

Light management in tree nurseries to produce *Pithecellobium dulce* for the reforestation of degraded lands in Southern Mexico's tropical dry forests

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Photo 1.
Mature *Pithecellobium dulce* tree chosen as seed source.
Photo E. Basave-Villalobos.

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RÉSUMÉ

Gestion de la lumière dans les pépinières produisant des plants de *Pithecellobium dulce* pour le reboisement de terres dégradées dans les forêts tropicales sèches du sud du Mexique

Le choix des pratiques en pépinière est important pour la production de semis de haute qualité et pour augmenter les taux de survie des plantations de reboisement en milieu tropical sec. Cependant, des pratiques adéquates doivent être établies pour les espèces indigènes pour lesquelles les informations sur la propagation sont rares. La présente étude indique que la gestion de la lumière en pépinière est une pratique et une étape culturelle clé pour le succès futur de la plantation, en raison des changements morpho-physiologiques que les plants subissent habituellement dans différentes conditions de lumière. Nous avons examiné les variations de la morphologie, de l'efficacité de la photosynthèse et de la croissance de plants de *Pithecellobium dulce* produits en pépinière sous quatre niveaux de lumière (20 %, 40 %, 60 % et 100 % du rayonnement photosynthétiquement actif [RPA]). Nous avons également évalué la survie après repiquage en fonction des conditions de lumière dans lesquelles les plants ont été cultivés. Les variables morpho-physiologiques ont été examinées sur des plants de trois mois. Une plantation a été établie sur le terrain avec les plants cultivés en pépinière, et leur taux de survie enregistré tous les mois pendant 17 mois. Les effets des niveaux de lumière en pépinière étaient significatifs pour la morphologie, l'efficacité de la photosynthèse et la croissance des plants. Le niveau de 60 % de RPA était favorable à des résultats optimaux pour la plupart des variables, alors que les résultats les moins bons ont été trouvés pour les plants cultivés à 20 % de RPA. Sur le terrain, le taux de survie des plants varie significativement en fonction du niveau de lumière en pépinière, les meilleurs taux étant observés sur les plants ayant bénéficié d'une plus grande intensité lumineuse en pépinière. Nous avons observé un taux de survie de 100 % pour les plants produits sous 100 % de RPA, tandis que le taux de survie le plus faible (53 %) a été constaté pour les plants cultivés sous 20 % de RPA. La gestion de la lumière apparaît ainsi comme une pratique culturelle clé en raison de son impact sur la qualité des plants de *P. dulce*, qui s'améliore à 60 % de RPA en pépinière. Cependant, le meilleur taux de survie est obtenu pour les plants produits en plein soleil. Ces résultats devraient contribuer à améliorer la gestion des pépinières et la reprise de plants de *P. dulce* utilisés pour les projets de restauration de terres dégradées en milieu tropical sec.

Mots-clés : Balsas River, restauration écologique, transfert au champ, *pinzán*, berges, qualité des plants, Mexique.

ABSTRACT

Light management in tree nurseries to produce *Pithecellobium dulce* seedlings for the reforestation of degraded lands in Southern Mexico's tropical dry forests

The choice of nursery practices is important to the production of high-quality seedlings and to increase the survival rates of reforestation plantations in the dry tropics. However, adequate practices need to be established for native species for which propagation information is scarce. This study suggests that light management in nurseries is a key cultivation practice for future planting success, because of the morpho-physiological changes that plants usually undergo in different light conditions. We examined variations in the morphology, photosynthesis efficiency and growth of *Pithecellobium dulce* plants produced under four levels of light in nursery conditions (20%, 40%, 60%, and 100% of photosynthetically active radiation [PAR]). We also assessed survival after planting out according to the light conditions under which the plants were grown. Morpho-physiological variables were examined in three-month-old plants. A plantation was established in the field using the nursery-grown plants, and their survival was recorded monthly for 17 months. In the nursery, the light levels had significant effects on morphology, photosynthesis efficiency and growth. The 60% PAR level was favourable to optimum results for most of the variables, whereas the least successful results were found in plants grown at 20% PAR. Seedling survival in the field differed significantly according to the nursery light level, increasing with greater light intensity in the nursery during seedling production. 100% survival was observed in seedlings produced under 100% PAR, whereas the lowest survival rate (53%) was found in seedlings grown under 20% PAR. Light management is thus shown as a key cultivation practice by affecting the quality of *P. dulce* seedlings, which is improved in the nursery at 60% PAR. However, better survival after planting out is obtained with plants produced under full sun. These results should help to improve nursery management and establishment in the field of *P. dulce* in projects to restore degraded lands in the dry tropics.

Keywords: Balsas River, ecological restoration, field transplanting, *pinzán*, riverbank, seedling quality, Mexico.

