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# PERFORMANCE OF FOUR BROAD-LEAVED TREE SPECIES IN A *PINUS* ENRICHMENT TRIAL IN CENTRAL HIGHLANDS OF SRI LANKA

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Large-scale pine plantations established in the mountainous regions of Sri Lanka cause many environmental and social issues. This paper describes a pine enrichment trial that investigated the potential to convert a *Pinus caribaea* stand to a mixed species stand using four broad-leaved tree species in Hantana, Sri Lanka. These trees were transplanted under three light treatments (full shade: *Pinus* understorey, partial shade: three pine rows removed, and full light: open grassland) in 2004. All pine trees were removed in 2010. We compared the performance of these tree species in 2010 and 2015. In 2010, the highest percentage survival (99.0%) was under the partial shade while the highest carbon sequestration ($50.2 \times 10^{-4}$ C t year$^{-1}$) and carbon stock ($0.044 \times 10^{-3}$ C t ha$^{-1}$) were under full light by *Artocarpus nobilis*. In 2015, the highest percentage survival (79.3%) was recorded by *Michelia champaca*, and the highest relative growth ($4.2 \times 10^{-3}$ m year$^{-1}$), carbon sequestration ($56.7 \times 10^{-3}$ C t year$^{-1}$) and carbon stock ($0.049 \times 10^{-3}$ C t ha$^{-1}$) were recorded by *A. nobilis*. *Artocarpus nobilis* and *M. champaca* can be used to convert monoculture pine plantations to mixed species stands in mountainous regions in Sri Lanka.

Keywords: Carbon sequestration, carbon stock, enrichment planting, percentage survival, relative growth rate

## INTRODUCTION

In most tropical degraded lands, monocultures are established using several exotic tree species such as *Eucalyptus*, *Pinus*, *Acacia*, *Tectona* and *Swietenia* (Liu et al. 2018). In Sri Lanka, the Forest Department planted *Pinus*, *Acacia* and *Eucalyptus* to reforest degraded lands in wet and intermediate climatic zones of the island considering their ease of establishment in fire-prone and open grass environments, their known market access, and the availability of improved seeds (Ashton et al. 2014a). Although over 30,000 ha of pine plantations were established in Sri Lanka between the 1970s and 1990s, they have hardly been managed using silvicultural prescriptions since their establishment (Ashton et al. 2014a, Jayawardhane & Gunaratne 2020). These fast-growing monocultures have often met with strong community opposition after their establishment as they do not provide traditional goods and services valued by local communities and provide less ecological services than the native vegetation they replaced (Erskine et al. 2006).

Studies on the conversion of monocultures into mixed-species stands revealed that the latter result in higher delivery of ecosystem services, namely, increased individual tree growth rates, increased stand-level productivity, enhanced biodiversity, improved potential to restore degraded lands, and reduced risk of tree diseases (Asner et al. 2018, Jonsson et al. 2019, Zhang et al. 2019, Huuskonen et al. 2021). Selecting native tree species over exotic tree species is important for reforestation projects since exotic species can have negative ecological and social impacts (Chechina & Hamann 2015). Thus, investigations are needed to identify appropriate silvicultural prescriptions and site-specific plant species to convert exotic monocultures into broad-leaved mixed-species stands to reinstall the ecological services valued by local communities. Enrichment planting under thinned overstorey is prescribed to introduce valuable species to exotic monocultures in the tropics (Paquette et al. 2006, Ashton et al. 2014a). Planting mixtures of native trees accelerated the conversion of monoculture plantations into mixed-species stands compared with natural regeneration (Liu et al. 2018).

 

Forest restoration on degraded lands reduces poverty, enhances environmental protection and improves human well-being in line with the Sustainable Development Goals declared by the United Nations General Assembly in 2015 (Brancalion & Chazdon 2017, Bieng et al. 2021). Furthermore, the restoration efforts help to offset carbon losses from deforestation through accumulation and long-term storage of carbon in plant biomass and soil organic matter (Silver et al. 2004). Thus, establishment of tree plantations on cleared lands in the tropics to reduce the rate of increase in atmospheric $CO_2$ is a popular carbon stocking strategy (He et al. 2013, Bieng et al. 2021). As trees grow, they sequester carbon in their tissues, and gradually the amount of tree biomass increases (within forest products), mitigating atmospheric $CO_2$ levels (Losi et al. 2003). Tree growth is utilised to assess the demographic variation of performance among tree species in relation to their responses to biotic and abiotic factors (Asner et al. 2018, Rüger et al. 2011). Gibbs et al. (2007) mentioned that using plant species with a life span longer than 10 years for restoration projects will sequester carbon more effectively, resulting in a net reduction of $CO_2$ from the atmosphere to be included and absorbed into long-term natural sinks. Another study revealed that 15 years after reforestation, carbon stocks were 11% higher in mixed-species plantations than in monoculture plantations in China (Zhang et al. 2019).

Recognising the importance of forests for the removal of atmospheric carbon, the Paris Agreement set out a global action plan to limit global warming to well below 2 °C, preferably to 1.5 °C, compared with pre-industrial levels in order to achieve a climate-neutral world by mid-century through economic and social transformations (UNFCCC 2016). Climate change has led many countries to study the carbon budgets and carbon sequestration of their forest resources in order to understand their importance in mitigating climate change (Eneji et al. 2014, Schulte-Uebbing & de Vries 2018). Valuation of carbon provides incentives for users to change their use of forest resources, if benefits reach them in a timely, appropriate and effective manner that builds confidence in the process (Vashum & Jayakumar 2012).

