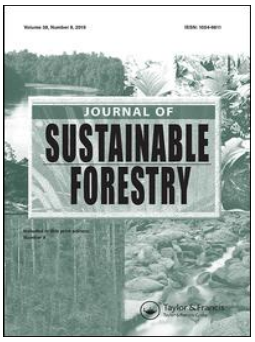

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A Comparison of Growth, Structure and Diversity of Mixed Species and Monoculture Reforestation Systems in the Philippines

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ABSTRACT

Forests in the Philippines, and many other developing countries in the tropics, have been extensively cleared over recent decades. There have been increasing efforts to reforest these cleared lands to achieve both socio-economic and environmental objectives. To date, planted forests have been dominated by monocultures. There has however been increasing calls to use mixtures of species, although there is limited evidence to support mixed-species plantations being a better or win-win approach to reforestation. To address this, we compared the tree growth, forest structure, and tree species diversity performance of monoculture and mixed-species tree plantations across 168 sites (251 survey plots) on Leyte Island, the Philippines. Our results indicate 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. Our results suggest that mixtures of exotic or native species can provide benefits over monoculture plantations. Mixtures of productive exotic species are most suited to situations where the production function of the forest is most important, while mixtures of native species are most suited to situations where the biodiversity function of the forest is most important.

KEYWORDS

Forest plantations; forest growth; forest structure; forest diversity; forest restoration; reforestation types

Introduction

Over the last century, tropical forests have been cleared at rapid rates with 350 million ha deforested and a further 500 million ha degraded (ITTO, 2002). For example, the Philippines has experienced extensive deforestation over recent decades and up to 59% (9.3 million ha) of the country's official forest lands are not forested at present, being either grassland, shrubland, or under cultivation (Chokkalingam et al., 2006). The rapid loss of tropical forests has resulted in the loss of biodiversity and serious environmental, social, and economic impacts because of the reliance of local populations on forest products and ecosystem services provided by forests (Dudley et al., 2005). To address these negative impacts, large-scale reforestation programs have been implemented across many developing countries, for example, the United Nations Billion Tree Campaign

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Supplemental data for this article can be accessed publisher's website.

(UNEP, 2012). The total tropical forest plantation area more than doubled in the period 1995–2005 (from 32.2 million ha to 67.5 million ha) with an average annual growth of 8.6% (FAO, 2006; STCP, 2009). The highest growth rate was in the Asia-Pacific region at 9.4% per year, and the slowest was in Latin America and the Caribbean at 4.3% per year (STCP, 2009). In the Philippines, the national government is currently investing heavily in the reforestation of denuded areas through the Philippine National Greening Program (NGP, 2011) and therefore requires information on the most appropriate reforestation approaches.

The most common way to reforest cleared areas where natural regeneration is no longer a viable option is to plant monocultures of fast-growing exotic species (Erskine et al., 2006; Evans & Turnbull, 2004; Kelty, 2006; Kanowski, 2018; Lamb et al., 2001; Lugo, 1997; Stephens & Wagner, 2007). The establishment of monocultures is driven largely by industry and governments to satisfy a growing demand for industrial wood products and dwindling supplies from natural forests (Cossalter & Pye-Smith, 2003; Powers, 1999; Sedjo, 1999; Verheyen et al., 2016). A principal advantage of monocultures over mixed-species forests is the ability to concentrate all site resources on the growth of a species with desirable characteristics (generally faster growth rates for the same wood quality), the simplicity of stand management, and product uniformity (Evans & Turnbull, 2004; Kelty, 2006; Siry et al., 2005).

Despite the extensive use and ease of establishment, there are many concerns regarding the continued expansion of monocultures due to their low species diversity (Carnevale & Montagnini, 2002; Kohli et al., 1996; Lamb, 1998; Stephens & Wagner, 2007), susceptibility to disturbances such as fire and pests (Jactel & Brockerhoff, 2007; Nichols et al., 1999; Riihimäki et al., 2005), low resource-use efficiency (Cannell, 1999; Dünisch et al., 2003; Evans, 1999; Khanna, 1997), and low level of product diversification (Lamb, 1998; Lamb et al., 2005; Odoom, 2002). Although overtime and depending on functional traits of the species planted and management strategies, even monocultures can recruit additional biodiversity from the seedbank or because of dispersal from the surrounding matrix (Firn et al., 2007).

Recent research has emphasized the potential advantages of mixed-species plantations (Erskine et al., 2006; Hartley, 2002; Hung et al., 2011; Lamb, 2011; Lamb et al., 2005; Nguyen et al., 2012; Piotto et al., 2010) and many authors are advocating their expansion (Erskine et al., 2006; Forrester et al., 2006; Kelty, 2006; Montagnini et al., 1995; Nichols et al., 2006; Piotto, 2008). Research has shown that when mixed-species plantations are appropriately designed, they offer a number of potential advantages, such as the potential to restore degraded areas by improving nutrient cycling and soil fertility (Binkley et al., 2003; Guariguata et al., 1995; Lamb, 1998; 2011; McNamara et al., 2006; Wormald, 1992), enhancing biodiversity (Butterfield & Malvido, 1992; Carnevale & Montagnini, 2002; Hartley, 2002; Stephens & Wagner, 2007), higher stand productivity (Debell et al., 1997; Erskine et al., 2006; Forrester et al., 2006; 2007; Lamb, 2011; Parrotta & Knowles, 1999; Potvin & Gotelli, 2008; Richards et al., 2010), and better resistance to pests and diseases (Hung et al., 2011; Jactel & Brockerhoff, 2007; Kaitaniemi et al., 2007; Lamb, 2011; Montagnini et al., 1995; Riihimäki et al., 2005). In addition, mixed-species plantations may achieve high product diversification (Erskine et al., 2006; Lamb, 2011; Lamb et al., 2005; Liu et al., 2018; Nguyen et al., 2018; Oliveira et al., 2018; Vanclay, 2006; Verheyen et al., 2016).

Despite the respective benefits and drawbacks of monocultures and mixed-species plantations, few studies have compared the performance of different reforestation strategies. Here we compare three approaches of planted forest reforestation used within the Philippines, namely monoculture plantations, mixed introduced species plantations, and mixed native species plantations. For each reforestation approach, we measured the growth performance, structure, and tree species diversity (as all plantations types have recruited additional understory tree species and in the case of the older plantations even overstory species) in order to assess the relative ability of each approach to provide the joint benefits of timber production and biodiversity conservation. The results of the study can provide the basis for selecting appropriate reforestation approaches to achieve objectives of sustainable forest management in the study area in particular and in tropical developing countries in general.

Methods

Study region

The study was conducted on Leyte Island (Figure 1), which is the eighth largest island in the Philippines (Wernstedt & Spencer, 1967), with a total land area of 750,000 ha (Groetschel, 2001). Leyte Island is located in the Eastern Visayas region (Region 8), at about 9°55′ N–11°48′ N latitude and 124°17′ E–125°18′ E longitude, covering a latitudinal range of 214 km from north to south (Langenberger et al., 2006). The average annual precipitation is relatively high, at about 2900 mm (Kucharski, 2010). The island regularly experiences typhoons with winds that sometimes reach more than 100 km/hr. (Dargantes, 1996).

As in most parts of the Philippines, forests were the major natural resource on Leyte with estimated forest cover of 70% in the early 1900s (Agoncillo et al., 2011). Large-scale logging operations and conversion of forest into agriculture, however, have resulted in a massive decline of forest cover (Groetschel, 2001). Records show that the island had a forest cover of about 42% in 1939, and by 1987 the cover had been reduced to 12%, a loss of around 240,000 ha of forest (Dargantes, 1996). In 1994 only 2% of the island's area remained under primary forest (Dargantes & Koch, 1994). More recent data show that about 40% of the land area of Leyte is now covered by grassland and barren land, resulting from abandoned cultivation and grazing land that lost productivity through erosion and nutrient leaching (DENR, 1998). About 40% of the island's area is under coconut plantations. The remaining area is composed of settlements, agricultural land, and forest.

