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Yield Performance and Response to High Plant Densities of Dry Bean (*Phaseolus vulgaris* L.) Cultivars under Semi-Arid Conditions

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Abstract: To identify eco-efficient bean cultivars that can be planted at high densities for sustainable bean production under climate change, this study analyzed the performance of ten dry bean (*Phaseolus vulgaris* L.) cultivars grown at 90,000, 145,000 and 260,000 plants ha^{-1} under rainfed semi-arid conditions in Mexico. The study compared the yield and yield components (leaf area index (LAI), pods per plant, and hundred seed weight) of the cultivars. We also analyzed the dry matter distribution (DMD), growth rate (GR), radiation use efficiency (RUE), and harvest index (HI) of the best performing cultivars to determine how they respond to higher densities. The cultivars were established under similar planting and management conditions during two growing seasons. The precipitation for the first and second seasons were 175 and 492 mm, respectively, representing 57% and 160% of the mean precipitation in the area during the July–October growing period. Pinto Saltillo, a drought-tolerant indeterminate semi-prostrate cultivar, and Azufrado 2, a determinate shrub cultivar, performed best at high densities under low-precipitation conditions (175 mm). Both cultivars responded to the highest density (260,000 plants ha^{-1}) with increases of 54% to 69% (0.7 to 1.1) in LAI and 21% to 86% (0.32–0.81 Mg ha^{-1}) in yield. The two cultivars responded to increasing plant density with a modification in their fraction of DMD over plant parts and a change in their GR from 0.23–0.25 at low density to 0.96–1.74 gr m^{-2} day^{-1} at high density. The two cultivars had an RUE of 3.8 to 4.4 g MJ^{-1} and HI of 0.31 to 0.36 at high planting density. Farmers' use of these commercially available cultivars proven to have high yields and the ability to respond favorably to high densities under rainfed conditions can be a viable short-term strategy to increase dry bean production for sustainable agriculture in semi-arid temperate regions.

Keywords: *Phaseolus vulgaris*; Pinto Saltillo; dry matter distribution; radiation use efficiency; growth rate; harvest index; leaf area index

1. Introduction

Mexico is considered the center of origin of the common bean (*Phaseolus vulgaris* L.), an essential food crop in the country and in many other parts of the world [1,2]. The crop plays important nutritional and economical roles [3] in Mexico, where it is grown on 1,411,550 ha, 88% under rainfed conditions [4]. Despite major improvements in crop breeding and more precise management practices, yields of common bean have not increased, and great variability in yields persists that may be due to differences in production techniques and also to drought stress from insufficient rainfall or inadequate irrigation [5,6]. The use of high-yielding cultivars able to withstand water stress is advantageous for drylands in Mexico, where drought is endemic and occasionally intense [7,8]. With the predicted increase in the severity of drought conditions due to climate change, an important goal for bean production and breeding is improving crop yield and resilience while minimizing water deficit impacts [3].

Planting at high densities can be a strategy for obtaining optimum yield [9,10], although some studies have also shown its limiting effects on aspects of plant growth and development [11–13]. In this regard, it is essential to understand the effects of plant density on yield and its components by analyzing influencing factors and identifying major yield–density response curves [14]. Previous studies have shown that optimal plant density for increasing yield varies according to such factors as water supply, cultivar and soil type as well as to solar radiation and planting methods [15–18].

While the impacts of planting density and crop cultivar on crop yields and yield components have been explored previously in bean [19–21], field-based information on these and their temporal dynamics is limited [7], particularly under rainfed semi-arid conditions. The same is true of production efficiency factors, such as radiation use efficiency (RUE) and harvest index (HI) of cultivars [22]. Additional studies on these important variables can help in identifying and developing eco-efficient bean cultivars [7] that can be planted at high densities for sustainable bean production, particularly in smallholder farms under rainfed conditions. To this end, this study had the following objectives: (1) evaluate the yield and yield components (LAI, pods per plant and hundred seed weight) of ten dry bean cultivars planted at high plant densities under rainfed semi-arid conditions in Mexico; (2) determine the response to higher densities of the best-performing cultivars by analyzing their dry matter distribution, growth curve and rate, radiation use efficiency, and harvest index.

2. Materials and Methods

2.1. Study Area

The study was conducted at the Pabellon Research Station of INIFAP (National Institute of Forestry, Agriculture and Livestock Research) in Aguascalientes, Mexico (22°11′ N; 102°20′ W; 1912 m a.s.l.) during the 2011 and 2013 growing seasons. The soil is Calcisol, with sandy-loam texture, 7.9 pH, 2% organic matter and 0.48 m depth [23]. The study area, located in the highlands, has a semi-arid climate with an annual mean temperature of 22.1 °C and precipitation occurring mainly in summer [24]. The annual mean precipitation is 460 mm [25], 308 mm of which is recorded during the July–October growing period of dry bean [26].

2.2. Cultivars

The study analyzed ten dry bean cultivars (Table 1) from the Bean Genetic Improvement Program of INIFAP. Nine are growth habit III cultivars (indeterminate, with semi-prostrate architecture) from the Pinto and Flor de Mayo groups, while one (Azufrado 2) is a growth habit I cultivar (determinate, with bush-type architecture) [27]. All ten cultivars are grown in the north-central highlands of Mexico, with the indeterminate cultivars reported as the most common commercial dry beans in the region [28]. Their characteristics have been reported in other studies [29–35].

Table 1. Dry bean (*Phaseolus vulgaris* L.) cultivars established at 90,000 plants ha^{-1}, 145,000 plants ha^{-1}, and 260,000 plants ha^{-1} under rainfed conditions during the 2011 and 2013 growing seasons in Pabellon de Arteaga, Aguascalientes, Mexico.

Cultivar	Growth Habit †, Days to Physiological Maturity ‡, Seed Size § and Color of the Grain
Pinto Bravo	Type III, intermediate, medium grain, cream color with brown spots
Pinto Centauro	Type III, intermediate, medium grain, cream color with brown spots
Pinto Coloso	Type III, early, medium grain, cream color with brown spots
Pinto Saltillo	Type III, intermediate, medium grain, cream color with brown spots
Pinto Centenario	Type III, intermediate, medium grain, cream color with brown spots
Pinto Libertad	Type III, intermediate, medium grain, cream color with brown spots
Flor de Mayo Bajio	Type III, intermediate, small grain, beige with pink spots
Flor de Mayo Dolores	Type III, intermediate, medium grain, cream color with pink spots
Flor de Mayo Eugenia	Type III, intermediate, medium grain, cream color with pink spots
Azufrado 2	Type I, intermediate, large grain, light yellow color

† Growth habit: Determinate shrub, Type I; Indeterminate semi-prostrate, Type III. ‡ Physiological maturity: Early < 90 days; Intermediate 91 to 115 days. § Grain size: Small, <25 g 100 seeds^{-1}; Medium, 25 to 40 g 100 seeds^{-1}.