RESUMEN

Manejo de la luz en los viveros de árboles para producir plantío de *Pithecellobium dulce* destinado a la reforestación de tierras degradadas en las selvas secas tropicales del sur de México

La elección de las prácticas de vivero es importante para la producción de plantío de alta calidad y para aumentar las tasas de supervivencia de las plantaciones de reforestación en los trópicos secos. Sin embargo, es necesario establecer prácticas adecuadas para las especies autóctonas sobre las cuales la información de propagación es escasa. Este estudio sugiere que la gestión de la luz en los viveros es una práctica de cultivo clave para el éxito futuro de la plantación, debido a los cambios morfofisiológicos que suelen sufrir las plantas en diferentes condiciones de luz. Examinamos las variaciones en la morfología, la eficiencia fotosintética y el crecimiento de plantones de *Pithecellobium dulce* producidas con cuatro niveles de luz en condiciones de vivero (20 %, 40 %, 60 % y 100 % de radiación fotosintéticamente activa [RFA]). También se evaluó la supervivencia tras la plantación según las condiciones de luz en las que se cultivaron los plantones. Se examinaron las variables morfofisiológicas en plantones de tres meses. Se estableció una plantación en el campo con las plantas cultivadas en vivero y se registró su supervivencia mensualmente durante 17 meses. Los niveles de luz en el vivero tuvieron efectos significativos en la morfología, la eficiencia de la fotosíntesis y el crecimiento. El nivel de RFA del 60 % favoreció la obtención de resultados óptimos para la mayoría de las variables, mientras que los resultados menos satisfactorios se encontraron en las plantas cultivadas con una RFA del 20 %. La supervivencia del plantío en el campo difería significativamente según el nivel de luz del vivero, aumentando con una mayor intensidad de luz en el vivero durante la producción del plantío. Se observó un 100 % de supervivencia en el plantío producido con un 100 % de RFA, mientras que la tasa de supervivencia más baja (53 %) se encontró en el plantío cultivado con un 20 % de RFA. Por lo tanto, el manejo de la luz muestra su potencial como práctica de cultivo al afectar a la calidad del plantío de *P. dulce*, que mejora en el vivero con un 60 % de PAR. Sin embargo, la mejor supervivencia después de la plantación se obtiene con las plantas producidas a pleno sol. Estos resultados deberían ayudar a mejorar la gestión de los viveros y el establecimiento en el campo de *P. dulce* en proyectos de restauración de tierras degradadas en los trópicos secos.

Palabras clave: río Balsas, restauración ecológica, plantación forestal, *pinzán*, ribera, calidad del plantío, México.

Introduction

The deciduous tropical forest, or seasonally dry tropical forest, is widely extended in the dry tropic of Latin America and is characterized by its high biodiversity and endemism (Ceballos *et al.*, 2010). In Mexico, this type of vegetation is mainly present in the biogeographic province known as *Depresión del Balsas* (i.e., Balsas River basin), a priority ecoregion for nature conservation on a global scale (Olson and Dinerstein, 2002).

However, some areas in the Balsas basin have been affected by natural disasters (García *et al.*, 2015). For example, in September 2013, torrential rains caused by tropical cyclone Manuel resulted in flooding and changed the course of the river, affecting large tracts of land in the areas adjacent to the lower Balsas watershed, which includes several municipalities in the state of Guerrero, Mexico (García *et al.*, 2015). Riparian areas lost tree coverage, and debris flows mainly of sand and gravel affected the productivity of agroecosystems in rural populations (García *et al.*, 2015). National statistics show that 55,781 ha of annual crops and perennial plants were affected by floods in Guerrero, and economic losses in the primary sector were as high as one billion Mexican pesos (García *et al.*, 2015).

As a result, carrying out research studies focused on the recovery of damaged areas acquired higher relevance. Reforestation initiatives using pioneer native forest species is the work plan established for that purpose. This decision is based on the fact that plantations of this type of species accelerate vegetation succession and increase the recovery rate of damaged areas in the different stages of ecological restoration (Lamb *et al.*, 2005).

For restoration activities, *Pithecellobium dulce* (Roxb.) Benth. is a suitable local species. This is a typical arboreal element in the deciduous tropical forest of the Balsas watershed (Fernández *et al.*, 1998) recognized as a useful pioneering legume for enhancing reforestation work due to its characteristics of fast growth, atmospheric nitrogen-fixing ability and multiple uses. The main uses of *P. dulce* are as a shade tree, for firewood, as a living fence, for forage, and as wood for construction. It is also a source of food for humans and wildlife (Olivares-Pérez *et al.*, 2011; Palma and González-Rebeles Islas, 2018).

However, according to Bonfil and Trejo (2010), the low representativeness of deciduous tropical forest native species in the nurseries is a significant limitation for reforestation plans. This lack of materials is attributed, in part, to limited knowledge on how to propagate high-quality plants. Producing high-quality plants is crucial to increase the survival of individuals planted in reforestations (Riikonen and Luoranen, 2018). Cultural practices are paramount for this purpose (Vallejo *et al.*, 2012); therefore, it is necessary to improve existing practices and implement alternative techniques using a larger number of species, including deciduous tropical forest native species.

Exploring the potential of sunlight management in forest nurseries is a possible approach to these alternative cultural practices. As a nursery cultural practice, light

management is based on the importance of sunlight on plant growth and development and their acclimation responses at a morpho-physiological level to increase light use efficiency when availability is heterogeneous (Lambert *et al.*, 2008; Pallardy, 2008). Several studies on tropical forest species have been carried out to optimize the establishment and growth of plants in reforestation or forest restoration activities and to define suitable environments and sunlight requirements for their adequate performance (Cheng *et al.*, 2013; Guzmán *et al.*, 2016; Kelly *et al.*, 2009; Kenzo *et al.*, 2011; Tang *et al.*, 2015; Yang *et al.*, 2013); growth, biomass allocation patterns, and photosynthetic capacity are often analyzed under different light conditions. This experimental approach is often carried out in nursery conditions, so there is support to examine nursery light management with a cultural practice approach, focused on its potential to produce high-quality seedlings for reforestation work, thereby increasing the probability of survival in the field after planting (Grossnickle and MacDonald, 2018).