Two restoration trials using different silvicultural prescriptions were conducted to determine the potential for converting *Pinus caribaea* plantations to mixed-species stands in the Sinharaja Man and the Biosphere Reserve and Hantana Environmental Protected Area in Sri Lanka (Ambagahaduwa et al. 2009, Ashton et al. 2014b). *Pinus caribaea* was planted in the Hantana Mountain range between 1980 and 1985 by the Forest Department under the upper Mahaweli water catchment reforestation project. In 2003, a pine enrichment demonstration trial was initiated by the Department of Botany, University of Peradeniya to improve stand structure, composition and ecosystem services offered by these monoculture stands. The silvicultural treatments included strip cutting of pines in 2003, enrichment planting of four broad-leaved tree species into the strip cuts in 2004 followed by total thinning of pines in 2010. It is mandatory to measure the performance of broad-leaved tree species transplanted into the pine stand at different time scales to assess the success of the silvicultural treatments and to select potential species for enriching pine stands in mountainous wet climatic zone of Sri Lanka.

Thus, the objectives of the study were to assess the survival, relative growth in diameter at breast height ($RGR_{DBH}$), carbon sequestration and carbon stock of the four broad-leaved species transplanted into the monoculture pine plantation in Hantana. Measurements were taken in 2010 (six years after enrichment planting) and in 2015 (five years after total pine canopy removal).

## MATERIALS AND METHODS

### Study site

The study was conducted at the lower elevations of the Hantana mountain range (7° 05' N, 80° 30' E) which is in the wet zone of Sri Lanka (Figure 1). The topography of the study site is moderately hilly and, in some places, it is steeply undulating spanning between an altitudinal range of 504 to 585 m. This site belongs to the tropical humid region, which receives an annual rainfall of 2000–2500 mm and has a mean annual temperature of 29.3 °C (Jayawardhane & Gunaratne 2020). This area consists of rocks of the highland series, which have a metamorphic origin and the soil type of Kandy district, where the study site is located, is red-yellow Podzolic soil (Ultisols) (Indraratne 2020).

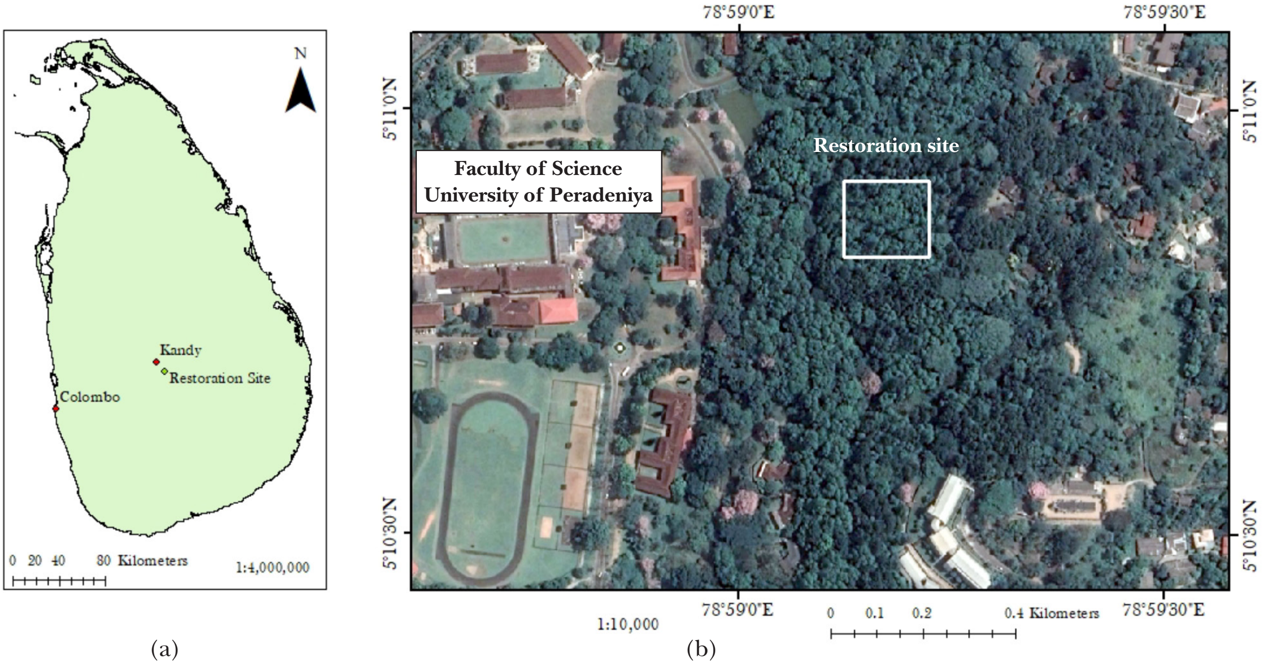


**Figure 1** (a) Location of the pine enrichment site in Sri Lanka (green diamond) and (b) the pine enrichment site in Hantana (square) (Google Earth Pro 2021)

## Experimental design

The enrichment of the *Pinus* plantation in Hantana using four broad-leaved tree species was initiated in 2003 by the Department of Botany, University of Peradeniya. The light treatments in this trial, viz, partial shade (PS: partial shade level was stimulated by removing three adjacent rows of *Pinus* trees in north-east–south-west direction along the slope), full shade (FS: *Pinus* understorey), and control (FL: full light in open grassland area), were established in 2003 (Ambagahaduwa 2008). In 2004, four broad-leaved tree species, namely, *Artocarpus nobilis* (Moraceae, endemic), *Madhuca longifolia* (Sapotaceae, native), *Michelia champaca* (Magnoliaceae, exotic) and *Terminalia bellirica* (Combretaceae, native) were planted in a split-plot design with a two-factor factorial combination, comprising three replicates (three blocks) into partial shade, full shade and full light. At present, the exotic *M. champaca* is naturalised in the country and it also provides good quality timber to local markets, thus, it was selected for this study. In 2010, all the remaining *Pinus* trees in between treatments were removed from the partial shade and full shade (total pine canopy removal) treatments (Figure 2). In 2010 and 2015, diameter at breast height (DBH) and height of the broad-leaved species were measured using DBH tape and hypsometer respectively.

