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Effect of plant density on yield components of common bean grown under inter-Andean mountain conditions of Ecuador

Efecto de la densidad de plantas sobre los componentes del rendimiento de fréjol cultivado en condiciones de campo en un valle interandino de Ecuador

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Abstract

Common bean is an important crop due to its high nutritional value. However, its production in Ecuador has decreased due to biotic and abiotic factors. Understanding the mechanisms that determine the yield components of this crop is essential to establish strategies that allow increasing the yield. In this study, the plant density was modified to evaluate its impact on yield and its two main components, the grain number and grain weight under field conditions in an Andean region of Ecuador. Two experiments planted on different dates were performed, where two planting densities 4 and 11 plants m^{-2} were evaluated. The effect of the treatments was studied on the length of the period, from emergence to anthesis, the number of full and empty pods, grain number, 100 grain weight and grain yield. The results indicate that the plant density has a significant effect ($p<0.05$) on the yield, reaching an average of 257.15 g m^{-2} in high density, and 151.45 g m^{-2} in low density. The yield main components showed a different response to plant density modification; the grain number exhibited a strong variability and was positively associated with final grain yield ($p<0.05$) while the grain weight was not affected.

Keywords: Grain number, grain weight, *Phaseolus vulgaris*, plant density, plant population, yield components.

Resumen

El fréjol es un cultivo importante debido a su alto valor nutritivo. En los últimos años la producción en Ecuador de este cultivo ha disminuido drásticamente debido entre otros factores a ineficientes procesos y falta de tecnificación en la producción. Entender cómo se generan y determinan los componentes del rendimiento del grano es primordial para diseñar estrategias que permitan aumentar el rendimiento del cultivo. En este estudio, se modificó la densidad de plantas con el objetivo de evaluar su impacto sobre el número de granos, peso de granos y rendimiento, bajo condiciones de campo en una región andina de Ecuador. Se realizaron dos experimentos sembrados en fechas distintas, donde se evaluaron densidades de plantas contrastantes 4 y 11 plantas m^{-2}. El efecto de los tratamientos se estudió sobre la duración del periodo emergencia - antesis, el número de vainas llenas y vanas, el número de granos, el peso seco de 100 granos y el rendimiento de grano. Los resultados indican que la densidad de plantas tiene un efecto significativo ($p<0{,}05$) sobre el rendimiento, alcanzando un promedio de 257,15 g m^{-2} en alta densidad y 151,45 g m^{-2} en baja densidad. Los componentes principales del rendimiento mostraron una respuesta distinta a la modificación de la densidad de plantas; el número de granos presentó una fuerte variabilidad y fue positivamente asociado con el rendimiento final del grano ($p<0{,}05$), mientras que el peso del grano no fue afectado.

Palabras clave: Componentes del rendimiento, densidad de siembra, fréjol, número de granos, peso de grano, *Phaseolus vulgaris*, población de plantas.

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1 Introduction

Bean (*Phaseolus vulgaris* L.) is an important crop due to its high nutritional value, containing between 20 - 30% protein (Celmeli et al., 2018), and is one of the important crops sowed in several Andean areas of Ecuador (Valarezo et al., 2008; Bustamante, 2017). Like other legumes, this species is used in crop rotation to reduce disease-causing agents, and to maintain soil fertility through atmospheric nitrogen fixation (Vásquez et al., 2015). In recent years the cultivated area and production of bean in Ecuador has decreased drastically, from 2011 to 2019 an approximate decrease of 50% was estimated (FAOSTAT, 2019). Among the factors that have contributed to the reduction in harvested area are droughts, incidence of pathogens, poor crop management, low technification and increased production costs, favoring the importation of bean grain (Sistema de Información Publica Agropecuaria de Ecuador, 2018).

Increasing the profitability of this crop requires improving productive efficiency and reducing production costs, thus plant density management would play an important role (Calero-Hurtado et al., 2018). Crop yield would respond to the modification of plant density, because the number of plants per unit area would be related to the growth rate of the crop under solar radiation and temperature (Boada and Espinosa, 2016).

