum GY average among the simulated dates as a function of L1, L2, L3, L4, and L5 for cultivar IPR Campos Gerais in the 20 years were 77, 36, 26, 9, and 6%, respectively.

For both cultivars, deficit irrigation management (L1, L2, and L3) showed a significant correlation ($p < 0.05$) between GY and all meteorological factors studied, before and after flowering (Table 6). Conversely, L4 and L5 had significant correlations of GY especially with global solar radiation (GSR). GY of both cultivars under L1, L2, and L3 managements had an indirect correlation with mean temperature after flowering, wind speed before and after flowering, and GSR after flowering, that is, as the averages of these meteorological factors increased, GY reduced. Both cultivars under L4 and L5 had a direct correlation between GY and GSR before and after flowering. Of these, the highest correlations were after flowering. When compared, the cultivar IPR Campos Gerais showed a significant correlation between GY and accumulated rainfall before flowering, while IAC Imperador did not.

Table 6. Pearson linear correlation of meteorological factors (mean temperature, mean relative humidity [RH], rainfall, wind velocity, and global solar radiation [GSR]) with grain yields of the common bean cultivars IAC Imperador and IPR Campos Gerais under different irrigation levels simulated by CSM-CROPGRO-Dry bean model.

IAC Imperador	Temperature		RH		Rainfall		Wind speed		GSR	
	BF	AF	BF	AF	BF	AF	BF	AF	BF	AF
L1	0.48**	-0.23**	0.52**	0.62**	0.52**	0.32**	-0.50**	-0.67**	0.30**	-0.37**
L2	0.33**	-0.29**	0.42**	0.47**	0.36**	0.17*	-0.39**	-0.59**	0.23**	-0.33**
L3	0.24**	-0.26**	0.34**	0.37**	0.30**	0.11^{ns}	-0.32**	-0.51**	0.20*	-0.24**
L4	0.07^{ns}	0.05^{ns}	0.07^{ns}	-0.01^{ns}	0.13^{ns}	-0.10^{ns}	-0.02^{ns}	-0.12^{ns}	0.17*	0.45**
L5	0.02^{ns}	0.05^{ns}	-0.04^{ns}	-0.16*	0.05^{ns}	-0.14^{ns}	0.12^{ns}	0.07^{ns}	0.18*	0.44**
IPR Campos Gerais	Temperature		RH		Rainfall		Wind speed		GSR	
	BF	AF	BF	AF	BF	AF	BF	AF	BF	AF
L1	0.48**	-0.22**	0.54**	0.65**	0.55**	0.35**	-0.51**	-0.67**	0.28**	-0.39**
L2	0.36**	-0.29**	0.47**	0.54**	0.40**	0.23**	-0.41**	-0.60**	0.23**	-0.38**
L3	0.29**	-0.27**	0.40**	0.46**	0.35**	0.18*	-0.36**	-0.54**	0.20*	-0.34**
L4	0.12^{ns}	-0.08^{ns}	0.17*	0.16*	0.21*	0.01^{ns}	-0.06^{ns}	-0.17*	0.18*	0.40**
L5	0.09^{ns}	0.01^{ns}	0.08^{ns}	0.03^{ns}	0.16*	-0.06^{ns}	0.09^{ns}	0.01^{ns}	0.17*	0.42**

BF: before flowering; AF: after flowering; L1 – 54% ETc; L2 – 70% ETc; L3 – 77% ETc; L4 – 100% ETc; L5 – 132% ETc; ^{ns}(p>0.05); *(p<0.05); **(p<0.01)

Under no water stress (L4), each unit increase (1 MJ m^{-2} day^{-1}) in GSR after flowering in both cultivars, GY increased by 55 and 50 kg ha^{-1} for the cultivars IAC Imperador and IPR Campos Gerais, respectively (Figure 6).

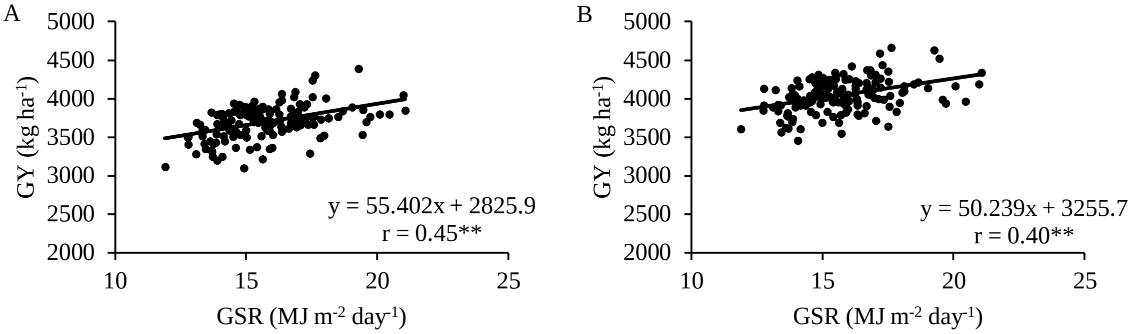


Figure 6. Grain yield (GY) variability for the cultivars IAC Imperador (A) and IPR Campos Gerais (B) as a function of daily global solar radiation (GSR) after flowering of common bean under 100% ETc irrigation (L4). **($p<0.01$)

In CSM-CROPGRO-Dry bean model calibration, growth and phenology-related genetic coefficients had to be higher than the standards in the DSSAT database, as the studied cultivars have high growth and yield. GY values of the cultivars IAC Imperador and IPR Campos Gerais (in experiment field) under L4 irrigation were 3800 and 4260 kg ha^{-1}, respectively (moisture = 0.13 kg kg^{-1}). These values are 64 and 83% higher than the average observed (2323 kg ha^{-1}) in 2019 for the winter crop in the study region (Conab, 2021), thus both cultivars have high agronomic performance. This is because both cultivars have longer cycles of 85 days after emergence (DAE) for IAC Imperador and 99 DAE for IPR Campos Gerais. González et al. (2021) reported that bean cultivars that take longer times to grain filling tend to have higher GY values.

The long cycles of the cultivars evaluated in this study can be attributed to the ideal growing conditions found in the experimental area. These conditions are related to high soil fertility, proper irrigation management, fertilization, and pest, disease, and weed control, besides climatically more favorable time for common bean cultivation, with milder temperatures and lower relative humidity. The association of all these factors provided ideal conditions for crop development and reaching high yields, directly interfering with the CSM-CROPGRO-Dry bean model calibration process.

For both cultivars, the error (RMSE) and bias (MBE) for the validation phase in this study were, on average, 72 and 92% lower than that observed by Heinemann et al. (2016), respectively. These authors tested the CSM-CROPGRO-Dry bean model for GY estimate accuracy for the cultivars BRS Radiante and Pérola and observed RMSE of 1053 kg ha^{-1} and MBE of 955 kg ha^{-1} for the validation phase. Thus, our calibration was adequate and promoted low errors in the model validation. Accuracy in our study was similar to that obtained by Oliveira et al. (2012). These authors observed an agreement index (d) for GY between model-simulated and field-observed values between 0.88 and 0.99, while in our study it ranged from 0.88 to 0.92.

Among all parameters used to calibrate and validate the model, total biomass accumulation over time and total biomass at physiological maturity were less accurate. For these, the CSM-CROPGRO-Dry bean model tended to underestimate values observed in the field. Santos et al. (2016) observed the same trend and reported that the same model underestimated, on average, by 1075 kg ha^{-1} biomass accumulation over the time during the calibration phase. Even though this variable had the lowest estimation accuracy, model accuracy was satisfactory in our study, with precision close to 70% and low error (RMSE ~ 950 kg ha^{-1}), with an error near 15% concerning average biomass accumulation. Additionally, this variable has less practical importance for common bean compared to others, such as GY. This underestimating trend for biomass accumulation by the model may be due to the ideal growth conditions under which plants were grown during the experimental period, as discussed above, favoring an ideal plant development throughout the cycle.

The long-term analysis showed that sowing until April 1 promoted high yields and low interannual variability under 54% ETc (L1) for IAC Imperador (determinate growth), whereas for IPR Campos Gerais it was verified for sowing until March 15. This 15-day difference in ideal sowing date between the cultivars is due to the cycle of each genotype. IPR Campos Gerais has an average cycle 15 days longer than does IAC Imperador. In tropical regions with dry winters in the southern hemisphere, as in the present study (Aw climate type), rainfall decreases significantly from April onwards, as seen in Table 2. Therefore, rainfall volumes in March and April minimize the impact of water deficit, providing good growth and yields for common bean. However, this effect may be greater on intermediate or late-cycle cultivars than on early ones, especially during grain filling. In short, to manage irrigation with 54% ETc, the sowing date for these genotypes must be no later than March 15, while for early cycle cultivars it can be extended until April 1.

Such a fact is seen in more moderate irrigation deficits (L2 and L3). Under these, the ideal sowing dates, that is, with high yields and low interannual variability, can be postponed by at least 15 days from that of L1. Both for IAC Imperador and IPR Campos Gerais, sowing on April 15 for L2 and on May 1 for L3 ensured satisfactory yields and low variability between years. As L2 and L3 promote a water deficit lower than does L1, the sowing date of both cultivars can be postponed without significantly reducing the interannual average and generating high variability. In this sense, L1 can be applied to the cultivar IAC Imperador when sowing is until April 1, as it ensures an average interannual yield similar to those observed for managements applying more water (L2 and L3), thus using less water. From that date until May 1, irrigation with a more moderate water deficit should be applied to ensure higher GY and lower interannual variability. For the cultivar IPR Campos Gerais, the reasoning is similar, only changing the date from April 1 to March 15.

In the same region of the present study, Coelho et al. (2021) performed a long-term simulation using the CERES-Barley model to optimize irrigation management (11, 31, 60, 87, and 100% ETc) in white oat as a function of eight sowing dates. These authors observed that even though white oat is highly sensitive to high temperatures, an irrigation level of 31% ETc promoted high average yields and low interannual variability in the sowing dates of April 1 and April 15, while irrigation without deficit obtained the highest yields on sowing dates between May 15 and June 15. According to the same authors, this occurs because water deficit restricts white oat development, increasing interannual variability rather than the sowing date itself. We observed the same for common bean, as poor irrigation with sowing from May onwards significantly reduced mean GY.

As for no water deficit irrigation (L4 and L5), high interannual variations in GY were not observed as a function of the sowing date, except for cultivar IPR Campos Gerais under L4 with sowing on June 15. These managements promoted small differences in average GY estimated as a function of the sowing date, whereas the highest averages were observed in the sowing dates of March 1 and June 1, for both cultivars. However, differences in estimated mean GY between sowing dates were small during the 20 years, with a maximum variation between 150 and 300 kg ha^{-1}. Moreover, the maximum yields estimated for IAC Imperador and IPR Campos Gerais under no stress irrigation (L4) were 4944 and 5257 kg ha^{-1}, respectively (grain moisture = 0.13 kg kg^{-1}), characterizing the yield potential of cultivars for winter crops in the study region. According to IAC (2021), the productive potential of the cultivar IAC Imperador can reach 4600 kg ha^{-1}, which is close to that observed in this study.

By using the CSM-CROPGRO-Dry bean model, Teixeira et al. (2017) observed that anticipation of sowing time for winter crops to March or April increases irrigation water-use efficiency in common bean cultivars. According to the authors, this occurs because the months of March and April still have significant amounts of rainfall, which reduces irrigation needs. It is noteworthy that these authors studied a region with the same climatic classification as ours (Aw). The authors also observed that the cultivar Pérola (indeterminate growth - normal cycle) had the highest yields for sowing dates between March 1 and 20 and between June 1 and 20, which is similar to what was observed in the present study. For the BRS Radiante cultivar (determinate growth, early cycle), the authors noted that the highest GY values were reached only for sowing dates between March 1 and 20.

Under a water deficit, the GY of both common bean cultivars correlated with all meteorological factors studied, both before and after flowering. This is due to the rainfall regime in the region under study, as higher yields were achieved in sowing seasons with higher rainfall and the lowest in times of lower rainfall (Table 2); therefore, GY is directly correlated with rainfall when plants were under irrigation deficit. The same is true for mean temperature before flowering, relative humidity before and after flowering, and GSR before flowering. This is because the higher GY values under these managements occurred when higher rainfall volumes are recorded, and consequently higher values of those meteorological factors. For mean temperature and GSR after flowering, as well as for wind speed in the entire crop cycle, such correlation was indirect. This is due to the contribution of June sowing dates in the correlation analysis, where the period after flowering of cultivars coincides between August and September, when temperatures, GSR, and wind speed are higher (Table 2), but yields under these irrigation management levels are low.

Under no deficit irrigation (L4 and L5), only GSR was correlated with GY, with higher values after flowering for both cultivars. The findings in the literature have indicated that low radiation availability during flowering and grain filling of common bean is more harmful to grain yields than during vegetative stages (Worku et al., 2004). This could also be verified in the present study, where the highest correlations between

GY and GSR were seen after the flowering of the cultivars. Hadi et al. (2006) found that common bean under low radiation availability have the number of grains per pod and grains per plant reduced. Likewise, Acosta-Gallegos (1996) demonstrated that reductions in GSR cause common bean yield reductions.

Thus, according to the long-term simulation, the common bean sowing at times in which the flowering and grain filling periods coincide with the month with the lowest GSR should be avoided for irrigation management without deficit. For the conditions of the present study, this month is, especially, June (Table 2). Regarding irrigation with excess water (L5), relevant differences were found in GY compared to L4 only for the cultivar IPR Campos Gerais at sowing on June 15, generating less interannual variability. Therefore, only in this situation, excess water irrigation may be more feasible to ensure less interannual GY variability, as for the other treatments tested, excess water did not generate increases in GY compared to L4, increasing water consumption without positive effects on GY.