## Data analysis

The percentage survival and relative growth rates were calculated using values from 2005 and 2007 as baseline data respectively. These data were collected by the University of Peradeniya. Due to the small size of seedlings/saplings in 2005, DBH values were taken from the 2007 data set. The data collected on height and DBH during the previous censuses (2005 and 2007) were used to calculate the performances of the four tree species before total canopy removal.

Percentage survival was calculated using the equation below:

$$\text{Survival rate} = 100 \times \left(\frac{N_f}{N_i}\right)$$

where, $N_f$ = number of individuals (final) and $N_i$ = number of individuals (initial). The relative growth rate of the trees was calculated using the equation below (Wright et al. 2010).

$$\text{Relative growth rate (RGR)} = \frac{\ln(DBH_f/DBH_i)}{(t_f - t_i)}$$

where, $DBH_f$ and $DBH_i$ = final and initial DBH values, $t_f$ and $t_i$ = final and initial year of the census.

 


**Figure 2** Partial shade treatment in the pine enrichment site using four broad-leaved species in Hantana, Sri Lanka; (a) 2004: after transplantation, (b) 2007: three years after transplantation, (c) 2009: five years after transplantation and (d) 2015: 11 years after transplantation

The method modified by Eneji et al. (2014) was adopted to calculate carbon sequestration for the tropical forest species where: W= aboveground total (green) weight of tree (kg), D = diameter of the trunk (cm), H = height of tree (m), and S = wood density (g $cm^{-3}$). For trees with $D \leq 10$, the equation used was: $W = 0.25D^2HS$ and for trees with $D \geq 10.1$, $W = 0.15D^2HS$. If the root system weighs about 20% as much as the aboveground weight of tree,

Total green weight of the tree (Wg)
= W × 120%
Dry weight of the tree (Wd)
= weight of the tree (Wg) × 72.5%
Weight of carbon in the tree (Wc)
= Wd × 50%
Weight of $CO_2$ sequestrated in the tree $W_{CO2}$
= Wc × 3.6663
Weight of $CO_2$ sequestrated in the tree per year
= $W_{CO2}$/ the age of the tree

The method used by Liu et al. (2014) was used to determine the carbon stock.

$$AGB = \rho.\exp(-1.239 + 1.980\ln(DBH) + 0.207(\ln(DBH))^2 - 0.0281(\ln(DBH))^3)$$

where, ABG = aboveground biomass (kg), DBH = diameter at breast height (cm), and ρ = wood density (g $cm^{-3}$). The wood densities were taken as 0.58 g $cm^{-3}$ for *A. nobilis*, 0.43 g $cm^{-3}$ for *M. champaca*, 0.72 g $cm^{-3}$ for *T. bellirica* and 0.74 g $cm^{-3}$ for *M. longifolia* (Brown 1997).

For the estimation of carbon (C) stock of tree, the equation used was

$$C\ (t) = \frac{AGB}{2}$$

The belowground biomass carbon (t C $ha^{-1}$) values were

$$BGBC = 0.235 \times AGB \text{ if } AGBC > 62.5 \text{ t C ha}^{-1}$$
$$BGBC = 0.205 \times AGB \text{ if } AGBC \leq 62.5 \text{ t C ha}^{-1}$$

Total carbon stock of a tree = AGB carbon of a tree (AGBC) + BGB carbon (BGBC) of a tree.

*Year 2010 data (six years after transplantation of four broad-leaved species into light treatments)*

The mean values of relative growth rate, carbon sequestration, carbon stock and percentage survival of the four species were compared using Minitab 17 software (2015) to detect the influence of different light treatments on performance of the four broad-leaved species. From the census conducted in 2010, the individuals and the numbers used to calculate percentage survival in 2010 were *A. nobilis* (513), *M. champaca* (495), *M. longifolia* (394) and *T. bellirica* (293). The number of individuals used to calculate relative growth rate, carbon sequestration and carbon stock were *A. nobilis* (362), *M. champaca* (437), *M. longifolia* (322) and *T. bellirica* (220). The calculation of percentage survival and relative growth rate was done using

2005 data as baseline data. Normality and outlier tests were performed on all data sets to determine the quality and outliers of the population respectively. Three general linear models were fitted to data with the three response variables (i.e. relative growth rate, carbon sequestration and carbon stock). The experimental variables for the above three models were species, light treatment and interaction between species and light treatment. The mean values obtained from the percentage survival for 2010 were compared using the Tukey's pairwise comparison test (at 95% confidence level) using 1695 data points. A binary logistic regression model was fitted to percentage survival data collected in 2010. Here, the response variable was the percentage survival, while the experimental variables were the type of species and light interaction. The values of variance inflation factor (VIF) were used to express the level of correlation between predictors.

*Year 2015 data (five years after total removal of pine canopy in 2010 and 11 years after initial transplantation in 2004)*

The normality and outlier tests were performed for 1370 data points in each data set to determine the quality and the outliers of the population respectively. One-way ANOVA was used to test the significance of light treatment on the relative growth rate, carbon sequestration and carbon stock in *A. nobilis* (352 individuals), *M. champaca* (376), *M. longifolia* (296) and *T. bellirica* (213). This was followed by Tukey's pairwise comparison test (at 95% confidence level) to determine the statistical significance of the two factors. Finally, a binary logistic regression model was fitted to percentage survival data of *A. nobilis* (401 individuals), *M. champaca* (398), *M. longifolia,* (331) and *T. bellirica* (240). The VIF values were used to express the level of correlation between predictors.