Study data set

The reforestation approaches examined in this study were exotic monoculture plantations (MONO), mixed introduced species plantations (MIS), and mixed native species plantations (MNS), which are the most commonly practiced forms of reforestation on former forest land on Leyte Island. Mixed-species plantations are often established using two or more species on the same area, coexisting at any developmental stage and sharing common resources (light, water, and/or soil nutrients) (Bravo-Oviedo et al., 2014; Nguyen et al., 2014). Mixed plantings of native species are a relatively new type of

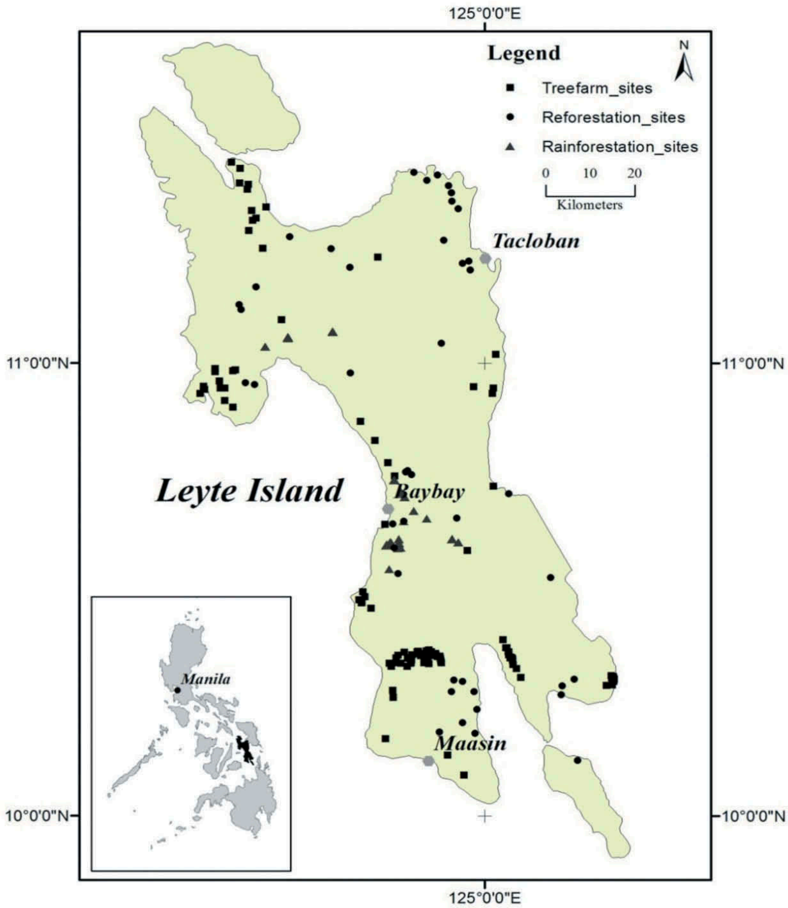

Figure 1. Study location (Leyte and Southern Leyte provinces, the Philippines). Source: Adapted from Herbohn et al. (2014).

plantation system in the Philippines and at the time that the study was undertaken no MNS plantings older than 20 yr could be located on Leyte Island, which contributed to an imbalance between the number of plots sampled in each forest type and ages. The MONO and MIS plantations contained exotic species commonly planted in the Philippines because they are fast growing and germplasm is available (Gmelina (*Gmelina arborea*), Mahogany (*Swietenia macrophylla*), Acacia (mostly *Acacia mangium* and *Acacia auriculiformis*), Teak (*Tectona grandis*)) (Chokkalingam et al., 2006; Tolentino, 2008). The MIS plantations typically comprised of mixtures of two or three exotic species. The MNS sites were all established under the 'Rainforestation' program (Margraf & Milan, 1996; Nguyen et al., 2012), and comprised of diverse assemblages of predominantly native species and fruit trees, with a small number of exotic species. The native species included in the rainforestation sites were a combination of fast-growing species which were established first and then underplanted with slower growing dipterocarp species and fruit trees about 1 yr later. From 7 to 40 species were planted at each site (see Table 1 for a list of species contained within the MONO, MIS, and MNS plantations).

Table 1. Species list for surveyed forest plots (MONO: Monoculture plantations; MIS: Mixed Introduced Species plantations; MNS: Mixed Native Species plantations).

Revegetation method	Species list
MONO	MONO plantations contained exotic species including Mangium (*Acacia mangium*) (n = 10), Gmelina (*Gmelina arborea*) (n = 123), and Mahogany (*Swietenia macrophylla*) (n = 64). Most of MONO plantations were on tree farms.
MIS	MIS plantations contained mixed exotic species, including Mangium (*Acacia mangium*), Gmelina (*Gmelina arborea*), Mahogany (*Swietenia macrophylla*), Teak (*Tectona grandis*), Auri (*Acacia auriculiformis*), Ipil-ipil (*Leucaena leucocephala Lam.*), and others. Most of MIS plantations were on tree farms and reforestation projects and included a mixture of at least two exotic species.
MNS	MNS plantations contained native species including Agoho (*Casuarina equisesetifolia*), Alagasi (*Leukosyke capitellata*), Almaciga (*Agathis philippinensis*), Anislag (*Securinega flexousa*), Antipolo (*Artocarpus blancoi*), Badbad (*Turpinia sp.*), Bagalunga (*Melia dubia*), Bagras (*Eucalyptus deglupta*), Bagtikan (*Parashorea malaanonan*), Banai-Banai (*Radermachera pinnata*), Banato (*Mallutus philippinensis*), Bitanghol (*Calophyllum blancoi*), Bunod (*Knema cf. korthalsii*), Dao (*Dracontomelon dao*), Kalumpit (*Terminalia microcarpa*), Mangkono (*Xanthostemon verdugonianus*), Mayapis (*Shorea palosapis*), Molave (*Vitex parviflora*), Nangka (*Artocarpus heterophylla*), Narra (*Pterocarpus indicus*), Paguringon (*Cratoxylum celebicum*), Rain tree (*Samanea saman*), Santol (*Sandoricum koetjape*), Saplongan (*Hopea plagata*), Tamayuan (*Strombosia philippinensis*), Tangile (*Shorea polysperma*), Tibig (*Ficus nota*), and others. Most of MNS plantations were on rainforestation farms.

Data were collected from randomly selected tree farms or private smallholder woodlots and reforestation projects and all accessible rainforestation sites (because of the small number available) (Table 2). A detailed description of the data collection process including site selection procedures and data collection methods is set out in Herbohn et al. (2014). In total, 168 sites were surveyed. Some sites had multiple discrete woodlots (e.g., blocks of different species or of different ages) resulting in a total of 251 plots being surveyed. These plots covered a range of ages (for details see Table 3) and for the analysis were classified into three age classes: 'young' (≤10 yr), 'middle-aged' (11–19 yr), and 'old' (≥20 yr) (for details, see Table 3).

A site of natural forest (NAFO), located within a similar range of environmental conditions as the reforested sites, was selected as a reference site. The natural forest site was located at the central foothill of Mt. Pangasugan, approximately 8 km north of Baybay, Leyte, Philippines (10°45′154″ N latitude and 124°48′588″ E latitude) and 174–224 m a.s.l. on a slope of about 33%. The site was within a reserved rainforest that forms part of a 594 ha range encompassing Mt. Pangasugan, one of the few remaining patches of pristine forests on Leyte Island. No recent logging has been observed within the site; however, rattan collection and hunting has occurred (Langenberger et al., 2006). Rattan palms belong to the genus Calamus and the stems are used to make wickerwork.

Table 2. Study data sources.

		Number of forest plots					
Data source	Number of sites	MONO	MIS	MNS	NAFO	Total	Survey year
Tree farms	107	179	7	0		186	2005–2006
Rainforestation farms	18	1	7	14		22	2005–2006
Reforestation projects	42	17	19	6		42	2010–2011
Natural forests	1				1[a]	1	2011–2012
Total	168	197	33	20	1	251	

[a]1 ha permanent plot containing 100 subplots (10 × 10 m).
MONO: Monoculture plantations; MIS: Mixed Introduced Species plantations; MNS: Mixed Native Species plantations; NAFO: Natural Forests.

Table 3. Age distribution of surveyed forest plots.

	Stand age (yr)					Stand age class			
Revegetation method	Min	Max	Mean	Median		Young (≤10 yr)	Middle-aged (11–19 yr)	Old (≥20 yr)	Total
MONO	5	31	12	11		77	102	18	197
MIS	7	30	15	15		8	18	7	33
MNS	6	15	10	10		15	5	0	20
NAFO								1	1
Overall	5	31	12	11	**Total**	100	125	26	251

MONO: Monoculture plantations; MIS: Mixed Introduced Species plantations; MNS: Mixed Native Species plantations; NAFO: Natural forest.

Data collection methods

We collected data from a circular plot located within the center of at least one forest block within each of the MONO, MIS, and MNS sites (for some sites, data were collected from only one plot, while for large plantations there were several forest blocks, so data were collected from several plots). Each circular plot had a 5 m radius; however, if a plot did not contain at least seven trees with a diameter at breast height (DBH) of at least 10 cm then the plot radius was extended to 10 m. For each plot, canopy cover (% projective foliage cover), understorey and ground cover (%), diameter at breast height (DBH cm) of all trees ≥5 cm DBH, total height (Ht m) of all trees ≥10 cm DBH, height of tallest tree (m), and tree species name and age of all trees were recorded. Projective foliage cover (PFC) was measured at the center of each plot using digital photos (Kanowski et al., 2008). Only vegetation >2 m above ground level was included in PFC measurements. Tree DBH was measured using a DBH tape, and tree heights were measured using a digital hypsometer (LaserAce 150 Hypsometer). Understorey, shrub, vine and scrambler, coarse woody debris, and litter cover were measured at three 1 × 1 m quadrats within each plot, located at the center of the plot and 4 m either side of the center along a transect.

