ORIGINAL RESEARCH

# Competition in a Mixed-Species Planting with Four Contrasting Tree Species

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## Abstract

Mixed-species systems are well-suited to smallholder and community forestry, but reliable evidence regarding and procedures to assess species performance in such systems is scarce. This field trial uses a pair of clinal plots with varying spacing and species composition to gain insights into competition between four species proposed for landscape rehabilitation in the Philippines. We examine the efficiency of this compact clinal trial in revealing growth traits of four species (*Paraserianthes falcataria, Pterocarpus indicus, Shorea palosapis, Swietenia macrophylla*) in mixed plantings. The use of a size-distance competition index allowed an assessment of the competitive and collaborative influences between four tree species. Within the expected general trend for diameter increment to decline with increasing competition, there were indications that *Shorea palosapis* is a benign competitor that may stimulate the growth of neighbouring individuals. *Paraserianthes falcataria* is a strong competitor that is also strongly impacted by competition, especially through antagonistic intraspecific competition. *Paraserianthes falcataria* appears well suited as a solitary tree in a field or village, whereas *Shorea palosapis* seems ideal for plantations, in both monoculture and mixed plantings. The clinal spacing and mixture trial, when examined using a size-distance competition index based on diameter increment, revealed useful insights into species performance. *Pterocarpus indicus* exhibits strong intraspecific, but low inter-specific competition, so appears well-suited for polyculture plantings. Of the four species trialled, *Swietenia macrophylla* appears to be best-suited as a monoculture species as it exhibits the lowest intraspecific competition.

**Keywords** *Paraserianthes falcataria* · *Pterocarpus indicus* · *Shorea palosapis* · *Swietenia macrophylla* · Philippines · Polyculture · Clinal experiment · Forest landscape restoration

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## Introduction

In recent years here has been increasing interest in mixed-species plantings to establish plantations that provide multiple services in the tropics (Kelty 2006; Nguyen et al. 2015). However, the proportion of new plantings with mixtures is low, and Nichols et al. (2006) has estimated that mixtures comprise less than 0.1% of industrial plantations worldwide. Dickinson et al. (2008) argues that a lack of information exacerbates the reputation for mixed-species plantings to involve greater cost and complexity, especially with respect to species selection and site-matching (Manson et al. 2013; Trogisch et al. 2021).

In a systematic review of the available evidence related to the performance of mixed-species plantings, Nguyen et al. (2018) found that most studies focused on the effects of species mixtures on stand production or ecological functioning relative to that in monocultures (i.e. 167 studies comprising 72% of biophysical studies identified). In contrast, very few studies (n = 29) investigated interactions or competition between species. It is fundamental that studies of mixed-species stands should include species that are complementary, for instance with a range of traits such as shade tolerance, height growth rate, crown structure and root depth (e.g., Lui et al. 2018).

Mixed-species systems are well-suited to smallholder and community forestry (Chechina and Hamann 2015). This is particularly so for situations where smallholders rely on forests for multiple products in support of their livelihood strategies. Similarly, mixed species systems are also well suited to forest and landscape restoration initiatives undertaken as part of the Bonn Challenge and similar international commitments to reforestation (Temperton et al. 2019). In particular, many of these initiatives will be achieved through some form of community or smallholder forestry using mixtures of species. There is also an increasing desire by implementing agencies and local stakeholders to use species native to the areas being restored.

In the case of the Philippines, the National Greening Program (Goltiano et al. 2021) is a substantial reforestation initiative that commenced in 2011 and was renewed in 2016 with a commitment to reforest 7 million hectares. Many of the plantings have been mixtures of native and exotic species, and biodiversity restoration is one of the four goals of the program – but there is little evidence on which to base the selection of species and the way that species are combined. In particular, information is needed on what species are best suited for inclusion in diverse mixtures and conversely, what species should be avoided. While there is undoubtedly some knowledge about species performance, little formal literature has been published on both the performance of native species and the species that grow (or do not grow) well together. The species involved often appear to be ad hoc mixtures of whatever planting stock is available at the time of planting.

Previous research on mixed-species plantations in the Philippines has revealed that mixtures of fast-growing exotics species had better growth performance compared to monocultures of fast-growing exotics species, and also better tree species diversity performance at both the plot and landscape scale (Le et al. 2021).