Traditionally, farmers use plant densities between 15 600 to 20 800 plants ha^{-1} with furrow spacings of 0.80 to 1.00 m for manual weeding (Parreira et al., 2011), paying little attention to yield response and its components. Bean genotypes can vary when generating reproductive structures due to phenotypic plasticity in response to plant density (Andrade and Abbate, 2005), with consequences in plant cover, biomass, competition with weeds, generation of yield components and therefore in final grain yield.

Some studies show that increased density can avoid water loss. As the distance between rows is reduced and the distance between plants is maintained it is possible to increase the vegetative cover of the crop, and consequently reduce direct water losses by evaporation by covering the soil more quickly (Osuna et al., 2012). In addition, for the bean crop to have competitive advantages with weeds, increasing the density allows total soil cover once the crop reaches full vegetative development (Parreira et al., 2011).

Number of grains (NG) and average grain weight (WG) are major components of grain crop yield (Peltonen-Sainio et al., 2007; Sadras, 2007; Slafer et al., 2014). In many crops, NG is related with yield, while grain weight shows less variation; however, it has also been found that WG can compensate for the decrease in NG when the source decreases (Ghobadi et al., 2006; Labra et al., 2017).

Studies in bean have evaluated the effect of plant density on yield mainly under tropical and Mediterranean agroclimatic conditions, however, the response of yield components may vary in different genotypes and environments. For example, Soratto et al. (2017) evaluated densities of 5, 7 and 9 plants m^{-2}, and only found yield differences in one genotype with the highest plant density. In another study, Ahmed et al. (2016), evaluated densities of 4, 5, 7 and 14 plants m^{-2}, and report that grain weight increased with the lowest density (4 plants m^{-2}), while yield was maximized with 5 plants m^{-2}. On the other hand, Gabisa et al. (2017), studied high plant densities: 12, 15, 19 and 25 plants m^{-2}, indicating that densities of 14 and 19 plants m^{-2} exhibited the highest yields; this background suggests that the response to plant density is conditioned by environment and genotype. To date, there is little information on the individual response of numerical yield components and their relationship with grain yield when resource supply is modified in local bean genotypes under mountainous environments in the Andean zones of Ecuador.

A better understanding of yield determination and its components is a prerequisite for developing strategies aimed at increasing yield through plant breeding, as well as for agronomic crop management (Foulkes et al., 2011). The objective of the research is to determine the effect of plant density modification on yield components of beans grown in an Andean region of Ecuador.

2 Materials and Methods

2.1 Location of the experiment and crop management

The study was carried out at La Argelia Experimental Station of the National University of Loja (4°02′19.2″S 79°12′00.6″W) at 2150 m.a.s.l., in a silty loamy soil. Percal bush bean cv. Percal, widely cultivated in the province of Loja, Ecuador, was used as planting material. Prior to sowing, a seed germination test was carried out, showing a germination higher than 95%. Weeds were controlled manually approximately every 20 days, starting from the first trifoliate leaf stage until the grain filling stage, covering the critical period of weed interference reported by Ngouajio et al. (1997). When the first symptoms of damage caused by phytopathogens were observed, preventive applications were made using synthetic fungicide and insecticide. In addition, when rainfall was scarce, supplemental irrigation was applied by sprinkling. Before planting, bocashi was incorporated 7 t h^{-1}, and later, fertilization was applied with 120 kg ha^{-1} N partialized at phenological stages V4 and R6 (Fernández de Córdova et al., 1986).

2.2 Experimental Design

The trial was arranged in a factorial design with a randomized distribution. Two experiments were set up with different sowing dates, Experiment 1 (E1) sown on October 26, 2018 and Experiment 2 (E2) sown on November 26, 2018. The experiments were established at two sowing densities, 11 plants m^{-2} (0.60 m between furrows and 0.30 m between plants) and 4 plants m^{-2} (0.80 m between furrows and 0.60 m between plants), placing two seeds per site. The plots were 3.20 m long and 2.80 m wide, with three replications for each treatment.