It is worth noting that the direct correlation between GSR and GY in this study was mostly due to the experiment being carried out in the winter. During this time of year, in the study region, the climate is favorable for the growth and development of common bean, that is, has milder temperatures and lower relative humidity, rainfall, and GSR than in the spring/summer. For plants with a C3 photosynthetic pathway, the optimal temperatures for plant growth are close to 28 °C, with a maximum of 32 °C (Taiz et al., 2017), from which photosynthesis significantly reduces due to impairment of Rubisco enzyme, starting the photorespiration process, that is, the synthesized energy is consumed in photorespiration. According to Didonet and Silva (2004), the ideal temperature range for the growth and development of common bean is from 12 to 30 °C, with GSR between 13 and 22 MJ m^{-2} day^{-1}. If correlation analysis had been performed using data from the entire year, an inverse correlation would likely occur between temperature and GY and, as the temperature is directly associated with GSR, this would also indirectly correlate with GY.

Notably, defining an optimal sowing date for common bean must also consider previous and following crops to be grown in the same area. This is because the ideal sowing date for given irrigation management in common bean can interfere with the sowing time of other crops, thus affecting GY and producer income.

6.4 Conclusions

The CSM-CROPGRO-Dry bean model showed high accuracy to simulate the growth and yield of the common bean cultivars. To bring forward the sowing date for winter season (March/April), irrigation can be managed with a regulated water deficit, without significantly affecting grain yield, as higher rainfall occurs at this time of the year. For deficit irrigation, the sowing date should be limited to May 1, and, depending on the water deficit, indeterminate growth cultivars (normal cycle), such as IPR Campos Gerais, should be sown 15 days before the cultivars of determinate growth (early cycle), such as IAC Imperador, thus ensuring satisfactory yields. For sowing from May 15 onwards, irrigation must be managed without a deficit for both cultivars. Moreover, for irrigation without water deficit (L4), sowing dates should be avoided when the flowering and grain filling periods would coincide with times of low global solar radiation (GSR), for the conditions studied, especially the month of June. This is because this meteorological factor is the one that most correlates with grain yield for both common bean cultivars studied. Grain yields of the cultivars IAC Imperador and IPR Campos Gerais increase by 55 and 50 kg ha^{-1} for each increment of 1 MJ m^{-2} day^{-1} in GSR.

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CHAPTER 7 - Yield forecast of common bean cultivars with contrasting growth habits using spectral indices: applications, models accuracy and evaluation period[6]

ABSTRACT: This study aimed to analyze and compare the accuracy of models to forecast the grain yield (GY) of common bean cultivars with contrasting growth habits using spectral indices. The analyses were performed in southeastern Brazil from 2019 to 2020. The common bean cultivars used were IAC Imperador and IPR Campos Gerais, which have determinate and indeterminate growth habits, respectively. The plants were grown under five irrigation levels to generate variability. The normalized difference vegetation (NDVI) and leaf chlorophyll (LCI) indexes were measured at the following phenological stages: V_4 (third trifoliate leaf), R_5 (pre-flowering), R_6 (full flowering), and R_8 (grain filling). The spectral indices were used individually for each phenological stage and associated with linear models (SLR) and artificial neural networks (ANN) to forecast GY. The data generated were used for model calibration in 2019 and validation in 2020. Then, stratified models by cultivar and general models were established using data from both cultivars. The accuracy of NDVI-based GY forecasting for both models (stratified and general) was satisfactory ($R^2 = 0.64$; RMSE $= 0.37$ Mg ha^{-1}; MBE $= -0.14$ Mg ha^{-1}) but poor for LCI forecasting. The association of the two indices in a single model does not significantly increase the accuracy compared to the NDVI-only model. The highest accuracies were observed at reproductive phenological stages, mainly R_6. The ANNs did not increase GY forecasting accuracy compared to SLR. NDVI-based remote sensing is feasible to forecast and monitor common bean yield potential using cultivar-specific and general models.

Keywords: *Phaseolus vulgaris* L.; NDVI; portable chlorophyll meter; remote sensing; artificial neural network.

7.1 Introduction

Common bean (*Phaseolus vulgaris* L.) has high socioeconomic importance worldwide. It is grown in more than 100 countries, with a planted area exceeding 30 million hectares (FAO, 2019). Brazil is one of the world's largest producers, with an area of about 1.6 million ha, total production of 2.4 million Mg, and a mean yield near 1.5 Mg ha^{-1} (Conab, 2021). Common bean can be grown for up to three growing seasons a year in tropical regions such as Brazil, from high to low rainfall and temperature conditions. This climatic variability, together with different technology

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levels and cultivar availability, has led to yield differences. This, in turn, has made it difficult to define similar technologies between crops, crop predictions, and yield potential.

Some common bean cultivars have a determinate growth habit (i.e., vegetative development ceases at flowering), while others show an indeterminate growth habit (i.e., vegetative growth continues after flowering). Such differences directly affect plant structure, biomass production, sensitivity to biotic stresses, and crop yield (Emam et al., 2012; Lemos et al., 2015). As Brazil is the world's largest producer, common bean prices vary with production and population demand. In this sense, production must be forecast each season to set product prices, and therefore producer profitability. Such a forecast can also help producers define crop and production management.

In this sense, remote sensing has emerged as a precise and accurate technique for crop yield forecasting (Bredemeier et al., 2013; Coelho et al., 2019; Sandrini et al., 2019). Several remote sensing indices can be used in crop forecasting such as vegetation and chlorophyll indices. Among them, the normalized difference vegetation index (NDVI) is the best known and most used (Rouse et al., 1974). The NDVI reflects the physiological state of vegetation through spectral responses at red and near-infrared wavelength bands, showing high correlations with crop biomass, nitrogen accumulation, and yield (Monteiro et al., 2012; Sandrini et al., 2019). Leaf chlorophyll index (LCI) can be determined by many devices and indirectly indicate plant vigor and physiological state, which in turn directly affect crop yield (Schlichting et al., 2015; Maia et al., 2017; Coelho et al., 2019).

In the literature, few studies have used remote sensing to forecast common bean yields (Monteiro et al., 2012; Sandrini et al., 2019). New studies are thus needed to guide farmers and technicians to properly use such a tool. To this end, the best time for evaluating common bean must be defined, which can directly influence its accuracy (Coelho et al., 2019; Sandrini et al., 2019) and applicability of results obtained by farmers and government agencies. At the beginning of the crop cycle, a high correlation between spectral indices and yield can help define fertilizer rates, irrigation depths, and spray doses to improve yields in case of low yield potential. Such correlations can also aid to manage spraying and harvesting operations at the end of the crop cycle. Finally, regardless of the phenological stage, these correlations can help public agencies to forecast harvests and set prices.

Model type and its association with more than one spectral index may interfere with forecast accuracy. Artificial neural networks (ANNs) modeling has stood out for mimicking human brain functioning, learning from experiences, and interpreting data patterns (Haykin, 2001). This characteristic directly interferes with accuracy compared to other types of models, such as linear and non-linear models, ensuring more accurate forecast in some cases (Castro et al., 2017).

Our study proposed the following hypotheses: (i) satisfactorily accurate models can be established to forecast the yield of common bean cultivars with contrasting growth habits using spectral indices, (ii) the phenological stage alter forecast accuracies, and (iii) artificial neural networks have the highest forecast accuracy. Given the above, this study aimed to analyze and compare the accuracy of models to forecast the grain yield of common bean cultivars with contrasting growth habits from spectral indices (NDVI and leaf chlorophyll index).

7.2 Material and methods

The experiment was carried out in the winter growing season of 2019 and 2020 at the São Paulo State University (Unesp), School of Agricultural and Veterinarian Sciences, Jaboticabal, São Paulo, Brazil, close to the geographical coordinates 21°14′44″ S and 48°17′00″ W, with an altitude of 545 m. The regional climate, according to the Köppen classification, is Aw, that is, a tropical climate with a dry winter, summer rains, an average annual temperature of 22 °C, and average annual precipitation of 1,425 mm.

The soil in the experimental area is classified as an Oxisol (Soil Survey Staff, 2014). Three undisturbed and disturbed soil samples were collected for the physical characterization of the experimental area before sowing the experiment in 2019 (Table 1). Fifteen simple soil samples were collected 30 days before sowing the experiment in each year, forming a composite sample for fertility analysis (Table 2).

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

Layer (m)	Ds g cm^{-3}	Moisture FC $m^3\ m^{-3}$	Moisture PWP $m^3\ m^{-3}$	Clay g kg^{-1}	Silt g kg^{-1}	Sand g kg^{-1}
0.00–0.20	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) of the experimental area in 2019 and 2020.

Year	pH	H+Al	Al	K	Ca	Mg	SB	CEC	V
	$CaCl_2$	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.

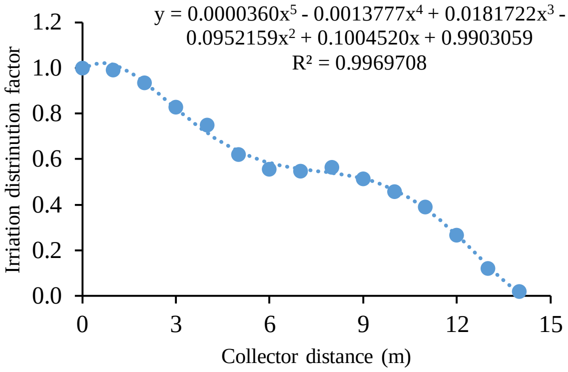
Two common bean cultivars, of the Carioca commercial group, with contrasting growth types, were used, namely IAC Imperador and IPR Campos Gerais. The first has a determinate growth habit (Type I), erect architecture, and a 75-day cycle, while the latter has an indeterminate growth habit (Type II), erect architecture, and a mean cycle of 90 days.

Sowing was carried out mechanically on May 7, 2019, and May 18, 2020, with a density of 240,000 plants ha^{-1} and inter-row spacing of 0.45 m. The area had been previously cultivated with corn, using a no-till seed-cum-fertilizer drill. The corn hybrid P4285VYHR was used in both years, with a density of 75,000 plants ha^{-1} and inter-row spacing of 0.90 m.

Pre-sowing fertilization was based on soil analysis (Table 2) and according to Ambrosano et al. (1997). It consisted of 200 kg ha^{-1} of the 04–20–20 formula in both years, providing 8 kg ha^{-1} N, 40 kg ha^{-1} P_2O_5, and 40 kg ha^{-1} K_2O. Topdressing was performed at the V_{4-3} stage, which is characterized by the third trifoliate leaf fully expanded (Fernández et al., 1985). This consisted of applying urea at 100 kg ha^{-1} N (Ambrosano et al., 1997) 0.10 m apart from sowing rows at 19 and 21 days after emergence (DAE) in 2019 and 2020, respectively.

The experimental design used was strip-plot. The study factors were five irrigation levels and two common bean cultivars, with four replications. Each subplot had 15 rows of beans, with a dimension of 6.75 m long and 2.4 m wide. The first row of beans at each end and the initial 50 cm of the central rows were considered as borders. Six out of the remaining 13 cultivation rows were used to forecast yield and the other seven for destructive analysis.

The line-source sprinkler system was used, allowing the distribution of the irrigation water with variable application depths as the treatment moves away from the central sprinkler line (Hanks et al., 1976). A field test enabled the definition of the distribution fractions of the sprinkler precipitation (Figure 1). In model fit, the regression that generated the highest precision (R^2) was used, aiming to estimate the most accurate irrigation distribution factor possible in each treatment. Senninger 4023-2 sprinklers and ¾″ M 08Qx05 nozzles were used spaced every 6 m on the central line. The water application intensity of the sprinklers was measured in the field in tests with collectors placed at 1 m from each other up to the limit distance of water application by the sprinklers in a line perpendicular to the irrigation line, with four replications.



Distance (m)	Treatment	Irrigation distribution factor
0.00–2.40	L5	1.002 (132%)
2.40–4.80	L4	0.754 (100%)
4.80–7.20	L3	0.584 (77%)
7.20–9.60	L2	0.532 (70%)
9.60–12.00	L1	0.407 (54%)

Figure 1. Sprinkler irrigation distribution factor as a function of the distance from the irrigation line, with sprinklers spaced at 6 m from the line, obtained in field tests. Service pressure: 250 kPa

For study purposes, the treatments consisted of five irrigation levels (L1, L2, L3, L4, and L5), which were set up after the establishment of the water application regression by the sprinkler line (Figure 1). The L4 level was used as a standard, receiving 100% of the water required by the bean crop. The L5 level received excess water, with 132% of the water requirement by the bean, while the L3, L2, and L1 levels provided 77, 70, and 54% of the water requirement, respectively.

The irrigation management was carried out based on the crop water demand, according to the FAO 56 method, using climate data obtained daily from an automated agrometeorological station located 1,500 m from the experiment. The reference evapotranspiration (ETo) was estimated daily using the FAO 56 method (Allen et al., 1998). The evapotranspiration of the bean crop (ETc) was calculated using the product of ETo by the crop coefficients (Kc) (Allen et al., 1998). The used Kc values 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 from 1.15 to 0.35 (maturation). For the Kc range between 0.40 and 1.15, the values were interpolated daily up to the maximum value (1.15). The daily increment was calculated as the ratio of the difference between the Kc range (1.15 – 0.40) and the number of days between the initial Kc (0.40) and maximum Kc (1.15).

Irrigation was carried out when the water deficit in the area was equal to 18 mm. This water depth was calculated according to the soil physical attributes (Table 1) and the bean crop. The calculation considered an effective root depth of 0.25 m and a water availability factor of 0.40 (Allen et al., 1998). Two water depths of 15 mm were applied for the plant emergence considering a uniform initial stand in all treatments.

Average maximum and minimum temperatures during 2019 were 27.8 and 13.9 °C, respectively, with accumulated precipitation of 48.7 mm (Figure 2a and b).