## RESULTS

### Performance of broad-leaved tree species in 2010

Six years (i.e. in 2010) after the initiation of the enrichment trial in the pine stand, the light treatments significantly affected the percentage survival of the four species (df = 3, p = 0.000). The interaction between the species and light treatments was statistically significant (df = 6, p = 0.000). The highest percentage survival was observed in *A. nobilis* (99.0%) under partial shade, followed by *M. longifolia* (98.7%) under full light and *M. champaca* (97.9%) under partial shade. Multicollinearity existed in the regression and it was highly correlated in partial light. *Madhuca longifolia* and *T. bellirica* had high VIF values (> 10) under partial shade treatment, showing that there could be other factors affecting their survival. Other groups were moderately correlated, where VIF values were between 5 and 1. The lowest percentage of survival was observed in *T. bellirica* (18.3%) under full shade (Figure 3a).

The light treatments significantly affected the $RGR_{DBH}$ of all four species (df = 3, p = 0.000) before total canopy removal in 2010. The interaction between species and light treatments was significant (df = 6, p = 0.000) during this time. The highest $RGR_{DBH}$ ($6.0 \times 10^{-3}$ m year$^{-1}$) under full shade was achieved by *M. champaca* with a notable difference in the rest of the light treatments and species. The highest $RGR_{DBH}$ under partial shade was achieved by *A. nobilis* ($5.3 \times 10^{-3}$ m year$^{-1}$) (Figure 3b). *Madhuca longifolia* and *T. bellirica* had the lowest $RGR_{DBH}$ under full shade ($3.9 \times 10^{-3}$ m year$^{-1}$ and $3.6 \times 10^{-3}$ m year$^{-1}$ respectively).

The carbon sequestration of tree species under different light treatments varied significantly (df = 3, p = 0.000) by 2010. The interaction between species and treatments (df = 6, p = 0.000) was statistically significant. The highest carbon sequestration was recorded for *A. nobilis* ($50.2 \times 10^{-4}$ C t year$^{-1}$) under full light followed by *M. champaca* ($18.5 \times 10^{-4}$ C t year$^{-1}$) under partial shade. The lowest carbon sequestration in all four species was recorded under the full shade treatment and *T. bellirica* ($0.4 \times 10^{-4}$ C t year$^{-1}$) recorded the lowest value (Figure 3c).

By the year 2010, carbon stocks of the four species were significantly different under light treatments (df = 3, p = 0.000) and the interactions between species and treatments (df = 6, p = 0.000) were significant. The highest value for carbon stock was recorded for *A. nobilis* ($4.4 \times 10^{-5}$ C t ha$^{-1}$) under full light and it was significantly greater than in partial shade and full

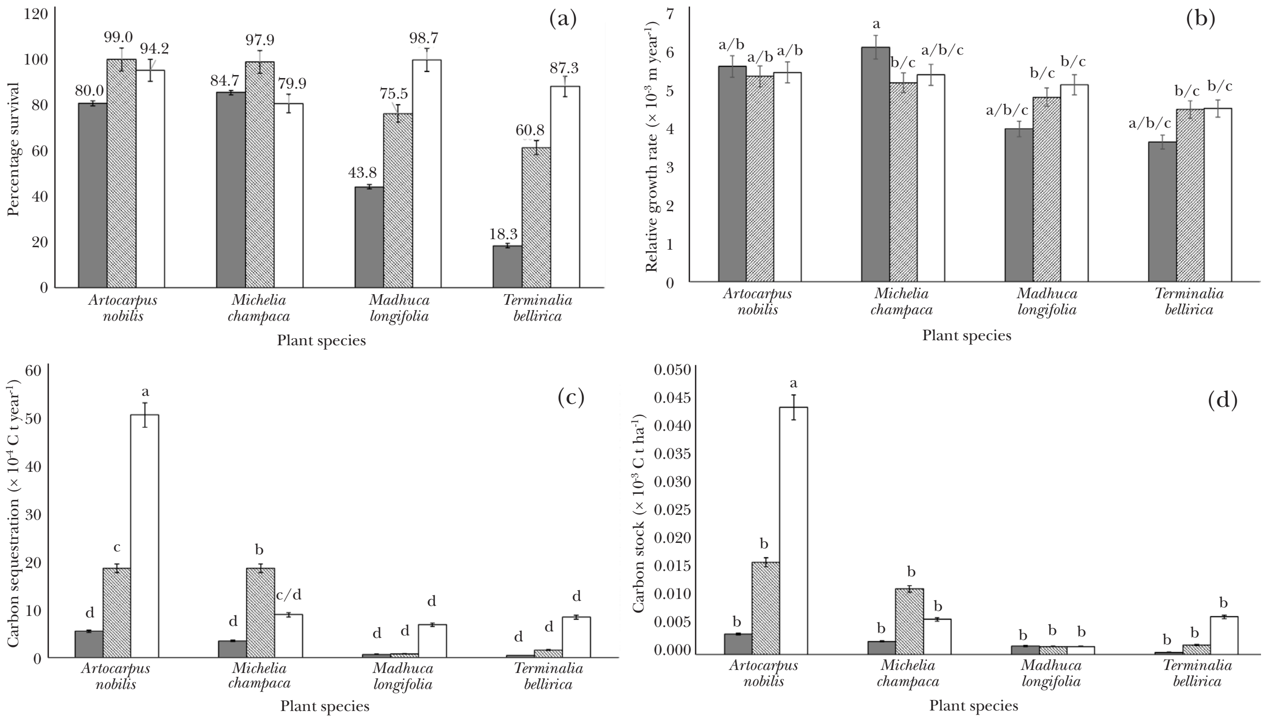


**Figure 3** Performance of *Artocarpus nobilis*, *Madhuca longifolia*, *Michelia champaca* and *Terminalia bellirica* under three light treatments: full shade (dark grey), partial shade (light grey) and full light (white) in 2010 (6 years after the transplantation) in a silviculturally managed pine plantation in lower Hantana, Sri Lanka; (a) percentage survival, (b) relative growth rate, (c) carbon sequestration, and (d) carbon stock