Based on these considerations, analyzing the morphological and physiological changes of deciduous tropical forest species at different light intensities in the nursery and their survival in the field would be an ideal way to develop better management techniques to improve the nursery production and the field establishment of plants in restoration activities in the Balsas watershed. In this context, the present study pursued the following aims: 1) to examine the effects of different light levels in nursery on the morphology, photosynthetic efficiency, and growth of *Pithecellobium dulce* plants; 2) to analyze the survival of the plants in the field as a function of light levels used in nursery.

Materials and Methods

Effect of light intensity level on morphology, photosynthetic efficiency, and growth of *Pithecellobium dulce* seedlings in the nursery

The experiment was conducted in an outdoor nursery located in the village of La Bajada (municipality of Coyuca de Catalán, Tierra Caliente, Guerrero, Mexico, 18°19'01" N and 100°40'19.83" W). During the study period, average maximum, and minimum temperatures of 41 °C and 29 °C were registered between May and August 2018, with an average relative humidity of 32% and an irradiance of 498 W/m² per day. The above information was obtained from the records of the Agrometeorological Station of the *Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias* (INIFAP), located in Cutzamala del Pinzón, Guerrero, Mexico (figure 1).

In the nursery, the *P. dulce* seedlings were grown from seeds collected in March 2018 from 10 scattered trees in the municipalities of Arcelia and Coyuca de Catalán (Tierra Caliente, Guerrero, Mexico). Selected trees were vigorous specimens with abundant fruit production and free of pests or diseases (photo 1). Plant production began in May 2018. The seeds were sowed directly into polybags. Black

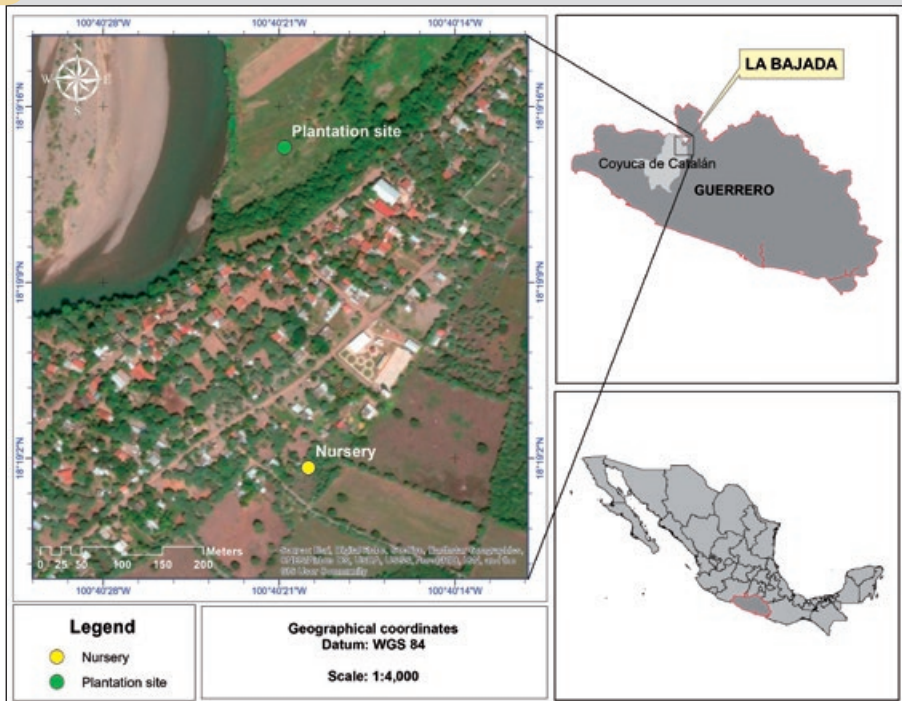


Figure 1.
 Geographical location of the study area.
 Photo E. Basave-Villalobos.

10 × 20 cm (3.9 × 7.8 in) 400-gauge polyethylene bags were used. Growing media consisted of a 2:1:1 mixture of peat moss, perlite, and vermiculite. A controlled-release fertilizer was added (Multicote 8^o,18N, 6P₂O₅, 12K₂O, 2MgO, ME; Haifa Chemicals Ltd.) at a dose of 6 g/L. The collected seeds were mixed, and the larger ones were sowed after soaking them in water at ambient temperature for 12 h to favor rapid and uniform germination. The germination stage was kept under a 20% shade condition. Seedlings emerged 15 days after sowing. Irrigations were applied three times per week at field capacity. Also, a pyrethroid insecticide based on cypermethrin was applied (CIMA® 19.6% CE; Química Sagal S. A.) at a dose of 50 mL/L, to control the mealybug (*Planococcus* sp.) when the plants were two-month-old.