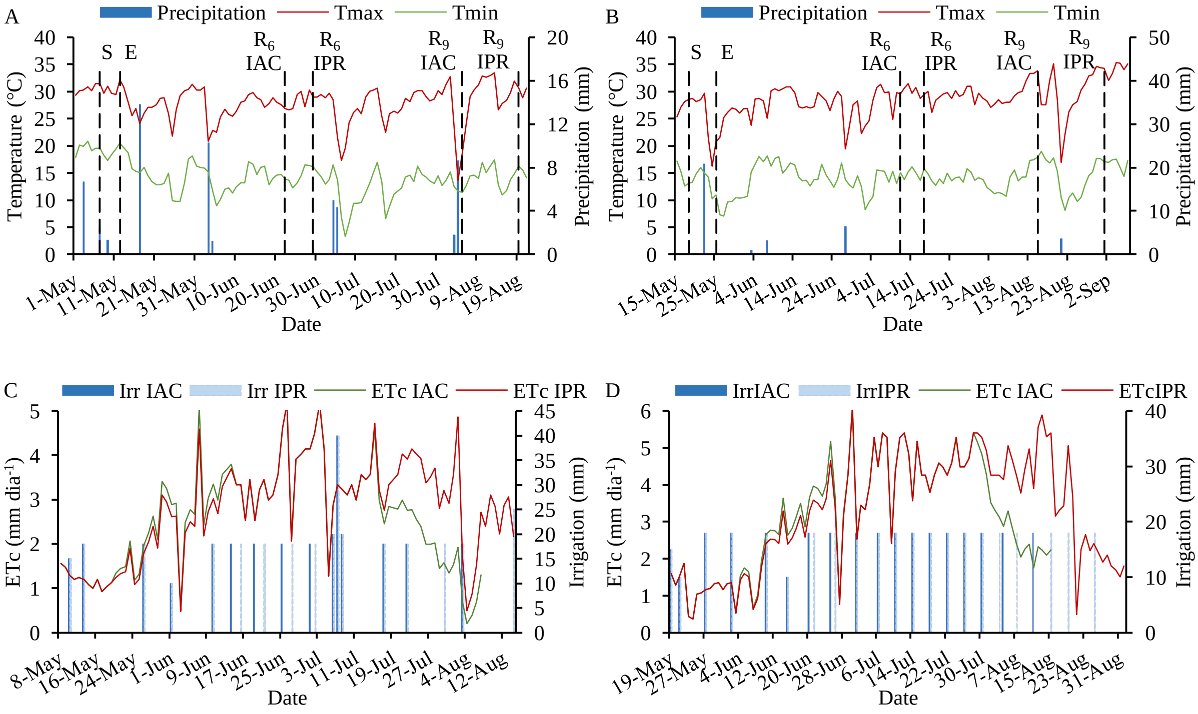


Figure 2. Daily maximum temperature, minimum temperature, precipitation (A and B), crop evapotranspiration, and irrigation (C and D) of common bean cultivars during the experimental period from May 7, 2019, to August 19, 2019 (A and C) and May 18 to September 1 (B and D). S: sowing; E: emergence; R_6: full flowering; R_9: physiological maturity; Irr: irrigation; ETc: crop evapotranspiration.

Low temperatures were observed in 2019, especially between July 5 and 8 and July 16 and 18. The minimum temperature was 3.3 °C on July 7, which caused frost in the experimental area. The number of trifoliate leaves reached after the frost in each cultivar was counted, with an average of 10% in the cultivar IAC Imperador and 12% in the cultivar IPR Campos Gerais. In 2020, the average maximum and minimum temperatures during the experimental period were 28.4 and 13.9 °C, respectively, with accumulated precipitation of 35 mm (Figure 2c and d). Minimum temperatures below 5 °C were not observed in 2020.

Grain yield was estimated by harvesting six useful rows from each plot, with moisture standardized at 0.13 kg kg^{-1}. Normalized difference vegetation (NDVI) and leaf chlorophyll (LCI) indexes were associated with grain yield (GY) to generate models for common bean GY forecasting by using remote sensing in the experimental plots. Forecast accuracy was compared using simple linear regression (SLR), multiple linear regression (MRL), and artificial neural network (ANN) models.

NDVI was measured by the ground sensor GreenSeeker HandHeld^{TM}. This is active and automatically generates NDVI (Eq. 1) from measurements of spectral response from red (650 nm) and near-infrared (770 nm) bands. Data were collected by manually passing the sensor 0.50 m above the crop canopy. Again, the six useful rows of each plot were used to estimate grain yield.

$$\mathrm{NDVI} = \frac{\rho\mathrm{nir} - \rho\mathrm{r}}{\rho\mathrm{nir} + \rho\mathrm{r}} \quad (1)$$

Wherein: NDVI is the normalized difference vegetation index, ρnir is the near-infrared reflectance (770 nm), and ρr is the red reflectance (650 nm).

Chlorophyll index (LCI) was measured using the Falker ClorofiLOG 1030 portable chlorophyll meter, which is a dimensionless value. This index is proportional to laboratory measurements in chlorophyll grams per leaf gram; however, it varies with the studied species. The measurements were taken at the middle of five leaves per plot (15 readings per plot), using the third trifoliate fully expanded from the apex down (Maia et al., 2017), totaling 20 plants per treatment.

In 2019, the same leaves used for LCI were also used to determine chlorophyll contents by a destructive method (Arnon, 1949) and N contents (Bataglia et al., 1983) at each phenological stage. This was performed to correlate LCI with the actual chlorophyll and N contents, besides correlating chlorophyll and N contents. The purpose was to verify whether the portable chlorophyll meter was able to monitor the nutritional status of common bean.

Leaf area index (LAI) was determined in three plants of each subplot throughout crop cycles, using an LI-COR LI-3100C area meter. It was estimated from the leaf area per plant and for the entire plant population in each subplot. Equations were plotted in each subplot to estimate LAI throughout the crop cycle. The generated equation was used to estimate LAI on the evaluation days and associate them with spectral indices to model NDVI and LCI as a function of LAI. For this purpose, regression analyses were performed. The best fit of NDVI variation as a function of LAI was by quadratic-plateau response model and LCI variation by quadratic model. This analysis was performed to assess and verify NDVI saturation as a function of LAI, which has already been reported in the literature (Cao et al., 2017).

SLR and MLR were used to verify the accuracy of models to forecast common bean GY and nutritional status as a function of NDVI and LCI. These indices were associated with GY to generate equations. The accuracy of models using data of both cultivars (general models) was compared with models for each cultivar (specific models). We also verified whether forecast accuracy was increased with the association of NDVI with LCI in the same model.

NDVI and LCI readings were performed at four phenological stages, namely: V_4, R_5, R_6, and R_8 (Fernández et al., 1986). In 2019, cultivar IAC Imperador plants were evaluated at 24, 36, 43, and 66 days after emergence (DAE), while IPR Campos Gerais at 24, 36, 49, and 86 DAE. In 2020, IAC Imperador was evaluated at 26, 36, 48, and 67 DAE, and IPR Campos Gerais at 26, 36, 53, and 83 DAE. Each replication comprised an average of indices, which was correlated to the GY of each plot for model analysis. The models were calibrated with data obtained in the first year (2019), using indices individually and in an association. From this, the models generated for each index and phenological stage were tested for their generalizability (validation) with data from the second year (2020). The accuracy of the general model (with data from both cultivars) for each index and stage was compared to the cultivar-specific models.

Forecast accuracy from SLRs and MLRs were compared with models by artificial neural networks (ANNs). The same procedures described above were performed for SLRs and MLRs for calibration and validation of ANNs. The software Statistica 7 was used to forecast the GY of common bean cultivars using ANNs. The networks were calibrated (trained) in Intelligent Problem Solver mode. This mode allows randomly training several ANNs with different architectures, returning the amount previously established based on those with the least error. For this, ANNs with two hidden layers were established with the number of neurons ranging from 6 to 50 in each layer, and 25 ANNs were returned by the program. The most accurate ANN was selected for analysis.

Multilayer perceptron ANNs were used for data calibration and validation. The variables were standardized before calibration. The used training algorithm was backpropagation (Haykin, 2001). The criterion for stopping the used calibration algorithm was the total number of cycles equal to 500 or a mean square error lower than 1%. The used activation function consisted of the hyperbolic tangent (Eq. 2).

$$f(v) = \frac{1 - e^{-av}}{1 + e^{-av}} \tag{2}$$

Wherein: $f(v)$ is the hyperbolic tangent activation function, a is the estimation of the parameter determining the hyperbolic tangent steepness, and v is the function activation potential.

The goodness of fit and performance of the models ($p<0.05$) was evaluated by the statistical indices adjusted coefficient of determination (R^2) (Cornell & Berger, 1987), root mean square error (RMSE), mean bias error (MBE), and Willmott’s agreement index (d) (Willmott, 1981). Outliers were removed according to the methodology proposed by Belsley et al. (1980), up to the limit of 10% of the total data.

7.3 Results and discussion

The descriptive statistics showed that the lowest variability of NDVI values for the IAC Imperador occurred at the R_6 phenological stage in both years, followed by R_8, R_5, and V_4, when considering the standard deviation and data range (Table 3). This pattern was not observed in the IPR Campos Gerais, as the lowest variability of NDVI values occurred at the stages R_8 in 2019 and R_6 in 2020.

Comparing the years, the variability in the maximum NDVI value for the IAC Imperador was 23, 7, 2, and 2% at stages V_4, R_5, R_6, and R_8, respectively, while this interannual variation for the maximum value for the IPR Campos Gerais was 35, 11, 1, and 3%, respectively. The minimum NDVI value showed an interannual variation at stages V_4, R_5, R_6, and R_8 of 36, 8, 8, and 3%, respectively, for the IAC Imperador, and 77, 26, 2, and 28%, respectively, for the IPR Campos Gerais.

The leaf chlorophyll index (LCI) showed higher data variability than NDVI. The only pattern consisted of the lowest variability in LCI values for the IAC Imperador observed at the R_5 phenological stage in both growing seasons. The interannual variability of the maximum LCI value at phenological stages V_4, R_5, R_6, and R_8 reached 2, 16, 17, and 6% for the IAC Imperador and 1, 26, 21, and 5% for the IPR Campos Gerais, respectively. Moreover, the interannual variability of the minimum LCI value at phenological stages V_4, R_5, R_6, and R_8 was 4, 26, 22, and 4%, respectively, for the IAC Imperador and 11, 12, 22, and 6%, respectively, for the IPR Campos Gerais.

Grain yield (GY) of the IAC Imperador ranged from 2.76 to 4.48 Mg ha^{-1} in 2019 and 2.19 to 4.11 Mg ha^{-1} in 2020, generating a range of values of 1.73 Mg ha^{-1} in 2019 and 1.91 Mg ha^{-1} in 2020. Furthermore, the interannual variability for the minimum and maximum GY of the IAC Imperador was 26 and 9%, respectively. The GY of the IPR Campos Gerais ranged from 3.19 to 5.01 Mg ha^{-1} in 2019 and 2.53 to 4.49 Mg ha^{-1} in 2020, generating a range of values of 1.82 Mg ha^{-1} in 2019 and 1.96 Mg ha^{-1} in 2020. The interannual variability for the minimum and maximum GY of the IPR Campos Gerais was 26 and 12%, respectively.

Table 3. Descriptive statistics of NDVI and leaf chlorophyll index (LCI) in the common bean cultivars IAC Imperador and IPR Campos Gerais at each phenological stage evaluated in two years.

Variable	------------- V_4 – 2019-------------				------------- V_4 – 2020-------------			
	NDVI	NDVI	LCI	LCI	NDVI	NDVI	LCI	LCI
	IAC	IPR	IAC	IPR	IAC	IPR	IAC	IPR
Mean	0.842	0.864	39.74	37.46	0.661	0.560	40.75	42.14
Standard error of the mean	0.012	0.007	0.49	0.55	0.011	0.011	0.42	0.33
Standard error	0.055	0.033	2.21	2.45	0.047	0.048	1.87	1.47
Range	0.197	0.123	8.82	9.52	0.214	0.227	6.54	6.14
Minimum	0.709	0.781	35.56	35.14	0.521	0.441	36.96	38.92
Maximum	0.907	0.904	44.38	44.66	0.735	0.669	43.50	45.06
Variable	R_5 – 2019				R_5 – 2020			
	IAC	IPR	IAC	IPR	IAC	IPR	IAC	IPR
Mean	0.872	0.861	51.68	45.75	0.811	0.758	41.00	38.81
Standard error of the mean	0.010	0.006	0.37	0.61	0.008	0.009	0.39	0.31
Standard error	0.042	0.027	1.63	2.57	0.036	0.041	1.73	1.38
Range	0.154	0.113	4.96	10.80	0.148	0.187	7.60	4.66
Minimum	0.768	0.777	49.14	41.26	0.714	0.618	39.08	36.78
Maximum	0.922	0.890	54.10	52.06	0.861	0.805	46.68	41.44
Variable	R_6 – 2019				R_6 – 2020			
	IAC	IPR	IAC	IPR	IAC	IPR	IAC	IPR
Mean	0.861	0.867	49.23	47.79	0.851	0.860	41.86	38.88
Standard error of the mean	0.005	0.004	0.50	0.40	0.006	0.004	0.56	0.32
Standard error	0.022	0.015	2.14	1.71	0.028	0.016	2.50	1.44
Range	0.074	0.060	8.04	7.08	0.118	0.075	8.52	6.26
Minimum	0.814	0.825	45.84	44.16	0.754	0.806	37.46	36.34
Maximum	0.888	0.885	53.88	51.24	0.872	0.881	45.98	42.60
Variable	R_8 – 2019				R_8 – 2020			
	IAC	IPR	IAC	IPR	IAC	IPR	IAC	IPR
Mean	0.831	0.879	46.20	43.20	0.850	0.834	44.70	40.82
Standard error of the mean	0.005	0.003	0.74	0.63	0.008	0.012	0.61	0.58
Standard error	0.019	0.012	3.07	2.66	0.034	0.053	2.74	2.57
Range	0.079	0.043	10.94	8.24	0.114	0.206	9.54	8.02
Minimum	0.788	0.855	41.12	39.06	0.767	0.669	39.62	36.82
Maximum	0.867	0.897	52.06	47.30	0.881	0.874	49.16	44.84

The simple linear regression (SLR) to forecast GY from NDVI showed that the models generated at the V_4 stage were not significant for the forecast in the calibration phase (Table 4). All models were significant to forecast common bean GY ($p<0.05$) from the R_5 phenological stage. Cultivar-specific models showed higher precision (R^2)

than the general model, except for the cultivar IPR Campos Gerais at the R$_6$ phenological stage and the cultivar IAC Imperador at R$_8$ (Table 4). The highest precisions and lowest errors for GY forecasting were observed at R$_6$ for the general model, R$_5$ for the IAC Imperador model, and R$_8$ for the IPR Campos Gerais model. Regarding the overall mean of GY (3.91 Mg ha^{-1}), the minimum error of the general model at the R$_6$ stage (0.33 Mg ha^{-1}) corresponded to 8.7% of the mean value, while the IAC Imperador (3.66 Mg ha^{-1} at R$_5$) and IPR Campos Gerais (4.16 Mg ha^{-1} at R$_8$) showed minimum errors corresponding to 5.5 and 7.2% of the mean GY, respectively. The highest precision found for the IAC Imperador (0.85) was 33% higher than that found for the IPR Campos Gerais (0.64) in the calibration phase.