Mixed species plantations in the Philippines are dynamic. Nguyen et al. (2014a) found that over time, shade-intolerant species became less important and native shade-tolerant species (often Dipterocarps) increase in importance, with at least part of this change being driven by anthropogenic influences such as harvesting of fast-growing exotic species. Despite the widespread use of mixtures within the National Greening Program, there is little guidance on which to design mixtures. The only substantive attempt has been by Nguyen et al. (2014b) who found that wood density offered some potential to identify complementary species for the design of mixed species plantings. Several other studies have reported growth performance of individual native and exotic species grown in mixtures (Herbohn et al. 2014; Nguyen et al. 2016; Schneider et al. 2014) and the stand productivity of mixed-species planting (e.g., Nguyen et al. 2012; Veridiano et al. 2020; Le et al. 2021). However none of these studies presented an analysis about the impacts of individual species interactions on growth or productivity.

Provision of suitable data (Vanclay 1991; Vanclay et al. 1995) remains an obstacle to the development of models to support forest landscape restoration, although robust models for data-poor situations are emerging (Vanclay 2010, 2017). This study draws on earlier work (Vanclay et al. 2013) to evaluate competition in four species that are potential candidates for both smallholder plantations and forest landscape restoration. Practical constraints precluded a large comprehensive trial, and the current study deals with a compact design to shed light on preconceptions regarding the utility of native and nitrogen-fixing species in landscape restoration.

This trial was formulated to test the hypothesis that competition has a major influence on early growth of plantation trees, and that this competition varies between species, both in the competition caused and the response to the competition experienced. Furthermore, it demonstrates that these traits can be revealed with a compact clinal trial that provides strong empirical and visual evidence of both competitive and facilitative interactions between species.

## Methods

Prior work with mixed-species plantings has revealed important interactions between nitrogen-fixing and other species (e.g., Forrester et al. 2006), and this influenced our decision to create a contrast between nitrogen-fixing and non-leguminous trees, and between exotic and native species. Species selection was guided by the popularity of species in smallholder tree farming and reforestation programs in the Philippines (Gregorio et al. 2020; Le et al. 2021), and by the preferences of the landowner where the trial was established. The final choice was also influenced by the availability of seedlings suited to the site. The species ultimately included Falcata (*Paraserianthes falcataria*), Mahogany (*Swietenia macrophylla*), Narra (*Pterocarpus indicus*) and Mayapis (*Shorea palosapis*). Nursery and establishment techniques for these species are well established (e.g., Gregorio et al. 2009, 2012).

The trial is located in the Sambulawon community near Leyte township in the eastern Philippines, approximately 11°22'N 124°30'E and 20 m above sea level. The field trial site is part of a long-established *hacienda,* and had been cropped

with sugarcane for many years until the 1970s. During the five years before the trial was commenced, the site was used for livestock grazing by the local community. The site was covered predominantly with grasses including *Chrysopogon aciculatus*, *Axonopus compressus* and *Saccharum spontaneum*, and included patches of the invasive weeds *Chromolaena odorata* and *Lantana camara*. The soil is a volcanic clay loam with pH 5.7. Soil organic matter and nitrogen content were 2.3% and 0.15% respectively, and extractable phosphorus was 1.3 mg kg$^{-1}$.

The trial used high quality seedlings (Gregorio et al. 2015, 2017) propagated in the nursery of ACIAR Project ASEM/2006/091 at Visayas State University. Weed control was minimal and limited to brushed lines, because we wished to examine likely performance of these species in smallholder and restoration situations where herbicides are not used (Fig. 1).

The seedlings were planted in December 2007 (Herbohn et al. 2009) and measured on 15 occasions at 3-month (until 2010), 6-month (2010–12) or annual intervals (2012–13). The plots were badly damaged during Typhoon Haiyan (also known as Typhoon Yolanda, 7–8 November 2013), and this paper draws only on data collected prior to the typhoon. Nine of the 15 measurements were selected to provide regular observations at approximately 6-month intervals (07/2008, 01/2009, 08/2009, 02/2010, 09/2010, 03/2011, 09/2011, 04/2012, 04/2013), resulting in eight intervals for the computation of diameter increment. During this five year period, these tropical tree species attained an average diameter of 15 cm dbh, with 2% of the trees exceeding 25 cm dbh, a substantial size given that the clinal plot included close spacings with trees only 70 cm apart (Table 1).

The trial was established using a paired clinal design (Vanclay 2006a) created to evaluate the performance both of mixtures at a standard spacing (3 × 3 m), and of a monoculture with a variable spacing (from 0.6 to 7.5 m; Figs. 2 and 3).



