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Provenance affects the growth and mortality of teak (*Tectona grandis* L.f.) plantations cultivated in central Nicaragua

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Abstract: Teak has been planted extensively by smallholders in Central America within reforestation programmes and has become one of the most valuable timbers. The five-year growth and mortality of teak cultivated in a plantation in central Nicaragua, representing sites at the low limit of teak ecological valence, were evaluated. From 2006 to 2010, 72 pure teak stands were established, with 48.93 ha in total. For afforestation, planting stock from five provenances was used and planted at 1 m × 1 m spacing to stimulate the height growth and reduce broad crowns formed by self-pruning. In the pure teak stands, 144 permanent sample plots of 0.01 ha in size were established in 2011. From 2011 until 2015, the tree height and stem girth of all individuals in the studied sample plots were measured, and mortality based on the stand density was assessed. Significant differences between the provenances were observed. The highest growth was noted in the Local provenance originated from the studied area, whereas the Semilla provenance from Costa Rica, characterised by the lowest growth ability, was characterized by lower radial increment and mean tree height with high mortality.

Keywords: agroforestry system; farmland; radial increment; stand density; stem girth; tree height

Teak (*Tectona grandis* L.f.) is the most valuable tropical hardwood (Prasetyo et al. 2020; Yang et al. 2020) that gets on the market due to its natural resistance, stability, and wide usability (Ladrach 2009; Kollert, Kleine 2017). The optimum growth conditions for teak are characterised by the high amount

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of precipitation (1 300 mm to 2 500 mm per year), the dry season lasting from 3 to 5 months, and increased mean annual air temperatures in the range of 22–27 °C (Kaosa-Ard 1981); however, the teak even copes with moderate frost (Louppe et al. 2008; Zhou et al. 2012). Furthermore, high-quality plantations are frequently established in regions with no dry season (Ugalde Arias 2013).

Teak naturally occurs in India, Laos, Myanmar and Thailand (Amoah, Inyong 2019). It was introduced to Java about 400 to 600 years ago, and presently it is also naturalised there (Kadambi 1972; White 1991). In Central America, teak was first planted in 1926 at the Summit Botanical Garden in the former Channel Zone of the Panama Canal (FAO 2002), specifically in Honduras, Panama, and Costa Rica; the first teak plantations were established between 1927 and 1929 (Ball et al. 2000). Since then, it has been cultivated in nearly all Central American countries (Ladrach 2009). Currently, teak plantations represent roughly 4.35 million ha worldwide (Kollert, Cherubini 2012) and constitute approximately 75% of the world's high-quality tropical hardwood production (FAO 2001). In Central America, the total planted area is about 225 000 ha, and teak plantations cover 41 000 ha (i.e. 18.1% of the total cultivated area; FAO 2002). Presently, teak is planted in 70 tropical countries worldwide (Kollert, Walotek 2015; Prasetyo et al. 2020).

Initially, teak stands were cultivated in a long-term rotation period (120–150 years) with a 30-year thinning interval (Pandey, Brown 2001). In the 50s of the 20th century, a short-term rotation period concept was introduced in tropical countries. Recently, the long-term rotation period for teak has already been completely abandoned (Moya et al. 2014), and a shorter rotation period of 50–60 years (Pandey, Brown 2001), 40–80 years (Prasetyo et al. 2020) or even 15–30 years (Moya et al. 2014) is routinely applied depending on site conditions, management intensity and a teak provenance.

This study aimed to analyse the radial and height growth and mortality in teak plantations established in 2006–2010 using different provenances of planting stock in central Nicaragua.

MATERIAL AND METHODS

Site description. The research was conducted on a private farm with teak plantations in central Nicaragua near Diriamba (11°49'02''N; –86°13'10''W). The studied area occurs in the tropical and subtropical dry broadleaf forest biome (MARENA/INAFOR 2002). The characteristic climate is dry and hot, with annual precipitation of about 1 400 mm and a five to six-month dry season (Erikson et al. 1997). In the studied area with a mean altitude of 220 m a.s.l., the most common soil types are Alfisols and Ultisols (INETER 2004; Haninec et al. 2016).