Within the natural forest reference site, we collected data within a 1-ha (10,000 m^2) permanent plot that contained 100 subplots, each 100 m^2. The permanent plot was located at least 100 m from the edge of the Mt. Pangasugan rainforest reserve. DBH of trees ≥5 cm DBH, height of trees ≥10 cm DBH, height of tallest tree (m), and tree species name were recorded for all trees in all 100 m^2 subplots. Two opposing diagonal transects running through the center of the permanent plot were used to measure PFC, understorey, shrub, vine and scrambler, coarse woody debris, and litter cover. PFC was measured at the center of each 100 m^2 subplot along the diagonal transects using digital photos. Understorey, shrub, vine and scrambler, coarse woody debris, and litter cover were measured within one 1 m^2 quadrat located at the center of each 10 × 10 m subplot along the diagonal transects.

Data analysis methods

We calculated a number of indices to compare forest growth performance, forest structure, and tree species diversity between the different plantation types (see Table 4 for a description of the indices). These selected indices are based on the conceptual model for assessing reforestation success in tropical developing countries developed by Le et al. (2012). For MONO, MIS, and MNS, these indices were calculated for each circular plot

Table 4. Indices used to compare growth performance, forest structure, and tree species diversity of different plantation types.

Indicator	Derivation
Forest growth performance indices	
DBH (cm) of trees DBH ≥5 cm	Plot average DBH of trees with DBH ≥5 cm
Total height (m) of trees DBH ≥10 cm	Plot average total height of trees with DBH ≥10 cm
Basal area of trees DBH ≥5 cm (m^2/ha)	Cross-sectional area of trees, calculated from DBH of trees: BA (m^2 per ha) = $\Sigma\pi(DBH_i)^2/40000$, where DBH_i is the diameter (cm) of the ith tree with DBH ≥5 cm.
Total volume of trees DBH ≥10 cm (m^3/ha)	TV = $0.0509 \times DBH^2 \times Ht/1000$ (Chave et al., 2005) where TV: estimate total volume for live trees in cubic meters, DBH: the diameter at breast height in centimeters, Ht: the total height in meters of trees DBH≥10 cm.
Aboveground biomass of live trees DBH ≥ 10 cm (tonnes/ha)	AGB = $0.0509 \times \rho \times DBH^2 \times Ht/1000$ (Chave et al., 2005) where AGB: estimate aboveground biomass for live trees in tonnes, DBH: the diameter at breast height in centimeters, H: the total height in meters of trees DBH≥10 cm, ρ: wood density or wood gravity.
MAI DBH; MAI Total height; MAI basal area of trees DBH ≥5 cm (m^2/ha/yr); MAI Total volume of live trees DBH ≥10 cm (m^3/ha/yr); MAI AGB of live trees DBH ≥10 cm (tonnes/ha/yr)	Mean annual increments (MAI) of these variables were calculated by dividing the current values of DBH, Ht, BA, TV, AGB by the stand age.
Forest structure indices	
Density of trees DBH ≥5 cm and DBH ≥10 cm (number of stems/ha)	Number of tree stems per hectare were calculated
Woody stems (number of stems/ha)	Count of stems in two diameter classes (5–20, >20 cm DBH) and three height classes (2–10, 11–20, and >20 m) for each plot and calculate for hectare
Number of tree DBH strata present	Number of tree size classes represented by at least one stem. Size classes are 5–10, 10–20, 20–30, 30–40, 40–50, 50–75, >75 cm (i.e., maximum value = 7)
Tree size (DBH) diversity: Shannon index (Shannon, 1948)	An index of the DBH size-class distribution of trees. Values are higher when distributions are more evenly distributed across more size classes. Calculated as Shannon (H) index of proportion of trees in each dbh class: $H = -\Sigma p_i * \ln(p_i)$, where p_i is the proportion of stems in the ith size class
PFC or canopy cover (%)	Plot average PFC
Canopy height (m)	Height of tallest tree within plot
Understorey cover (index, 1–6)	Cover of grass, herbs and ferns classified as follows: 1: <1%; 2: 1–5%; 3: 5–25%; 4: 25–50%; 5: 50–75%; 6: >75%.
Shrub cover (index, 1–6)	Cover of woody vegetation <2.5 cm diameter (including seedlings) classified as follows: 1: <1%; 2: 1–5%; 3: 5–25%; 4: 25–50%; 5: 50–75%; 6: >75%.
Vine and scrambler cover (index, 1–6)	Cover of vines and multistemmed thorny shrubs (scramblers) classified as follows: 1: <1%; 2: 1–5%; 3: 5–25%; 4: 25–50%; 5: 50–75%; 6: >75%.
Coarse woody debris cover (index, 1–6)	Cover of woody debris >10 cm diameter within 1 m of the ground classified as follows: 1: <1%; 2: 1–5%; 3: 5–25%; 4: 25–50%; 5: 50–75%; 6: >75%.
Litter cover (index, 1–6)	Cover of leaf litter and fine woody debris (<10 cm diameter) within 1 m of the ground classified as follows: 1: <1%; 2: 1–5%; 3: 5–25%; 4: 25–50%; 5: 50–75%; 6: >75%.
Tree species diversity indices	
Simpson's Diversity Index for trees DBH ≥5 cm (0–1)	Simpson's Diversity Index is a measure of diversity (Simpson, 1949). In ecology, it is often used to quantify the biodiversity of a habitat. It takes into account the number of species present, as well as the abundance of each species.$D = 1 - \left(\frac{\sum^{n_i}(n_i - 1)}{N(N-1)}\right)$where D = diversity index, n_i = number of organisms of species i, N = total number of organisms of all species found. The value of D ranges between 0 and 1. With this index, 1 represents infinite diversity and 0, no diversity.
Species richness for trees DBH ≥5 cm	Number of different species per plot

and extrapolated for a hectare; however, for the natural forest reference site, these same indices were calculated for the entire 1-ha permanent plot (not for the subplots).

The indices were analyzed using mixed effects models developed in IBM SPSS Statistics 20 (2011) software. We modeled the indices as a function of revegetation method (MONO, MIS, MNS), and stand age class (≤10, 11–19, and ≥20 yr) (fixed effects) with a random effect structure of site. Prior to modeling, we used diagnostic plots and tests of normality (Kolmogorov–Smirnov test) to check if the indices of continuous variables satisfied the assumption of normality (Pinheiro & Bates, 2000). We found several indices were not normally distributed (DBH, basal area (BA), total volume (TV), aboveground biomass (AGB), mean annual increment (MAI) DBH, MAI Ht, MAI BA, MAI TV, MAI AGB and density of woody stems in the classes DBH ≥5 cm, DBH 5–20 cm, and Ht 2–10 m) and data were subsequently transformed into normal distributions. After transformation, we used a linear regression for the target distribution in the mixed effect models. For indices of ordinal variables (grass, herb, fern, litter, shrub, vine and scrambler, and coarse woody debris cover indices) we used a multinomial logistic regression for the target distribution and a cumulative logit link function in the mixed effects models. To compare the predictive power of the models with different fixed effects, we used information-theoretic model selection procedures (ΔAIC) (Burnham & Anderson, 2002) (for details, see Supplementary Tables S1 and S2).

We also conducted pair-wise comparisons (using Hochberg's GT2 test because the sample sizes for subgroups are very different) (Field, 2017) on the mixed effects models to identify statistically significant differences (level of rejecting the null hypothesis was fixed at $\alpha = 0.05$) in forest growth performance, forest structure, and tree species diversity between the three revegetation methods (MONO, MIS, MNS) across three age classes (≤10, 11–19, and ≥20 yr). Forest structure, tree species diversity, and some forest growth performance indices were also compared with the natural forest reference site.

Results

Forest growth performance

The combination of revegetation method and age class best explained the variation in Ht ($F_{7,202} = 2.78$, $P = .009$), BA ($F_{7,204} = 6.62$, $P = .000$), TV ($F_{7,205} = 6.03$, $P = .000$), AGB ($F_{7,206} = 6.74$, $P = .000$), and MAI Ht ($F_{7,199} = 48.58$, $P = .000$) (Table S2, Models 2.3, 3.3, 4.3, 5.3, 7.3). Age class alone best explained the variation in DBH ($F_{2,226} = 15.52$, $P = .000$), MAI DBH ($F_{2,234} = 54.12$, $P = .000$), and MAI BA ($F_{2,203} = 7.14$, $P = .001$) (Table S2, Models 1.2, 6.2, 8.2) while revegetation method alone best explained the variation in MAI TV ($F_{2,210} = 3.20$, $P = .043$) and MAI AGB ($F_{2,208} = 3.86$, $P = .023$) (Table S2, Models 9.1, 10.1).