**Fig. 1** The variable spacing plot at 11 months old (November 2008), with Mahogany (*S. macrophylla*) in the right foreground, Narra (*P. indicus*) on left, and Falcata (*P. falcataria*) in the background. The ground vegetation visible in the foreground is representative of the level of weed control maintained throughout the trial

**Table 1** Summary of data recorded on 9 occasions (07/2008 to 04/2013). Note the long-tailed distributions (e.g., maximum competition tends to be 9 times the mean)

| Attribute | Minimum | Mean | Maximum | Standard deviation |
|---|---|---|---|---|
| Measurement Interval (years) | 0.4 | 0.6 | 1.0 | 0.2 |
| Tree height (m) | 0.2 | 4.2 | 15.1 | 3.0 |
| Diameter (cm dbhob) | 0.3 | 7.4 | 29.8 | 5.9 |
| Narra | 0.7 | 6.7 | 20.8 | 3.7 |
| Mayapis | 0.3 | 4.3 | 19.2 | 3.9 |
| Falcata | 0.9 | 12.5 | 29.8 | 6.6 |
| Mahogany | 1.0 | 9.1 | 22.7 | 5.0 |
| Diameter increment (cm/yr) | 0.0 | 3.0 | 10.0 | 2.1 |
| Narra | 0.1 | 2.2 | 8.8 | 1.6 |
| Mayapis | 0.0 | 2.6 | 9.1 | 1.7 |
| Falcata | 0.1 | 3.8 | 17.5 | 3.1 |
| Mahogany | 0.2 | 3.6 | 9.7 | 1.7 |
| Competition from Narra | 0.0 | 1.8 | 21.2 | 3.3 |
| Competition from Mayapis | 0.0 | 0.8 | 16.2 | 2.1 |
| Competition from Falcata | 0.0 | 3.9 | 29.1 | 5.8 |
| Competition from Mahogany | 0.0 | 2.5 | 22.6 | 4.4 |
| Total competition (Hegyi index, per tree) | 0.0 | 9.0 | 63.7 | 10.7 |
| Number of same-species neighbours | 0 | 5 | 8 | 2.4 |
| Number of species in 8-tree neighbourhood | 1 | 1.9 | 4 | 0.9 |
| Inter-row spacing (m) | 0.6 | 3.0 | 7.5 | |
| Growing space (m$^2$) | 0.5 | 11.1 | 56.3 | 11.9 |

## Analysis

This experiment sought to reveal growth patterns in stands planted with different proportions of species, and at different spacings. These clinal plots (Fig. 3) involve a wide range of spacing and mixing, so the resulting data is diverse. Conventional graphs exploring trends between stem diameter and these various treatments are interesting (Fig. 4), but are hard to interpret because of the many factors involved, and the inability to reflect the dynamic situation experienced by each tree (e.g., competition changes continually as neighbours grow or die). Figure 4 correctly shows that Mahogany thrives in monoculture (Fig. 4a and b), and that Narra performs better in mixed plantings at close spacings (Fig. 4b and c), but it fails to expose other important growth trends revealed by a more thorough analysis. Thus it is instructive to examine relative diameter increment rather than diameter, and to estimate competition at the individual tree level rather than with plot level proxies (such as spacing).

Diameter increment in young stands is typically heteroscedastic, with small trees exhibiting small increments and larger trees having large increments. A robust approach to minimize this issue is to use the relative diameter increment, and in the

**Fig. 2** Google Earth image of the trial plots (4 July 2011). Differences in treatments (spacing, composition) and crown characteristics are evident
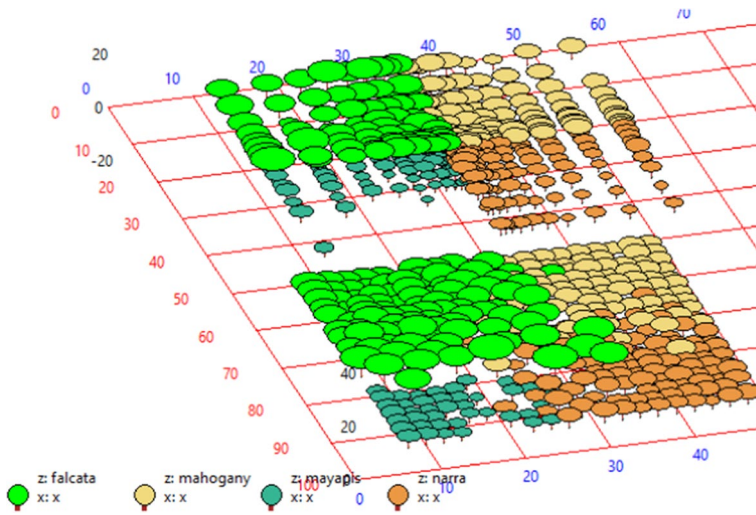