The farm area was 211 ha and it was composed of secondary forests, high and low shrubs, abandoned pastures and fields for growing crop plants. On the farm, 75 ha were afforested by several tree species, specifically *Tectona grandis*, *Swietenia humilis*, *Acacia mangium*, *Azadirachta indica*, and *Gmelina arborea*. For the growth and mortality analysis performed in this study, 72 pure teak stands with an area of 48.93 ha were established in 2006–2010 (Table 1).

For afforestation, the high-quality containerised teak planting stock with a height of 30 cm (± 5 cm) and a root collar circumference of 2.5 cm (± 0.5 cm) was used. Pure teak stands were planted at 1 m × 1 m spacing to stimulate the height growth and reduce broad crowns formed by self-pruning, and planting stock from five different provenances was applied. The planting stock was cultivated from five various available seed origins in the own forest nursery located directly on the farm. Expressly, Lote 0-2008162TEc01; CETROPIC Nicaragua; *Tectona grandis* CATIE Costa Rica; Don Victor Nicaragua; Semilla certificada C hojancha, Costa Rica herein referred to as Local; Cetropic; Catie; don Victor; Semilla, respectively, were employed for planting stock cultivation (Table 1). No public information about the localities of seed origin is available for the abovementioned seed sources.

Field measurements. In 72 pure teak stands, 144 permanent sample plots (Local 16; Cetropic 22;

Table 1. Area (ha) and years of afforestation for used provenances in the presented study

Provenance	Year of planting					Total area of plantings
	2006	2007	2008	2009	2010	
Local	6.27	1.21	–	–	–	7.48
Cetropic	–	5.43	0.41	–	–	5.84
Catie	–	–	1.20	2.17	–	3.37
Don Victor	–	–	3.43	2.41	–	5.84
Semilla	–	–	–	6.24	20.16	26.40
Total area	6.27	6.64	5.04	10.82	20.16	48.93

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Catie 12; don Victor 20; Semilla 74) with an area of 10 m × 10 m were established from November 2011 to February 2012. Research plots were arranged in a random design, and the number of plots for each provenance depended on the availability of high-quality commercial seed material in particular years of plantation. Each plot contained 100 trees originally, and 14 400 trees were repeatedly measured every year since their planting (establishment). The sample plots were surveyed using the GPS Trimble GeoExplorer GeoXH 6000 (TRIMBLE, USA) with a sub-meter position accuracy of 0.25 m (post-processed differential corrections were applied). Plot corners and corner trees were marked by iron rods and coloured stripes in the field.

All field measurements were performed in the sample plots mentioned above from 2011 to 2015. For all trees present in the sample plots, tree heights and stem girth at breast height (*GBH*) were measured using a tree-height measuring rod to the nearest 10 cm and a measuring tape to the nearest 0.1 cm, respectively. Furthermore, the tree mortality was documented during each measurement campaign.

Data processing. All data were analysed using TIBCO Statistica™ (Version 13.3.1, 2018) with a confidence interval of 95% throughout the study. Before the principal analysis, the normality of data distribution was tested using the Shapiro-Wilk test. The main effects and their interaction were employed with the multifactor ANOVA with repeated measurement. The analysis applied the planting year and provenance as the main effects, and the interaction between them was assessed in the present study. After the ANOVA analysis, the Tukey HSD test was used to identify differences between the main effects and their interactions.

RESULTS

Height growth. From 2011 to 2013, the highest mean tree height was observed in teak plantations established in 2006, 2007 and 2008. Since 2014, the plantations with the oldest individuals planted in 2006 reached the highest mean tree height of all studied stands. Plantations planted in 2007 and 2008 showed almost identical tree height growth between 2011 and 2013 to the plantations established in 2006. The lowest mean tree height was observed in the youngest plantations (planted in 2010) throughout the studied period. However, these stands recorded the most significant height growth acceleration during the last three years (i.e. 2013–2015 period) (Figure 1A).