Light levels and experimental design

One month after sowing, 256 *P. dulce* plants with average heights of 15 cm were divided in groups of 16 and subjected to four light levels or intensities inside the nursery: 20%, 40%, 60%, and 100% of photosynthetically active radiation (PAR). The placement of individuals followed a completely randomized experimental design composed of four blocks, in each of which the four light levels were represented.

Black monofilament shade clothes were used to reduce sunlight at levels of 20%, 40%, and 60% PAR. These sunlight intensities were defined after determining the transmittance (T; %) of commercial shade-clothes with different percentages of shade based on simultaneous measurements of PAR ($\mu\text{mol}/\text{m}^2/\text{s}$) above and below of them. A light meter was used for this purpose (LightScout® Light Sensor Reader, Spectrum Technologies, Inc., USA). Transmittance was determined applying the following formula: $T = \text{PAR under the shading net} / \text{PAR above the shading net}$. Individual domes were built using the shade-cloth for each experimental unit according to the required PAR level. Maxi-

mum and minimum temperature (°C) and relative humidity (%) were monitored in each condition using a digital thermo-hygrometer (TER-150, Steren) (table I). Also, PAR levels ($\mu\text{mol}/\text{m}^2/\text{s}$) were recorded throughout an entire sunny day to calculate daily light integral (DLI; $\text{mol}/\text{m}^2/\text{day}$) (table I; photo 2).

Morphology, photosynthetic efficiency, and growth measurement

At the end of the cultivation period in nursery, *i.e.*, when plants were three-month-old, 16 plants per light treatment (four plants per block) were randomly sampled for morphology. First, the growing media was removed carefully from the roots using a water stream; subsequently, shoot height and stem diameter were measured. The shoot height (cm) was recorded from the root-collar to the apex. The stem diameter at the root-collar (mm) was measured with a millimeter ruler and a Digimatic CD-4 "AX Mitutoyo" caliper. Then, all leaves were cut out to measure their area (cm^2) using an LI-3100C leaf area meter (LI-COR Inc., USA). The samples were washed with distilled water and oven dried at 70 °C for 72 h with a forced-air oven (FELISA® FE-291AD). Later, dry mass (± 0.0001 g) of leaves, stem, root, and total biomass were determined with an analytical balance (AND® GR-120, A & D Company, Ltd.). The following ratios related to biomass allocation patterns were then calculated: leaf mass ratio (LMR [%]; ratio of leaf mass to total dry mass × 100), stem mass ratio (SMR [%]; ratio of stem mass to total dry mass × 100) and root mass ratio (RMR [%] ratio of root mass to total dry mass × 100).

Table I.
 Mean values of climatic variables monitored in each nursery light condition.

Climatic variables	Light level (PAR; %)			
	20	40	60	100
Maximum temperature (°C)	40	38.7	40.1	41.4
Minimum temperature (°C)	23	23.8	22.7	21.8
Relative humidity (%)	40.1	39.6	34.9	32.8
Daily light integral ($\text{mol}/\text{m}^2/\text{day}$)	10.8	21.7	32.6	54.3



Photo 2.
 Schematic representation of each nursery light condition evaluated during the seedling production of *Pithecellobium dulce*.
 Photo E. Basave-Villalobos.

Additionally, the specific leaf area was determined (cm^2/g) based on leaf area and leaf dry mass.

Concerning photosynthetic efficiency, it was measured in terms of net assimilation rates (NAR; $\text{mg}/\text{cm}^2/\text{day}$). NAR was analyzed according to the following equation (Hunt, 1990):

$$\text{NAR} = \frac{(TDM_2 - TDM_1) (\ln LA_2 - \ln LA_1)}{(LA_2 - LA_1) (T_2 - T_1)}$$

where NAR is the net assimilation rate, TDM is the total dry mass, LA is the leaf area in absolute and logarithmic values (\ln), and T is time. In all cases, 1 and 2 refer to an initial and final evaluation, respectively, which were conducted 60 days apart.

Additionally, growth (total biomass increase) was evaluated in terms of relative growth rates (RGR; $\text{mg}/\text{g}/\text{day}$) and absolute growth rates (AGR; g/day), using the following equation (Hunt, 1990):

$$\text{RGR} = (\ln TDM_2 - \ln TDM_1) / \Delta t \text{ (days)}$$

$$\text{AGR} = (TDM_2 - TDM_1) / \Delta t \text{ (days)}$$

where RGR is the relative growth rate, AGR the absolute growth rate, TDM is the total dry mass in logarithmic values (\ln) and absolute values in the initial (1) and final evaluation (2) Δt = time between both evaluations (60 days).

The initial sampling required for evaluating variables NAR, RGR, and AGR was made at the time the plants were subjected to the different light intensities (June 2018).

The effect of the light levels was examined using a one-way analysis of variance (ANOVA) at a significance

level $\alpha = 0.05$. Prior to the ANOVA, data assumptions of normality and homogeneity of variances were checked. Some variables were log (root and total dry mass) and arcsine (LMR, SMR, RMR) transformed to meet the assumptions. If significant treatment differences were detected, a post-hoc Tukey's test was performed for multiples comparisons. Statistical software InfoStat (2008) was used for all data analysis.