**Fig. 3** Diagram of the trial, viewed from the south and looking northwards (for comparison with Fig. 2), with the variable spacing plot at the top, and the variable composition plot at the bottom. Symbol size reflects dbh of the trees at age 3 (in 2010)
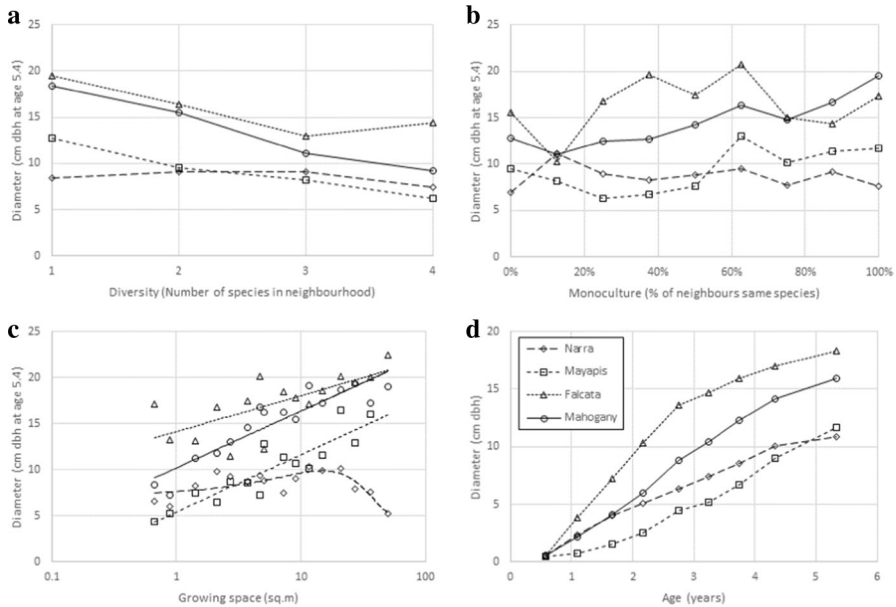
**Fig. 4** Growth trends evident from examining raw data, showing final diameter (cm at age 5.4 years) versus (**4a**, top left) species diversity (number of species in 8-tree neighbourhood); (**4b**, top right) the number of same-species neighbours; (**4c**, bottom left) the nominal growing space, and (**4d**, bottom right) the growth trend with age

present study the transformation increment/(diameter)$^{0.5}$ was chosen to achieve the usual statistical requirements for independent identical distribution of residuals.

In forest modelling, there is a long tradition of using a modifier function to reduce potential growth to account for suboptimal conditions (e.g., Botkin et al. 1972; Ek and Monserud 1974), but this approach requires an independent estimate of the potential growth, unavailable in the current study. A more flexible approach used in the present study is to estimate growth (e.g., diameter increment) directly from tree characteristics (e.g., species, size) and competition: $\Delta D = f$(size, competition). This approach deals with the two contrasts involved, the trees size (e.g., dbh) representing the ability to capture resources (sunlight, water, nutrients), and competition representing the risk that a tree is denied these resources. Ideally, this competition should be represented as a single variable, to facilitate comparisons between species.

The competition neighbourhood was calculated following Vanclay (2006b), using a search radius of $40 \times D$ and estimating competition following Hegyi (1974) as $\Sigma_i\{(d_i/d_j)/D_{ij}\}^{0.5}$ for all $D_{ij} < 0.4(d_i + d_j)$ where $D_{ij}$ is the distance between trees $i$ and $j$, $d$ is their observed tree diameter (cm), calculated as a partial sum for each species combination of all perpetrators $i$ seen by victim $j$. Previous studies (Vanclay et al. 2013) have shown that this competition index can exhibit a simple linear relationship with diameter increment, and this same linear trend is evident in the present data (Fig. 5).

Preliminary investigation of the untransformed data revealed that the relationship between increment and competition departed from the ideal linear relationship, so
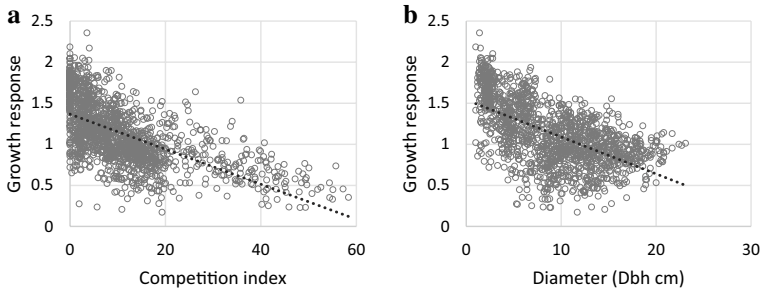
**Fig. 5** Linear trends between mahogany (S. macrophylla) growth response (square root of the relative increment, (increment/diameter$^{0.5}$)$^{0.5}$) and competition (**5a**, left) and diameter (**5b**, right). The dotted line is not the final model (Eq. 1), but a simple trendline prepared as preliminary data exploration