In the Semilla provenance, the lowest mean tree heights were observed throughout the measured period. Since 2013, the most rapid tree height increment was noted for the Local provenance compared to the others. However, the Local's tree heights are taller than in other provenances except for Cetropic, when the tree heights of the latter were identical in 2011–2012 (Figure 1B).

At the beginning of measurement (in 2011), the tallest mean tree height was found in the Catie provenance planted in 2008, forming the first homogeneous group. The second homogeneous group encompassed the Local (planted in 2007) and don Victor (2008) origins, which were not significantly different from the first and the third group. The third homogeneous group involved the Cetropic (2007) and Local (2006) provenances. The fourth group consisted of Cetropic (2008), don Victor (2009), Catie (2009) and Semilla (2009). Finally,

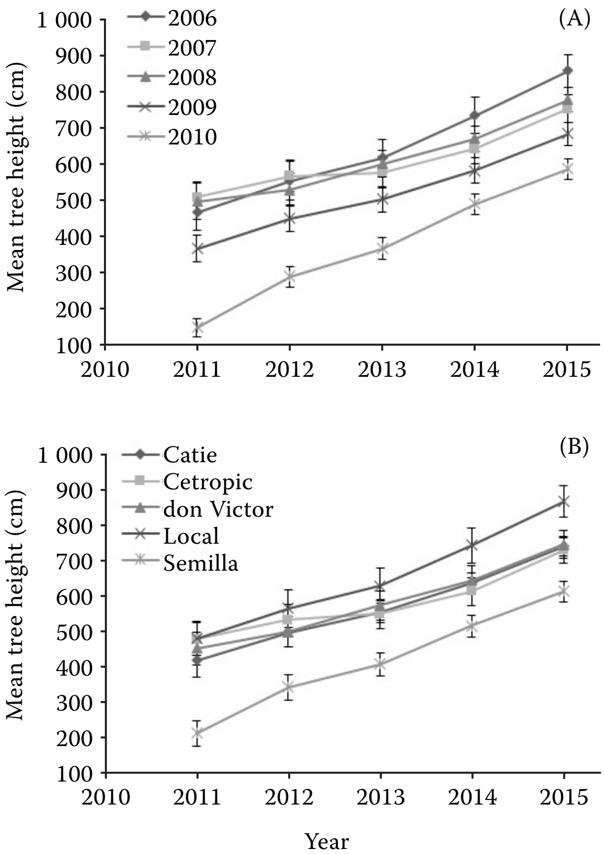

Figure 1. Mean tree height depending on the (A) planting year and (B) used provenances; the bars are standard deviations

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the lowest mean height of the studied period represented the last homogeneous group, recorded in the Semilla provenance (2010; Figure 2).

Contrariwise in 2013–2015, the tallest mean height was found in the Local provenance (2007), forming the first homogeneous group. The second one included trees from Local (2006), don Victor (2008) and Catie (2008). Provenances Cetropic (2007 and 2008), Catie (2009), don Victor (2009), and Semilla (2009) were incorporated into the third homogeneous group, and Semilla (2010) separately created the fourth homogeneous group (Figure 2).

Radial increment. Generally, the earlier the stands were established, the higher the mean stem *GBH* was recorded during all measured years. Except the stands established in 2007, the abovementioned trend is applicable to all planting years. The mean stem *GBH* in a teak stand planted in 2007 was among the mean stem *GBH* values of stands established in 2006, 2008, and 2011. In 2015, the mean stem *GBH* within stands established in 2007 was lower than in stands planted in 2008, and even the parameter resembled *GBH* values noted in stands established in 2009 (Figure 3A).

The highest mean stem *GBH* was found in the Local provenance during all measurement years, primarily due to its earlier planting (in 2006 and 2007). On the contrary, the lowest mean stem *GBH* was observed during the whole measured period in Semilla provenance because of its later planting (2009 and 2010). However, Cetropic provenance was established earlier (2007, 2008) than don Victor and Catie (2008, 2009). Similar stem *GBH* values were recorded in all these provenances in 2011 and 2012. In 2013-2015, the mean stem *GBH* in Cetropic provenance resembled Semilla, significantly lower than in don Victor and Catie (Figure 3B).