Table 4. Accuracy of simple linear regression models to forecast grain yield of common bean cultivars based on NDVI and leaf chlorophyll index (LCI).

Model	**Equation**	**R^2**	**p-value**	**RMSE Mg ha^{-1}**	**Equation**	**R^2**	**p-value**	**RMSE Mg ha^{-1}**
	V$_4$ – NDVI				V$_4$ - LCI			
General	GY = 1151*NDVI + 2927.6	0.01	0.54ns	-	GY = -49.05*LCI + 5802.7	0.05	0.15ns	-
IAC	GY = -107.1*NDVI + 3750.8	0.01	0.96ns	-	GY = 63.65*LCI + 1131	0.08	0.21ns	-
IPR	GY = -463.5*NDVI + 4558.2	0.01	0.90ns	-	GY = -63.38*LCI + 6532	0.10	0.17ns	-
	R$_5$ – NDVI				R$_5$ – LCI			
General	GY = 9879.3*NDVI - 4611.5	0.40	<0.001	0.42	GY = -83.33*LCI + 7949	0.36	<0.001	0.47
IAC	GY = 10985*NDVI - 5904.2	0.85	<0.001	0.19	GY = -98.79*LCI + 8722.3	0.12	0.14ns	-
IPR	GY = 12231*NDVI - 6307.9	0.51	<0.001	0.31	GY = -50.96*LCI + 6495.3	0.11	0.19ns	-
	R$_6$ – NDVI				R$_6$ – LCI			
General	GY = 22775*NDVI - 15728	0.63	<0.001	0.33	GY = -172.17*LCI + 12245	0.42	<0.001	0.40
IAC	GY = 20245*NDVI - 13748	0.79	<0.001	0.23	GY = -138.1*LCI + 10398	0.40	<0.01	0.35
IPR	GY = 22053*NDVI - 14905	0.55	<0.001	0.30	GY = -136.94*LCI + 10731	0.29	0.02*	0.36
	R$_8$ – NDVI				R$_8$ – LCI			
General	GY = 13276*NDVI - 7487.9	0.51	<0.001	0.37	GY = -105*LCI + 8604.1	0.38	<0.001	0.42
IAC	GY = 14565*NDVI - 8483.9	0.36	0.02*	0.36	GY = -47.58*LCI + 5863.1	0.09	0.23ns	-
IPR	GY = 32821*NDVI - 24724	0.64	<0.001	0.28	GY = -139.54*LCI + 10180	0.53	<0.001	0.34

**Significant at 0.01; *Significant at 0.05; ns-not significant; RMSE: root mean square error; R^2: coefficient of determination.

Just as the models using NDVI, those using leaf chlorophyll index (LCI) were not significant for GY forecasting at the V$_4$ phenological stage. However, unlike NDVI-based models, the cultivar-specific models for IAC Imperador at R$_5$ and R$_8$ and for IPR Campos Gerais at R$_5$ were not significant for GY forecasting. Moreover, GY forecasting accuracies based on LCI were lower than those observed for NDVI. The accuracy of the general model was closer to that of cultivar-specific, with its maximum at R_6, for LCI and NDVI. The highest accuracy for the models of the IAC Imperador and IPR Campos Gerais were observed at stages R_6 and R_8, respectively. Only the IAC Imperador showed a difference between the stage with higher accuracy based on NDVI (R_5) compared to LCI (R_6). The lowest error for the general model corresponded to 11% of the mean, a value higher than the minimum error due to NDVI. The lowest errors for GY of IAC Imperador and IPR Campos Gerais-specific models were 10.9 and 8.7%, respectively.

The association between NDVI and LCI in a single model by multiple linear regression (MLR) increased the forecast accuracy compared to SLR models, especially regarding the general model (Table 5).

Table 5. Accuracy of multiple linear regression models to forecast grain yield of common bean cultivars based on the association between NDVI and leaf chlorophyll index (LCI).

Model	Equation	R^2	p-value	RMSE Mg ha^{-1}
	V_4			
General	GY = 422.1*NDVI - 46.97*LCI + 5362.59	0.05	0.348	-
Cultivar IAC	GY = 465.0*NDVI + 66.12*LCI + 641.53	0.08	0.469	-
Cultivar IPR	GY = -1.371.3*NDVI - 66.71*LCI + 7841.7	0.11	0.365	-
	R_5			
General	GY = 10.062.5*NDVI - 78.37*LCI - 950.6	0.68	<0.001	0.32
Cultivar IAC	GY = 10.954.3*NDVI - 36.04*LCI - 4.012.9	0.87	<0.001	0.20
Cultivar IPR	GY = 12.477.9*NDVI - 6.88*LCI - 6.835.5	0.51	0.004	0.34
	R_6			
General	GY = 18.598.4*NDVI - 98.70*LCI - 7.327.9	0.72	<0.001	0.30
Cultivar IAC	GY = 19.197.4*NDVI - 33.61*LCI - 11.190.8	0.80	<0.001	0.24
Cultivar IPR	GY = 16.845.5*NDVI - 93.43*LCI - 5.899.3	0.64	0.001	0.25
	R_8			
General	GY = 9.327.24*NDVI - 66.74*LCI - 1.157.3	0.63	<0.001	0.35
Cultivar IAC	GY = 11.701.7*NDVI - 39.86*LCI - 4.303.9	0.43	0.045	0.38
Cultivar IPR	GY = 25.028.3*NDVI - 69.21*LCI - 14.908.6	0.78	<0.001	0.26

**Significant at 0.01; *Significant at 0.05; ns-not significant; RMSE: root mean square error; R^2: coefficient of determination.

The highest accuracy of the general model by MLR was obtained at the R_6

phenological stage, with this same stage for SLR models as a function of NDVI and LCI. The maximum accuracy of MLR for the IAC Imperador-specific model was observed at R_5, just as for SRL models. The increase in the forecast accuracy of GY by MLR was small for this cultivar compared to SLR models. The forecast accuracy of MLR for the IPR Campos Gerais-specific model showed a high increase compared to SLR. The maximum precision for MLR was 0.78 and the lowest error reached 0.26 Mg ha^{-1}, while SLR as a function of NDVI had a maximum precision of 0.64 and minimum error of 0.30 Mg ha^{-1}.

The use of artificial neural networks (ANNs) to forecast common bean GY through the same data and vegetation index (NDVI) used for SLR in the calibration phase resulted in higher forecast accuracy and lower error (Table 6). The maximum accuracy for the general models and the IPR Campos Gerais was obtained at stages R_6 and R_8, respectively, as observed for SLR. However, the accuracy of IAC Imperador-specific model at R_5 stage was similar to that at R_6 stage. Moreover, the cultivar-specific models were more accurate for GY forecasting than the general model, as observed for SLR. Different from SLR, the models calibrated at the V_4 stage were significant ($p<0.05$) for GY forecasting, with satisfactory accuracies for cultivar-specific models.

The association between LCI and models by ANNs to GY forecasting showed a high increase in the forecast accuracy (Table 6) compared to SLR. The accuracy of LCI-based model by ANNs for GY forecasting was similar to that of the NDVI-based model. Models by ANNs for GY forecasting from LCI were significant ($p<0.05$). The highest accuracy of the general model was obtained at the R_8 stage, whereas IAC Imperador and IPR Campos Gerais-specific models showed the highest accuracies at stages R_5 and R_8, respectively. The increase in accuracy of the GY forecasting models from LCI using ANNs was higher than models using NDVI compared to SRL models; therefore, the cultivar responses for LCI are more non-linear than for the vegetation index since ANNs present better performance for non-linear data.

Table 6. Accuracy of models by artificial neural networks (ANNs) to forecast grain yield of common bean cultivars based on NDVI, leaf chlorophyll index (LCI), and their association.

Model	No. of Neurons	R^2	p-value	RMSE	No. of neurons	R^2	p-value	RMSE	No. of neurons	R^2	p-value	RMSE Mg ha^{-1}
		V_4 – NDVI				V_4 - LCI				V_4 - NDVI x LCI		
General	06 – 01*	0.31	<0.01	0.45	50 - 28	0.26	<0.05	0.46	50 - 20	0.51	<0.001	0.38
IAC	50 – 30	0.53	<0.001	0.33	23 - 10	0.80	<0.001	0.22	50 - 35	1.00	<0.001	0.00
IPR	50 – 34	1.00	<0.001	0.00	50 - 14	0.40	<0.001	0.36	50 - 26	1.00	<0.001	0.00
		R_5 – NDVI				R_5 – LCI				R_5 - NDVI x LCI		
General	50 – 10	0.57	<0.001	0.36	50 - 28	0.40	<0.001	0.42	50 - 32	0.81	<0.001	0.24
IAC	50 – 25	0.88	<0.001	0.17	50 - 24	0.88	<0.001	0.17	50 - 31	0.88	<0.001	0.17
IPR	26 – 13	0.70	<0.001	0.24	50 - 26	0.47	<0.001	0.33	50 - 25	0.70	<0.001	0.24
		R_6 – NDVI				R_6 – LCI				R_6 - NDVI x LCI		
General	47 – 6	0.67	<0.001	0.31	50 - 33	0.40	<0.001	0.41	06 - 06	0.67	<0.001	0.31
IAC	50 – 29	0.91	<0.001	0.15	11 - 06	0.33	<0.01	0.40	50 - 25	0.91	<0.001	0.15
IPR	49 – 16	0.49	<0.001	0.27	50 - 29	0.45	<0.001	0.29	50 - 36	0.49	<0.001	0.27
		R_8 – NDVI				R_8 – LCI				R_8 - NDVI x LCI		
General	27 – 06	0.64	<0.001	0.33	50 - 22	0.58	<0.001	0.35	50 - 31	0.72	<0.001	0.29
IAC	50 – 29	1.00	<0.001	0.00	06 - 06	0.98	<0.001	0.01	50 - 28	1.00	<0.001	0.00
IPR	44 – 10	0.80	<0.001	0.22	50 - 25	0.88	<0.001	0.17	50 - 28	0.88	<0.001	0.18

*Numbers indicate the number of neurons in the first and second hidden layer, respectively. **Significant at 0.01; *Significant at 0.05; ns-not significant; RMSE: root mean square error; R^2: coefficient of determination.

The common bean GY forecasting as a function of NDVI associated with LCI (Table 6) based on the ANNs showed an increase in accuracy compared to MLR, with some models presenting a perfect fit (R^2 = 1 and RMSE = 0), as observed for cultivar-specific models at R_8. The maximum accuracy for the general model when associating both indices with ANNs was observed at the R_5 stage.

The validation of GY forecasting models through SLR from NDVI showed that cultivar-specific models were significant for forecasting at all phenological stages (Figure 3), while the general model was only not significant for GY forecasting at the R_5 phenological stage. The models were not significant for GY forecasting at the V_4 stage during the calibration phase and, therefore, this stage was not presented in the validation. The R_6 stage had the highest precision and lowest forecast error in the validation, regardless of the type of model. The accuracy of cultivar-specific models at this stage was similar to the general model, with a mean precision (R^2) of 64%, error

(RMSE) of 0.37 Mg ha^{-1}, and a trend (MBE) to overestimate yield by 0.14 Mg ha^{-1}. Although significant, the general and IAC Imperador-specific model at R_8 and IPR Campos Gerais-specific model at R_5 and R_8 showed no satisfactory accuracy, which was related to their high error and trend. In addition to all models at R_6, only the model of the cultivar IAC Imperador at R_5 showed satisfactory accuracy.