shade treatments (Figure 3d). The lowest carbon stock in all four species was recorded under the full shade treatment, where both *T. bellirica* and *M. longifolia* ($0.01 \times 10^{-4}$ C t $ha^{-1}$) had lower values than the other two species.

## Performance of broad-leaved tree species in 2015

Eleven years after the initiation of the enrichment trial, the highest percentage of survival was obtained by *M. champaca* (89.8%), followed by *A. nobilis* (87.5%). The lowest survival was recorded by *T. bellirica* (68.8%). The p-values of *M. champaca* and *M. longifolia* under full shade ($p = 0.310$ and 0.132 respectively ), and *A. nobilis* under partial light condition ($p = 0.107$) were greater than 0.05 significance level, indicating that not only light but other factors may have affected the relative growth rate of the trees (Figure 4a).

In 2015, five years after total removal of all remaining *P. caribaea* trees between the treatment plots, i.e.11 years from transplanting, the highest $RGR_{DBH}$ was obtained by *A. nobilis* ($4.2 \times 10^{-3}$ m $year^{-1}$) (Figure 4b). The lowest relative growth rate was obtained by *M. longifolia* ($3.6 \times 10^{-3}$ m $year^{-1}$). Although *M. champaca* recorded a significant difference in the $RGR_{DBH}$ under full shade than the other species and light treatments, in 2010, their $RGR_{DBH}$ did not vary significantly compared with the other three species in 2015.

Eleven years after transplanting, the highest carbon sequestration was obtained by *A. nobilis* ($56.7 \times 10^{-3}$ C t $year^{-1}$) followed by *T. bellirica* ($38.5 \times 10^{-3}$ C t $year^{-1}$) (Figure 4c). The lowest value was obtained by *M. longifolia* ($24.3 \times 10^{-3}$ C t $year^{-1}$). In the first six years after the initiation of the enrichment plantation, *A. nobilis* recorded a significant difference in carbon sequestration under full light condition compared with the other three species and treatments, but there was no such significant difference between this species and the other three species in 2015 after the total canopy opening.

In 2015, the highest carbon stock was obtained by *A. nobilis* ($4.9 \times 10^{-5}$ C t $ha^{-1}$) followed by *T. bellirica* ($3.0 \times 10^{-5}$ C t $ha^{-1}$) (Figure 4d). The lowest carbon stock was obtained by *M. longifolia* ($2.0 \times 10^{-5}$ C t $ha^{-1}$). However, the total carbon stock of *A. nobilis* accumulated per year during 2010–2015 ($0.98 \times 10^{-5}$ C t $ha^{-1}$) was less than that of during 2004–2010 ($1.06 \times 10^{-5}$ C t $ha^{-1}$).