At the beginning of the monitoring period (in 2011), the highest *GBH* was observed in Catie

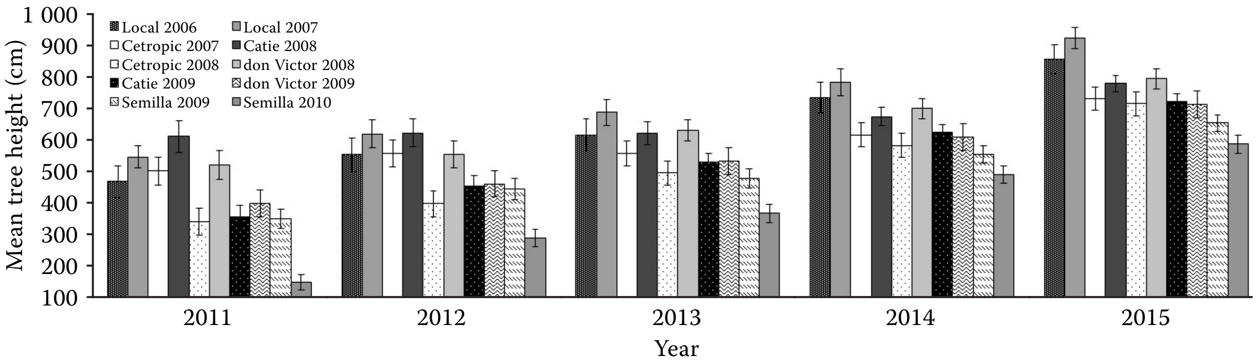

Figure 2. Mean tree height of all applied provenances in 2011–2015; whiskers signify standard deviations

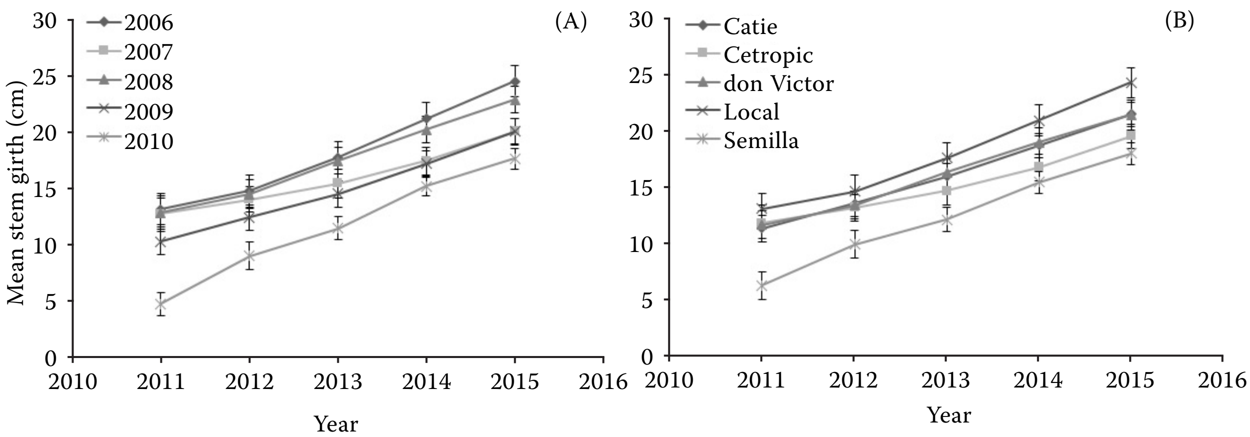

Figure 3. Mean stem girth at the breast height (*GBH*) depending on the (A) planting year and (B) and applied provenances; the bars are standard deviations