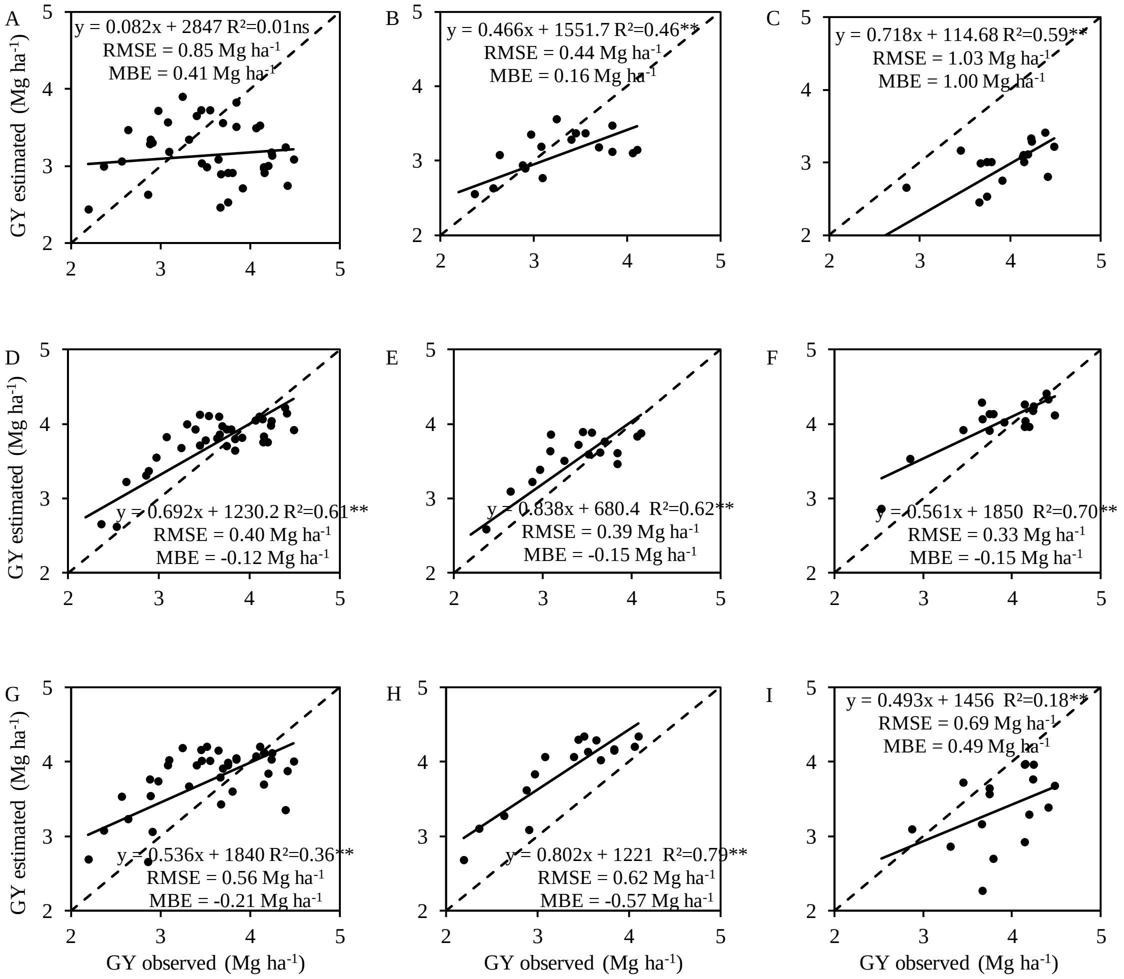


Figure 3. Yield forecasting of common bean cultivars based on NDVI using simple linear regression. General (A, D, and G) and cultivar-specific model for the cultivars IAC Imperador (B, E, and H) and IPR Campos Gerais (C, F, and I) at phenological stages R_5 (A, B, and C), R_6 (D, E, and F), and R_8 (G, H, and I). ns: not significant; *Significant at 5% probability; **Significant at 1% probability.

The accuracy in validating models based on NDVI presented similar indices (Figure 4) to those obtained by SLR when using ANNs (Figure 3). In this situation, the highest accuracies were also observed at the R_6 stage. The mean precision of the models at the R_6 stage was 63%, with an error of 0.35 Mg ha^{-1} and a trend to overestimate the values by 0.18 Mg ha^{-1}, with these values being similar to those obtained by SLR. Thus, ANNs did not significantly contribute to improving the forecast accuracy relative to SLR.

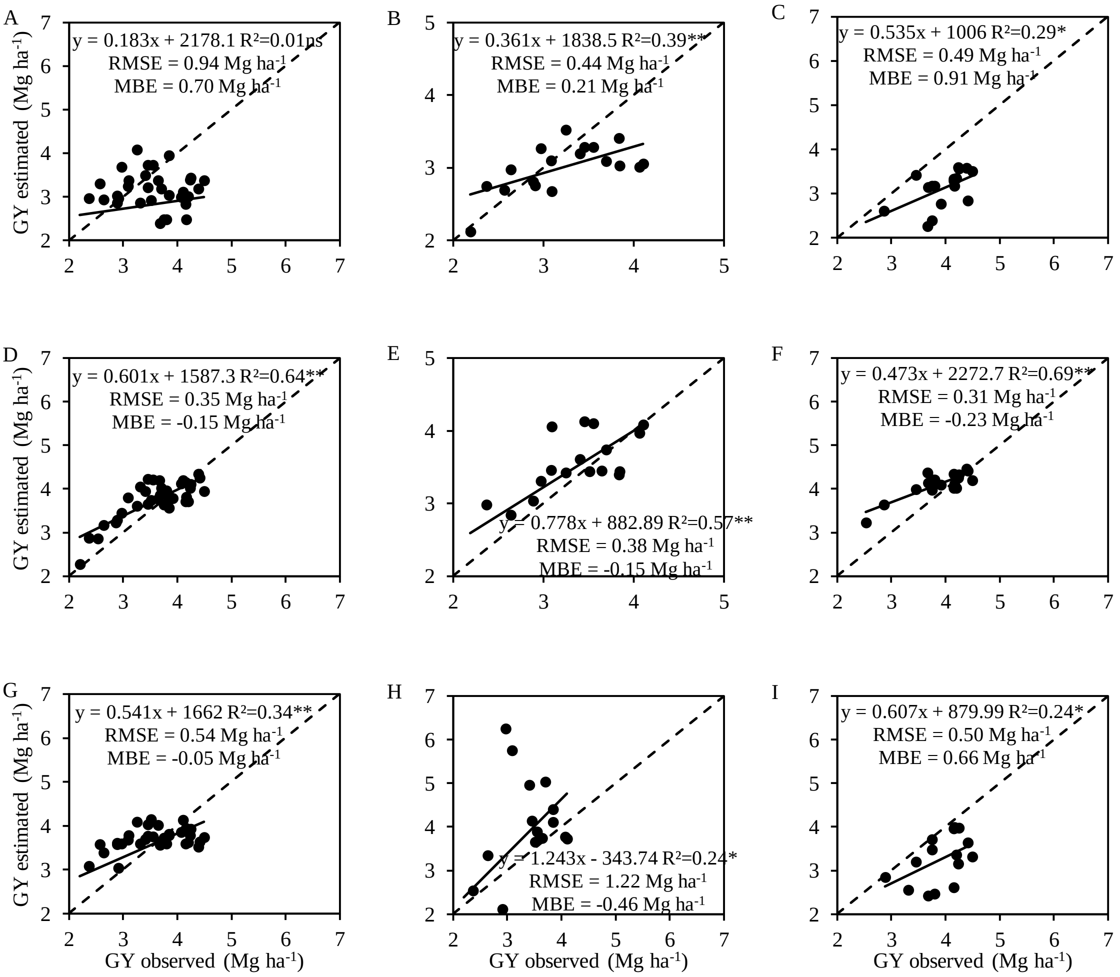


Figure 4. Yield forecasting of common bean cultivars based on NDVI using artificial neural network modeling. General (A, D, and G) and cultivar-specific model for the cultivars IAC Imperador (B, E, and H) and IPR Campos Gerais (C, F, and I) at phenological stages R_5 (A, B, and C), R_6 (D, E, and F), and R_8 (G, H, and I). ns: not significant; *Significant at 5% probability; **Significant at 1% probability.

The use of LCI to validate the forecasting of common bean yield using SLR showed that the accuracy was not satisfactory for the types of models and evaluation stages (Figure 5). The error and trend to overestimate yield were very high even with accuracies of up to 60%. It was due to the high interannual variations of LCI, which was higher than the NDVI variations (Table 3).

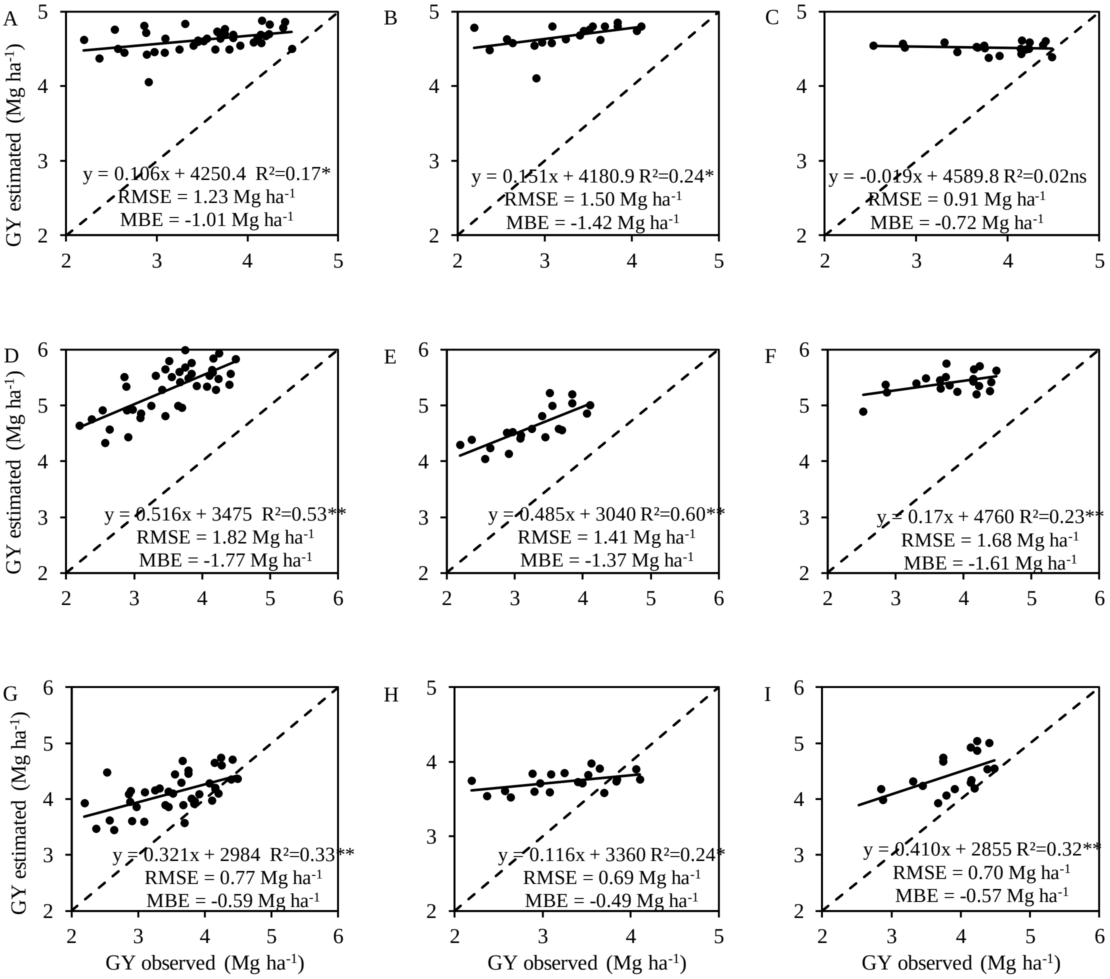


Figure 5. Yield forecasting of common bean cultivars based on the leaf chlorophyll index (LCI) using simple linear regression. General (A, D, and G) and cultivar-specific model for the cultivars IAC Imperador (B, E, and H) and IPR Campos Gerais (C, F, and I) at phenological stages R_5 (A, B, and C), R_6 (D, E, and F), and R_8 (G, H, and I). ns: not significant; *Significant at 5% probability; **Significant at 1% probability.

The application of ANNs based on LCI to validate the common bean yield forecasting showed that the accuracy was higher than SLR in some cases, with lower error and trend (Figure 6). However, accuracy was still not satisfactory for the forecasting, with values much lower than the accuracy observed using NDVI.

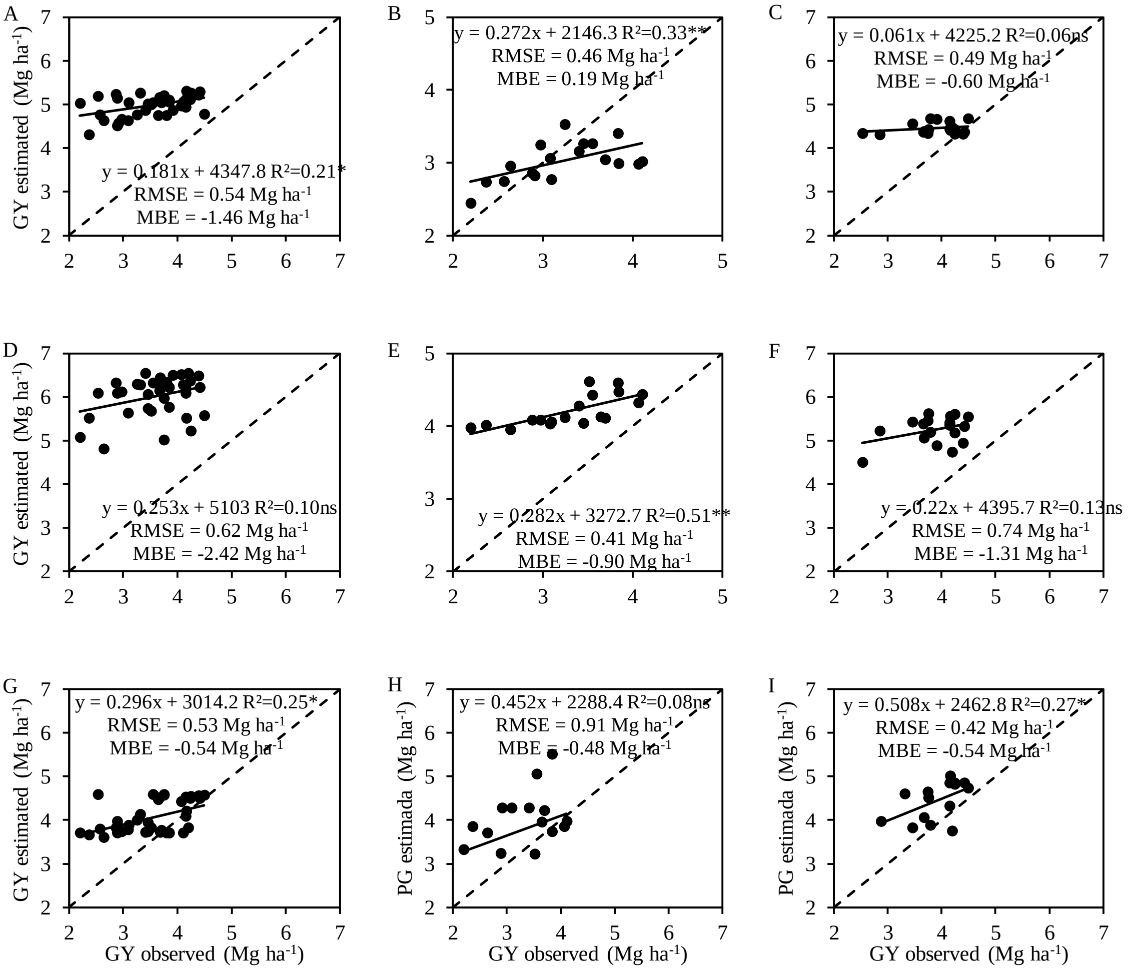


Figure 6. Yield forecasting of common bean cultivars based on the leaf chlorophyll index (LCI) by modeling using artificial neural networks. General (A, D, and G) and cultivar-specific model for the cultivars IAC Imperador (B, E, and H) and IPR Campos Gerais (C, F, and I) at phenological stages R_5 (A, B, and C), R_6 (D, E, and F), and R_8 (G, H, and I). ns: not significant; *Significant at 5% probability; **Significant at 1% probability.