2.3. Crop Culture and Precipitation Conditions

The beans were planted as follows for each cultivar: (a) low density (Ld)—90,000 plants ha^{-1} in conventional furrows of 0.76 m width and 30 m length (total of four rows); (b) medium density (Md)—145,000 plants ha^{-1} in two three-row beds of 1.52 m width and 30 m length each, with inter-row spacing of 0.40 m; and (c) high density (Hd)—260,000 plants ha^{-1} in two six-row beds of 1.52 m width and 30 m length each, with inter-row spacing of 0.20 m. Hence, the experimental unit for each cultivar consisted of 4, 6 and 12 rows for Ld, Md and Hd, respectively, with a total area of 91.2 m^2 for each planting density.

The seedbed was prepared with a multi-plow to break the soil surface, but without soil inversion; disking was done before sowing. Pre-sowing irrigation of 60 mm was applied during the first year to ensure plant establishment. Seeds were sown using a mechanical seeder prototype developed by INIFAP [36] that was capable of establishing bean at three plant densities, with different distances between plant rows.

Sowing was done on 30 July 2011 and 31 July 2013. Planting and management of the crop were similar in both years. At time of sowing, the seeds were inoculated with *Rhizophagus irregularis*. The dose of the micro-substrate was 350 g ha^{-1} [23]. Weeding was performed 17 days after sowing (DAS). A fertilizer solution equivalent to 5.5 kg of nitrogen and 4.5 kg of phosphorus per hectare was sprayed on the leaves at grain-filling during the two growing seasons.

As the plants were grown under rainfed conditions, an analysis of precipitation during the growing seasons was made by comparing historical data (1996–2010) from Ruiz-Corral et al. [26] with data for the two years of study (2011 and 2013) obtained from an automated weather station at Pabellon Research Station.

2.4. Field Measurements

The data gathered from the field were leaf area index (LAI), pods per plant, hundred seed weight (HSW, g), yield (Mg ha^{-1}), and above- and below-ground biomass. LAI and biomass were measured only in 2011 (a critical year due to low precipitation). All other variables as well as precipitation were measured during the two growing seasons.

2.5. Yield and Yield Components

2.5.1. Leaf Area Index

To measure LAI, five sampling points per planting density were randomly established in the central rows of each treatment in the experimental unit of each cultivar. LAI data were gathered using an AccuPAR LP-80 ceptometer (Decagon, Pullman, WA, USA). DAS measurements were used so that LAI could be compared during the same period of plant growth. Data were gathered during the first growing season at 19, 25, 40, 45, 79 and 87 DAS for all cultivars.

The ceptometer was calibrated before each measurement, and care was taken not to shade any part of the ceptometer sensor with the researcher's shadow. We did not use any ceptometer external sensor. The readings were made 10 cm above ground level and above canopy between 10:00 a.m. and 1:00 p.m., when the incidence solar radiation was relatively stable. The ceptometer was inserted at a 45° angle from the row orientation; the base of the ceptometer was thus anchored in the middle of the furrow and the tip pointed into the row. In each sampling point, ten simultaneous ceptometer's readings above and below canopy were done. The measurements, automatically averaged by the ceptometer, were used for the mean LAI measurements.

2.5.2. Number of Pods, Hundred Seed Weight and Yield

At harvest during the two growing seasons, five plots per planting density, each measuring 1.52 m width by 2 m length, were randomly located in the central part of each treatment in the experimental unit of each cultivar. Before each plot was harvested, a plant was randomly selected from its central part, from which the number of pods per plant was quantified. Then, all plants in the quadrant were harvested for seed yield (Mg ha^{-1}) determination. The weight (g) of 100 seeds (HSW) was recorded from a sample of the seeds obtained in each plot.

2.6. Response to High Plant Densities

2.6.1. Dry Matter Distribution

To determine dry matter distribution, we sampled above- and below-ground biomass during the first growing season, considering seven phenological stages [37]—from the vegetative stage V3 (first trifoliate leaf) to the reproductive stage R9 (maturation).

Sampling was performed when 50% of the plants in the experimental plot showed signs corresponding to each of the phenological stages under study. The destructive sample consisted of five random samples of 0.50 m^2 each from the central two rows of each plant density treatment in the experimental unit of each cultivar. Both above- and below-ground biomass were obtained from each quadrant. An excavation approximately 40-cm deep was made to obtain as many secondary roots as possible. The samples were placed in paper bags and taken to the laboratory, where the plants from each quadrant were separated and identified. The above-ground biomass was separated into leaves, stems, flower buds and pods. The roots were washed with water. Each organ was weighed and dried in a forced oven at 65 °C for 72 h and weighed for the determination of dry matter (DM) production.

In this paper, we present the results of our detailed analysis of the biomass data of three cultivars that performed best in yield at high density under low-precipitation conditions. Dry matter distribution at different development stages of the plant under three planting densities was analyzed to determine how the cultivars responded to increasing density. In addition, we provide a brief summary of the results of the dry matter distribution of the seven other cultivars.

For the detailed analysis, P. Saltillo was selected because it showed the highest production among the Pintos under the three plant densities in the two years of study, i.e., under different precipitation conditions. The cultivar Bajio was chosen among the Flor de Mayo cultivars because it showed the highest LAI value and the highest yield under any plant density during the year with low precipitation (58% of historical average for the growing period). The lone determinate cultivar Azufrado 2 was also selected because it showed increases in yield at high plant density even during low precipitation conditions (i.e., first growing season).

2.6.2. Growth Rate, Radiation Use Efficiency and Harvest Index

To derive additional information on the response of the three best-performing cultivars to high density, their growth rate, RUE, and HI were also analyzed. In the calculation of growth rate (GR, $g\ m^{-2}\ day^{-1}$), the days that elapsed between sowing and each phenological stage were quantified and presented as DAS.

To calculate RUE, the plant growth ($g\ m^{-2}$) was divided by the daily irradiance within the PAR (Photosynthetically Active Radiation) waveband (0.4 to 0.7 μm) that fell upon the site. The conversion of solar radiation to PAR was assumed to be 0.50, which is considered appropriate for the tropics as well as temperate latitudes [38–40]. Solar radiation information was gathered from an automated weather station close to the experimental site.

The HI was calculated as the ratio of yield to above-ground biomass.

2.7. Statistical Analysis

To determine any significant differences between plant densities of each cultivar, ANOVA and Student's *t* tests were performed using the GraphPad Prism 5® (GraphPad Software, Inc., San Diego, CA, USA) statistical software at $p \leq 0.05$ and $p \leq 0.01$ probability levels [41].

3. Results and Discussion

3.1. Precipitation during the Growing Seasons

The present study was carried out under precipitation conditions that prevailed during recent decades in the Mexican Plateau regions, thus allowing the analysis of the response of dry bean cultivars to different plant densities in the targeted environment, as highly recommended in agronomic trials [42]. The precipitation recorded during the two growing seasons were 175 and 492 mm for the first and second seasons, respectively (Figure 1). These values represent 57% and 160% of 308 mm, the historical average (1996–2010) for July–October, which corresponds to the growing period of dry bean in the study area [26].