Overall, the growth performance indices for MIS plantations were either similar to (i.e., not significantly different from) or significantly higher than MONO or MNS plantations across all age classes (Figure 2a-j). Young MONO plantations exhibited a significantly higher MAI Ht (Figure 2g) compared with MIS plantations. All growth performance indices for MNS plantations were never significantly higher than those for MONO or MIS plantations.

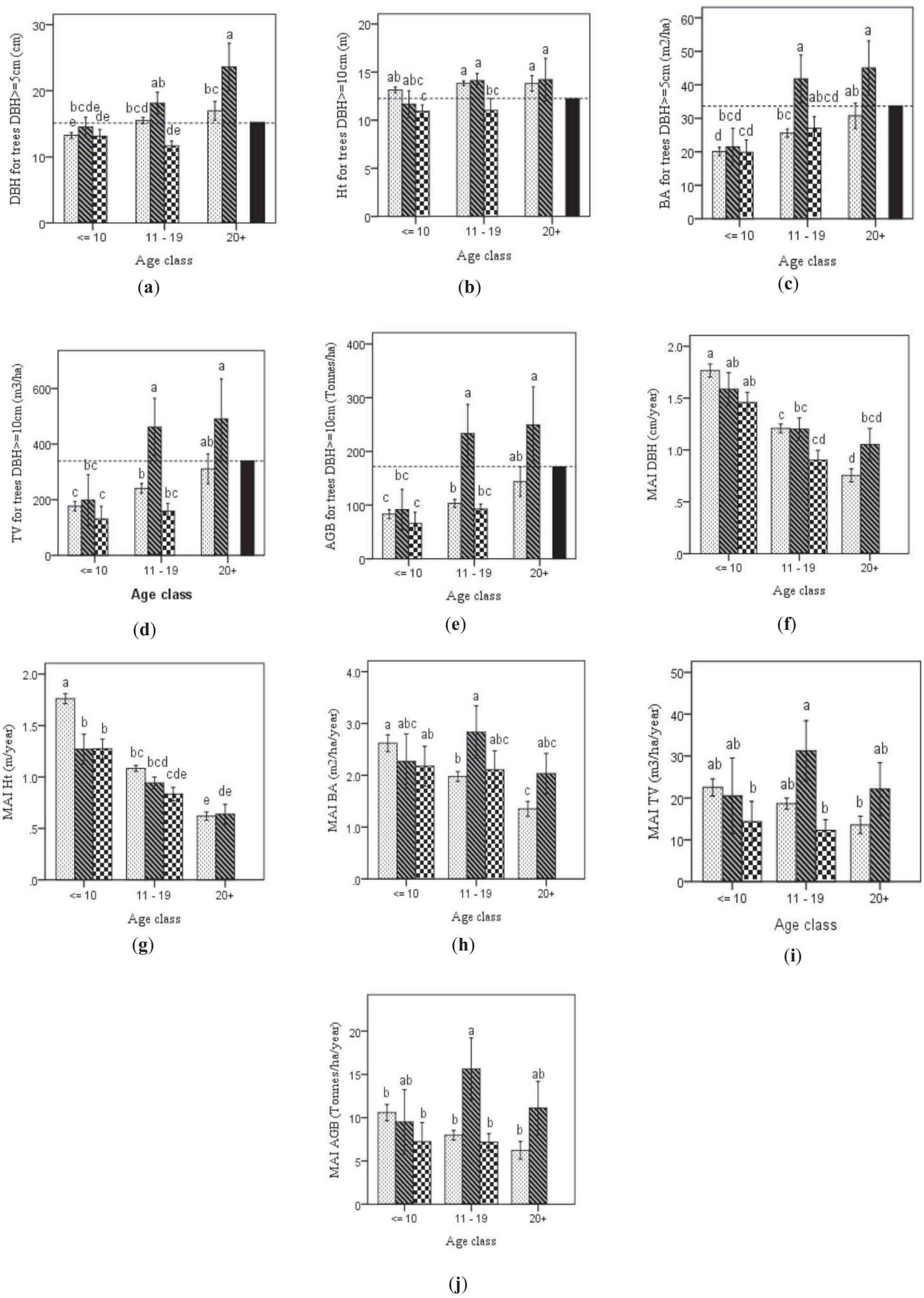

Figure 2. Forest growth performance (Mean, S.E.) for revegetation method by stand age class (= MONO (Monoculture plantations) = 197 Plots, = MIS (Mixed Introduced Species Plantations) = 33 plots, = MNS (Mixed Native Species Plantations) = 20 plots, ■ = NAFO (Natural forest) = 1 ha (100 subplots (10 ×10 m), ----- = NAFO reference line). Note: Significant differences in mean values between revegetation methods in each age class and between age classes in each revegetation method are indicated by different lowercase letters (Pair-wise comparisons are conducted to identify statistically significance differences at α = 0.05).

Middle-aged and old MIS plantations had a higher DBH, Ht, BA, TV, and AGB compared to natural forest (Figure 2a-e, Photos 1–4). MONO plantations achieved a greater height than natural forest across all age classes (Figure 2b). Only old MONO plantations had greater DBH than natural forest (Figure 2a). MNS plantations did not perform better than natural forest for any growth performance indices.

Photo 1. MIS plantation at age 13 in Leyte Island, the Philippines.

Photo 2. Mahogany monoculture plantation age 15 in Leyte island, the Philippines.

Photo 3. Mixed native species plantation at age 15 in Leyte island, the Philippines.

Photo 4. Natural forest at Mt. Pangasugan rainforest reserve, Leyte island, the Philippines.

Forest structure

Overstorey

Woody stems. The combination of revegetation method and age class best explained the variation in total woody stem density with DBH≥5 cm ($F_{7,205}$ = 2.03, *P* = .053) (Table S2, Model 11.3), DBH 5–20 cm ($F_{7,207}$ = 3.79, *P* = .001) (Table S2, Model 12.3), and DBH>20 cm ($F_{7,207}$ = 4.45, *P* = .000) (Table S2, Model 13.3); and with Ht 2–10 m ($F_{7,211}$ = 3.20, *P* = .003) (Table S2, Model 15.3), Ht 10–20 m ($F_{7,208}$ = 2.23, *P* = .033) (Table S2, Model 16.3), and Ht>20 m ($F_{7,211}$ = 1.84, *P* = .081) (Table S2, Model 17.3). Age class alone best explained the variation in the number of tree DBH strata present ($F_{2,203}$ = 10.03, *P* = .000) (Table S2, Model 18.2) and tree size DBH diversity ($F_{2,207}$ = 19.03, *P* = .000) (Table S2, Model 19.2). Variation in total woody stem density with DBH≥10 cm was not explained by either revegetation method or age class (Table S2, Model 14).

Overall, compared to MONO and MNS plantations, MIS plantations either had the same or significantly lower total woody stem density with DBH ≥ 5 cm (Figure 3a) and woody stem density with DBH 5–20 cm (Figure 3b) across all age classes. In contrast, MIS plantations either had similar or significantly higher woody stem density with DBH > 20 cm (Figure 3c) compared to MONO and MNS plantations across all age classes. Middle-aged MNS plantations had significantly higher total woody stem density with DBH ≥ 5 cm (Figure 3a) and DBH 5–20 cm (Figure 3b) compared to MONO and MIS plantations. Compared to natural forest, middle-aged MNS plantations had much higher woody stem density with DBH ≥ 5 cm (Figure 3a) and DBH 5–20 cm (Figure 3b), while middle-aged and old MIS plantations had much higher woody stem density with DBH > 20 cm (Figure 3c).

Overall, MIS plantations had similar or significantly higher woody stem density compared to MONO and MNS plantations with Ht 2–10 m (Figure 3e) and Ht >20 m (Figure 3g) across all age classes. Overall, MONO plantations had similar or significantly higher woody stem density compared to MIS and MNS plantations with Ht 10–20 m (Figure 3f). Natural forest had much higher woody stem density with Ht 2–10 m compared to all plantation types (Figure 3e). However, all plantation types had similar or higher woody stem density compared to natural forest with DBH≥10 cm (Figure 3d), Ht 10–20 m (Figure 3f) and Ht >20 m (Figure 3g), with the exception of MNS plantations, which had lower woody stem density with Ht >20 m (Figure 3g).

Overall, there were no significant differences in the number of DBH strata present (Figure 3h) or tree size DBH diversity (Figure 3i) among plantation types. Across age classes, only middle-aged and old MONO plantations had a significantly higher number of DBH strata present and significantly higher tree size DBH diversity compared to young MONO plantations (Figure 3h,i). All plantation types had a similar or lower number of DBH strata present and tree size DBH diversity compared to natural forest (Figure 3h,i).