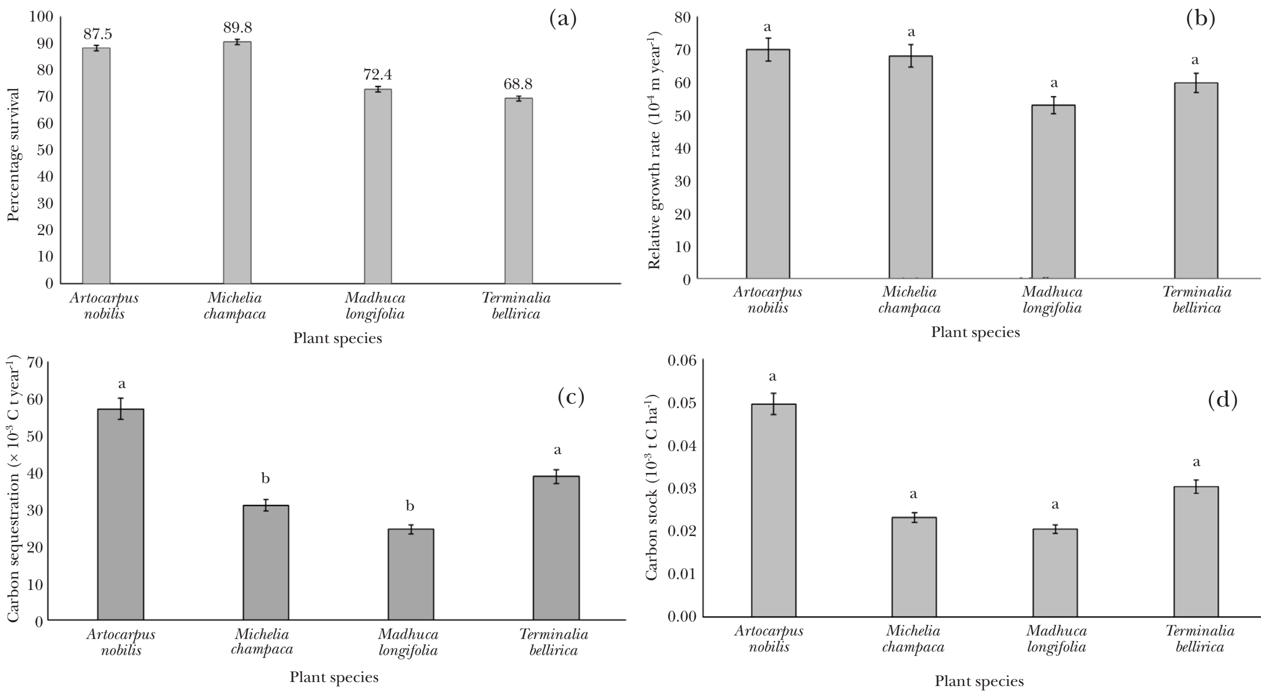


**Figure 4** Performance of *Artocarpus nobilis*, *Madhuca longifolia*, *Michelia champaca* and *Terminalia bellirica* in 2015 (11 years after trasplantation followed by total thinning of pines) in a silviculturally managed pine plantation in lower Hantana, Sri Lanka; (a) percentage survival, (b) relative growth rate, (c) carbon sequestration, and (d) carbon stock

## DISCUSSION

Use of native broad-leaved tree species for enrichment planting of monoculture is a common practice in forestry (Chu et al. 2019). Our study demonstrated the relative performance of four broad-leaved tree species in a pine enrichment trial in the lower montane region of Sri Lanka. The trees performed differently to changes in light intensity under different silvicultural treatments.

By 2010, *A. nobilis*, *M. longifolia* and *T. bellirica* recorded comparatively higher values for percentage survival in partial shade and full light than under the *Pinus* understorey (full shade) confirming that light availability is a key limiting factor for photosynthetic carbon gain, which in turn influences growth and mortality of plant species (Wright et al. 2010). Ambagahaduwa (2008) attributed the low growth performance of transplants at the same study site to the differences in total daily photosynthetic photon flux at ground level between the full light (27 mol $m^{-2}$ $day^{-1}$), partial shade (13 mol $m^{-2}$ $day^{-1}$) and full shade (5 mol $m^{-2}$ $day^{-1}$). With decreasing stand density due to strip cutting of pines in 2003 followed by total thinning in 2010, the competition for above- and belowground resources between transplants and pines may have decreased drastically, which is advantageous for transplants of broad-leaved tree species. Ambagahaduwa (2008) also attributed the low growth performance of transplants to competition with *P. caribaea* trees for nutrients and soil moisture.

In 2010 *A. nobilis* recorded the highest percentage survival under partial light, and it recorded the second-highest value for percentage survival under the full light. Further, it recorded the highest values for $RGR_{DBH}$ for both partial shade and full light treatments in 2010 indicating that seedlings and saplings of the endemic *A. nobilis* performed well under different light intensities. Even after the total pine canopy removal in 2010, *A. nobilis* recorded the highest $RGR_{DBH}$ in 2015. Thus, these results suggest that this species can tolerate different light regimes and achieve higher $RGR_{DBH}$ compared with the rest of the species in this trial. Moreover, the highest carbon sequestration and carbon stock was obtained by *A. nobilis* under full light in 2010 and 2015, i.e. five years after the total removal of pines in 2015. Thus, considering all these attributes of *A. nobilis,* as well as production of edible fruits for fauna, it is the best tree species out of the four tested broad-leaved species to enrich strip cuts of pine plantations and to restore open grasslands in the lower montane regions (1000–1500 m) of Sri Lanka.

Although *M. champaca* is an exotic species, it was selected for the enrichment trial since it is presently naturalised on the island and yields economically valuable timber (Ambagahaduwa 2008, Chu et al. 2019). Under partial shade, it recorded the second-highest percentage survival in 2010. Furthermore, the percentage survival of *M. champaca,* five years after the total removal of pines decreased from 97.9% in 2010 to 89.8% in 2015 under full light. This variation was due to averaging of the percentage of survival values across the three light treatments in 2015 as they had the same microclimatic conditions after 2010 due to the total pine canopy removal in 2010. Further, *M. champaca* obtained the highest value for $RGR_{DBH}$ under the full shade treatment and the second-highest $RGR_{DBH}$ ($5.1 \times 10^{-3}$ m $year^{-1}$) under partial shade treatment in 2010. Although *M. champaca* is a light-demanding tree species during its adult stage, its saplings perform well under partial shade condition (Orwa et al. 2009). In this study, it recorded the second-highest value for carbon stock under partial shade in 2010. This result confirms that *M. champaca* saplings favour partial shade for establishment rather than full light even though *M. champaca* is considered a light-demanding tree species (Orwa et al. 2009). *Michelia champaca* recorded the second-highest value for carbon sequestration in 2010 under partial shade and the third highest in 2015. Although *M. champaca* is an exotic species, it is now naturalised on the island and produce animal-dispersed seeds (personal observation). It also has several good growth attributes that can be used to convert pine stands to mixed-species stands resulting in improved ecosystem services by manipulating light conditions (partial shade condition during the sapling stage and full light beyond the sapling stage).

Light-demanding trees have low wood density, and their growth rates are negatively correlated with the wood density (King et al. 2006). Thus, the lower wood densities of *A. nobilis* (0.58 g $cm^{-3}$) and *M. champaca* (0.43 g $cm^{-3}$) than that of *T. bellirica* (0.72 g $cm^{-3}$) and *M. longifolia* (0.74 g $cm^{-3}$) (Brown 1997) may have resulted in higher $RGR_{DBH}$ in *A. nobilis* and *M. champaca* compared with *T. bellirica* and *M. longifolia* in 2010 and 2015.