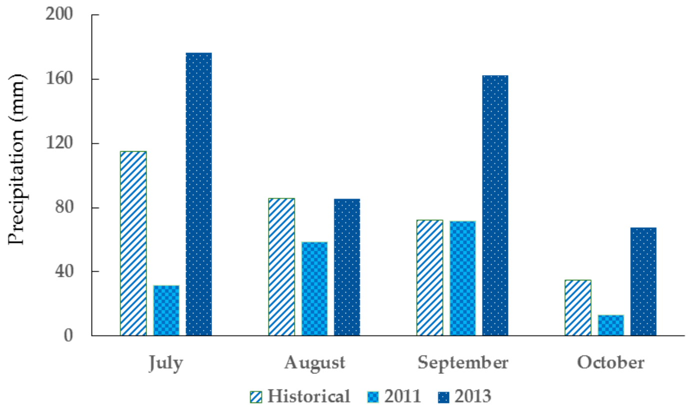

Figure 1. Precipitation during the 2011 and 2013 growing seasons (July–October) of dry bean (*Phaseolus vulgaris* L.) in Pabellon de Arteaga, Aguascalientes, Mexico.

The precipitation analysis showed that during the first growing season, monthly precipitation values from the automated weather station were less than historical data (Figure 1), except in September, during which the value was similar to the historical value (72 mm). During the second growing season, monthly precipitation values were equal to or greater than historical values, with September precipitation being twice as high as the historical precipitation (162 vs. 72 mm). September is a critical month for bean development as it marks the reproductive phase of the plant. It must be considered that the timing of water deficits during a season, and not only the total seasonal water supply, affects farm crops [43].

3.2. Yield Components

3.2.1. Leaf Area Index

Planting density is considered a significant determinant of LAI, which is a key driver in light interception and, consequently, crop growth in most crops [15,44]. In the present study, the maximum LAI values (Figure 2) varied according to the plant density and cultivar. The Pintos reached their highest LAI values (2.4–3.0) at Hd, while the Flor de Mayo cultivars achieved theirs (3.2–3.4) at Md (Figure 2). Both the Pintos and Flor de Mayo cultivars are growth habit III cultivars (indeterminate, with semi-prostrate architecture). Azufrado 2, a growth habit I cultivar (determinate, with bush-type architecture), also achieved its highest LAI values (1.6–2.7) at Hd.

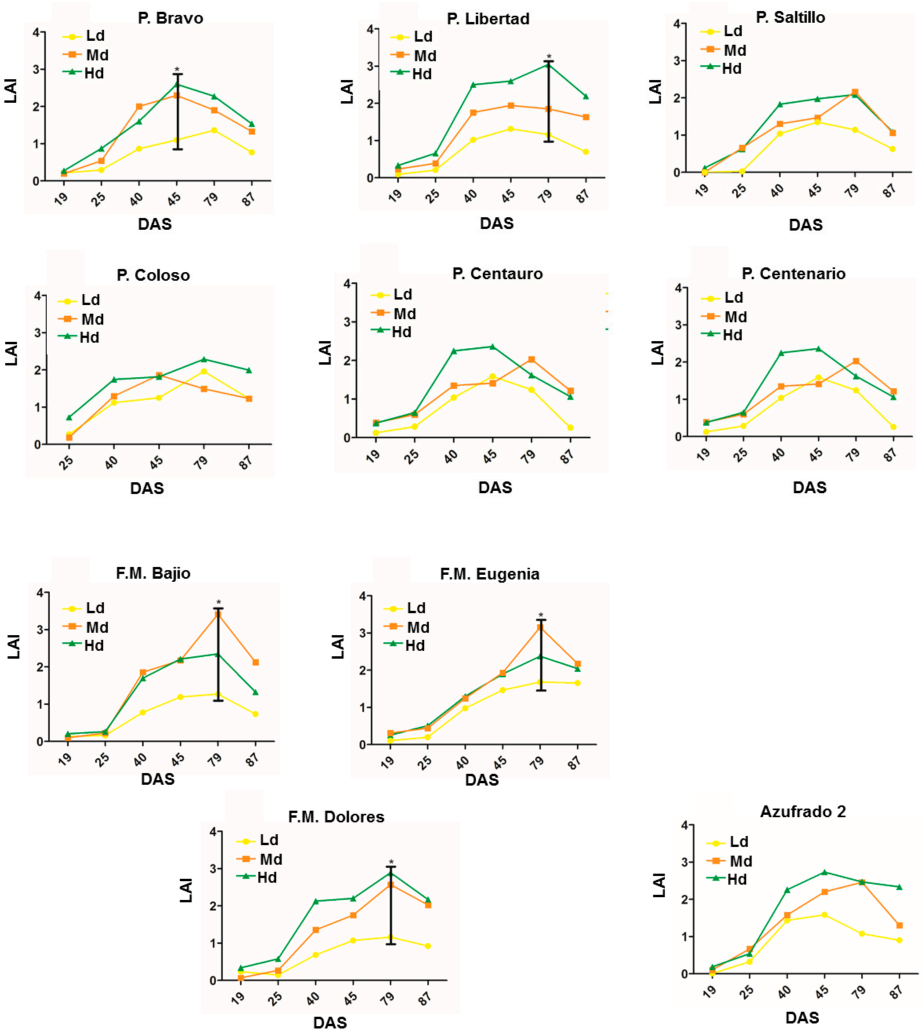

Figure 2. Leaf area index (LAI) at different days after sowing (DAS) of growth habits III Pinto (P) and Flor de Mayo (F.M.) and growth habit I Azufrado 2 dry bean (*Phaseolus vulgaris* L.) cultivars established at 90,000 plants ha^{-1} (Low density, Ld), 145,000 plants ha^{-1} (Medium density, Md) and 260,000 plants ha^{-1} (High density, Hd) under rainfed conditions in Pabellon de Arteaga, Aguascalientes, Mexico during the 2011 growing season.

Previous studies [45] have shown a strong effect of plant density on LAI for common bean, with a faster increase in LAI at high plant density than at low and medium densities. In our study, faster increase of LAI at Hd was observed only in the cultivar P. Bravo, which achieved maximum LAI at 45 DAS at Md and Hd vs. 79 DAS at Ld (Figure 2). In contrast, P. Saltillo and P. Libertad showed delays of up to 34 days in achieving maximum LAI in relation to Ld (79 vs. 45) (Figure 2). For Flor de Mayo cultivars, maximum LAI was reached at 79 DAS under any plant density. For the determinate cultivar Azufrado 2 as well as the indeterminate cultivars P. Centenario and P. Centauro, the DAS when maximum LAI was achieved did not show a definite pattern of increase with increasing density. Maximum LAI was reached at 45 DAS at Ld and Hd and at 79 DAS at Md (Figure 2). These results suggest that the response of bean to high planting densities is a cultivar's own response to plant-to-plant competition rather than an intrinsic characteristic of the crop, as mentioned by Sennhenn et al. [45].