Canopy cover, canopy height. The combination of revegetation method and age class best explained the variation in canopy cover ($F_{7,204}$ = 8.34, *P* = .001) and canopy height ($F_{7,204}$ = 2.59, *P* = .014) (Table S2, Models 20.3, 21.3). Overall, MIS and MNS plantations had the highest canopy cover across all stand age classes and canopy cover generally increased with stand age. This increase was significant between middle-aged or young

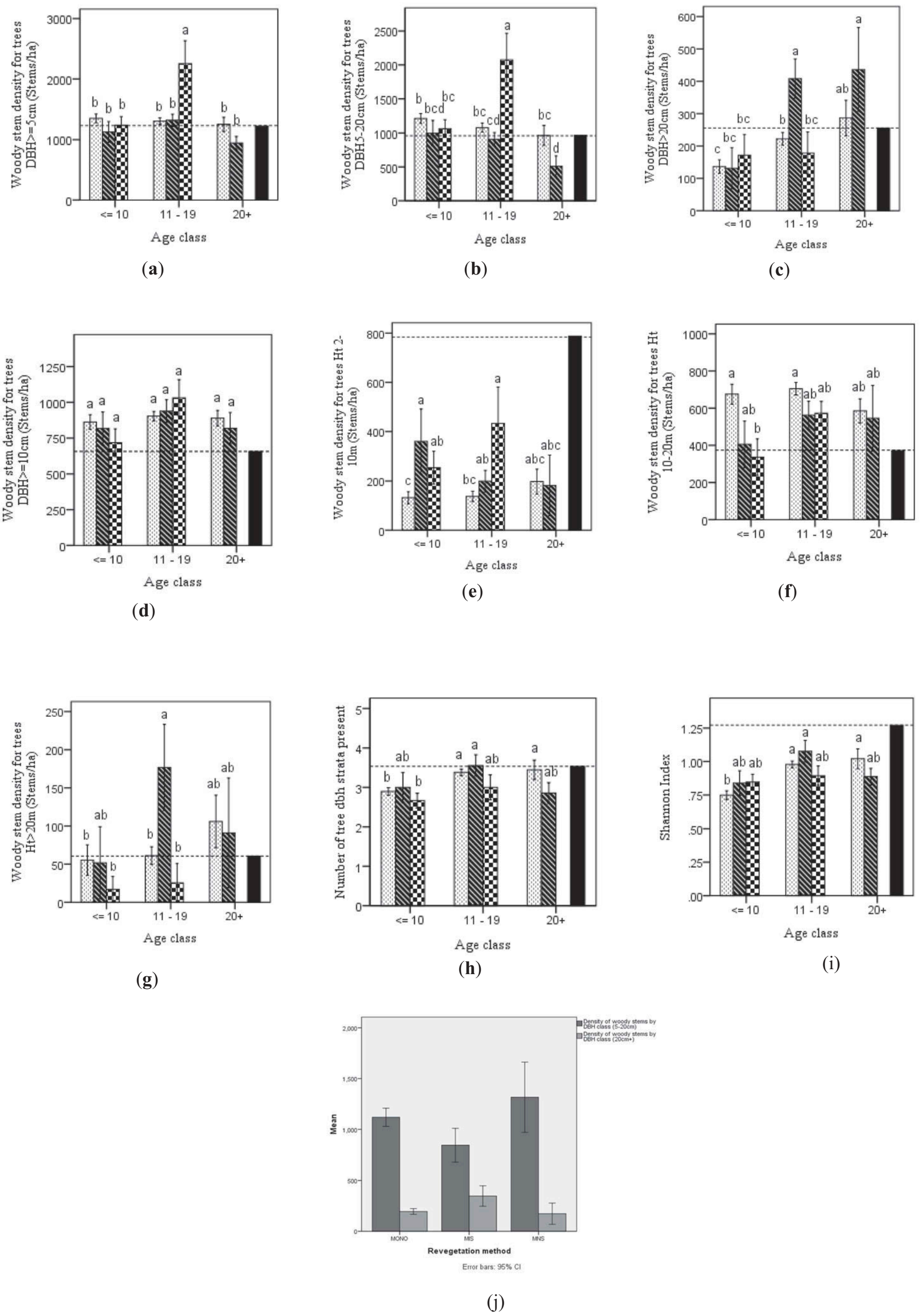

Figure 3. Density of woody stems, number of tree (DBH) strata present and Shannon index (Mean, S.E.) for revegetation method by stand age class (▩ = MONO (Monoculture plantations) = 197 plots, ▧ = MIS (Mixed introduced species plantations) = 33 plots, ▦ = MNS (Mixed native species plantations) = 20 plots, ■ = NAFO (Natural forest) = 1 ha (100 subplots (10 × 10 m), ----- = NAFO reference line). Note: Significant differences in mean values between revegetation methods in each age class and between age classes in each revegetation method are indicated by different lowercase letters (Pair-wise comparisons are conducted to identify statistically significance differences at α = 0.05).

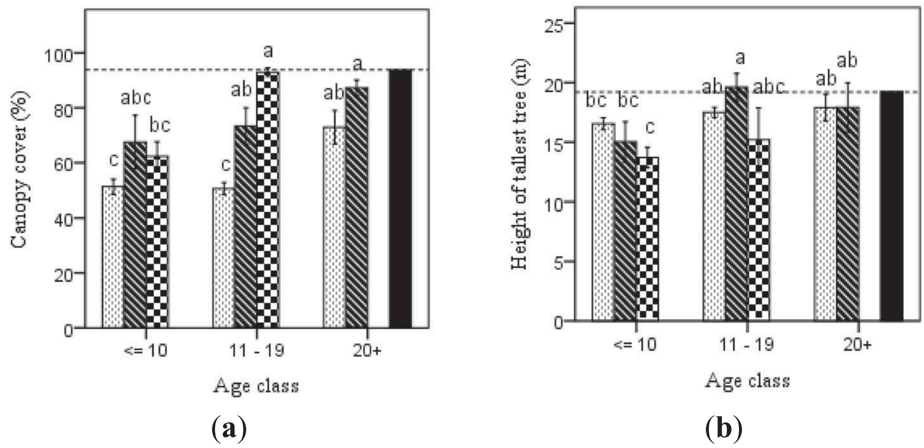

Figure 4. Canopy cover and canopy height (Mean, S.E.) for revegetation method by stand age class (▨ = MONO (Monoculture plantations) = 197 plots, ▧ = MIS (Mixed introduced species plantations) = 33 plots, ▩ = MNS (Mixed native species plantations) = 20 plots, ■ = NAFO (Natural forest) = 1 ha (100 subplots (10 × 10 m), ----- = NAFO reference line). Note: Significant differences in mean values between revegetation methods in each age class and between age classes in each revegetation method are indicated by different lowercase letters (Pair-wise comparisons are conducted to identify statistically significance differences at α = 0.05).

and old MONO plantations (Figure 4a), and between young and middle-aged MNS plantations (Figure 4a). For middle-aged plantations, the canopy cover of MIS and MNS plantations was significantly higher compared to that of MONO plantations (Figure 4a).

Overall, MIS and MNS plantations had the highest canopy cover across all stand age classes and canopy cover generally increased with stand age. This increase was significant between middle-aged or young and old MONO plantations (Figure 4a), and between young and middle-aged MNS plantations (Figure 4a). For middle-aged plantations, the canopy cover of MIS and MNS plantations was significantly higher compared to that of MONO plantations (Figure 4a).

Overall, there was no significant difference in the height of the tallest tree among all plantation types, across all age classes (Figure 4b). In general, the height of the tallest tree increased with stand age; however, this increase was only significant between young and middle-aged MIS plantations (Figure 4b).

Overall, natural forest had a higher canopy cover and height of tallest tree compared to all plantation types except for middle-aged MNS plantations, which had a similar canopy cover, and middle-aged MIS plantations, which has a similar height of tallest tree (Figure 4a,b).

Understorey cover

The variation in grass, herb, and fern cover was best explained by random effects alone (Table S2, Models 22, 23, 24) and not by either revegetation method or age class. Overall, there was no significant difference in herb cover or fern cover among plantation types (Figure 5b,c).