Although native species *M. longifolia* and *T. bellirica* showed relatively lower percentage survival and $RGR_{DBH}$ under full and partial shades than the other two species in 2010, their percentage survival at initial seedling and sapling stages were greater under full light, confirming that the young life stages of these species required full light. At the same study site, Ambagahaduwa (2008) reported that 28 months after the initiation of enrichment planting, *T. bellirica* and *M. champaca* had the highest growth rates (considering DBH and root collar diameter) under full light in the open grassland area and the lowest values under the full shade of the *Pinus* understorey. Since both survival and growth of these two species are higher under full light, they can be used to restore open areas in lower mountainous regions in Sri Lanka as well.

By 2010, due to low growth rate compared to the other two species, the contribution of *M. longifolia* and *T. bellirica* to carbon sequestration and carbon stock were less in light manipulated treatments. The lowest values for most of the tested response variables were obtained by *T. bellirica* under different light treatments in 2010. However, by 2015, the carbon stock of *T. bellirica* increased, probably due to more light availability due to canopy opening, demonstrating its high light requirement for successful establishment. Since many saplings of *T. bellirica* at the research site were damaged by herbivores such as porcupines (personal observation), this could have led to their lower performance in this trial in 2010. Orwa et al. (2009) also noted *T. bellirica* required good protection from grazing. High wood density, damage resistance, and unpalatability to herbivores are traits that enhance the survival of trees (King et al. 2006). Although *T. bellirica* has the second-highest wood density of the four species, due to its high palatability, to introduce this valuable medicinal species into pine stands, larger canopy removal is required along with herbivore exclusion from initial phases of establishment. This species can also be used to restore open degraded grasslands or shrublands using appropriate silvicultural prescriptions in lower montane regions of Sri Lanka.

Although we considered only light conditions as a major factor affecting the performance of the tree species, other factors such as allelopathy effects and competition for soil moisture with mature pine trees may affect the performance of the transplants where both intraspecies and interspecies interactions would be impacted (King et al. 2006, Piotto 2008). Kanowski and Catterall (2010) reported that the restoration plantations stored significantly more carbon in aboveground biomass than monoculture plantations of conifers. Further, they mentioned that tree species used in restoration planting had high wood densities which stocked more densely than any monocultures. A 55–61-year-old reforestation project with native and non-native species in similar elevation range to our study site in Puerto Rico has accumulated carbon at a rate of 1.4 Mg $ha^{-1}$ $year^{-1}$ (Silver et al. 2004). In our study, which spanned only 11 years, the carbon accumulation rate was $7.9 \times 10^{-6}$ Mg $ha^{-1}$ $year^{-1}$.

The use of silvicultural prescriptions to convert monoculture pine plantations into mixed-species stands provides a promising strategy to sequester carbon to mitigate climate change while gaining social acceptability. Further, this study provides insights to the selection of tree species and silvicultural prescriptions to convert monoculture pine plantations to multi-structural and multi-species tree stands with enhanced ecological, economical and social benefits in lower montane regions in Sri Lanka.

## CONCLUSION

Monoculture *Pinus* plantations can be converted into mixed-species tree plantations successfully using species with high survival and growth potential such as *A. nobilis* and *M. champaca* and species with high carbon sequestration and carbon stock potential such as *A. nobilis* and *T. bellirica*. Following appropriate silvicultural prescriptions for requirements of different species would speed up the conversion of pine plantations to mixed-species stands in lower montane regions of Sri Lanka.

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## REFERENCES

Ambagahaduwa IM. 2008. Restoration of plant diversity in a monoculture *Pinus* plantation in Lower Hantana, Sri Lanka. MPhil dissertation, University of Peradeniya, Peradeniya.

Ambagahaduwa IM, Prasad N, Gunatilleke IAUN, Seneviratne G & Gunatilleke CVS. 2009. Estimation of above ground biomass of a *Pinus caribaea* Morelet stand in lower Hantana. *Journal of National Science Foundation of Sri Lanka* 37: 195–201. doi: 10.4038/jnsfsr.v37i3.1213

Ashton MS, Goodale UM, Bawa KS, Ashton PS & Neidel JD. 2014a. Restoring working forests in human dominated landscapes of tropical South Asia: an introduction. *Forest Ecology and Management* 329: 335–339. https://doi.org/10.1016/j.foreco.2014.05.035

Ashton M, Gunatilleke CVS, Gunatilleke IAUN et al. 2014b. Restoration of rain forest beneath pine plantations: a relay floristic model with special application to tropical South Asia. *Forest Ecology and Management* 329: 351–359. https://doi.org/10.1016/j.foreco.2014.02.043

Asner GP, Brodrick PG, Philipson C et al. 2018. Mapped aboveground carbon stocks to advance forest conservation and recovery in Malaysian Borneo. *Biological Conservation* 217: 289–310. https://doi.org/10.1016/j.biocon.2017.10.020

Bieng MAN, Oliveira MS, Roda JM et al. 2021. Relevance of secondary tropical forest for landscape restoration. *Forest Ecology and Management* 493: 119265. https://doi.org/10.1016/j.foreco.2021.119265

Brancalion PH & Chazdon RL. 2017. Beyond hectares: four principles to guide reforestation in the context of tropical forest and landscape restoration. *Restoration Ecology* 25: 491–496. https://doi.org/10.1111/rec.12519

Brown S. 1997. *Estimating Biomass and Biomass Change of Tropical Forests: A Primer.* Volume 134. Food & Agriculture Organization, Rome.