2.3 Measurements and statistical analysis

Crop phenology was recorded weekly according to the scale proposed by Fernández de Córdova et al. (1986), from sowing to harvest maturity. Meteorological data on temperature, relative humidity and precipitation were recorded daily at La Argelia-Loja meteorological station (INAMHI) located near the experiment.

At harvest maturity, all plants were taken from 1 m linear of the two central rows of each plot, avoiding the plants at the edges, and the number of grains, the number of full and empty pods were counted. The dry weight of the grains was determined after leaving them in the oven for 3 days at 65 ± 5 °C. The number and weight of grains were used to calculate the grain yield.

A factorial analysis of variance and a Fisher's test of means ($\alpha = 0.05$) were used to evaluate the effect of the treatments. Prior to the ANOVA, the statistical assumptions of normality, independence of observations and homogeneity of variance were evaluated. The model described by Equation 1 was used to evaluate the differences between treatments.

$$y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \tag{1}$$

Where y_{ijk} represents the observations corresponding to the i-th level of the factor density and j to the level of the factor experiment; μ represents the overall mean; α_i is the effect produced by the i-th level of the factor plant density; β_j is the effect produced by the j-th level of the factor experiment; $(\alpha\beta)_{ij}$ is the effect produced by the interaction between density and experiment; and ε_{ijk} represents the experimental error.

3 Results and Discussion

3.1 Phenology and climate

The duration of the sowing-anthesis stage was not affected by sowing density or sowing date (p>0.05); on average the crop in the two experiments took 61.72 (± 0.74) days to reach flowering (Table 1). The crop cycle from sowing to harvest lasted approximately 119 and 125 days for the high and low density treatments, respectively. The small difference in the duration of the stages and the crop cycle between experiments and densities could be related to the small temperature variation experienced by the plants of the different treatments (Figure 1), since this is the main factor that modifies crop ontogeny (Luo, 2011). A previous study with the same cultivar indicates that the crop took 141.67 days to harvest maturity; however, the average temperature of the cycle was 12.47 °C (Goyes, 2014), suggesting that this difference would occur by the colder temperatures that delayed the thermal accumulation of the crop.

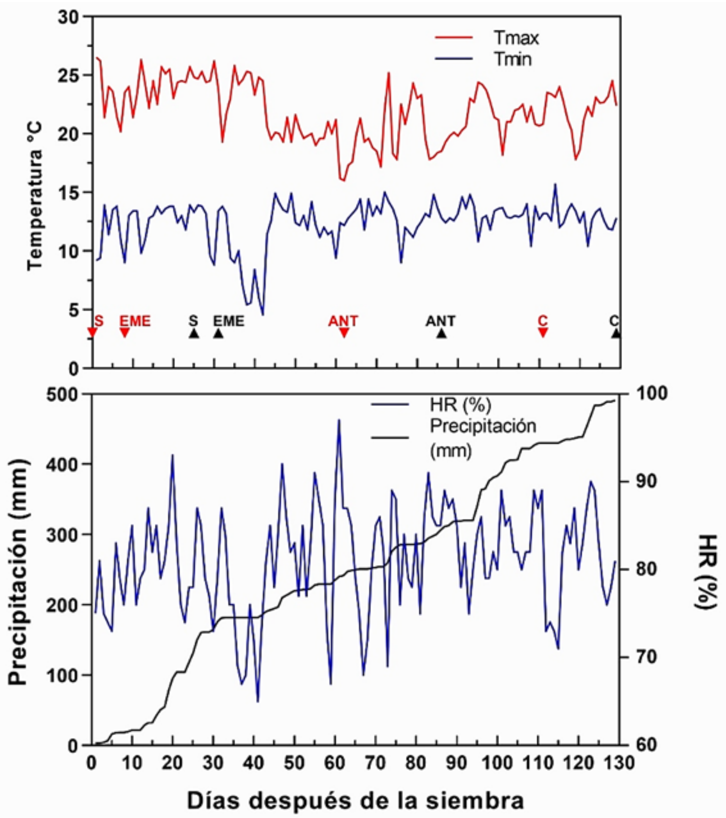

Figure 1. Diagram of the duration of phenological stages and climatic variables of precipitation, temperature and relative humidity during the growing cycle of the two experiments. Red triangles indicate experiment 1 and black triangles indicate experiment 2. S (sowing), EME (emergence), ANT (anthesis), C (harvest).