Like what was observed for LCI, the forecasting of common bean yield based on MLR, associating NDVI and LCI, showed no satisfactory accuracy (Figure 7). The accuracy associating both indices was higher than the models with only LCI, but not higher than the models with only NDVI. Thus, it is preferable to use only one index to forecast yield, reducing time and costs.

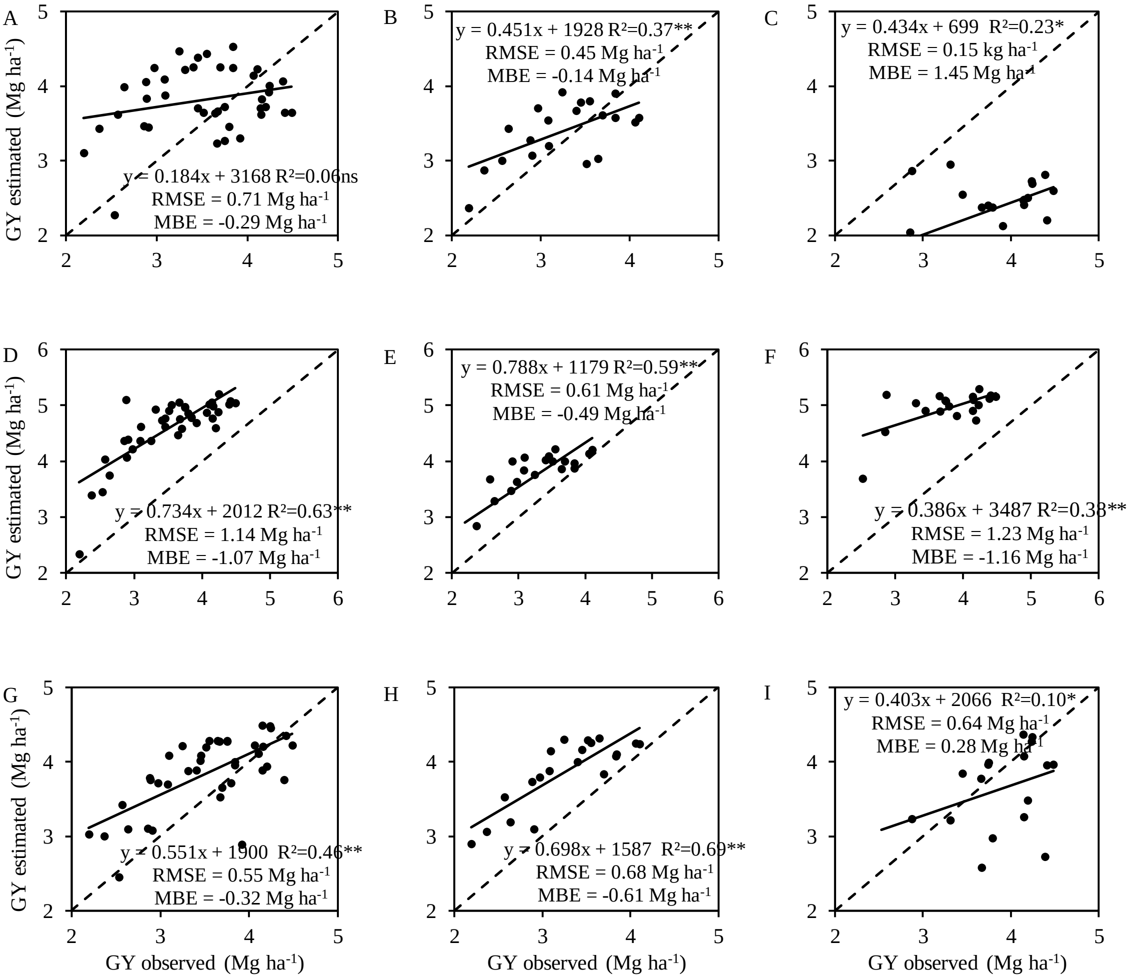


Figure 7. Yield forecasting of common bean cultivars based on the association between NDVI and leaf chlorophyll index (LCI) using multiple linear regression. General (A, D, and G) and cultivar-specific model for the cultivars IAC Imperador (B, E, and H) and IPR Campos Gerais (C, F, and I) at phenological stages R_5 (A, B, and C), R_6 (D, E, and F), and R_8 (G, H, and I). ns: not significant; *Significant at 5% probability; **Significant at 1% probability.

The association between NDVI and LCI to forecast common bean yield using ANNs increased the accuracy relative to the models by MLR (Figure 8). In this situation, all models at R_6 and the general model at R_8 presented a satisfactory forecast accuracy. However, the association of indices did not increase the accuracy regarding the use of NDVI alone. Thus, the use of only one index to forecast yield is preferable, reducing time and costs, as observed for SLR models.

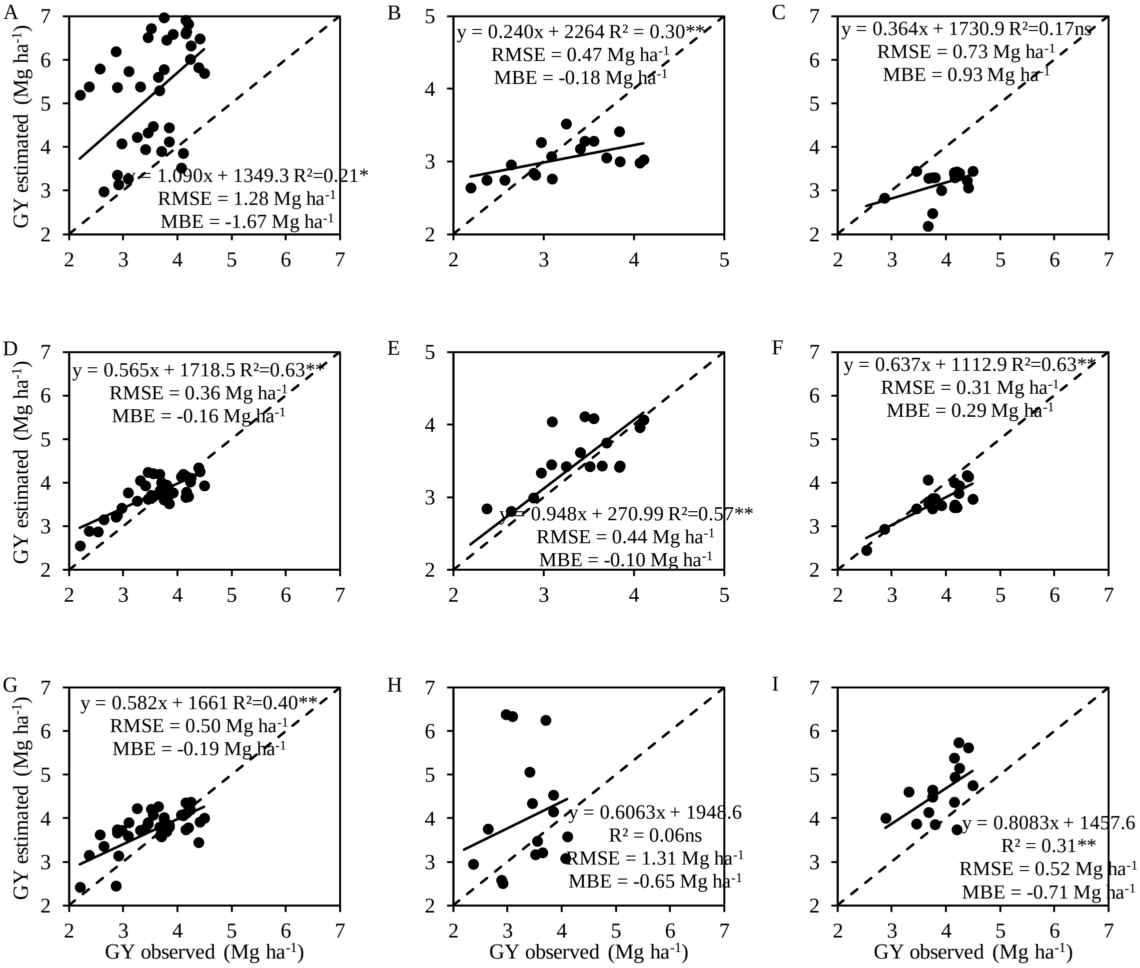


Figure 8. Yield forecasting of common bean cultivars based on the association between NDVI and leaf chlorophyll index (LCI) by modeling using artificial neural networks. General (A, D, and G) and cultivar-specific model for the cultivars IAC Imperador (B, E, and H) and IPR Campos Gerais (C, F, and I) at phenological stages R_5 (A, B, and C), R_6 (D, E, and F), and R_8 (G, H, and I). ns: not significant; *Significant at 5% probability; **Significant at 1% probability.

A significant correlation was observed between LCI and the chlorophyll content determined in the laboratory for phenological stages R_6 and R_8 (Figure 9). At these stages, the chlorophyll content determined in the laboratory increased by 0.273 mg per gram of green leaf at R_6 and 0.24 mg per gram of green leaf at R_8 for every 10-unit increase in LCI. No significant correlations were observed between leaf N content and LCI and between the chlorophyll content determined in the laboratory and leaf N content at the phenological stages.

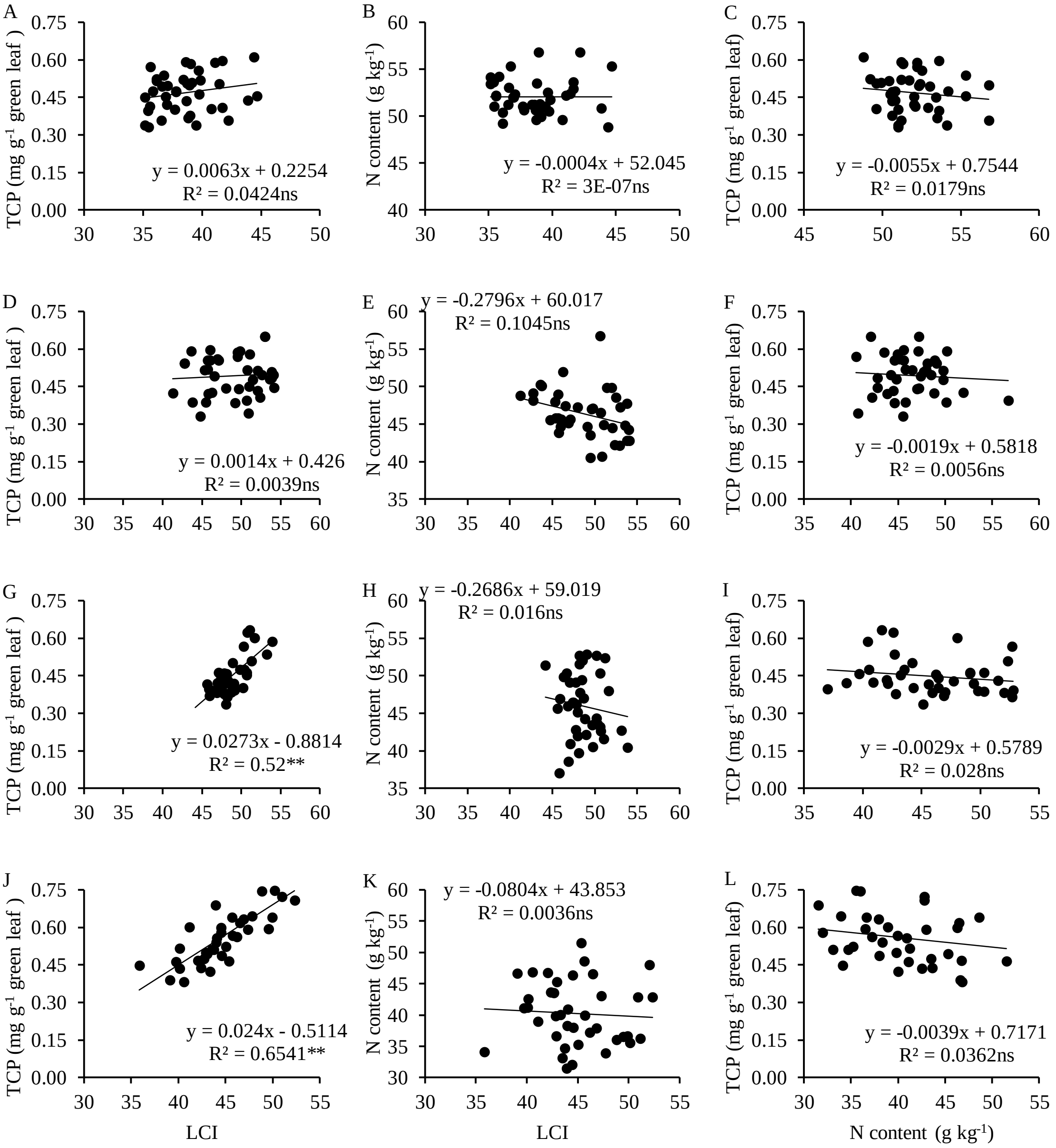
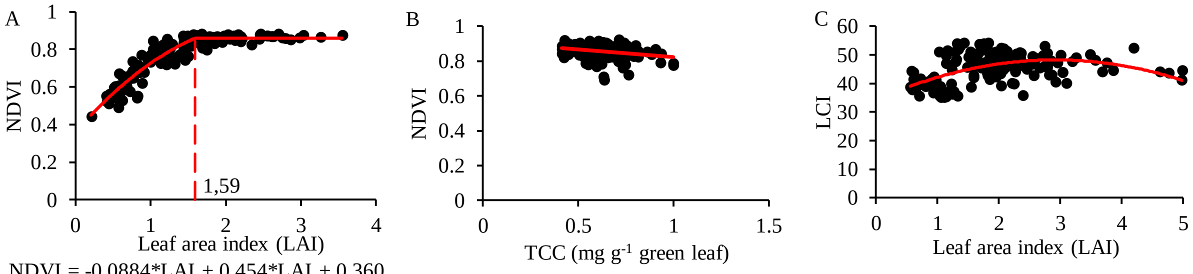


Figure 9. Variation of total chlorophyll content (TCP) determined in the laboratory as a function of the leaf chlorophyll index (LCI) (A, D, G, and J), leaf N content as a function of the leaf chlorophyll index (LCI) (B, E, H, and K), and leaf chlorophyll content determined in the laboratory as a function of leaf N content (C, F, I, and L) at phenological stages V_4 (A, B, and C), R_5 (D, E, and F), R_6 (G, H, and I), and R_8 (J, K, and L).