Effect of light intensity on survival of *P. dulce* seedlings in the field

In August 2018, a plantation was set up using *P. dulce* plants issued from each light intensity regime evaluated in the nursery. Previously, the plants growing under the shading nets hardened gradually as they were subjected to full sunlight exposure for one week. The plantation was established in the community of La Bajada (Coyuca de Catalán, Guerrero, Mexico), in an area adjacent to the Balsas River shore at an altitude of 256 masl ($18^\circ 19' 15''$ N and $100^\circ 40' 18''$ W). The land was used for agroforestry until 2013, when the described flood occurred. After the event, most of the surface was covered by natural regeneration with *Ricinus communis* L. and *Muntingia calabura* L. The climate in the area, according to Köppen's classification as modified by García (2004), is tropical dry with a summer rainfall regime (BS_0). Cumulative rainfall per year is 978 mm which occurs between June and September. July and August have the highest precipitation amount, whose average ranges between 220 and 240 mm. Mean annual temperature is 28.6°C (García, 2004). May presents maximum temperatures of 40°C (photo 3).

Plants were planted in a living fence system in a row array and spaced three meters apart from each other. Planting holes were 20 cm wide and 40 cm deep. Weeds were controlled around the planting holes using a machete and a hoe when needed. Auxiliary irrigation was not used: water came only from the regular rain in the season. The soil had a sandy-loam texture with 58.2% sand, 22.3% silt, and 19.4% clay, as well as an apparent density of $1.25 \text{ g}/\text{cm}^3$, $\text{pH} = 7.4$, organic matter = 1.87%, electrical conductivity = $0.14 \text{ dS}/\text{m}$, and total nitrogen = 0.061%. Twenty individuals chosen randomly of each nursery light treatment were planted under a randomized complete block experimental design with four replications and five plants per experimental unit. Possible variability of soil moisture and fertility in the site was assumed as the blocking criterion.

The survival rate of transplanted trees was recorded monthly for 17 months by giving values of 0 and 1 for dead and living plants, respectively.

Differences in survival depending on light levels were analyzed using the Log-Rank test based on survival curves through the Kaplan-Meier method, which defines survival as: $S(t) = P(T \geq t)$

Where $S(t)$ is the probability that a plant dies in a time T greater than or equal to the research study time t (Kaplan and Meier, 1958); this analysis was carried out using the LIFETEST procedure in the SAS (Statistical Analysis System) software version 9.2 (SAS, 2009).



Photo 3.
Conditions of the plantation site before outplanting.
Photo E. Basave-Villalobos.

Table II.
ANOVA results for the effects of different light intensities in nursery on morphological and physiological variables measured in *Pithecellobium dulce* seedlings.

Variables	F-value	P-value
Shoot height	7.62	0.0005
Stem diameter	17.22	< 0.0001
Leaves dry mass	15.10	< 0.0001
Stem dry mass	15.41	< 0.0001
Root dry mass	14.25	< 0.0001
Total dry mass	15.52	< 0.0001
Leaf mass ratio	8.50	0.0002
Stem mass ratio	3.58	0.0235
Root mass ratio	11.79	< 0.0001
Leaf area	15.10	< 0.0001
Specific leaf area	13.79	< 0.0001
Net assimilation rate	25.87	< 0.0001
Relative growth rate	23.14	< 0.0001
Absolute growth rate	15.52	< 0.0001

Results

Effect of light intensity level on morphology, photosynthetic efficiency, and growth of *Pithecellobium dulce* seedlings in the nursery

The ANOVA test showed significant differences ($p < 0.05$) among photosynthetically active radiation levels in all evaluated variables when examining changes in morphology, photosynthetic efficiency, and growth of *P. dulce* plants produced under different light levels in the nursery (table II).

In general, the values for shoot height, stem diameter, leaf, stem, root, and total dry mass, as well as leaf area, specific leaf area, net assimilation rate, and relative and absolute growth rates increased with higher light levels but declined at full sunlight exposure (table III). Plants produced in the 60% PAR level achieved the highest values in most of the variables, except the net assimilation rate, although their values were not statistically different from the values observed for plants in the 100% PAR level (table III); however, 60% of PAR was found to be the optimal light level in the nursery because it promoted the highest values, as opposed to the 20% PAR, which resulted in the lowest values. In the case of the 40% PAR, the different variables measured showed intermediate values between those obtained for 20% and 60% PAR (table III). The *P. dulce* plants subjected to the 60% PAR level had a shoot height and a stem diameter 41% and 70%, respectively, higher than those grown in the 20% PAR level (table III). Similarly, the amount of biomass produced displayed higher values in the 60% PAR level. The amount of dry mass in leaves and stems was between three and four times greater compared to plants subjected to the 20% PAR level, while root dry mass was almost 5-fold larger, thus total dry mass values were also higher when comparing plants subjected to 20% PAR with plants subjected to 60% PAR (table III). Additionally, the plants subjected to 60% PAR had a fourfold increase in the leaf area in relation to the value shown by plants grown at 20% PAR; however, in terms of specific leaf area, the differences between the values of both light levels were lower with a difference of only 16% (table III).

Regarding the biomass allocation patterns, the biomass ratio of aboveground components (leaves and stem combined) increased as the light level received by the plants decreased, at the expense of a reduction in root biomass (figure 2). However, in general, *P. dulce* plants allocated more than 80% of their biomass to the aboveground components (figure 2).