3.2.2. Pods Per Plant and Hundred Seed Weight

Common bean studies have shown a linear decrease in pods per plant with increasing density [13]. In this study, the response of the cultivars to planting density in terms of pods per plant and hundred seed weight (HSW) varied between growing seasons according to cultivar and available soil moisture (Figure 3A,B). The indeterminate cultivars P. Saltillo, P. Centauro, P. Libertad and the Flor de Mayo Bajio and Eugenia cultivars as well as the determinate Azufrado 2 were able to withstand competition between plants to some degree at Md even under low precipitation conditions (175 mm). There were no adverse effects on the number of pods per plant or HSW. However, at Hd, only P. Saltillo showed no difference in HSW during the two growing seasons (Figure 3B). Belonging to the drought-resistant Mesoamerican Durango race [46], P. Saltillo demonstrated the ability to respond to Hd without negative effects on pods per plant and HSW even under low precipitation conditions.

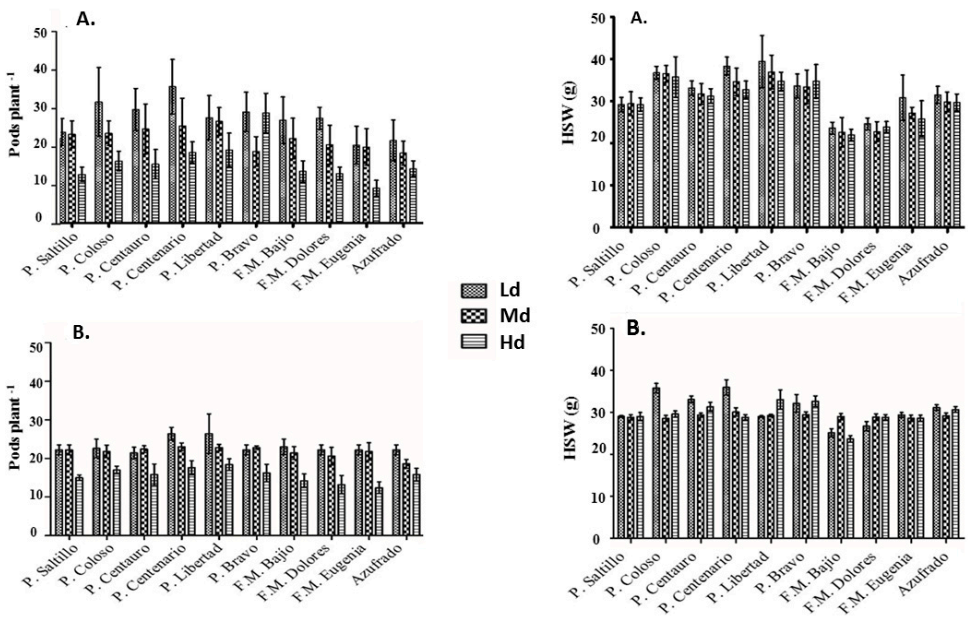

Figure 3. Number of pods per plant and hundred seed weight (HSW) of ten dry bean (*Phaseolus vulgaris* L.) cultivars established at 90,000 plants ha^{-1} (Low density, Ld), 145,000 plants ha^{-1} (Medium density, Md) and 260,000 plants ha^{-1} (High density, Hd) under rainfed conditions, with 175 mm (**A**) and 492 mm (**B**) of precipitation during the 2011 and 2013 growing seasons in Pabellon de Arteaga, Aguascalientes, Mexico. The standard error of the mean of five plants for number of pods per plant and the mean of five plots for HSW is indicated by the vertical bars.

Azufrado 2 responded to Hd by significantly decreasing the number of pods (16–29%) during the two years of the study, but increasing HSW (6%) when precipitation was greater (492 mm) (Figure 3A,B).

The statistical analysis of the interaction between plant density and cultivar for the year with low precipitation (175 mm) showed that pods per plant had a difference ($p \leq 0.05$) in Ld vs. Md only in P. Coloso (31.7 vs. 23.5), P. Centenario (29.7 vs. 24.6), P. Bravo (29.1 vs. 18.7) and Flor de Mayo Dolores (27.4 vs. 20.5). In the analysis of Ld vs. Hd, all cultivars showed a difference ($p \leq 0.05$) except P. Bravo, which showed values of 29.1 vs. 28.8 pods per plant for Ld and Hd, respectively. A significant difference was also observed in Md vs Hd in all cultivars except Azufrado 2, whose values were 18.3 vs 14.2 pods per plant for Md and Hd densities, respectively. During the second year, when precipitation was 492 mm, a difference ($p \leq 0.05$) was observed in Ld vs. Md only in the cultivars P. Centenario (26.4 vs. 23.0), P. Libertad (26.4 vs. 22.8) and Azufrado 2 (22.2 vs. 18.6). However, in Ld vs. Hd and Md vs. Hd, all cultivars presented differences ($p \leq 0.05$).

Regarding HSW, with low rainfall (175 mm) during the first year, a difference ($p \leq 0.05$) was observed solely in Ld vs. Hd and only in P. Centenario (38.3 vs. 32.8 g), P. Libertad (39.4 vs. 34.7 g) and Flor de Mayo Eugenia (30.8 vs. 25.8 g). During the second year, with rainfall of 492 mm, a difference ($p \leq 0.05$) was observed in all the cultivar–plant density interactions except in P. Saltillo and Flor de Mayo Eugenia, which both had an average of 28.9 g HSW in Ld, Md and Hd (Figure 3B). The study results suggest that the response to plant densities, in terms of pods per plant and seed weight, depended in part on the response of the cultivar to the soil moisture conditions available for crop development during the growing cycle. Less pods per plant and HSW were obtained during the second year, when excess humidity occurred during the reproductive stage. As shown in Figure 1, the amount of precipitation was almost double than in historical data for the months of September and October, when the beans were in the reproductive stage. The stress caused by excess soil moisture (waterlogging) and humidity during some days of those months could have negatively affected yield components, such as the number of pods and weight of 100 seeds, as well as the source–demand relationship, or the photosynthetic rate [47–49], although this effect was cultivar-dependent.

3.2.3. Yield

In the present study, an increase in plant density did not necessarily result in an increase in dry bean yield (Figure 4). Cultivars varied in their response to density. During the first growing season, when precipitation was only 175 mm, four cultivars did not respond to the change in density, three produced the same yields in Md and Hd and only two responded to Hd with an increase in yield. However, during the second growing season, when precipitation was greater (317 mm more), three cultivars showed no difference between treatments, five responded to the increase in plant density with increased yield, while two produced lower yield at Hd.

In relation to the response by groups (i.e., Pinto and Flor de Mayo), the Pintos, not including P. Saltillo, responded to the change in planting density (from Ld to Md and Hd) with increases of 47% to 59% in yield (Figure 4) only under greater available soil moisture (i.e., with more precipitation during the second growing season). In the case of P. Saltillo, it stood out because it obtained the highest yields among the Pintos during the two growing seasons, regardless of available soil moisture (Figure 4). The yields of P. Saltillo at Ld, Md and Hd were 1.5, 1.9 and 1.9 Mg ha^{-1}, respectively, for the first growing season and 2.2, 2.2 and 2.3 Mg ha^{-1}, respectively, for the second season. These yields are much higher than the 0.34 ± 0.08 Mg ha^{-1} average farmers' dry bean yield under rainfed conditions for the area (Aguascalientes) reported for 2011–2019 [50] and are comparable to yields reported in countries with modernized agricultural systems, such as the USA and Brazil [8]. Other studies [46,51] have indicated that P. Saltillo, a drought-tolerant cultivar, exhibits effective regulation of the stomata response, which may be a contributing factor in water use efficiency. For this cultivar, high plant density did not have a negative effect on LAI development during the season with lower soil moisture (Figure 2). Some studies [1,52,53] report that when beans were grown under drought conditions, the stress did not necessarily involve a yield penalty, and lines of dry beans with superior yield showed higher LAI values under drought stress, as was observed in P. Saltillo in the present study.