Chechina M & Hamann A. 2015. Choosing species for reforestation in diverse forest communities: social preference versus ecological suitability. *Ecosphere* 6: 1–13. https://doi.org/10.1890/ES15-00131.1

Chu S, Ouyang J, Liao D et al. 2019. Effects of enriched planting of native tree species on surface water flow, sediment, and nutrient losses in a *Eucalyptus* plantation forest in southern China. *Science of the Total Environment* 675: 224–234. http://dx.doi.org/10.1016/j.scitotenv.2019.04.214

Eneji IS, Obinna O & Azua ET. 2014. Sequestration and carbon storage potential of tropical forest reserve and tree species located within Benue State of Nigeria. *Journal of Geoscience and Environment Protection* 2: 157–166. http://dx.doi.org/10.4236/gep.2014.22022

Erskine PD, Lamb D & Bristow M. 2006. Tree species diversity and ecosystem function: can tropical multi-species plantations generate greater productivity? *Forest Ecology and Management* 233: 205–210. https://doi.org/10.1016/j.foreco.2006.05.013

Gibbs HK, Brown S, Niles JO & Foley JA. 2007. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. *Environmental Research Letters* 2. http://dx.doi.org/10.1088/1748-9326/2/4/045023

He Y, Qin L, Li Z, Liang X, Shao M & Tan L. 2013. Carbon storage capacity of monoculture and mixed-species plantations in subtropical China. *Forest Ecology and Management* 295:193–198. http://dx.doi.org/10.1016/j.foreco.2013.01.020

Huuskonen S, Domisch T, Finér L et al. 2021. What is the potential for replacing monocultures with mixed-species stands to enhance ecosystem services in boreal forests in Fennoscandia? *Forest Ecology and Management* 479: 118558. https://doi.org/10.1016/j.foreco.2020.118558

Indraratne SP. 2020. Soil mineralogy. Pp 33–48 in Mapa RB (ed) *The Soils of Sri Lanka*. World Soils Book Series. Springer, Cham.

Jayawardhane J & Gunaratne AMTA. 2020. Restoration success evaluation of a thinned and enriched pine plantation in Sri Lanka. *Journal of Tropical Forest Science* 32: 402–413. http://dx.doi.org/10.26525/jtfs2020.32.4.402

Jonsson M, Bengtsson J, Gamfeldt L, Moen J, & Snäll T. 2019. Levels of forest ecosystem services depend on specific mixtures of commercial tree species. *Nature Plants* 5: 141–147. doi: https://www.nature.com/articles/s41477-018-0346-z

Kanowski J & Catterall CP. 2010. Carbon stocks in above-ground biomass of monoculture plantations,mixed species plantations and environmental restoration plantings in north-east Australia. *Ecological Management and Restoration* 11: 119–126. https://doi.org/10.1111/j.1442-8903.2010.00529.x

King D A, Davies SJ, Tan S & Noor NSM. 2006. The role of wood density and stem support costs in the growth and mortality of tropical trees. *Journal of Ecology* 94: 670–680. http://dx.doi.org/10.1111/j.1365-2745.2006.01112.x

Liu CLC, Kuchma O & Krutovsky KV. 2018. Mixed-species versus monocultures in plantation forestry: development, benefits, ecosystem services and perspectives for the future. *Global Ecology and Conservation* 15: e00419. https://doi.org/10.1016/j.gecco.2018.e00419

Liu X, Ekougoulou R, Loumeto JJ, Ifo SA, Becko YE & Koula FE. 2014. Evaluation of carbon stock in above- and below-ground biomass in Central Africa: case study of Lesio-louna tropical rainforest of Congo. *Biogeosciences Discuss* 11: 10703-10735. https://doi.org/10.5194/bgd-11-10703-2014

Losi CJ, Siccama TG, Condit R & Morales JE. 2003. Analysis of alternative methods for estimating carbon stock in young tropical plantations. *Forest Ecology Management* 184: 355–368. http://dx.doi.org/10.1016/S0378-1127(03)00160-9

Orwa C, Mutua A, Kindt R, Jamnadass R & Anthony S. 2009. *Agroforestree Database: A Tree Reference and Selection Guide Version 4.0.* World Agroforestry Centre, Nairobi.

Paquette A, Bouchard A & Cogliastro A. 2006. Survival and growth of under-planted trees: a meta-analysis across four biomes. *Ecological Applications* 16: 1575–1589. https://doi.org/10.1890/1051-0761(2006)016[1575:SAGOUT]2.0.CO;2

Piotto D. 2008. A meta-analysis comparing tree growth in monocultures and mixed plantations. *Forest Ecology and Management* 255: 781–786. https://doi.org/10.1016/j.foreco.2007.09.065

Rüger N, Berger U, Hubbell SP, Vieilledent G, & Condit R. 2011. Growth strategies of tropical tree species: disentangling light and size effects. *PloS One* 6. https://doi.org/10.1371/journal.pone.0025330

Schulte-Uebbing L & De Vries W. 2018. Global-scale impacts of nitrogen deposition on tree carbon sequestration in tropical, temperate, and boreal forests: a meta-analysis. *Global Change Biology* 24: e416-e431. https://doi.org/10.1111/gcb.13862

Silver WL, Kueppers LM, Lugo AE, Ostertag R & Matzek V. 2004. Carbon sequestration and plant community dynamics following reforestation of tropical pasture. *Ecological Applications* 14: 1115–1127.

UNFCCC. 2016. The Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement. Accessed 15 November 2020.

Vashum KT & Jayakumar S. 2012. Methods to estimate above-ground biomass and carbon stock in natural forests: a review. *Journal of Ecosystem & Ecography* 2. http://dx.doi.org/10.4172/2157-7625.1000116

Wright SJ, Wright SJ, Kitajima K et al. 2010. Functional traits and the growth-mortality trade-off in tropical trees. *Ecology* 91: 3664–3674. https://doi.org/10.1890/09-2335.1

Zhang H, Zhou G, Wang Y et al. 2019. Thinning and species mixing in Chinese fir monocultures improve carbon sequestration in subtropical China. *European Journal of Forest Research* 138: 433–443. https://doi.org/10.1007/s10342-019-01181-7