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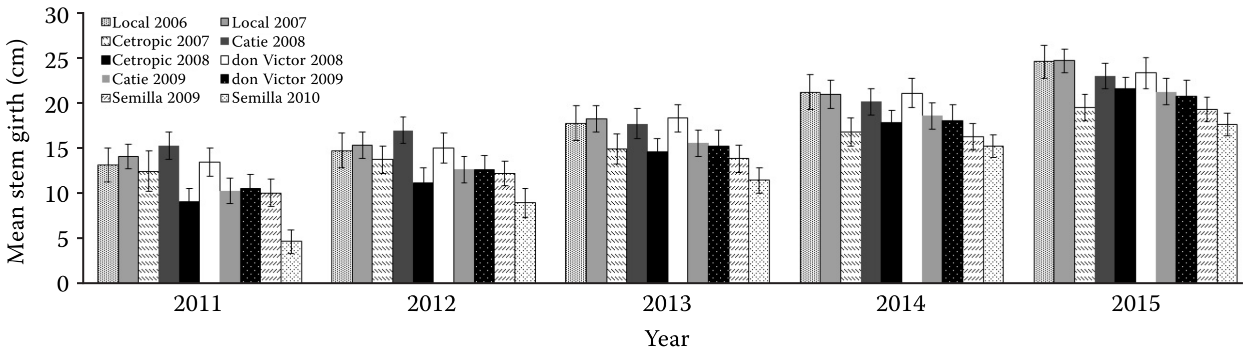

Figure 4. Mean stem girth at the breast height of all applied provenances in 2011–2015; whiskers signify standard deviations

(2008) provenance. On the other hand, the highest *GBH* value was recorded in Local (2007) provenance at the end of monitoring (in 2015). Provenances don Victor, Cetropic, and Catie showed the same stem *GBH*s between 2011 and 2013. In 2014 and 2015, the stem girth of Cetropic (afforested in 2007 and 2008) was significantly lower than the level of the Semilla provenance planted in 2009. Don Victor and Catie provenances were planted in 2008 and 2009. If plots established only in 2009 were compared, Semilla provenance showed lower stem *GBH* than Catie and don Victor (Figure 4).

Semilla provenance planted in 2009 shows the lower stem circumference than the other provenances planted in the same year. At the end of the measurement period, the stem girth was identical to Cetropic planted in 2007 and 2008. Semilla provenance was characterised by the lowest stem girth, mainly due to afforestation in 2010. Generally, this provenance showed a rapid increase similar to the Local one (Figure 4).

Mortality. In this study, the mortality was evaluated through the stand density in all 144 permanent sample plots every year from afforestation. The regression curve for the stand mortality values was interpolated to compare the data more consistently.

One year after planting (i.e. in one-year-old stands), the highest mortality was noted in stands