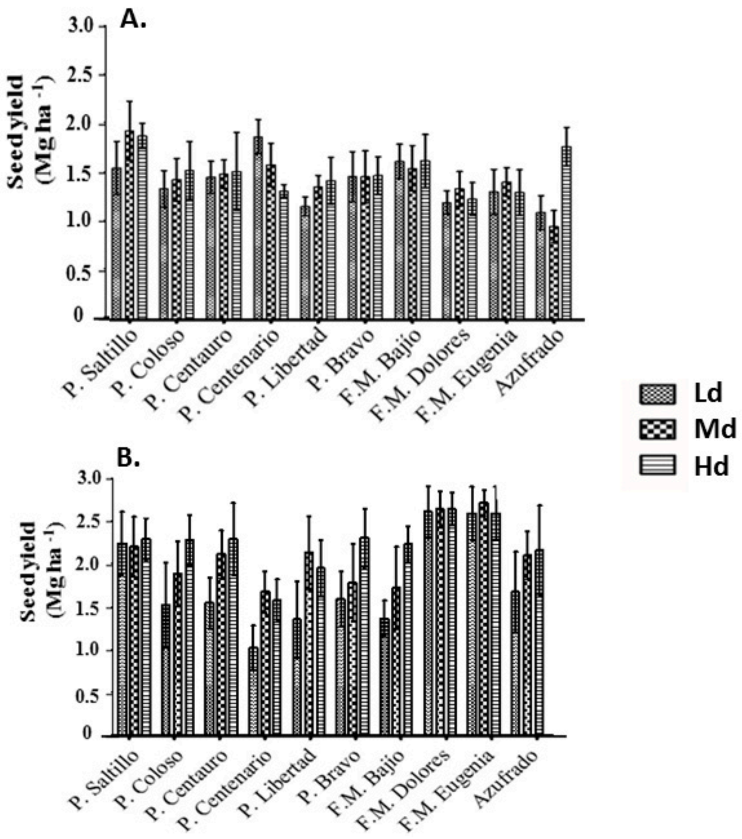

Figure 4. Yield of ten dry bean (*Phaseolus vulgaris* L.) cultivars established at 90,000 plants ha^{-1} (Low density, Ld), 145,000 plants ha^{-1} (Medium density, Md) and 260,000 plants ha^{-1} (High density, Hd) under rainfed conditions, with 175 mm (**A**) and 492 mm (**B**) of precipitation during the 2011 and 2013 growing seasons in Pabellon de Arteaga, Aguascalientes, Mexico. The standard error of the mean of five plots is indicated by the vertical bars.

The Flor de Mayo cultivars Eugenia and Dolores did not respond to the change in planting density from Ld to Md or Hd during the two growing seasons (Figure 4), but among the ten cultivars, they showed the highest yields during the second season, when there was greater available soil moisture. The yields were 2.6, 2.7, 2.6 Mg ha^{-1} for Ld, Md and Hd, respectively, for the cultivar Eugenia and 2.6 Mg ha^{-1} at all three densities for Dolores. These results indicate that these two cultivars can continue to be sown under conventional seeding (Ld); they can obtain higher yields in relation to the other studied cultivars when precipitation during the growing season is equal to or greater than the mean historical precipitation (i.e., 308 mm) for this region. On the other hand, Flor de Mayo Bajio responded to Hd with an increase in yield during the two growing seasons; it yielded more than the cultivars Eugenia and Dolores when available soil moisture was low. Therefore, this cultivar is considered a viable option for sowing at high planting densities in areas with erratic precipitation.

In the case of Azufrado 2, sowing at high density led to an increase of 0.80 Mg ha^{-1} in yield (Figure 4), even under the lower precipitation conditions of the first growing season. This indicates that, like P. Saltillo, it shows promise for bean production in areas with limited available soil moisture, a recurring condition affecting rainfed crops in semi-arid areas.

3.3. *Response of Best Performing Cultivars to High Plant Densities*

3.3.1. Dry Matter Distribution

In our analysis of the three best-performing cultivars, no difference was observed ($p \geq 0.05$) in the fraction of dry matter allocated to roots and shoots as an effect of plant density (Figures 5A, 6A and 7A). As for the distribution of dry matter over plant part components (i.e., leaves, stems, flower buds and pods), differences ($p \leq 0.05$) were observed in P. Saltillo and Azufrado 2 (Figures 5B and 7B), while Flor de Mayo Bajio (Figure 6B) showed no difference ($p \geq 0.05$). P. Saltillo (Figure 5B) showed a difference ($p \leq 0.05$) in the fraction of plant dry matter allocated to plant parts during the R6 (flowering) and R8 (seed filling) development stages. At flowering, allocated dry matter in flower buds was 0.03 for Ld and 0.02 for Md and Hd (Figure 5B). Differences were also observed at seed filling in dry matter allocated to leaves (0.23 for Md and 0.13 for Hd) and in dry matter allocated to pods (0.53 and 0.70 for Md and Hd densities) (Figure 5B). As for Azufrado 2, a difference ($p \leq 0.05$) was observed, but only in the fraction of plant dry matter distribution in pods (Figure 7B) during the seed filling development stage, with 0.61 for Md and 0.56 for Hd.