graphical analyses (Becker and Cleveland 1987; Cook and Weisberg 1999) were central to this analysis, assisting the search to find a suitable transformation to express competition as a single variable for each species. Inspection revealed that a variant of relative growth ($\Delta D/D^{0.5}$) resulted in a relatively linear relationship with competition for each of the four species (Fig. 5). A Box-Cox (1964) analysis indicated that a square-root transformation was required to stabilize variance, so subsequent analyses focused on the relationship $(\Delta D/D^{0.5})^{0.5} = f$(species, size, competition):

$$(\Delta D/D^{0.5})^{0.5} = \alpha_i + \gamma_i D + \beta_{ij} C_j \qquad (1)$$

where $D$ is tree diameter (dbhob, cm), $C_j$ is competition caused by species j, and α, γ, β are parameters to be estimated. The parameter estimates are given in Table 2, and the Analysis of Variance is given in Table 3. The large influence of Falcata, both in the slope of the relationships (Table 2), and in the proportion of the variance explained (Table 3), is noteworthy.

Table 3 presents an analysis of variance for Eq. 1 and the parameters in Table 2, using partial (Type III) sums of squares so that the contribution of each term to the final model is evident (Hector et al. 2010). Because these data are partially collinear, the partial sum of squares do not sum to the regression sum of squares, and the discrepancy gives an indication of the modest collinearity in the data (Table 3). Collinearity can also be assessed with variance inflation factors (VIF) – VIFs for variables

**Table 2** Parameter estimates for Eq. 1

| Species | Intercept $\alpha_i$ | Diameter $\gamma_i$ | Competition caused by $\beta_i$ | | | |
|---|---|---|---|---|---|---|
| | | | Mayapis | Narra | Mahogany | Falcata |
| Mayapis | 1.2835*** | − 0.00779* | − 0.00982ns | + 0.01364ns | − 0.01744ns | + 0.04766*** |
| Narra | 1.1374*** | − 0.01185*** | − 0.01535*** | − 0.02730*** | − 0.00709ns | + 0.00908ns |
| Mahogany | 1.5907*** | − 0.03541*** | − 0.00098ns | − 0.00690** | − 0.00748*** | − 0.01291*** |
| Falcata | 1.8174*** | − 0.02786*** | − 0.01172*** | − 0.01464*** | − 0.02716*** | − 0.05037*** |

Superscript indicates ns > 0.05, * < 0.05, ** < 0.01, *** < 0.001

**Table 3** Analysis of variance for fit displayed in Table 2

| Source | df | Partial SS | MS | F | P-value |
|---|---|---|---|---|---|
| Regression | 23 | 440.70 | 19.161 | 185.2 | <0.001 |
| Spp | 3 | 88.32 | 29.441 | 276.7 | <0.001 |
| Spp*Dbh | 4 | 77.52 | 19.381 | 182.2 | <0.001 |
| Spp*$C_{mayapis}$ | 4 | 8.39 | 2.097 | 19.7 | <0.001 |
| Spp*$C_{narra}$ | 4 | 12.61 | 3.152 | 29.6 | <0.001 |
| Spp*$C_{mahogany}$ | 4 | 3.45 | 0.863 | 8.1 | <0.001 |
| Spp*$C_{falcata}$ | 4 | 114.48 | 28.620 | 269.0 | <0.001 |
| (collinearity) | – | 135.93 | | | |
| Residual | 5458 | 564.68 | 0.103 | | |
| Lack of fit | 4881 | 484.80 | 0.099 | 0.7 | 1.000 |
| Pure Error | 577 | 79.88 | 0.138 | | |
| Total | 5481 | 1005.38 | | | |

Spp*Dbh indicates that a separate parameter is estimated for each species (i.e., the slope of the growth-size trend can vary by species). Spp*$C_{falcata}$ is the competition caused by Falcata, with different estimates for each of the 4 victims

in Table 3 range between 1.1 and 3.9, well within the range considered non-problematic ($1 < VIF < 5$, Shrestha 2020). Serial correlation is also minimal (Durbin-Watson $DW = 1.89$), well within the accepted range.