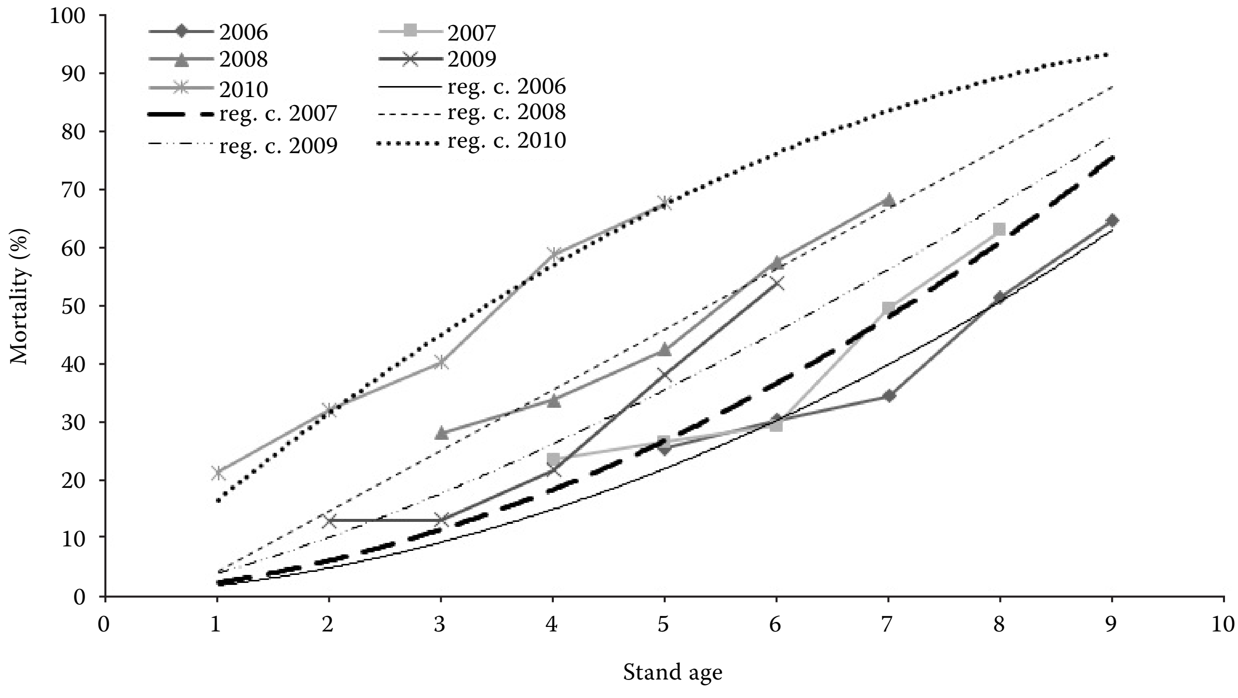

Figure 5. Mortality of studied teak stands with regression curve based on stand age (i.e. number of years from planting); dashed and dotted lines depict regression curves.

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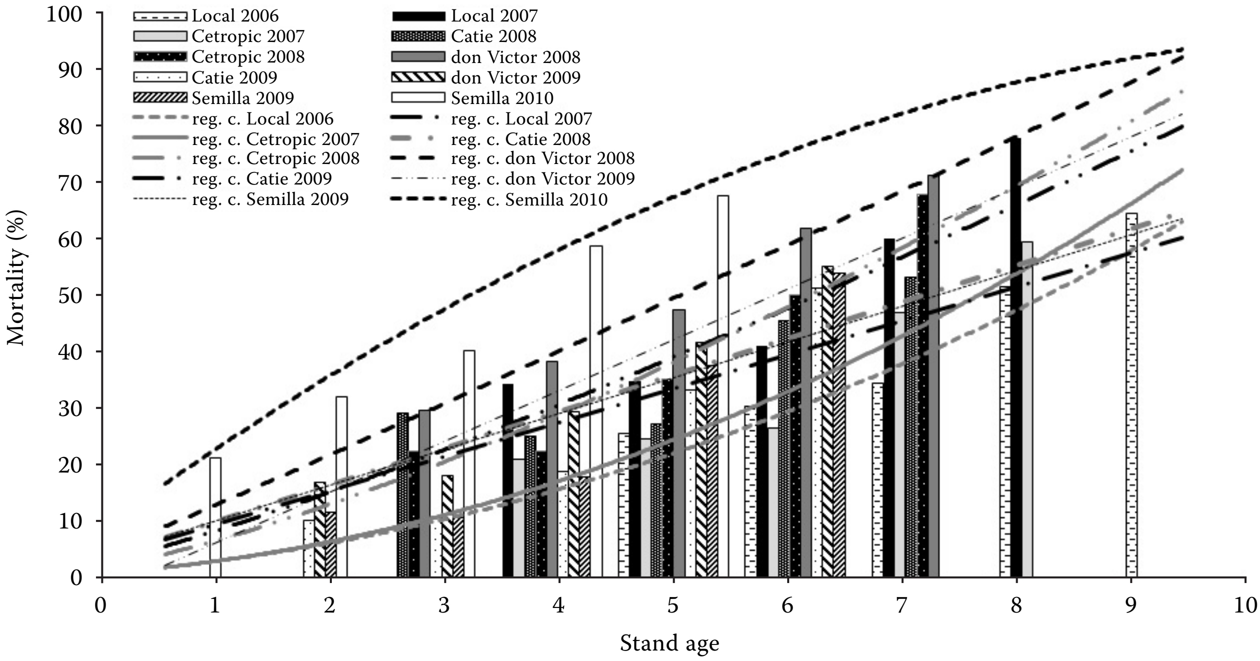