The NDVI values presented quadratic increments as a function of LAI up to a limit of 0.858, reached with an LAI of 1.59 (Figure 10A). It indicates saturation of NDVI values from an LAI of 1.59 onwards. Furthermore, no significant correlation ($p>0.05$) was found between NDVI and the total leaf chlorophyll content (Figure 10B). A quadratic variation was observed in LCI values as a function of LAI, with a maximum value (48.2) obtained with an LAI of 2.92 (Figure 10C). However, the correlation between LCI and LAI was lower than between NDVI and LAI.



NDVI = -0.0884*LAI + 0.454*LAI + 0.360
(0<LAI<1.59) $R^2 = 0.88$**
NDVI = 0.858 (LAI≥1.59)

$y = -0,0862x + 0,9103$
$R^2 = 0,07$ns

$y = -1.6637x^2 + 9.7048x + 34.073$
$R^2 = 0.25$*

Figure 10. Variation of NDVI values as a function of leaf area index (A) and total chlorophyll content (TCC) determined in the laboratory (B) and leaf chlorophyll index (LCI) as a function of leaf area index (C). ns: not significant; *$p<0.05$; **$p<0.01$.

The highest accuracies in forecasting the GY of common bean cultivars based on spectral indices were observed in evaluations carried out at reproductive stages, especially at pre-flowering (R^5) and full flowering (R_6). At R_5, only IAC Imperador-specific model showed satisfactory accuracy, while all models presented satisfactory accuracies at R_6. Only models based on NDVI showed satisfactory accuracies for the forecasting of common bean GY in both phases of analysis (calibration and validation), while models based on LCI and the association between NDVI and LCI presented high accuracies in the calibration phase, with poor accuracy in the validation phase due to high errors (RMSE) and trends (MBE).

Sandrini et al. (2019) evaluated the accuracy of GY forecasting models as a function of NDVI and IRVI of a common bean cultivar with a determinate growth habit (TAA Gol) and observed that the maximum forecasting accuracy also occurred at the reproductive phenological stages, especially R_6 and R_8. Monteiro et al. (2012) evaluated the correlation between NDVI and GY of the common bean cultivar Pérola (indeterminate growth habit) and observed a higher value at the R_6 phenological stage. These results are similar to those found in the present study, in which higher accuracies of GY forecasting based on vegetation indices were obtained at the reproductive phenological stages of the common bean crop. However, these authors did not validate the models with data from other years, not verifying the performance of the generalizability of the model to another set of data.

Evaluations at the beginning of the crop cycle, especially at vegetative stages, do not allow to accurately associate the plant vigor at that moment with the vigor at the end of the crop cycle. It is due to the plant growth throughout the cycle, in which cultivars with a determinate growth habit, for instance, have an emission of new leaves and branches until flowering (R_6), while cultivars with an indeterminate growth habit present growth of leaves and branches until the end of the crop cycle. Thus, places with low vigor plants and biomass accumulation at the beginning of the cycle can recover and present growth at least up to R_6, generating a higher productive potential over time. Higher correlations between GY and NDVI and LCI have also been observed in other crops, such as white oat and wheat, at reproductive stages (Bredemeier et al., 2013; Coelho et al., 2019).

This difference in the growth habit of common bean cultivars may also promote differences in the forecasting accuracy of GY between cultivars. Grain yield of the IAC Imperador can be forecast with high accuracies at phenological stages R_5 and R_6 for cultivar-specific models, while the IPR Campos Gerais presented a satisfactory accuracy only at R_6 since the R_5 stage showed a high error (RMSE) and trend (MBE) in the data validation. The IPR Campos Gerais has an indeterminate growth habit, i.e., its branches and leaves grow throughout the crop cycle, besides a longer flowering period than determinate growth cultivars, such as IAC Imperador, and climate conditions after flowering can affect more its productive potential. Thus, later evaluations, such as at R_6, tend to represent better the final productive potential of this type of cultivar compared to determinate growth cultivars.

Mercante et al. (2009) and Zerbato et al. (2016) studied the correlation between NDVI values and biophysical attributes of soybean and peanut crops and observed low R^2 values. According to the authors, these low R^2 values are due to the indeterminate growth habit of the soybean and peanut cultivars used in the studies, showing growth throughout the cycle and high capacity to compensate for empty spaces. In addition, Ma et al. (2001) evaluated the correlation between NDVI values and yield of 42 soybean cultivars and found the highest correlations in early cycle cultivars, with values up to 100% higher. Although all those cultivars had an indeterminate growth habit, these authors reported that the capacity for vegetative growth and compensation of spaces by early cultivars are lower compared to later cultivars. Thus, NDVI readings allow higher accuracy in GY forecasting before harvesting these cultivars.

The plants of both cultivars lodged after the R_6 phenological stage due to the weight of reproductive structures (pods and/or grains), which generated a high variability of NDVI readings between the applied treatments. It justifies the high variability between years in the accuracy of models for GY forecasting based on NDVI at the R_8 stage, with satisfactory values in one year and not in the other. Common bean plants with a high biomass and grain production tend to lodge due to their more herbaceous stem, a fact observed even in cultivars with a determinate growth habit and considered erect. Furthermore, the common bean has a high LAI at later phenological stages, which limits the sensor's capacity to change NDVI values, given the saturation problems in NDVI values under situations of high LAI values. In the present study, for example, we observed saturation in NDVI values above 0.858 with LAI above 1.59 (Figure 10A).

Common bean GY could not be forecast with satisfactory accuracy from LCI under any situation and type of model. The calibration phase showed a precision of up to 98%. However, the validation phase presented a poor accuracy, often with the models showing low precision and high errors and trends. The association between LCI and NDVI also did not significantly increase the accuracy compared to the models based on NDVI only due to the low accuracy of LCI in common bean GY forecasting. Thus, the use of only NDVI to GY forecasting shows higher ease and accuracy, similar to the association of this index with LCI.

As observed in the present study, LCI is more correlated to leaf chlorophyll contents (Figures 9 and 10) and accurately represents plant physiological state, whereas NDVI is more correlated with leaf area index (Figure 10). Such dynamics promotes differences in model generalizability for GY forecasting using these indices. This is because an index more correlated with leaf content, such as LCI, is more subject to interannual variations, with a low capacity of data generalization to an external dataset. In this case, LCI is a good alternative to assess the physiological and nutritional status, as well as the productive potential of the crop within the same year (Maia et al., 2017; Coelho et al., 2019), as factors such as different climate conditions, dilution due to an increase in plant biomass, and disturbance promoting factors, such as frost, can interfere with the generalizability of a model for data from other growing seasons. The correlation between NDVI and LAI represents more accurately the vigor and productive potential of crops and, although there is also interannual variation in this index, the differences in LAI from one year to the other more accurately represent the productive potential of the crop, as plants with higher LAI can absorb a higher amount of radiation, generate higher photosynthesis rates, and, consequently, have a higher productive potential (Camargo et al., 2016).

Coelho et al. (2019) compared the accuracy of NDVI and LCI in white oat GY forecasting and found higher precision and lower error in models based on NDVI. The authors evaluated data from only one year, corresponding to the calibration phase of the models, and observed that NDVI was more accurate than LCI even within the same year. This behavior was also observed in the present study for common bean, in which models based on NDVI had higher accuracy in the calibration phase. As discussed above, LCI is influenced by the dilution effect on the chlorophyll and nutrient contents, i.e., plants with higher biomass production may have lower chlorophyll and nutrient contents in the leaves and reduce LCI values. However, considering the leaf area, the amount of chlorophyll and nutrients in plants with higher biomass is higher than in plants with lower total biomass. It could be confirmed in the present study, as the SLR models used to GY forecasting based on NDVI presented a linear increase in the calibration phase, but a linear decrease for LCI (Table 4).

Moreover, the correlation between LCI and GY depends on the crop and type of study. Coelho et al. (2019) observed that models to white oat GY forecasting based on LCI presented an increase. Maia et al. (2017) conducted a study aiming to manage nitrogen fertilization in the common bean based on LCI and observed higher LCI values in treatments with a higher amount of applied N, which was directly associated with higher GY. However, the results found in this study may be more applicable from a practical point of view, as the amount of nutrients applied in commercial crops and conventional fertilization management is equal throughout the area. Thus, areas with higher potential for high yields present plants with higher growth, which can reduce LCI values due to the dilution effect concerning areas with lower productive potential. Therefore, the correlation between LCI and common bean GY may be indirect depending on the producer’s technological level, production system, productive potential, and crop growth, as observed in the present study.

LCI showed a direct correlation with the chlorophyll content determined in the laboratory (Figure 9), but no correlations were observed between LCI and leaf N content and between the chlorophyll content determined in the laboratory and leaf N content. It occurs because N is not only part of the structure of the chlorophyll molecule in leaves but part of other compounds. Moreover, as observed here, luxury N consumption may occur in high-fertility soils, which can explain the lack of correlation between LCI and leaf N content.

The comparison between types of models showed a high variation in the ANN accuracy between the data calibration and validation phases, while SLR showed a similar accuracy between phases, depending on the phenological stage. ANNs showed higher accuracy in the calibration, with higher precision and a lower error compared to SLR, with adjustments close to 100% in some cases. The difference in accuracy between models was small in the validation, with similar precision, error, and trend values between types of models. The high difference in the ANN accuracy between the calibration and validation phases of the models can be attributed to overfitting problems, i.e., the model presented a good fit in the calibration data and did not perform well in the validation (Haykin, 2001).

Overfitting occurs when the model is too complex for the dataset, showing a high variance, and its generalizability is restricted to the calibration dataset (Maciel et al., 2012). This problem may be associated with the small amount of data used to calibrate the model and the linearity of data variation, in which more complex models, such as ANNs, are not necessary to forecast what is desired. These two points can be observed in the present study, i.e., the linearity in the GY variation as a function of spectral indices and the small amount of data used in the model calibration may have caused overfitting of ANNs, in addition to not promoting a higher accuracy relative to SLR in the GY forecasting of common bean cultivars as a function of spectral indices in the validation phase.

7.4 Conclusions

Grain yield of common bean cultivars with contrasting growth habits can be accurately forecasting based on NDVI, but leaf chlorophyll index (LCI) and NDVI and LCI association have poor accuracy. It can be explained by high interannual variability of LCI between and within each phenological stage, which is affected by factors such as climate and soil conditions, dilution effect due to an increase in crop biomass, and physiological disturbances due to intense cold (frost). Conversely, NDVI has less variability and higher correlation with leaf area index and is more sensitive to identify areas with higher or lower productive potential. The highest forecast accuracies are obtained at reproductive phenological stages, mainly at R_6 (full flowering), both in cultivar-specific and general models. Overall, the models had an R^2 of 0.64, RMSE of 0.37 Mg ha^{-1}, and MBE (bias) of -0.14 Mg ha^{-1} at the R_6 stage. Regarding the model type, forecast accuracy using simple linear regression and artificial neural networks are similar; therefore, simpler models can be used to forecast common bean grain yield.

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CHAPTER 8 - Final considerations

From this multidisciplinary study, it was possible to understand some causes that promote variability in the production of common beans cultivated in the winter season, as well as to generate more specific recommendations for obtaining high yields. The information obtained here may help farmers, consumers, and government agencies in the definition of management such as irrigation management and cultivars that promote greater yield and grain technological and nutritional quality; increase food security; fertilization with macronutrients depending on the cultivar and irrigation strategy adopted; define best sowing date and irrigation management; and perform pre-harvest yield forecast as a function of spectral indices.

The highest grain yields were obtained in the cultivar IPR Campos Gerais, which has an intermediate cycle and an indeterminate growth habit. For this cultivar, yield increased linearly at 494 kg ha^{-1} for every 100 mm of irrigation depth applied. In the cultivar IAC Imperador, with an early cycle and determinate growth habit, the highest yields were obtained close to the irrigation level that provided 100% ETc. Overall, the increase in irrigation level promoted grain technological and nutritional quality. Additionally, the cultivar IPR Campos Gerais presented the best characteristics for technological and nutritional quality, highlighting larger grains, shorter cooking times, and higher levels of the most important nutrients for human consumption, such as Fe.

As for macronutrient extraction, severe water deficit reduced total accumulation by more than 20% compared to full irrigation, limiting plant growth. On average, the cultivar IPR Campos Gerais showed greater macronutrient uptake, except for K and Mg, for which uptake was similar between cultivars. This demonstrates the need for specific K and Mg fertilization management for IAC Imperador. Although the accumulation of these nutrients was similar between cultivars, IAC Imperador had an early cycle, that is, it had higher uptake rates than IPR Campos Gerais.

In long-term simulations (20 years) using the CSM-CROPGRO-Dry bean model, it was found that early sowing within the winter season (March) allows the use of regulated deficit irrigation management without drastically affecting the common bean yield. Management with full irrigation is more viable only for sowing from May 1st, as rainfall in much of Southeast Brazil is very scarce. For full irrigation management, it is recommended to avoid sowing at times when the reproductive phenological stages coincide with the period of lower global solar radiation (GSR), which for the conditions of the present study was June. This is because each unit reduction in GSR can reduce the common bean yield by 53 kg ha^{-1} on average.