Figure 6 illustrates the growth pattern implied by this relationship with typical levels of competition. This relationship (Eq. 1) is consistent with several classic growth equations (e.g., Von Bertalanffy 1949; Zeide 1993), but requires fewer
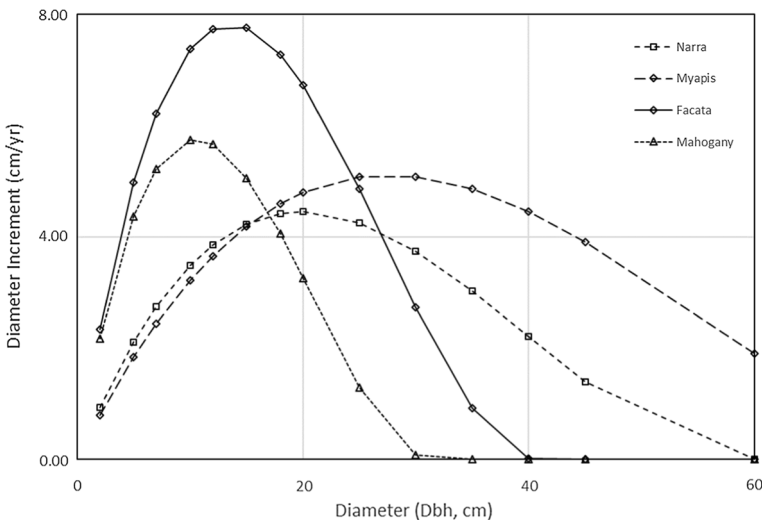


**Fig. 6** Pattern of diameter increment (dbh, cm/yr) implied by Eq. 1, with competition selected to illustrate the 90th-percentile of observed growth

parameters, and is thus convenient given the limited age range (0–6 years) of the present data. However, with Eq. 1, the shape of the curve (and hence the maximum diameter) is influenced by solely by the diameter coefficient ($\gamma_i$), whilst the height of the curve (i.e., the growth rate is influenced by the competition ($\beta_{ij}$).

In Fig. 6, it is evident that the maximum attainable diameter of Mahogany and Falcata (45 and 65 cm dbh respectively) are underestimated, a result of the simple equation (Eq. 1). However, these theoretical maxima are well beyond the range of the data used in this study (Table 1). This analysis was not aimed at providing a diameter increment function or at determining the maximum diameter, and these estimates simply arise from examining the adequacy of Eq. 1 and its fit to the data. Equation 1 was aimed at revealing competition effects presented in Tables 1 and 2, and the implications revealed in Fig. 6 simply examine possible shortcomings of the experimental design and analysis.

## Results

Competition may be viewed as an interaction between a perpetrator and victim, and Table 4 summarizes (from Table 2) such a view for each of our four species. Entries have been rounded deliberately to one significant digit to focus attention on major trends rather than minutiae, as response to competition may vary with environmental conditions (such as site and weather). Grey text indicates estimates that may be unreliable due to the small number of adjacencies between these species (and are not significantly different $P > 0.05$ from zero or from the overall response). Note that a positive entry in Table 4 does not necessarily imply a direct benefit by the perpetrator – there may be an indirect benefit such as shade, or suppression of grass (or other unquantified competition).

In Table 4, the rightmost column indicates the expected trend (across all competing species) in which increasing competition reduces relative growth, but the bottom row reveals that Mayapis (*S. palosapis*) is not only benign, but may assist the growth of neighbouring individuals (+3, $P < 0.001$, bottom row). Falcata (*P. falcataria*) is noteworthy as it is not only a strong competitor (−2, $P < 0.001$, rightmost column), but is also strongly impacted by competition (−3, $P < 0.001$, bottom row), and has antagonistic intraspecific competition (−5, P < 0.001). Mayapis (*S. palosapis*) is a contrast, with a high tolerance for competition (−1, $P < 0.001$, rightmost column),

**Table 4** The slope of the growth-versus-competition trendline

| Victim | Cause of competition (i.e., perpetrator) | | | | All perpetrators |
| | Mayapis | Narra | Mahogany | Falcata | |
|---|---|---|---|---|---|
| Mayapis | -1 | +1 | -2 | +5 | -1 |
| Narra | -2 | -3 | -1 | +1 | -1 |
| Mahogany | 0 | -1 | -1 | -1 | -2 |
| Falcata | -1 | -1 | -3 | -5 | -2 |
| All victims | +3 | -2 | -1 | -3 | -2 |

The most aggressive interactions are highlighted in yellow; the most benign in green, and potential polyculture candidates are highlighted in blue

and a tendency to stimulate the growth of its neighbours ($+3$, $P < 0.001$, bottom row), and exhibiting modest intraspecific competition in monocultures (-1, ns). Mayapis appears to benefit from Falcata ($+5$, $P < 0.001$), perhaps due to beneficial shading (Gregorio et al. 2012). It would appear that Falcata is best suited as a solitary tree in a field or village, whereas Mayapis (*S. palosapis*) seems well suited to plantations, both monoculture and mixed plantings. Of the four species, Mahogany (*S. macrophylla*) appears to be the preferred monoculture species as it has the lowest intraspecific competition ($-1$, $P = 0.001$).