Figure 6. Mortality of studied teak plantations fitted by regression curves depending on the stand age (i.e. the number of years from afforestation) and used provenances; dashed and dotted lines depict regression curves

established in 2010, attaining up to 20%, while mortality below 10% was observed in others. Five years after planting (i.e. in five-year-old stands), the highest mortality, about 70%, was found in stands planted in 2010, followed by stands established in 2008 and 2009, with mortality in the range of 30–40%. On the other hand, stands planted in 2006 and 2007 reached the lowest mortality, around 25%. Nine years after planting (i.e. in nine-year-old stands), almost complete mortality (i.e. 100%) was found in stands established in 2010 based on the regression curve, followed by stands planted in 2008 (above 80%), 2007 and 2009 (70–80%). Contrariwise, the most vigorous trees were found in stands established in 2006, with stand mortality of 65% (Figure 5).

Based on the year of afforestation and provenance, the highest mortality, about 20%, was found in Semilla provenance (planted in 2010) one year after planting. The recorded mortality almost doubled compared to don Victor (2008), Cetropic (2008), Catie (2008), don Victor (2009), Semilla (2009) and Local (2007); and it was even fourfold higher than in Local (2006) and Cetropic (2007).

Nine years after planting (i.e. in nine-year-old stands), the highest stand mortality above 90% was observed in provenances Semilla (planted in 2010) and don Victor (2008), followed by Cetropic (2008), don Victor (2009), Local (2007) with mortality around 80% and Cetropic (2007) reaching mortality above 70%. The lowest mortality, about 60%, was found in Local (2006), Catie (2008, 2009) and Semilla (2009; Figure 6).

DISCUSSION

Perez (2008) observed the mean tree height of 12.4 m in eight-year-old teak trees on a plantation in Costa Rica, whereas Kanninen et al. (2004) recorded tree heights and *GBH*s ranging from 17.7 m to 19.5 m and from 17.0 cm to 26.0 cm, respectively, in teak plantations of the same age under identical conditions. The presented data showed slower growth than the abovementioned studies, probably caused by climatic and geomorphological conditions. In Central America, sites with temperatures from 25 °C to 27 °C, the annual precipitation fluctuating between 1 250 mm and 1 500 mm, dry season from 3 to 5 months, and altitude below 600 m a.s.l. fit best for teak growth and yield (Ugalde Arias 1997). The teak can grow on sites with five-month dry periods. However, its optimal growth is in locations with a shorter dry period than three months, with annual precipitation ranging from 1 500 mm to 2 500 mm (FAO 2002). The studied area is located in the dry and

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hot region with an average annual temperature of 26 °C (MARENA/INAFOR 2002; INETER 2004), corresponding to the optimal temperature requirements of teak (Ugalde Arias 1997); however, both with significantly lower mean annual precipitation of about 1 400 mm (INETER 2004) and more extended dry season lasting five to six months (Erikson et al. 1997) resulting in its lower growth rate.

Furthermore, Thulasidas and Bhat (2009) compared the growth of 35-year-old teaks cultivated on wet and dry sites. They observed about 40% lower stem circumference of teak growing in dry sites compared to damp areas due to stem shrinkage (Drew, Downes 2009), indicating the shortage of available water (De Swaef et al. 2015). Although the mean altitude of 220 m a.s.l. in the studied area corresponds to optimal growth conditions (Ugalde Arias 1997), the hilly relief with deep valleys and steep hillsides can also be a limiting factor for optimal growth. It was also confirmed by Montero et al. (2001), who noted the best teak growth on flat areas or moderate hillsides. Moreover, Rugmini and Balagopalan (2000) reported that the teak vitality significantly decreased with increasing altitude and it grew more slowly in a hilly terrain.