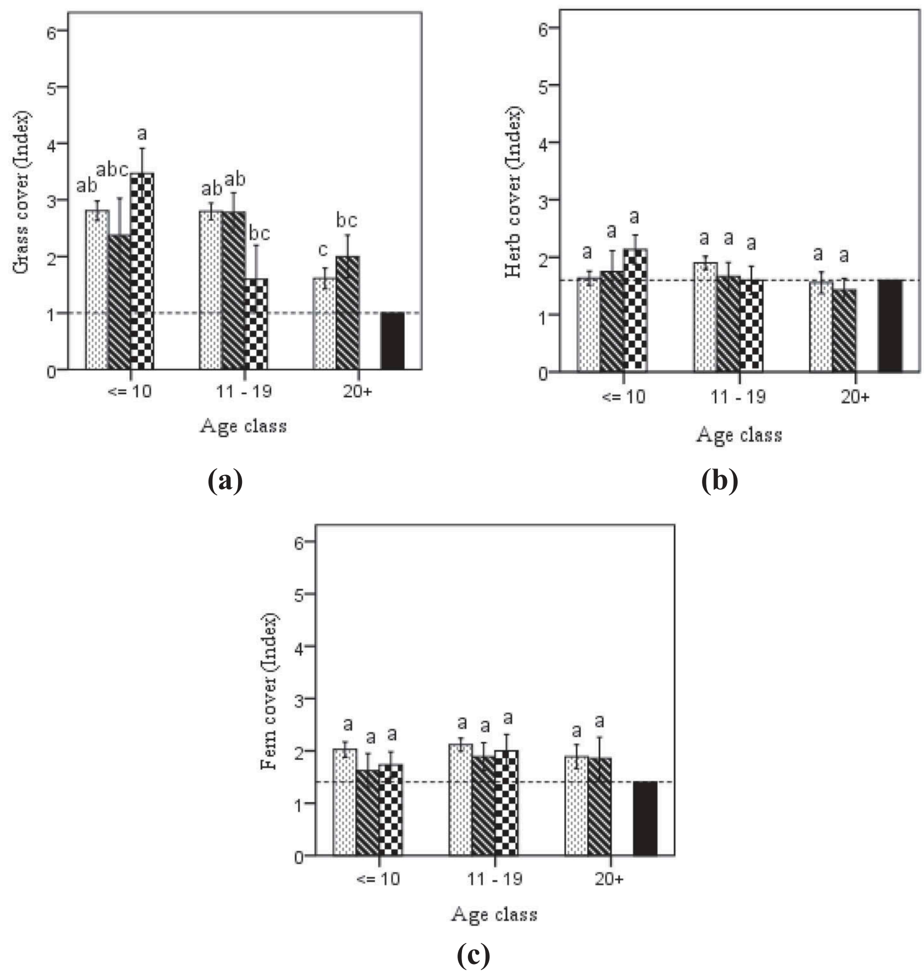

Figure 5. Understorey cover (Mean, S.E.) for revegetation method by stand age class (= MONO (Monoculture plantations) = 197 plots, = MIS (Mixed introduced species plantations) = 33 plots, = MNS (Mixed native species plantations) = 20 plots, = NAFO (Natural forest) = 1 ha (100 subplots (10 × 10 m), ----- = NAFO reference line). Note: Significant differences in mean values between revegetation methods in each age class and between age classes in each revegetation method are indicated by different lowercase letters (Pair-wise comparisons are conducted to identify statistically significance differences at α = 0.05).

Overall, there was no significant difference in herb cover or fern cover among plantation types (Figure 5b,c).

Old MONO plantations had a significantly lower grass cover compared to young and middle-aged MONO plantations (Figure 5a). Middle-aged MNS plantations had a significantly lower grass cover compared to young MNS plantations (Figure 5a). There was no significant difference in grass cover across age classes for MIS plantations (Figure 5a).

Grass cover of 250 surveyed plantation plots had a strong negative relationship with canopy cover (Significant Pearson correlation = – 0.33, $p < .01$). Stands with relatively open canopy (young plantations) typically had grassy understorey, while stands with a relatively closed canopy (old plantations) had less grass cover (Figure 5a).

Natural forest had a much lower grass cover compared to all plantation types across all age classes (Figure 5a). Herb and fern cover was greater than or similar to that of natural forest in all plantation types across all age classes (Figure 5b,c).

Ground cover AND Woody Debris

The variation in litter, vine and scrambler, and coarse woody debris cover was best explained by random effects alone (Table S2, Models 25, 27, and 28) and not by either revegetation method or age class. Age class alone best explained the variation in shrub cover ($F_{2,243} = 1.97$, $P = .142$) (Table S2, Model 26.2).

Overall, MONO plantations had similar or significantly higher shrub, vine and scrambler, and coarse woody debris cover than MIS and MNS plantations across all age classes (Figure 6b-d). Old MONO plantations had a significantly lower vine and scrambler cover compared to young and middle-aged MONO plantations, while old MIS plantations only had a significantly lower vine and scrambler cover compared to young MIS plantations (Figure 6c).

MIS and MNS plantations had higher litter cover than MONO plantations across all age classes; however, the difference was only significant between middle-aged MIS and MONO plantations (Figure 6a).

MIS and MNS plantations had similar or higher litter cover compared to natural forest, while MONO plantations had a lower litter cover (Figure 6a). All plantation types across all stand age classes had a similar or higher shrub cover, vine and scrambler cover, and coarse woody debris cover compared to natural forest (Figure 6b-d).

Tree species diversity

The combination of revegetation method and age class best explained the variation in the number of tree species per plot (tree species richness) ($F_{7,174} = 32.31$, $P = .000$) (Table S2, Model 29.3), while revegetation method alone best explained the variation in Simpson's diversity index ($F_{2,183} = 83.45$, $P = .000$) (Table S2, Model 30.1).

Overall, MNS plantations had similar or significantly higher tree species richness and Simpson's diversity index than MONO and MIS plantations (Figure 7a,b). For young MNS and MIS plantations, the tree species richness and the Simpson's diversity index was significantly higher than young MONO plantations. For middle-aged plantations, the tree species richness and Simpson's diversity index was significantly different among all plantation types. Middle-aged MNS plantations had the highest tree species richness and Simpson's diversity index, followed by middle-aged MIS plantations then middle-aged MONO plantations (Figure 7a,b).

As expected young and middle-aged MONO plantations had significantly lower tree species richness and Simpson's diversity index compared to old MONO plantations (Figure 7a,b). In contrast, young MIS plantations had a significantly higher tree species richness compared to middle-aged and old MIS plantations (Figure 7a). Young MNS plantations had a significantly lower tree species richness compared to middle-aged MNS

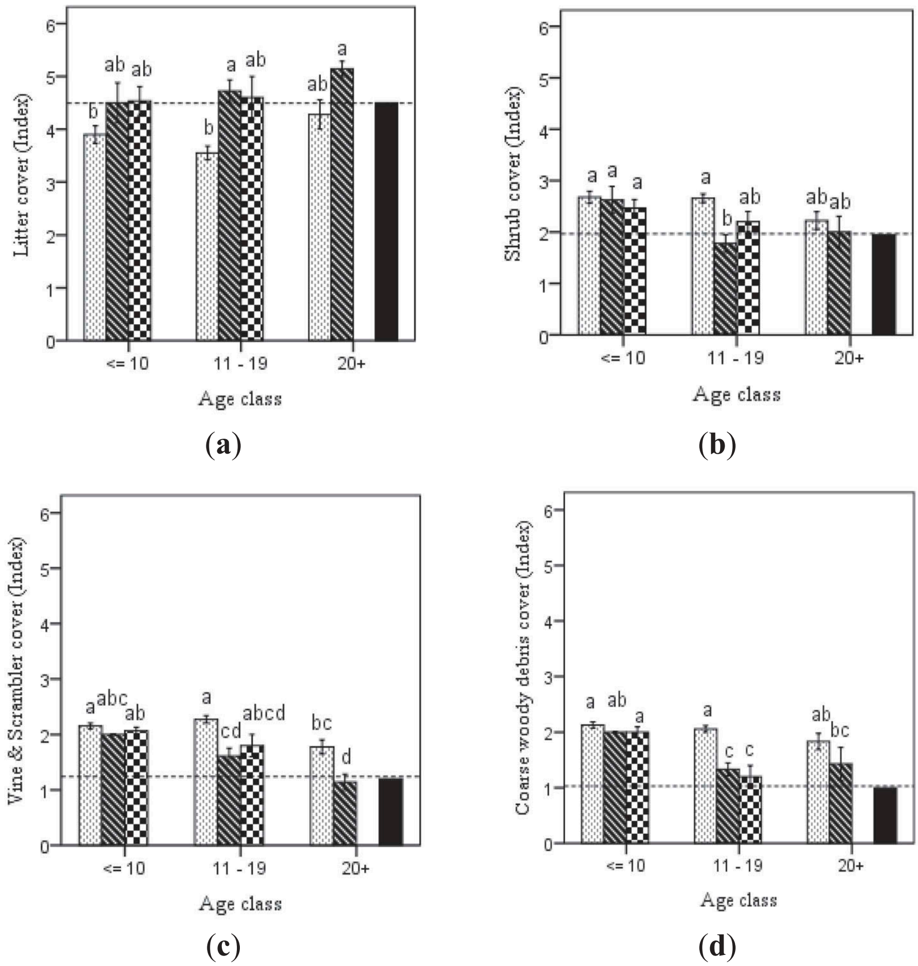

Figure 6. Ground and woody debris cover (Mean, S.E.) for revegetation method by stand age class (▨ = MONO (Monoculture plantations) = 197 plots, ▧ = MIS (Mixed introduced species plantations) = 33 plots, ▩ = MNS (Mixed native species plantations) = 20 plots, ■ = NAFO (Natural forest) = 1 ha (100 subplots (10 × 10 m), ----- = NAFO reference line). Note: Significant differences in mean values between revegetation methods in each age class and between age classes in each revegetation method are indicated by different lowercase letters (Pair-wise comparisons are conducted to identify statistically significance differences at α = 0.05).

plantations (Figure 7a). All plantation types across all stand age classes had lower tree species richness and Simpson's diversity index compared to natural forest (Figure 7a,b).