Narra (*P. indicus*) would appear to be an ideal polyculture species, as Table 2 reveals Narra to be tolerant of competition (the horizontal row in Table 4 has small or positive numbers), and to exhibit little impact on neighbours (the vertical column has small numbers). Table 2 suggests that combinations of Narra and Mayapis (*S. palosapis*), or Narra and Falcata (*P. falcataria*) could be successful. There is a hint that Narra may benefit Mayapis ($+1$, $P = 0.2$), and some evidence that Narra is benign towards Falcata (-1, $P = 0.01$). Even if direct benefit remains unconfirmed, an 'invisible' neighbour is preferable to a competitor, and indicates potential for a polyculture.

## Discussion

Several measures can be used to compare growth performance: diameter, height, volume or biomass can all be used, and all have merits. In this study, diameter increment is preferred, as diameter is the most direct, accessible and reliable measure of tree size, and because the use of increment (rather than diameter) avoids serial correlation (Vanclay 1994) and thus better satisfies conventional statistical assumptions.

Linear regression was used to estimate the slope of the relationship between modelled competition and observed relative increment. Our analysis draws entirely on diameter (at 1.3 m breast height, over bark) and competition index because these are well-established as major determinants of stand performance (Potvin and Dutilleul 2009; Forrester et al. 2017), and were empirically identified in our data as the major determinants of stand development. We relied on a linear model of increment versus size and competition to focus attention on competition, noting that this explained a large proportion of the variance ($r = 0.66$, $P < 0.001$), and that trends remained consistent when alternative models were examined. The use of relative growth rather than tree size as the dependent variable minimizes serial correlation, which is not problematic in this analysis (Durbin Watson statistic 1.89, ns).

Whilst Typhoon Yolanda/Haiyan caused complete defoliation and some destruction of this trial (Fig. 7), most trees have recovered surprisingly well (Fig. 8, in 2017, 4 years after the typhoon). This trial was intended primarily to reveal aspects of interspecific competition in mixed plantings, but it also contributed other interesting observations on the performance of these species. The trial demonstrated considerable differences in crown architecture, stem straightness and other species traits, as well as in understorey vegetation (Fig. 9) and in wind firmness (Fig. 7). This paper addresses a statistical analysis of competition, but the role of visual impressions gained from field visits should not be

**Fig. 7** Variable spacing trial, ten days after the eye of Typhoon Haiyan passed directly over the plot, showing the complete defoliation of all species, and stem breakage of many Falcata trees (left). Mayapis trees are defoliated but unbroken (right front)



**Fig. 8** Good recovery of the trees in the trial in 2017 – foreground shows pure Mahogany (*S. macrophylla*) in the variable composition plot; background shows the variable spacing plot

underestimated, especially for extension workers and smallholders. Figures 9 and 10 give an indication of stand structure and stem characteristics, but a walk through these plots is a memorable discussion-starter for most visitors, and the role of such demonstration plots should not be understated.

Our results make few assumptions other than the well-established presumption that competition should reduce growth (Assmann 1961). Thus it is useful

**Fig. 9** The variable spacing plot at 5 years old (July 2012) showing differences in stem characteristics. Falcata (*P. falcataria*) is in the foreground, with Mahogany (*S. macrophylla*) to the left rear and Mayapis (*S. palosapis*) in the right rear. Note differences in stem form, branching habit, understorey vegetation
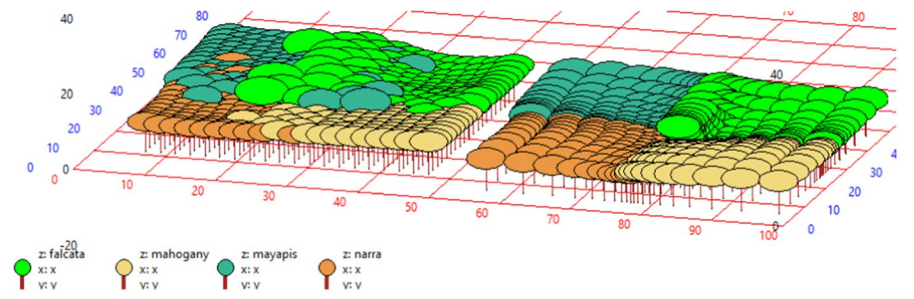


**Fig. 10** Prediction of stand development at age 10 (assuming no mortality). Species-specific responses to competition are evident

to compare our empirical finding with published observations of these species (Table 5), which tend to be consistent with the empirical data presented in Table 4.