3.2 Number of pods

Plants planted at low density (4 plants m^{-2}) had a higher number of pods $plant^{-1}$ compared to those planted at higher density (11 plants m^{-2}), increasing the number of pods by 36.2 and 29.2% in experiment 1 and 2, respectively (P<0.05). Also, significant differences were found between the experiments (Table 1), observing that the averages of experiment 2 were lower (P<0.05), maybe because experiment 2 had an incidence of pathogenic fungi that could affect the final number of pods (the incidence of diseases was not evaluated). When the number of empty pods was analyzed, no statistical differences were found, suggesting that there were sufficient resources for the establishment and growth of grains per pod at the densities evaluated.

The increment in the number of pods in plants grown at low density suggests that it is a consequence of lower intraspecific competition, which would result in greater availability of resources that could have generated increases in the number of branches and pods. Some grain crops, including bean, have the ability to modify their structure in response to source modification; previous work indicates that pod number is one of the most sensitive components to density modification in bean (Bennett et al., 1977; Mondo and Nascente, 2018). The results of this research agree with previous results (Abubaker, 2008; Osuna et al., 2012; Gabisa et al., 2017), in which when increasing the number of plants decreases the number of pods established per plant in bean crop.

Table 1. Average yield and its components, and duration of the sowing-anthesis stage.

E	DS	Days to anthesis	Pods Plant^{-1}	Empty Pods Plant^{-1}	Pods m^{-2}	Grains Pods^{-1}	Grains Plant^{-1}	Grains m^{-2}	Weight of 100 grains (g)	Performance (g m^{-2})
1	11	61.67	13.5	4.5	49.5	4.98	56.17	624.57	40.41	254.28
1	4	62	21.17	4.83	19.33	4.87	96.83	402.83	45.52	183.93
2	11	60.73	10.68	4.9	53.9	5.06	52.69	585.96	43.73	260.02
2	4	62.47	15	6.83	31.33	5.28	70.83	294.67	38.71	118.97
E. st		0.62	1.4	0.53	2.35	0.1	6.76	52.04	1.62	25.43
E		ns	*	ns	ns	ns	ns	ns	ns	ns
DS		ns	*	ns	*	ns	*	*	ns	*
ExDS		ns	ns	ns	ns	ns	ns	ns	ns	ns

*Significant effect $p<0.05$; E.st: standard error; ns: not significant; E: experiment; SD: plant density (plants m^{-2}). Values are averages of three replicates.

3.3 Number of grains

No statistical differences were found in the density treatments and experiments evaluated in the NG pod^{-1}, on average 5 ($\pm$ 0.17) grains were obtained in each pod. The number of grains remaining established in each pod would be related to the amount of available soil resources and photosynthesis (Hadi et al., 2006; Lake et al., 2019). The results obtained indicate that there was no limitation for grain formation in pods in the density ranges explored (Table 1), suggesting that when source availability is modified by plant density, the establishment of pod number plant^{-1} is more sensitive to the environment than NG pod^{-1}.

Both NG plant^{-1} and NG m^{-2} were affected by plant density ($P<0.05$). As previously shown, plants grown at low density had a higher number of pods, with no differences in the number of established grains per pod; consequently, NG plant^{-1} increased by 42 and 26 % in E1 and E2, respectively, compared to plants sown at high density (Table 1), observing a positive relationship between the number of pods plant^{-1} and NG plant^{-1} (Figure 2A).

On the contrary, when NG m^{-2} is used, it is observed that this component is significantly higher in the high-density treatment, because there was a greater number of plants per unit area in this treatment, thus increasing the number of reproductive structures. Although the plants grown in low density established a greater number of pods plant-1, this was not enough to compensate the NG m^{-2} nor the grain yield, observing a negative relationship between the number of pods plant^{-1} and yield (Figure 2B). Previous work also shows a decrease in NG plant^{-1}, when the plant population is increased and the spatial arrangement of the bean crop is modified (Osuna et al., 2012; Escalante-Estrada et al., 2015). One way to improve bean yield may be to improve the number of pods per plant, which as shown in this study responds satisfactorily to resource modification and is associated with final grain yield.