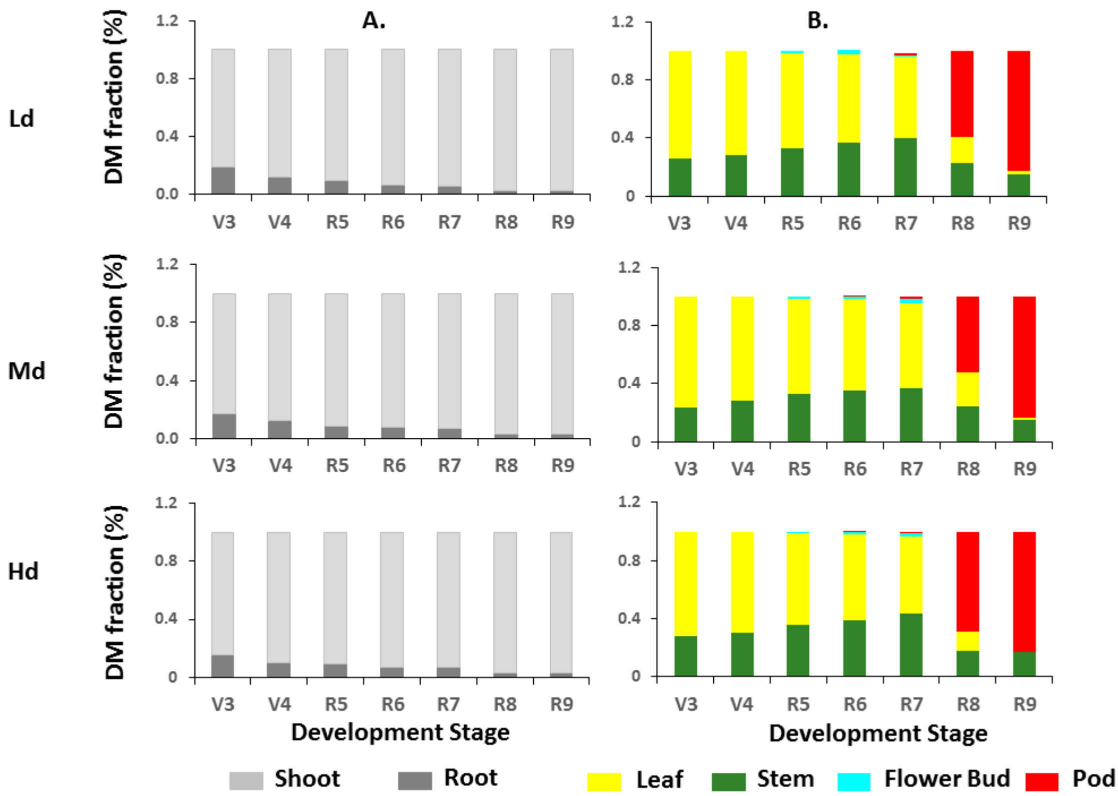

Figure 5. Average fractions (**A**) of roots and shoots in total biomass and (**B**) distribution of shoot biomass over leaves, stems, flower buds and pods of growth habit III Pinto Satillo dry bean (*Phaseolus vulgaris* L.) cultivar established at 90,000 plants ha^{-1} (Ld, Ld), 145,000 plants ha^{-1} (medium density, Md) and 260,000 plants ha^{-1} (high density, Hd) under rainfed conditions during the 2011 growing season in Pabellon de Arteaga, Aguascalientes, Mexico.

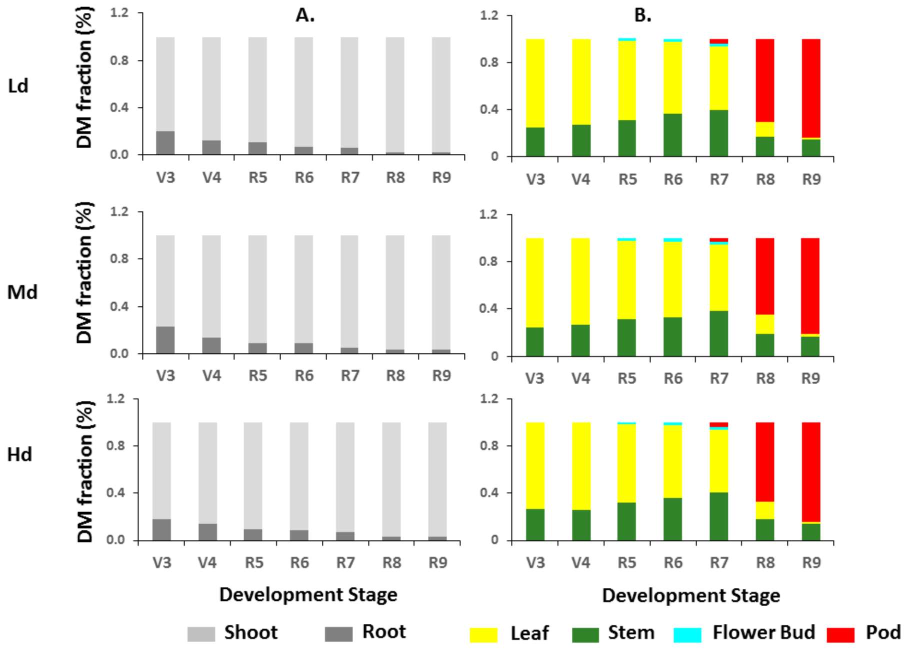

Figure 6. Average fractions (**A**) of roots and shoots in total biomass and (**B**) distribution of shoot biomass over leaves, stems, flower buds and pods of growth habit III Flor de Mayo Bajio dry bean (*Phaseolus vulgaris* L.) cultivar established at 90,000 plants ha^{-1} (Low density, Ld), 145,000 plants ha^{-1} (Medium density, Md) and 260,000 plants ha^{-1} (High density, Hd) under rainfed conditions during the 2011 growing season in Pabellon de Arteaga, Aguascalientes, Mexico.

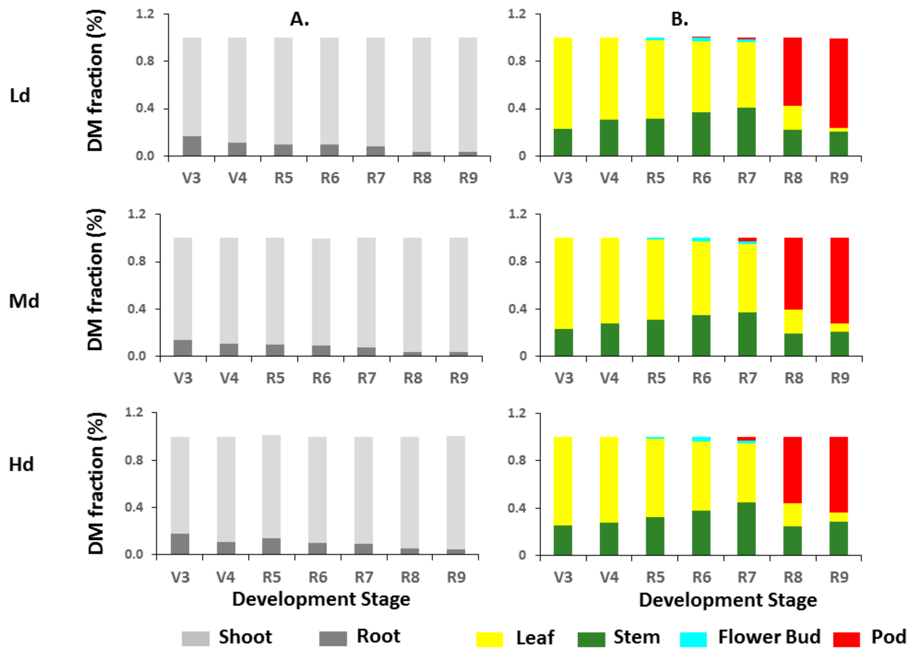

Figure 7. Average fractions (**A**) of roots and shoots in total biomass and (**B**) distribution of shoot biomass over leaves, stems, flower buds and pods of growth habit I Azufrado 2 dry bean (*Phaseolus vulgaris* L.) cultivar established at 90,000 plants ha^{-1} (Low density, Ld), 145,000 plants ha^{-1} (Medium density, Md) and 260,000 plants ha^{-1} (High density, Hd) under rainfed conditions during the 2011 growing season in Pabellon de Arteaga, Aguascalientes, Mexico.