The relationship fitted to our data (Eq. 1, Table 2) was intended to reveal competition trends, not to make predictions, but a prediction offers a demanding test of the equation, particularly as it was derived from annualized estimates based on observations over a period less than 5 years (7/2008 to 4/2013). Figure 10 represents such a prediction for what the stand may have looked like at age 10, assuming that all seedlings were 1 cm diameter at planting, and that all survived and avoided breakage. Typhoon damage to the field site means that this prediction cannot be formally tested, but the prediction seems plausible, and appears consistent with casual field observations (Fig. 8).

**Table 5** Species characteristics ascertained from published literature

| | Falcata *Paraserianthes falcataria* | Mahogany *Swietenia macrophylla* | Narra *Pterocarpus indicus* | Mayapis *Shorea palosapis* |
|---|---|---|---|---|
| Niche | Pioneer (Krisnawati et al. 2011a, b; Otsamo et al. 1997) | Light-demanding climax (Whitmore 1998); Pioneer (Snook and Negreros-Castillo 2004) | Pioneer (Lok 2011) | Climax (Swaine and Whitmore 1988) |
| Exotic/Native | Exotic | Exotic | Native | Native |
| Planted/ Regenerated | Widely planted (Krisnawati et al. 2011a, b) | Widely planted (Krisnawati et al. 2011b) | Widely planted (Lok 2011) | Potential for plantations (Bullecer and Socorin 2013) |
| Establishment | Light-demanding (Otsamo et al. 1996) | Light demanding (Brown et al. 2003) | Adaptable (Thompson 2006) | Shade needed (Gregorio et al. 2012) |
| Growth rate | Rapid (Krisnawati et al. 2011a) | Rapid (Krisnawati et al. 2011b) | Rapid (Thompson 2006) | Rapid (Bullecer and Socorin 2013) |
| Weed suppression | Casts light shade (Krisnawati et al. 2011a) | – | Casts heavy shade (Thompson 2006) | – |
| Use as nurse crop | Suitable (Kamo et al. 2009; Lok 2011) | – | – | – |
| Weed potential | Invasive (Hughes et al. 2011) | – | – | – |
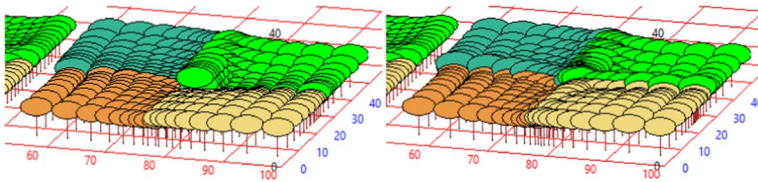
**Fig. 11** Prediction of tree diameters at age 10, without (left) and with (right) thinning at age 5 of two rows in the variable spacing plot. Note the difference in tree size where different species (different colours) are adjacent. The anticipated response to thinning is evident, but cannot be tested in the current trial

At the final measure in 2013, the plots exhibited a moderate correlation ($r = -0.29$) between tree size and competition. This is not surprising, as it is expected that the trees with the least competition will grow to be the largest, whilst those with the most competition grow more slowly, especially in the variable spacing plot. However, this correlation can be reduced easily by modest thinning in the variable spacing plot. Simulations show that the removal of two rows (9 and 12, near the centre of the 20-row plot) and two columns restores orthogonality (correlation $r = -0.03$). There is little benefit in further thinning, as the most effective additional option (removal of rows 5 and 15) provides modest improvement ($r = -0.01$). However, the correlation between diameter and competition of Falcata stems remains rather high ($r = -0.39$) and some additional thinning in row 8 may have improved predictions for Falcata ($r = -0.19$). Had the trial not suffered typhoon damage, it would have been desirable to thin rows 9 and 12 of the variable spacing plot to provide greater insights into tree growth, both for statistical efficiency and for demonstration purposes (Fig. 11).

## Conclusions

Our findings suggest that contrary to some published findings (e.g., Chamagne et al. 2017), the implications for tree growth of species diversity are not uniformly beneficial and are context dependent. It is clear from our findings that species vary widely in their interactions with potential competitors.

Mayapis (*S. palosapis*) is a premium species that exhibits growth trends desirable in polycultures and is recommended as a candidate for further plantation establishment and reforestation efforts in the Philippines.

This experiment design proved to be an efficient way to test species interactions of four species and gain insights into competitive interactions within five years of planting. The design provided a strong visual impression, well-suited for agroforestry extension (e.g., open days).

It is recommended that in any future plantings with this or related experimental designs, the correlation between tree size and competition be monitored, and that a modest thinning (such as Fig. 11) be considered when this correlation becomes high. This will enable stronger inferences about future growth patterns.

## Declarations

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