3.4 Grain weight

Grain weight was not affected by density treatment in the two experiments (Table 1). On average, the dry weight of 100 grains at harvest was 42.09 g ($\pm$ 3.1) in all treatments, confirming that this component is more stable than NG, supporting the idea that WG is a conservative trait and not very sensitive to the modification of the source-destination relationship as has been seen in other grain crops such as soybean and corn (Sadras, 2007). Studies with determined and undetermined habit genotypes in different environments also show that WG has little variation when plant density is modified (Osuna et al., 2012; Escalante-Estrada et al., 2015; Soratto et al., 2017). These results indicate a high challenge to increase grain weight possibly due to the strong interaction of genotype and environment exerted on this component in bean as reported by Pereira et al. (2017).

3.5 Yield

Grain yield was significantly affected by plant density in both experiments (P<0.05). A positive response of yield to the increase in the number of plants m^{-2} was observed, because in a first stage the number of plants per unit area would condition the formation of reproductive structures in the absence of restriction of nutrient resources and solar radiation (Slafer and Rawson, 1994; Kruk and Satorre, 2003; Véliz et al., 2021a).

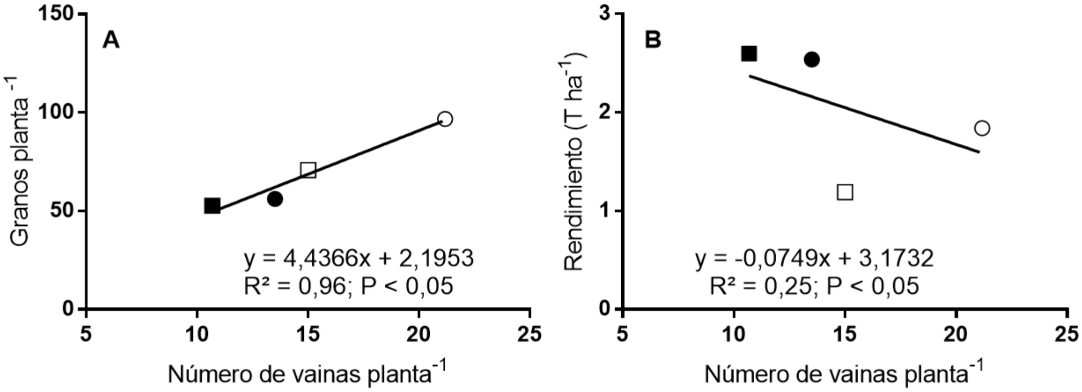

Figure 2. Relationship between the number of pods per plant and the number of grains per plant (A), and between the number of pods per plant and crop yield (B). Circles represent experiment 1 and squares represent experiment 2, filled symbols indicate density 11 plants^{-2} and empty symbols indicate density 4 plants m^{-2}. Each point is the average of three replicates.

The results suggest that although soil resources may have decreased at high density due to intraspecific competition, this was not limiting for yield gain in the high-density treatment, probably due to higher biomass generation per unit area, which translated into higher interception of photosynthetically active radiation (De Bruin and Pedersen, 2009; Véliz et al., 2021b), favoring the establishment of larger harvested organs as in previous studies (Egli, 1988; Soratto et al., 2017; Calero-Hurtado et al., 2018).

The yield in this research greatly exceeded previous studies (Calero-Hurtado et al., 2018) where higher densities were used such as 16 plants m^{-2} with grain yield of 1 t ha^{-1}, even surpassing investigations where densities between 22 to 28 plants m^{-2} were evaluated (Puente, 2009), possibly due to a low efficiency in those production systems, which could imply higher production costs due to the higher number of plants per unit area.