As for the seven other cultivars, no difference ($p \geq 0.05$) was observed in the fraction of dry matter allocated to roots and shoots as an effect of plant density. In the distribution of dry matter over plant part components, differences ($p \leq 0.05$) were observed in Ld vs. Md during the flowering stage in P. Centauro and Flor de Mayo Dolores and during seed filling in P. Centenario, P. Centauro and P. Libertad. A difference ($p \leq 0.05$) was also observed in P. Bravo in Ld vs. Hd during the seed filling stage. In Md vs. Hd, cultivars P. Liberad and Flores de Mayo Eugenia and Dolores showed differences ($p \leq 0.05$) during seed filling.

Changes in yield components may be a result of the plant's response to its environment, which may or may not allow the full genetic expression of each component [54], as plant-to-plant competition increased.

3.3.2. Growth Curve and Rate

Goudriaan and Montheith [55] posited that the plant growth curve shifts from exponential to linear, i.e., expolinear growth curve, to represent the linear growth during most of the growth stages. In the present study, the three best-performing cultivars showed linear trends in the growth curve from the first trifoliate leaf (V3) to pod formation (R7) (Figure 8).

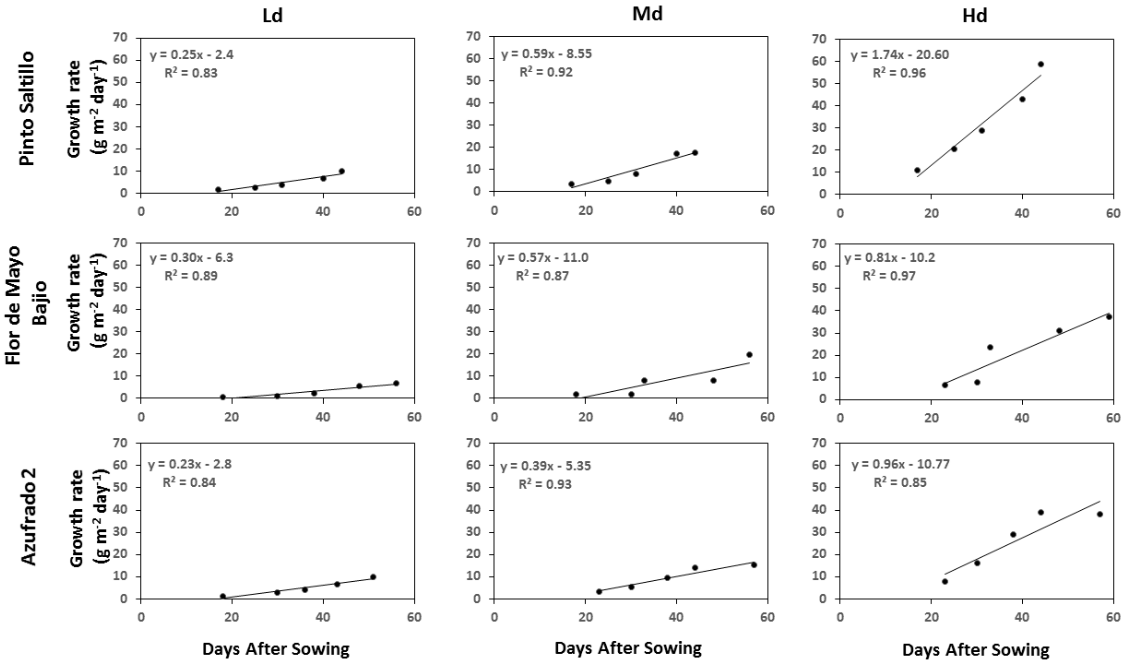

Figure 8. Growth rate of three dry bean (*Phaseolus vulgaris* L.) cultivars established at 90,000 plants ha^{-1} (low density, Ld), 145,000 plants ha^{-1} (medium density, Md) and 260,000 plants ha^{-1} (high density, Hd) under rainfed conditions, with limited soil moisture (175 mm of precipitation) during the 2011 growing season in Pabellon de Arteaga, Aguascalientes, Mexico.

In relation to growth rate, Flor de Mayo Bajio had growth rate values of 0.30, 0.57 and 0.81 gr m^{-2} day^{-1} in Ld, Md and Hd, respectively, whereas P. Saltillo obtained values of 0.25, 0.59 and 1.74 gr m^{-2} day^{-1} and Azufrado 2, 0.23, 0.39 and 0.96 gr m^{-2} day^{-1} in Ld, Md and Hd, respectively (Figure 8).

The growth rate values of the three cultivars increased with higher plant densities. According to Averbeke and Marais [15], higher LAI due to higher planting density can lead to higher growth rates at grain filling and higher yields, although, as mentioned by Asemanrafat and Honar [10], drought stress can be a limiting factor in areas with insufficient annual precipitation, causing a decrease in leaf area and thereby reducing dry matter production, yield and yield components. In the present study, P Saltillo, had higher yields at Hd than Flor de Mayo Bajio and Azufrado 2 during the two growing seasons regardless of the available soil moisture (Figure 4) and despite having lower LAI values compared with Bajio (2.2 vs. 3.4). The differences in the fraction of plant dry matter allocated to leaves, flower buds and pods (Figure 6B) and its growth rate (Figure 8) reflect the response of P. Saltillo when plant-to-plant competition increased.

3.3.3. Radiation Use Efficiency

The RUE values from the first trifoliate leaf (V3) to pod formation (R7) of the three best performing cultivars under different plant densities varied from 2.1 g MJ^{-1} to 4.4 g MJ^{-1} (Figure 9). Flor de Mayo Bajio obtained values of 2.1, 3.2 and 3.9 g MJ^{-1} for Ld, Md and Hd, respectively. RUE values of P. Saltillo were 2.2, 2.7 and 4.4 g MJ^{-1} and of Azufrado 2, 2.5, 2.8 and 3.8 g MJ^{-1} for Ld, Md and Hd, respectively.