Additionally, photosynthetic efficiency also reduced as light availability decreased. In this regard, the NAR values in plants grown at 20% PAR were smaller by a 2:3 ratio as compared to the NAR values in plants subjected to 60% and 100% PAR, which had similarly high values (table III). Finally, this effect reflects results on relative and absolute growth, where the highest growth rates were observed in plants subjected to the highest light intensities (60% and 100% PAR); specifically, values of *P. dulce* plants subjected to 60% PAR were twice higher in RGR, whereas those of AGR were four times higher than the rates registered by plants subjected to 20% PAR (table III).

Table III.

Mean values (\pm standard error) of the morphological and physiological variables measured in *Pithecellobium dulce* plants growing under different light levels in nursery.

Variables	Light levels of photosynthetically active radiation (PAR; %)			
	20	40	60	100
H (cm)	46.7 \pm 3.1a	48.8 \pm 3.1ab	65.6 \pm 3.3c	59.8 \pm 3.1bc
SD (cm)	3.10 \pm 0.23a	3.34 \pm 0.23a	5.26 \pm 0.25b	4.42 \pm 0.23b
LDM (g)	0.71 \pm 0.22a	0.76 \pm 0.22ab	2.63 \pm 0.24c	1.61 \pm 0.22b
SDM (g)	0.80 \pm 0.25a	0.91 \pm 0.25a	2.86 \pm 0.26b	2.23 \pm 0.25b
RDM (g)	0.23 \pm 0.11a	0.27 \pm 0.11a	1.13 \pm 0.12b	0.83 \pm 0.11b
TDM (g)	1.73 \pm 0.58a	1.94 \pm 0.58a	6.62 \pm 0.61b	4.67 \pm 0.58b
Leaf area (cm ²)	237.7 \pm 85.4a	257.5 \pm 85.4ab	967.5 \pm 90.1c	582.1 \pm 85.4b
SLA (cm ² /g)	321.0 \pm 5.4a	335.2 \pm 5.4a	365.7 \pm 5.7b	357.9 \pm 5.4b
NAR (mg/cm ² /day)	0.27 \pm 0.02a	0.30 \pm 0.02a	0.44 \pm 0.02b	0.45 \pm 0.02b
RGR (mg/g/day)	0.30 \pm 0.00a	0.40 \pm 0.00a	0.60 \pm 0.00b	0.50 \pm 0.00b
AGR (g/day)	0.03 \pm 0.01a	0.03 \pm 0.01a	0.12 \pm 0.01b	0.08 \pm 0.01b

H: shoot height; SD: stem diameter; LDM: leaves dry mass; SDM: stem dry mass; RDM: root dry mass; TDM: total dry mass; SLA: specific leaf area; NAR: net assimilation rate; RGR: relative growth rate; AGR: absolute growth rate; PAR: photosynthetically active radiation. Means in the same line with the same letter do not differ significantly at 5 % of probability by the Tukey's test.

Survival after outplanting of *Pithecellobium dulce* plants produced under different light levels in the nursery

Light intensities (PAR) in the nursery resulted in significant differences in plant survival in the plantation site ($p = 0.0064$). The overall survival of the plantation was 77% at 17 months. Survival increased as the light intensity increased in the nursery during the seedling production, thus 100% probability of survival was observed in plants grown under the highest level of PAR (100%), whereas the lowest probability of survival (53%) was observed in plants subjected to 20% PAR (figure 3). During the study period, most of the mortality events occurred within the first nine months (figure 3).

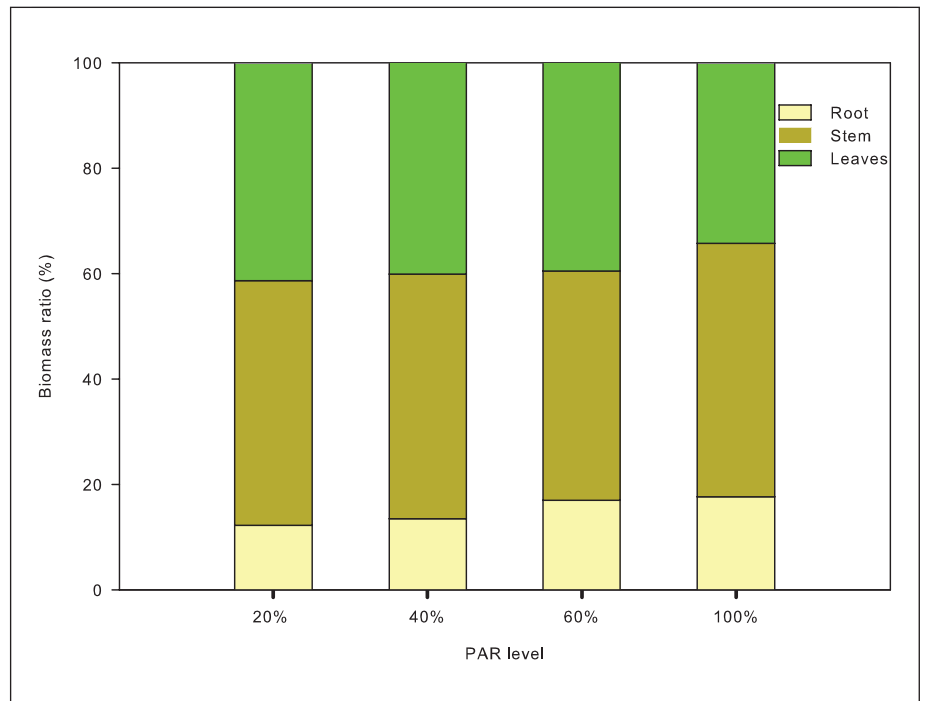


Figure 2.