In both cultivars, the highest accuracies for forecasting the common bean yield using spectral indices were obtained at the phenological stage of full flowering (R_6) and for the NDVI. This occurred because assessments at the beginning of the cycle cannot distinguish areas with greater productive potential given the similarity in plant growth, and delayed assessments present problems in the saturation of the NDVI and common bean variability due to plant lodging. Moreover, generalist models using data from the two cultivars can be used and present accuracies similar to those of individual models per cultivar.

APPENDICES

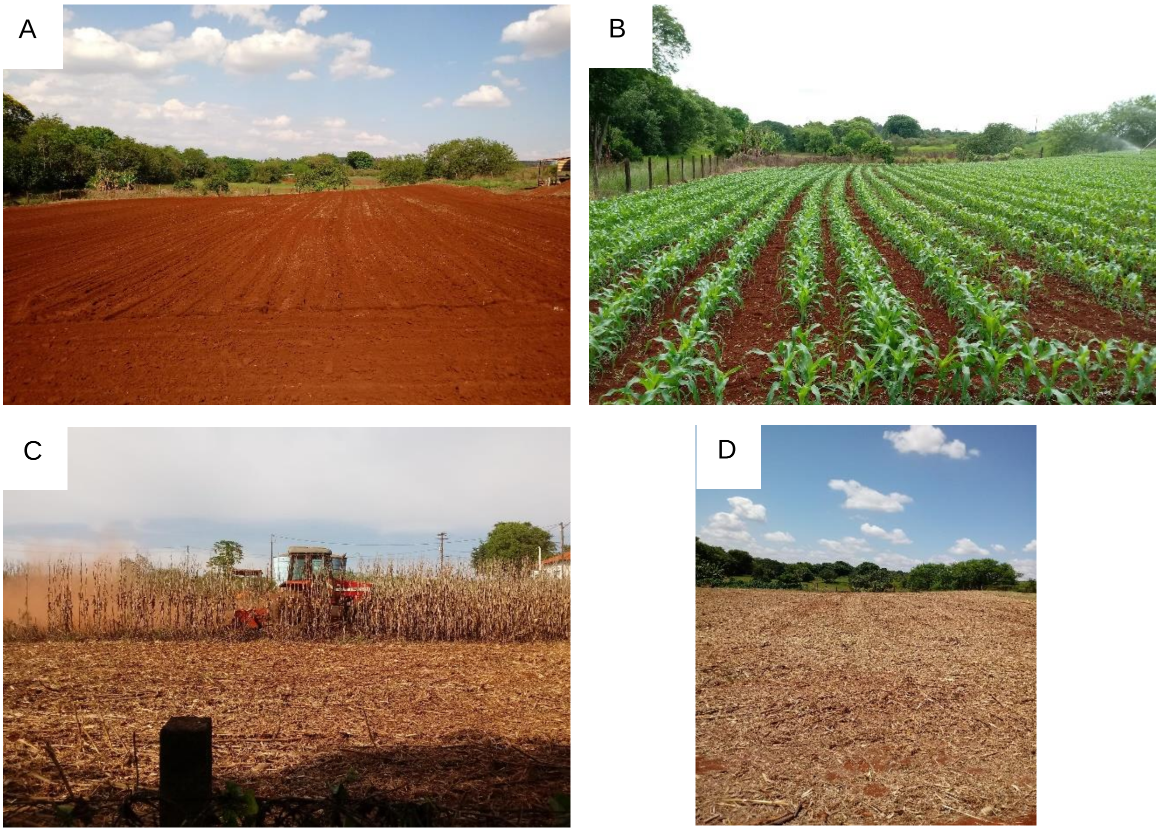

Figure 1. Corn cultivation aiming straw formation for the sowing of common bean cultivated in succession. (A) Corn sowing in the experimental area under conventional tillage; (B) Corn growth in the experimental area; (C) Management of corn crop residues with a straw crusher; (D) Soil covered with corn straw for common bean sowing under no-tillage system

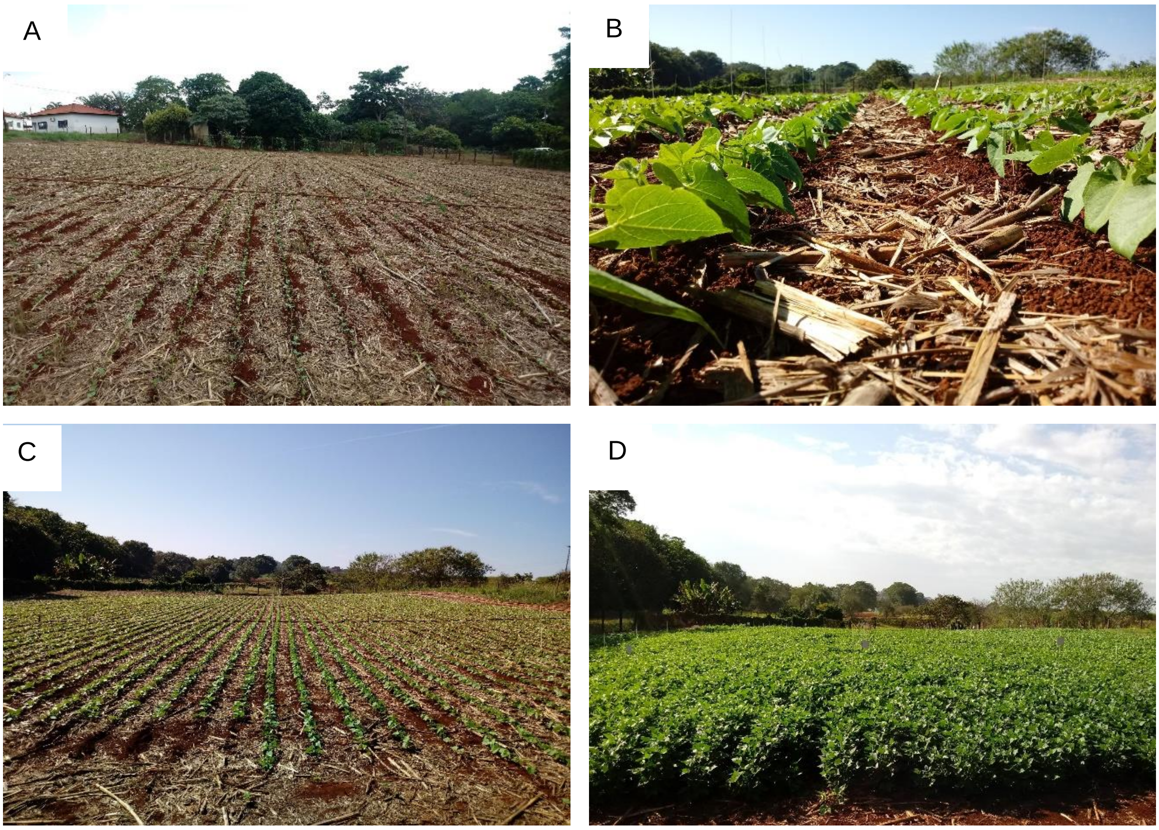

Figure 2. Cultivation of common bean cultivars in the experimental area. (A) common bean sowing in the experimental area under no-tillage; (B) Common bean initial growth; (C) Paronomic view of the experimental area with common bean at the beginning of the cycle; (D) Common bean at the phenological stage of flowering (R_6)

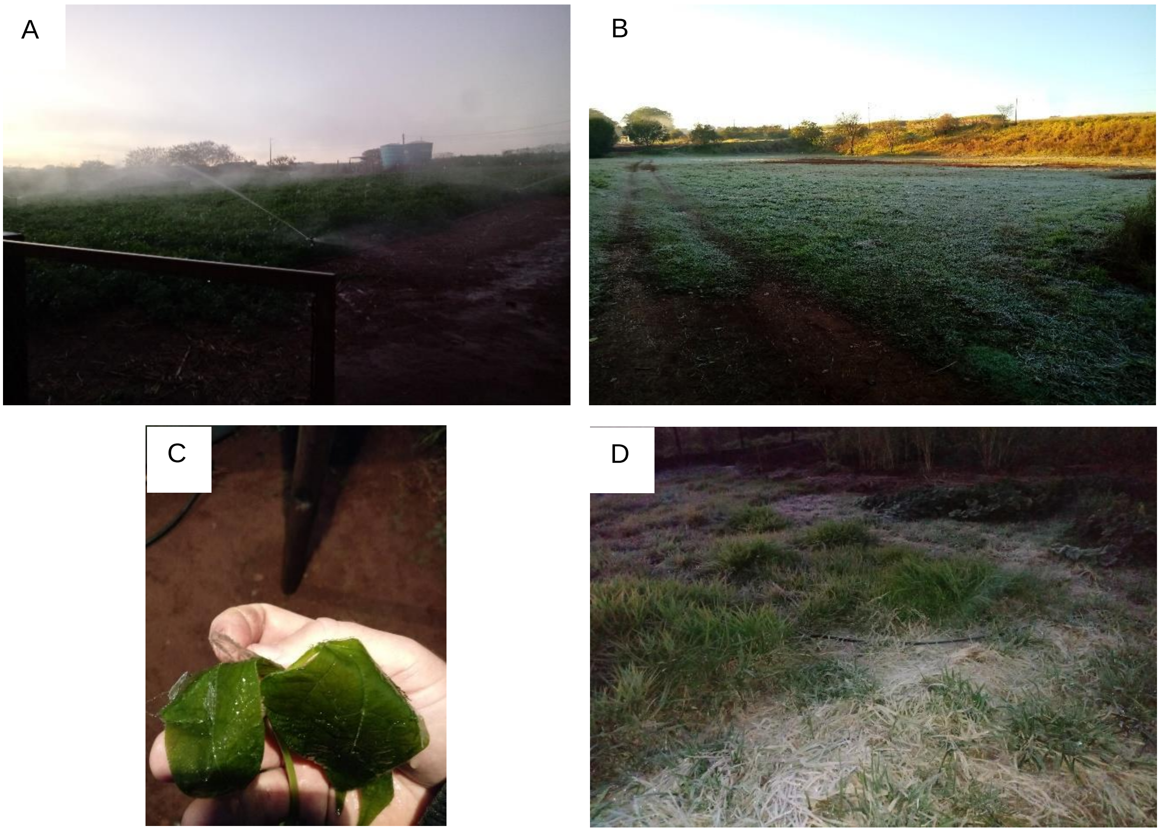

Figure 3. Frost in the experimental area in the year 2019. (A) Irrigation management to mitigate the effects of frost on common bean; (B) Area adjacent to the experiment covered by frost; (C) Common bean leaf with frost formation on the surface; (D) Area adjacent to the experiment covered by frost

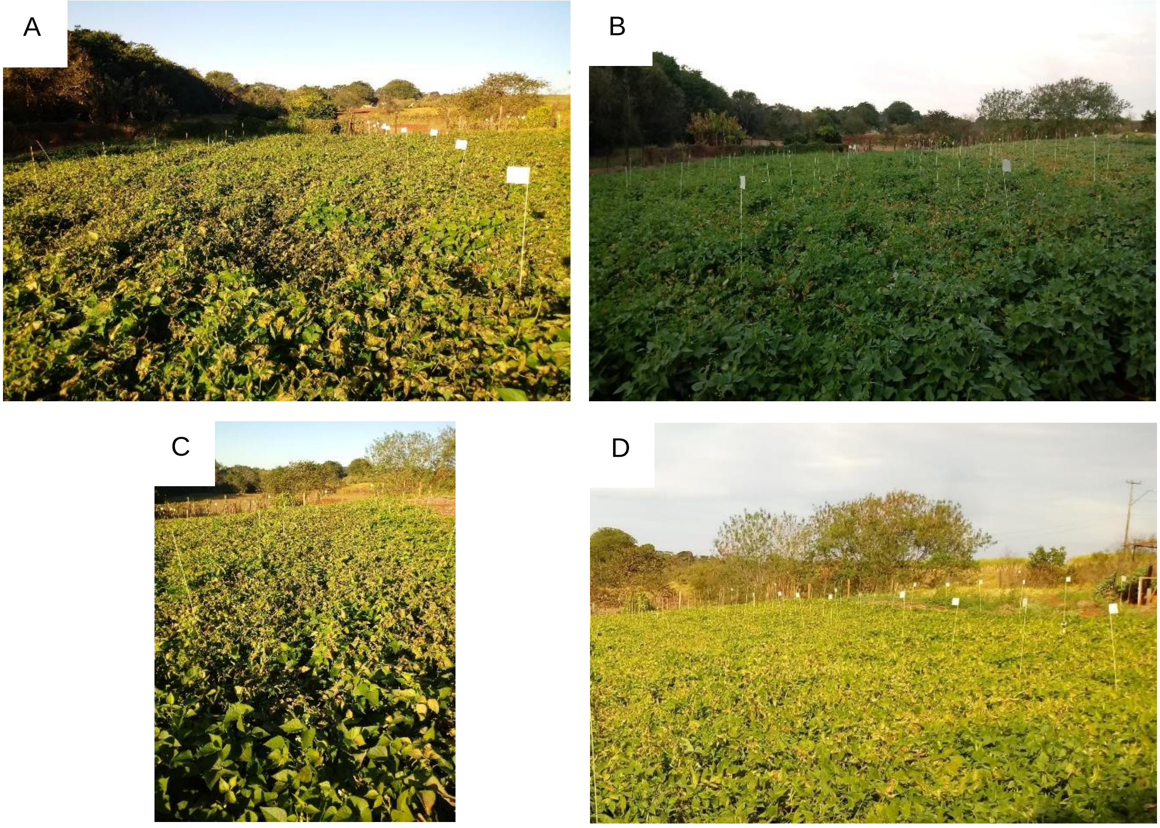

Figure 4. Effects of frost on common bean cultivars in the year 2019. (A) IPR Campos Gerais cultivar 7 days after frost; (B) IPR Campos Gerais cultivar 30 days after frost; (C) IAC Imperador cultivar 7 days after frost; (D) IAC Imperador cultivar 30 days after frost