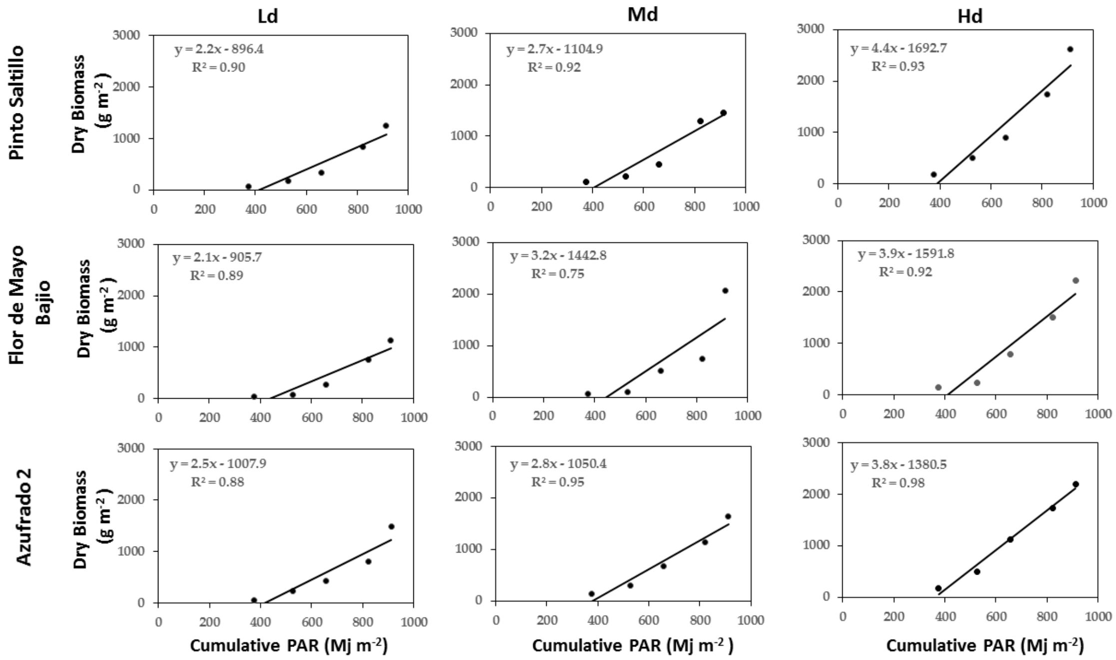

Figure 9. Radiation use efficiency of three dry bean (*Phaseolus vulgaris* L.) cultivars established at 90,000 plants ha^{-1} (Low density, Ld), 145,000 plants ha^{-1} (Medium density, Md) and 260,000 plants ha^{-1} (High density, Hd) under rainfed conditions during the 2011 growing season in Pabellon de Arteaga, Aguascalientes, Mexico.

Decreasing the radiant energy reaching the ground is a way of promoting the efficient use of incident solar radiation, as shown in cases of improved use of radiant energy when intercepted by more efficient biomass production or increased biomass partitioned to yield [22]. This is observed in the high RUE value (3.2 g MJ^{-1} at Md) of Flor de Mayo Bajio, the cultivar that also obtained the highest LAI value (3.4 at Md), based on the results of all studied cultivars and planting densities.

3.3.4. Harvest Index

A high harvest index is considered an indicator of high economic yield as it shows the extent to which plant photosynthetic materials are apportioned to grain production [56]. Table 2 shows the HI values obtained by the three cultivars under the different plant densities. The values of 0.31 and 0.36 in the Hd treatment of P. Saltillo and Azufrado 2 are similar to those reported by Tsubo et al. [22] and Baez-Gonzalez et al. [57].

Table 2. Harvest index of dry bean (*Phaseolus vulgaris* L.) cultivars established at 90,000 plants ha^{-1} (Low density, Ld), 145,000 plants ha^{-1} (Medium density, Md) and 260,000 plants ha^{-1} (High density, HD) under rainfed conditions, with limited soil moisture (175 mm of precipitation) during the 2011 growing season in Pabellon de Arteaga, Aguascalientes, Mexico.

Cultivar	**Plant Densities**		
	Ld	**Md**	**Hd**
Growth habit III			
Pinto Saltillo	0.28 ± 0.04	0.26 ± 0.04	0.31 ± 0.02
Flor de Mayo Bajio	0.22 ± 0.02	0.18 ± 0.03	0.22 ± 0.04
Growth habit I			
Azufrado 2	0.21 ± 0.03	0.17 ± 0.03	0.36 ± 0.04

A difference ($p \leq 0.05$) was observed (Table 2) in P. Saltillo only in Md vs Hd, while for Flor de Mayo Bajio, a difference ($p \leq 0.05$) was seen in Ld vs. Md and Md vs. Hd. On the other hand, Azufrado 2 showed a difference ($p \leq 0.05$) in all analyses: Ld vs. Md, Ld vs. Hd, and Md vs. Hd.

The HI values obtained by the indeterminate cultivar Flor de Mayo Bajio (0.22 for Ld and Hd and 0.18 for Md) were lower than those of P. Saltillo and Azufrado 2 (Table 2). However, as previously stated, this cultivar had higher RUE value at Md (3.2 g Mj^{-1}) (Figure 9) than P. Saltillo and Azufrado 2 and a growth rate of 0.57 g m^{-2} day^{-1} (Figure 8). One possible reason for the low HI value at Md, as explained by Averbeke and Marais [58], is that HI is closely related to the proportion of barren plants that contribute to total biomass but not to grain (such as in the case of Flor de Mayo Bajio). Increases in barrenness or seed/pod abortion in plants can result in reductions in the harvest index, especially in situations of increased planting density under limiting soil moisture available to plants [58].

In the management of plant tolerance to water stress, the HI is an important factor to consider [10]. P. Saltillo, a drought-tolerant cultivar, showed a high HI value (0.31) at Hd, with a growth rate of 1.74 g m^{-2} day^{-1} (Figure 8). It presented an adjustment in the fraction of dry matter allocated to component plant parts as plant density increased (Figure 5B), demonstrating its adaptation to the available water conditions and plant-to-plant competition at high planting densities.

The determinate Azufrado 2 obtained higher HI (0.36) also at Hd, though lower RUE values than those of the two indeterminate cultivars (Figure 9). Its growth rate showed an increase of 0.73 g m^{-2} day^{-1} as plant density increased from low to high plant density. Its yield also increased by 0.81 Mg ha^{-1} at Hd. Its shrub-like structure seemed to be an advantage. Several studies [10,59–61] mention that due to the competition among plants, plant density has a significant effect on plant height (leading to taller plants) which could promote the formation of new leaves at the top of the canopy, where, according to Martin and Downie [62], maximum photosynthesis takes place. This requires further study as plant heights under the different treatments were not recorded in this study.

4. Conclusions

Planting dry bean at high densities can improve production in rainfed semi-arid areas. However, this requires the use of cultivars able to respond favorably to increased plant-to-plant competition even under erratic precipitation conditions.

Of the 10 cultivars that were compared in this study, Pinto Saltillo and Azufrado 2, indeterminate and determinate cultivars, respectively, performed best at high density even under low-precipitation conditions (58% of historical average). They showed a positive response to the highest planting density (240,000 plants ha^{-1}), with an increase of 0.32–0.81 Mg ha^{-1} in production. The increase in planting density from 90,000 to 145,000 plants ha^{-1} did not have adverse effects on their yield components. Furthermore, these two cultivars showed the ability to respond favorably to high planting densities, as seen in changes in the distribution of dry matter, a modification in the growth rate, RUE values of 3.8 g MJ^{-1} to 4.4 g MJ^{-1} values and HI values of 0.31 to 0.36. Farmers' use of these commercially available cultivars planted at high densities can be a viable short-term strategy to increase dry bean production for sustainable agriculture in semi-arid temperate regions. They can also be useful in breeding programs for generating new cultivars able to withstand drought conditions that are likely to increase in severity because of the effects of climate change.

Author Contributions: A.D.B.-G. designed the study, contributed to the acquisition and analysis of data and the discussion of results, and wrote the first and final drafts; R.F.-D. contributed to data analysis; E.S.O.-C. contributed to crop establishment and the acquisition of data on yield and yield components; J.S.P.-R., J.R.K. and M.N.M. contributed to reviewing the results and editing the final draft. E.A.-D. contributed to reviewing the results. All authors have read and agreed to the published version of the manuscript.

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