Relationships between yield and its components were explored in this research, the results of which indicate that the number of grains and pods per unit area are closely related with yield, as has been seen in other grain crops (Peltonen-Sainio et al., 2007; Sadras, 2007; Slafer et al., 2014). On the other hand, WG is not related with yield (Figure 3 A, B, C). As previously shown NG and WG possess different sensitivity to density modification in bean, indicating that WG in bean is a stable trait in contrast to NG

Our results are similar to studies conducted in temperate cereals (Reynolds et al., 2021), where yield tends to be better related to grain number while WG is insensitive or marginally responsive when resource input is modified during grain filling (Serrago et al., 2013; Aisawi et al., 2015; Bonelli et al., 2020).

These results indicate that beans, as well as other grain crops such as cereals, are also limited by the destination or sink, because the modification of source resources, as a consequence of the change in the number of plants per unit area, modified the yield mainly by changes in the NG and not in the WG. These results support the idea that the little variation observed in WG may reflect an adaptive evolutionary response, and that reducing intraspecific variability in seed size and weight would allow optimal seed size, balancing the survival of individuals and the number of progeny produced as indicated by Sadras and Denison (2009) and Sadras and Slafer (2012).

Incrementing bean yield would imply increasing its two components to avoid possible trade-offs between NG and WG, however, traditionally grain crop improvement has focused on increasing NG (Mason et al., 2008; Sadras and Lawson, 2011). While WG has had less attention (Castillo et al., 2017), the low variability of PG found in this study highlights the need to improve this component, which could help increase yield in bean crop.

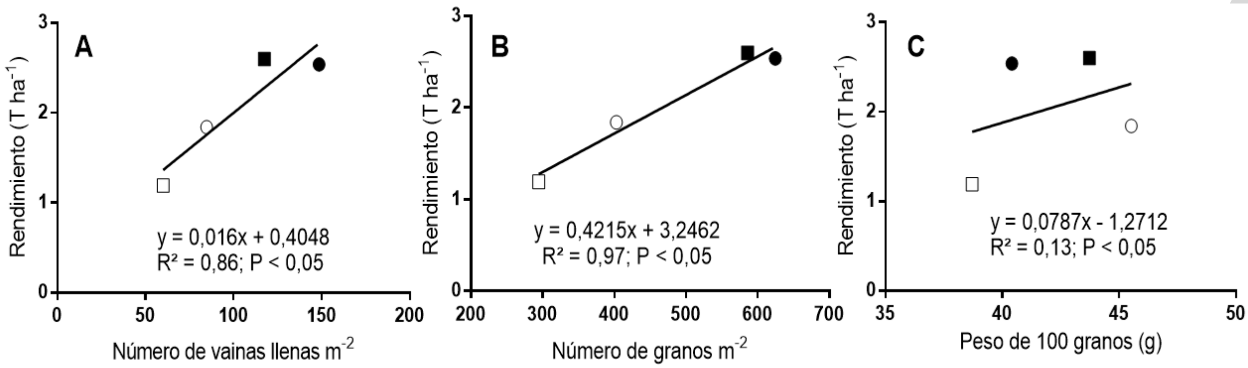

Figure 3. Relationship between yield and number of pods m^{-2} (A), number of grains m^{-2} (B), and 100-grain weight (C). Circles represent experiment 1 and squares represent experiment 2, filled symbols indicate density 11 plants^{-2} and empty symbols indicate density 4 plants m^{-2}. Each point is the average of three replicates.

4 Conclusions

Increasing bean plant density from 4 to 11 plants m^{-2} led to grain yield increases averaging $\approx 70\%$ in the two experiments. A different response of yield components to plant density modification was evidenced, NG is highly sensitive and increased by $\approx 73\%$ due to increase in the number of pods per unit area at high density. Furthermore, NG is closely related with final grain yield (R2 = 0.97), while grain weight was not affected by plant density modification, reaching on average 42 ± 3 g in all treatments.

To date, there is little evidence that has quantified the response of the numerical components of bean yield and their association with final yield under an ecophysiological approach in Andean environments, where soil and climatic conditions differ significantly from previous studies. Therefore, these results constitute a basis for designing strategies oriented to increase the yield of this important crop under these agroclimatic conditions, especially to improve grain weight and size, which has little response to resource supply.

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