When plots were randomly accumulated, the tree species richness increased with area for all plantation types and natural forest (Figure 7c). Simpson's diversity index for natural forest started high (0.98) and remained relatively constant as the number of plots were accumulated, while that of MNS and MIS plantation started lower than natural forest but increased quickly and leveled off at close to the value of natural forest at 0.95 and 0.93, respectively (Figure 7d). Simpson's diversity index for MONO plantations started much

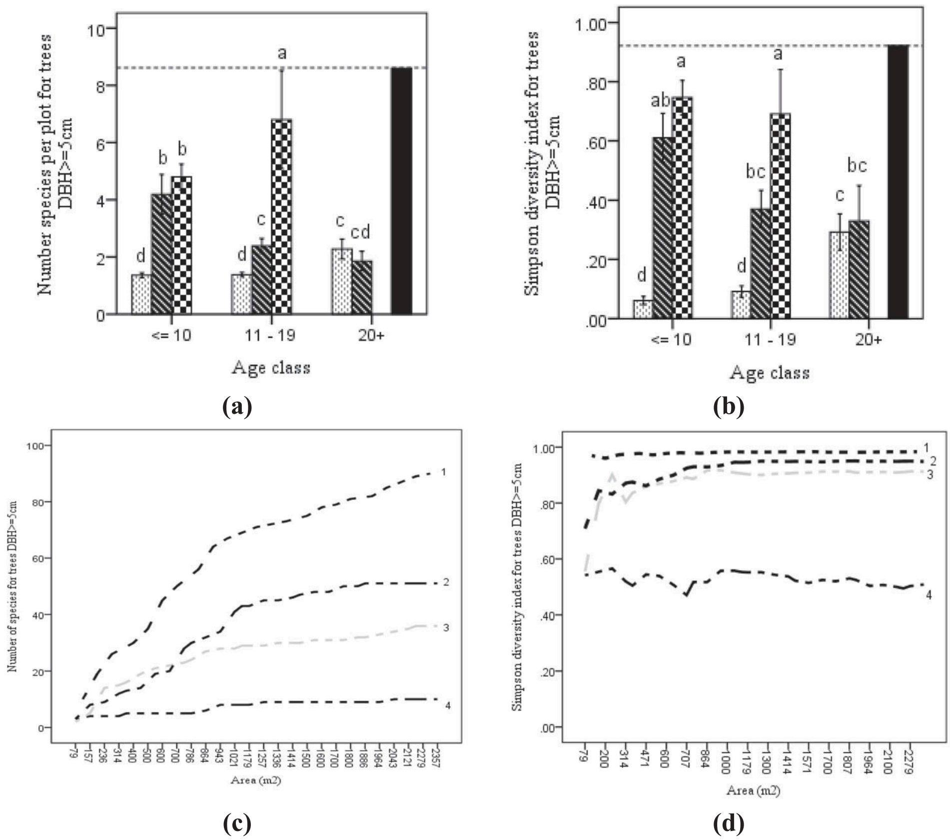

Figure 7. Tree species diversity (mean, S.E.) for revegetation method by stand age class (a and b, = MONO (Monoculture plantations), = MIS (Mixed introduced species plantations), = MNS (Mixed native species plantations), ■ = NAFO (Natural forest), ----- = NAFO reference line) and change in tree species diversity with increasing area (c and d, 1 = NAFO, 2 = MNS, 3 = MIS, 4 = MONO).

lower than natural forest and the other plantation types and remained lower (0.57) as the number of plots were accumulated (Figure 7d).

Discussion

While our data were collected in the Philippines, the results have broad applicability throughout Southeast Asia. The species in the mixed introduced species plantations (i.e., *Gmelina arborea, Acacia mangium, Swietenia macrophylla*) are commonly planted elsewhere (i.e., a relatively small number of fast-growing exotic species planted together). The mixed native species plantations, although different in species composition to other countries, are also typical of the type of planting systems put in place for mixtures of native species (i.e., a large number of native species planted in high densities in a random assemblage) (Göltenboth, 2011), and with species selection largely driven by available germplasm (N. Gregorio et al., 2017; N. O. Gregorio et al., 2005; Takoutsing et al., 2014).

Overall we found that mixtures of introduced or native species can provide benefits over monoculture plantations across a number of key indicators. However, mixed-species plantations are more difficult to establish and manage compared to monocultures of well-known species due to limited knowledge about appropriate design and management of mixed-species plantations (Dickinson et al., 2008). As a result, mixed-species plantations comprise less than 0.1% of industrial plantations worldwide (Nichols et al., 2006). Our results suggest that the use of mixed introduced species will tend to favor the 'production' function of plantations while the use of mixed native species favors the 'biodiversity' function of plantations. Mixtures (both of native and exotic species) as a whole, however, result in more structurally complex and biodiverse forests compared to monocultures. Reforestation in tropical developing countries needs to strike a balance between timber production and biodiversity conservation because people depend on forest products for their living. In many cases, the production function is considered most important by those relying on trees for their livelihoods. Our study suggests that when this is the case, revegetation using mixed plantings of productive introduced species may strike the most appropriate balance between production and biodiversity. The use of mixed introduced species may be a good alternative for small or medium-sized farms because mixtures of two to three species can provide diversification of forest products. Where biodiversity conservation is a specific goal of revegetation, then mixed native species plantings would be preferable.

Our results indicate that plantations of mixed introduced species performed best for most forest growth performance indices and some forest structure performance indices, while plantations of mixed native species performed best for tree species diversity. Monoculture plantations only out-performed mixed introduced and mixed native species plantations for one tree growth performance indicator (MAI Ht) and some forest structure performance indicators (the density of woody stems for height 10–20 m, shrub cover, vines and scramblers cover, and coarse woody debris cover). Monoculture plantations tended to perform better than mixed native species plantations for tree growth performance indices, however not significantly better. Our finding shows the same results as previous studies. The main reasons for this finding are first that planting many species in mixed stands could reduce pest and disease problems (Chokkalingam et al., 2006) while for a monoculture plantation, the risk of attack by insects is always there, whether the species is native or exotic (Wylie, 2002). Nair (2001) indicates that large monoculture plantations are most susceptible to pest outbreaks, and susceptibility in the Philippines. The next reason is the biological characteristics of forest trees. The results from case studies in the Amazon region also indicate that initially the growth of monoculture plantations was greater, but as mixed native species began to get larger, their rate of growth increased. The increase was due to partly to decreased competition from herbaceous weeds and grasses, and partly to an increasingly efficient use of light and nutrients (Montagnini & Jordan, 2005).

Our findings add further to the debate about whether mixed-species plantations can achieve greater productivity than monocultures (Erskine et al., 2006; Firn et al., 2007; Liu et al., 2018; Piotto, 2008; Wormald, 1992). Other studies have compared mixed-species plantations with monoculture plantations and have shown that mixtures can be highly productive (Binkley et al., 1992; Bristow et al., 2006; Debell et al., 1997; Forrester et al., 2005; Kelty, 1989; Nadrowski et al., 2010; Piotto, 2008; Potvin & Dutilleul, 2009; Potvin &

Gotelli, 2008). Further studies have reported that the effect of tree diversity on growth performance may be positive in young stands (Erskine et al., 2006) or negative in old stands (Firn et al., 2007). Some species may also grow better in mixed stands while others grow better in monocultures (Piotto et al., 2003a; Redondo-Brenes & Montagnini, 2006). Forrester et al. (2004) stated that when positive interactions are dominant (facilitation or competitive reduction), mixed stands can be more productive than monocultures; however, if the inter-specific competition is greater than these positive interactions, mixtures will be less productive.

There is growing evidence that some multi-species plantations can have greater levels of productivity than monoculture plantations of their constituent species (Biot et al., 1995; Cannell et al., 1992; Forrester et al., 2006; Kelty, 2006; Jones et al., 2005; Piotto, 2008). One study from tropical Australia compared mixed-species plantations and monoculture plantations, finding that most species were more productive when planted in mixtures than in monocultures (Erskine et al., 2006). Forrester et al. (2007) also reported that mixtures of *Eucalyptus globulus* and *Acacia mearnsii* were twice as productive as *Eucalyptus globulus* monocultures growing on the same site in East Gippsland, Victoria, Australia. A meta-analysis carried out by Piotto (2008) comparing tree growth in monocultures and mixed plantations found that mixing tree species generally increases plantation growth. Piotto et al. (2010) also found that mixed native plantations on degraded pasturelands in humid Costa Rica performed better than monoculture native plantations for all growth variables, including height, diameter at breast height, volume, and aboveground biomass. A further study in Costa Rica compared the same experimental pure and mixed-species plantations and found that mixed plantations had productivities either similar to or greater than the same species grown in monocultures (Petit & Montagnini, 2004; Piotto et al., 2003a; 2003b). However, studies have found that mixtures tend to outperform monocultures on poor sites (Binkley, 1992; Montagnini et al., 1995), whereas monocultures of a highly productive species can have higher merchantable yields on high-quality sites (Burkhart & Tham, 1992; Kelty, 1992).