Biomass allocation patterns in leaves, stem, and roots of *Pithecellobium dulce* seedlings produced under different light intensities in nursery.

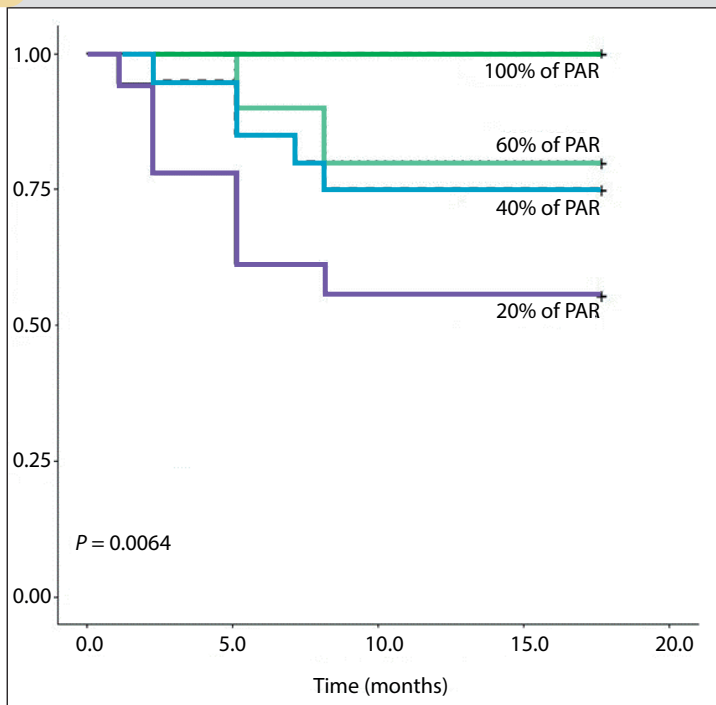


Figure 3. *Pithecellobium dulce* survival curves in the field, according to the Kaplan-Meier estimator, grown under different light levels in nursery (20%, 40%, 60%, and 100% of photosynthetically active radiation [PAR]).

Discussion

Morphology, photosynthetic efficiency, and plant growth of *P. dulce* plants varied according to the light intensity used in the nursery so that light management shows a strong potential to affect morpho-physiological seedling quality. Changes exhibited by *P. dulce* are associated, in general, with functional effects of light acclimation, similar to the changes observed in *Enterolobium contortisiliquum* (Naves *et al.*, 2018). These changes are attributed to the phenotypic plasticity that tree species usually undergo in different light environments (Gong *et al.*, 2016). In the case of *P. dulce*, high light intensities increased the values of each morphological attribute evaluated because of higher biomass gains at whole plant level. This effect suggests that the species needs high light intensities for adequate growth. The observed *P. dulce* response is consistent with Khurana and Singh's (2001) assertions that tropical deciduous species, especially pioneer species, achieve high growth rates under high light intensities. Each species requires an optimal light intensity for favorable growth depending on shade tolerance, succession phase, and acclimation capacity (Cheng *et al.*, 2013; Kelly *et al.*, 2009; Tang *et al.*, 2015). For *P. dulce* 60% of PAR was the light intensity that promoted the best morphology, photosynthetic efficiency, and growth results. Likewise, *Elaeocarpus grandis*, *Flindersia brayleyana* (Kelly *et al.*, 2009) and partially *Copaifera langsdorffii* (Reis *et al.*, 2016) showed high photosynthetic capacity

and growth under this light intensity. In contrast, *Torreya grandis*, a shade-tolerant species, had remarkably higher growth and photosynthetic capacity under a light intensity of 25% (Tang *et al.*, 2015).

Plants tend to produce proportionally more biomass in aboveground components and reduce the amount allocated to the root under low light intensities to increase their exposure to light and maintain a positive carbon balance (Masarovičová *et al.*, 2016); this was also demonstrated in *Cedrela salvadorensis* (Guzmán *et al.*, 2016), and we could confirm it by observing *P. dulce*'s biomass allocation patterns at 20% and 40% PAR. However, leaf area has also significantly changed. Plants increase in leaf area and specific leaf area as a plastic adjustment to the availability of light (Masarovičová *et al.*, 2016). Leaf plasticity adjustment was observed in *Cedrela salvadorensis* (Guzmán *et al.*, 2016), but not in *P. dulce* plants subjected to 20% and 40% PAR, since the low light availability limited leaf formation and growth. On the other hand, increased leaf area and specific leaf area were observed when comparing *P. dulce* plants subjected to 100% and 60% PAR. Shade induced increases in leaf area and specific leaf area in *P. dulce* plants subjected to 60% PAR, possibly as an acclimation strategy to use available light more efficiently, which is a response modulated by the morphological plasticity of the species (Masarovičová *et al.*, 2016). The effect in leaf area observed in *P. dulce* was comparable to the effect observed in *Prosopis laevigata* seedlings (Basave-Villalobos *et al.*, 2017).