The following factor causing lower teak growth and higher mortality can be spacing reflected in a stand density (i.e. the number of trees per ha after planting). The optimal stand density of plantations in the tropical zone ranged from 1 000 to 1 100 trees per ha (Ladrach 2004). Numerous experiments with various spacings have already been performed in the tropical zone, e.g. by Adegbehin (1982), Ola-Adams (1990), Sibomana et al. (1997), Nayak and Senapati (1998) and Rondon (2006). All studies mentioned above proved that the stem circumference increased more rapidly in sparser stands due to lower competition among individuals. The presented research was conducted on the plantation with a spacing of 1 m × 1 m (i.e. 10 000 trees per ha), and the stand density also probably led to decreased teak growth. Wider spacing among trees enables the broader crown formation within the canopy and higher radial increment. Contrariwise, the influence of the spacing on the tree height is different (Prodan et al. 1997; Adegbehin 2002). Some studies found no spacing effect on the tree height (e.g. Adegbehin 1982; Sibomana et al. 1997; Ola-Adams 1990), whereas Nayak and Senapati (1998) reported a more rapid tree height increment in dense stands. The optimal stand density to stimulate teak height growth can be 630–1 020 trees per ha (Pachas et al. 2019). Furthermore, as a light-demanding species, the teak generally increases its sun foliage amount within the crown canopy after the thinning treatment (Pokorný et al. 2008) and stimulates height growth (Lowe 1976). On the contrary, teak is very sensitive to shading; therefore, it can be why such high mortality in the studied plantations is characterised by high stand density.

Generally, the genetic quality (used provenances or clones) has a significant effect on the growth (height growth, radial increment) and mortality in teak plantations (Chaix et al. 2011; Callister 2013; Goh et al. 2013; Huang et al. 2019; Mulyadiana et al. 2020). This fact was also confirmed in the present study comparing five various provenances (Catie and Semilla – Costa Rica, don Victor – southern Nicaragua, Cetropis – northern Nicaragua, and Local from the studied plantation). Based on the results, the Local provenance is the most suitable from the viewpoint of the growth and mortality in the studied area. Similar results were reported by Kokutse et al. (2009), who also observed a higher radial increment of 7-year-old teak coming from a local provenance compared to the introduced one in Togo. Contrariwise, Chaix et al. (2011) recorded higher productivity in Malaysian teak originating from the clonal seed orchard families. On the contrary, Semilla provenance (from Costa Rica) employed in the study was characterised by lower radial increment and mean tree height with high mortality compared to others. Likewise, differences in growth, mortality and profitability between various teak provenances were found (Pedersen et al. 2007; Husen 2010; Isotupa, Tyynelä 2010) when, for instance, Pedersen et al. (2007) found 10% and even 40% dissimilarity in the tree height and the stand volume, respectively, for various provenances in a 30-year-old teak plantation in Tanzania.

CONCLUSION

The present study dealt with a five-year evaluation of teak plantation growth and mortality in central Nicaragua, characterised by the amount of precipitation and the dry season length at the bottom limit of teak ecological valence. For the study, the planting stock of five provenances was planted between 2006 and 2011 at a specific spacing of 1 m × 1 m.

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Based on the presented results, high stand density, hilly terrain and water scarcity caused lower height growth and radial increment than in other plantations of similar age within the Central American region. Although the high stand density should stimulate the height growth, the geomorphology and limited water availability decreased the radial and height growth of studied teak plantations. Moreover, a spacing of 1 m × 1 m elicited self-pruning, especially in suppressed and not vigorous trees. Sparser teak plantations are recommended in the Central American regions due to decreased economic incomes and increased stand yield with lower mortality. The teak growth and mortality also depended on the employed provenance of sampling stock. The Local provenance originated directly from the studied plantation was characterised by the highest radial and height growth with relatively low mortality and it was the most resistant to lower water availability caused by low precipitation and long dry period. Contrariwise, provenances originated from Costa Rica (mainly Semilla) suffered from adverse climatic conditions in the studied area, and they probably demand better resource (water) availability with the dry period absence to attain promising growth and economic yield.

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