Productivity increases in mixed-species plantations can be the result of a number of different mechanisms including complementarity, facilitation, and sampling effect. The complementarity hypothesis proposes that species-rich plantations are able to more efficiently access and utilize limited resources because they contain species with a diverse array of ecological attributes (Kelty, 1992). As a consequence, more diverse plantations should have higher net primary production, and in a well-managed plantation, this should translate into larger timber volumes. The facilitation hypothesis suggests that mixed-species plantations improve growing conditions (i.e., nitrogen-fixing trees) for other species, which facilitates increases in overall production of a mixed-species stand (Binkley et al., 2003; Forrester et al., 2006; Parrotta, 1999). Alternatively, the sampling effect hypothesis proposes that more diverse plantations demonstrate increased production because they have a higher chance of containing species that are "over-yielding" and highly efficient in their use of limited resources. That is, one or two species within the community are largely responsible for any increase in production (Loreau et al., 2001). The results of our study do not point to the exact mechanism by which mixed-species plantations achieved greater productivity than monocultures; however, the mixed introduced species plantations surveyed in our study did include nitrogen fixers (*Acacia mangium*, *Acacia auriculiformis*, and *Leucaena leucocephala* Lam.), which suggests that facilitation may have been one reason for the higher productivity observed in mixed introduced species plantations.

The expression of complementarity in tree stands generally depends on species-specific plant traits, the combination of planted species, and the availability of limited resources at a planting site (Grant et al., 2006; Forrester et al., 2005; Rothe & Binkley, 2001). Complementarity may become more important with increasing resource utilization during tree development (Delagrange et al., 2008; Forrester et al., 2006; Stanley & Montagnini, 1999). Richards et al. (2010) found that more than 50% of mixed-species studies reported a higher above-ground nutrient content compared to monocultures, indicating an increase in the proportion of resources captured from a site. Second, a meta-analysis showed that foliar N concentrations significantly increased for a given species in a mixture containing N_2-fixing species, compared to a monoculture, suggesting higher rates of photosynthesis and greater resource-use efficiency. Significant shifts in N- and *P*-use efficiencies of a given species, when grown in a mixture compared to a monoculture occurred in over 65% of studies where resource-use efficiency could be calculated. Such shifts can result from changes in canopy photosynthetic capacities, changes in carbon allocation, or changes to foliar nutrient residence times of species in a mixture (Richards et al., 2010).

In terms of forest structural performance, our study indicates that while mixed introduced species plantations performed best for several indices (medium to large tree density, canopy cover, and litter cover), monoculture plantations performed better for other indices (medium height tree density, shrub cover, vines and scramblers, and coarse woody debris), and structural performance was highly dependent on stand age. The development of structural complexity with stand age was most strikingly evident in monoculture plantations. While most young monoculture plantations had a relatively open canopy, an understorey of grass, herbs, and low litter cover, old monoculture plantations had a relatively complex structure, with higher canopy and litter cover, and significantly less grass cover. In part, this is simply a consequence of the maturity of trees, leading to larger diameter woody stems, greater canopy cover, litter, and woody debris. The link between plantation structural complexity and age has been noted elsewhere (Kanowski et al., 2003) and studies have found that structural complexity increased with stand age no matter how many species are planted at establishment (Munro et al., 2009).

Whilst structural complexity generally increased with age for all plantation types, our results indicate that tree species diversity did not necessarily increase with age. For instance, both the tree species richness and Simpson's diversity index decreased with stand age in mixed introduced plantations, while they significantly increased in monoculture plantations. The reason for this appears to be two-fold. The reduction in diversity in mixed-species plantations was due to a combination of anthropogenic factors associated with harvesting of mainly fast-growing exotic species and high mortality rates of light-demanding species due to competition (Nguyen et al., 2014; Wills et al., 2016). Other studies have also found that whilst plantation structural complexity increases with age, tree species richness does not necessarily increase (Finegan, 1996; Marín-Spiotta et al., 2007; Wilkins et al., 2003). This pattern may indicate that plantations can provide habitat for fauna in the form of structural complexity, but may not provide sites for the conservation of plants unless they are specifically planted or seed is introduced (E. Brockerhoff et al., 2008; Munro et al., 2009). The reason for the observed increase in tree species diversity with age in monoculture plantations could be that as the monoculture plantations matured, they provided habitat for other tree species and animals that disperse the seeds of new species (E. Brockerhoff et al., 2008; E. G. Brockerhoff et al., 2013). Observations of plantation understories in Puerto Rico suggest that high tree species richness can occur under monoculture stands and that reestablishment of tree species richness on degraded sites with arrested succession can be facilitated through monoculture plantings (Lugo, 1997). Munro et al. (2007) stated that there is currently an absence of information on how revegetation structure and floristic diversity develops, particularly under different vegetation establishment techniques. This information is important for understanding the biodiversity value of revegetation and for identifying establishment techniques, which will maximize the benefits of revegetation for fauna.

Our results show that litter production was higher, but not significantly higher, in mixed-species plantations (both introduced and native species mixtures) compared to monoculture plantations. Other studies have indicated that higher tree productivity in mixed-species plantations could be linked to higher litter production (Potvin & Gotelli, 2008; Scherer-Lorenzen et al., 2007). Greater litter production in mixed-species plantations could increase soil nutrient supply relative to monocultures, if decomposition rates are similar. Tropical tree diversity experiments conducted by Scherer-Lorenzen et al. (2007) and Potvin and Gotelli (2008) have shown that both above-ground wood production and litter production were higher in mixtures than in corresponding monocultures due to inter-specific interactions influencing growth and nutrient capture, while litter decomposition rates were unaffected.

Reforestation may be the best way to rehabilitate some of the most degraded areas and, at the same time, generate improvements in livelihoods and protection outcomes. There are currently a variety of reforestation forms on degraded land in tropical developing countries; however, at its simplest, there are two main ways in which reforestation can be achieved and these are by some forms of tree planting or by natural regeneration (Lamb, 2010). In which tree planting includes the following forms: pure or mixed exotic species, mixed native species forests. Each type of reforestation has its advantages and disadvantages and can be applied under different circumstances. The conditions and objectives of landowners or forest managers will determine which type of reforestation is eventually applied (Lamb, 2010). In the past, the central factor determining this choice for most industrial growers was the expected financial return. But private smallholders may take a different view. They desire the variety of forest goods and improvement of human livelihoods (Lamb, 2010). The majority of world plantation forests are monocultures with certain dominant tree species, which are favored for timber production due to the uniformity of trees and easy management. Meanwhile, mixed-species plantations are growing and becoming more popular, since they have been found to have more benefits in biodiversity, economy, forest health, and occasionally in productivity compared with monospecific plantations (Lamb, 2010; Liu et al., 2018). Natural regeneration is considered the least expensive form of reforestation, where it can occur, although its ability to produce specific goods and services varies greatly.

Although the issue of negative or positive effects of mixed-species forest tree stands on tree growth and ecosystem functions is still controversial, mixed-species plantations have been proposed as a 'win-win' situation for timber production and biodiversity under right conditions and appropriate management (Hartley, 2002; Herbohn & Harrison, 2000;

Keenan et al., 1999; Lamb, 1998; Liu et al., 2018; Piotto et al., 2004; Verheyen et al., 2016). Our research supports these propositions for reforestation in the Philippines, with the qualification that there appears to be differences between mixtures of native versus introduced species. We found that mixed introduced species plantations were more productive than both mixed native species and monoculture plantations; however, as plantations mature, monocultures may also result in improved biodiversity. Mixed native species plantations clearly had better outcomes in terms of tree species diversity; however, they have lower productivity, making them less suitable for timber production. Our results thus support that mixtures of introduced species are most suited to situations where the production function is considered to be most important while mixtures of native species are most suited to situations where improved biodiversity is the desired outcome.

Conclusions

In this study, we compared the forest growth, forest structure, and tree species diversity performance for different types of reforestation across 168 sites (251 survey plots) on Leyte Island, the Philippines. Our results indicate that the selection of right reforestation types is a dominant factor influencing outcomes of reforestation in the Philippines. Although there are still some study limitations such as unequal subsample size for different types of reforestation, a lack of analyzing the correlation between the forest growth, forest structure, biodiversity, and their influential factors, our study results can provide valuable references for stakeholders in carrying out successful reforestation projects and programs in the Philippines in particular and in tropical developing countries in particular.

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