The lower growth rates in plants subjected to low light intensities (20% and 40% PAR) compared with plants under high light intensities (60% and 100% PAR) is attributed to the impact of light restrictions on photosynthetic capacity since this is a determining factor in photosynthesis (Pallardy, 2008). Plants of the same species maintain higher photosynthetic rates when growing under high light intensities than when growing at low light intensities (Pallardy, 2008). The low net assimilation rates in plants subjected to 20% and 40% PAR suggests a limited photosynthetic efficiency due to the smaller size of the photosynthetic apparatus, which failed to favor a positive carbon balance to allocate sufficient resources for growth (Lambers *et al.*, 2008). Additionally, the heterogeneous nature of light conditions in which the *P. dulce* plants were grown could have affected other physiological processes, such as the water and nutrients use efficiency, which are also essential factors for growth (Lambers *et al.*, 2008). Although nutrients and water were methodically provided in the same amounts to all plants, the efficiency with which these resources were used might have been inconsistent, and microclimate environments generated by each light condition could have had an impact, as observed in *Pinus pinaster* (Rodríguez-García and Bravo, 2013), since the effects of light intensity are modified by interactions with different environmental factors (Pallardy, 2008). For example, a study using five different tropical shade tolerance species (Gong *et al.*, 2016) supports this assumption concerning nutrient acquisition and use. On the other hand, light intensity affected the effectiveness of the hydrogel used to improve their water status in *Enterolobium contortisiliquum* (Filho *et al.*, 2018). Subsequent stu-



Photo 4.
Surviving tree of *Pithecellobium dulce* growing
in the reforested site.
Photo E. Basave-Villalobos.

dies on *P. dulce* should elucidate the effect of light intensity on the efficiency of water and nutrient use by evaluating its physiological parameters.

In *P. dulce*, nursery results confirm the potential of light management to manipulate the morphological and physiological quality of plants; this response had effects on plant performance in the field, as verified by the survival analysis. In general, *P. dulce* survival in this research study was higher than the 50% survival rate recorded in reforestation programs in Mexico in dry tropics regions, although the planting scales are not comparable in both cases (CONAFOR, 2019). Our results allow for an initial recommendation of *P. dulce* as a suitable species for reforestation work in the study environment or others with similar soil and climate characteristics (photo 4). On the other hand, survival results after outplanting observed for plants growing in the nursery under 100% PAR have important implications, because nursery light management improve the seedling quality of *P. dulce*, but the best nursery plants (those produced at 60% PAR) do not performed better than those produced at full sun, which were apparently of lower quality according to nursery results. Therefore, the use of shade clothes in the nursery may not be a relevant practice for producing *P. dulce*. Nevertheless, shade clothes are often used in forest nurseries in places with high solar radiation and low relative humidity (Pimentel, 2009) to protect plants from damaging heat. Possibly, the field survival response of the

plants produced at 60% PAR could be different under other prevailing environmental conditions and using shading nets could be an important technique to facilitate the establishment of the plants because of its effects on improving plant quality during the nursery phase, which affects the survival after outplanting (Grossnickle and MacDonald, 2018). Therefore, subsequent research studies are needed to explore the survival of plants in other field conditions and to appraise the relationship between initial morpho-physiological plant attributes and their field performance. We attribute the high survival rate of plants subjected to 100% PAR in the research study environment to the fact that plants were fully acclimatized in the nursery. Leaves of plants subjected to 100% PAR were thicker in terms of specific leaf area. Higher leaf thickness results in more cell layers in the palisade parenchyma, which acts as a protection against high irradiance (Lambers *et al.*, 2008). Thus, damage by photoinhibition could have been reduced, as opposite to plants grown under shade, which could have been more prone to this phenomenon in the field (Alves *et al.*, 2002). Even though plants under shade were subjected to a hardening phase before planting, it could not have been enough to acclimatize them, and field stress due to full irradiation or high temperatures could have contributed to the mortality that shaded plants showed during the first nine months after outplanting.

Finally, the decrease in survival during the first nine months after plantation has also important implications for reforestation programs. Results suggest that these first nine months are critical for the survival of reforestations using *P. dulce* in the study environment; for that reason, intensive management actions are suggested for the first nine months after plantation to increase plant survival rates.

Conclusion

Light management in the nursery showed a strong potential as a cultural practice to modify the morphology, photosynthetic efficiency, and growth of *Pithecellobium dulce* seedlings, thereby affecting seedling quality of *P. dulce*. A level of 60% of PAR in the nursery enhances the morphological and physiological quality of plants. In the field, overall plant survival is high, and plants produced under full irradiation (100% PAR) present the highest odds for survival. The critical survival period in the field is the first nine months after plantation. These results have important implications to improve the nursery management and the establishment in the field of *P. dulce* in restoration activities of degraded lands in the dry tropics.

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Access to data

Supplementary datafile can be accessed at: <https://1drv.ms/u/s!ApH0RmNDb-HDp1EjUz890ehK0ZS?e=XktizS>.

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