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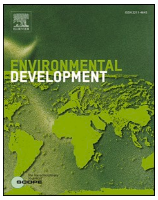

# Harnessing the socio-ecological benefits of agroforestry diversification in social forestry with functional and phylogenetic tools

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ABSTRACT

Following severe forest loss in recent decades, Southeast Asian countries are increasingly employing social forestry as a means to ensure the sustainable development of their forest-dwelling communities. Given the potential of agroforestry to provide multiple ecosystem services, habitat for the maintenance of biodiversity, and the economic and social development of communities that cultivate them, many civil society organizations and NGOs involved are turning to agroforestry to achieve the goals of social forestry. However, implementing agroforesty per se may not be sufficient if agroforestry systems are not adequately diversified to meet management goals and limited tools exist that facilitate appropriate species selection in diversification. Here we review the potential of diversified agroforestry for social forestry and similar schemes, critically evaluating its advantages and challenges, before detailing two methodological tools, one based on functional traits and the other phylogeny, that may aid in generating recommendations for the effective diversification of agroforestry. Diversified agroforestry was found to have great potential as a sustainable, multifunctional land-use that is predominantly held back by the availability of resources, technical aid and tailored market access. Appropriate species selection may be a bottle-neck that can be alleviated by the tools presented. The first tool enables comparable species (in this case woody species) to be delineated into functionally distinct groups from functional trait data, which is illustrated using data from agroforests in Central Kalimantan, Borneo. The second produces co-cultivation recommendations based on phylogenetic distances between species. The functional groups identified and the recommendations based on phylogenetic distance both correspond to product types and specific uses within agroforestry, further incentivizing on-farm income diversification due to additional environmental benefits. When applied appropriately, the tools presented would allow for the cultivation of complementary species that may lead to improved habitat and ecosystem service provision without compromising yields. When coupled with appropriate market mechanisms, cultivating diversified agroforests may ensure the sustainable use of land under social forestry in Southeast Asia. Additionally, the two tools presented here have applicability in silviculture, restoration and other agroecosystems worldwide.

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## 1. Introduction

Social forestry, a system of community forest management and land titling, is increasingly being promoted across Southeast Asia (SEA) as a route to climate change mitigation, ecosystem service provision and a way to achieve the UN's sustainable development goals (Rennaud et al., 2013; RECOFTC, 2020b; de Jong et al., 2018; Wong et al., 2020). Generally, social forestry aims to alleviate poverty and support rural livelihoods as well as conserve biodiversity and manage forests sustainably via devolution (Gilmour, 2016; Wong et al., 2020; see RECOFTC, 2020b for country specific definitions). Often the communities involved would have previously relied on local forests for their livelihoods which has been associated with forest degradation, in part due to a lack of land tenure (Medrilzam et al., 2014). In order to aid communities in achieving sustainable forest management while also ensuring social and economic development, a number of NGOs and civil society organizations are turning to agroforestry in order to meet the criteria set by national governments (Gilmour, 2016; Wong et al., 2020; RECOFTC, 2021; Catacutan et al., 2019). Agroforestry "is the purposeful growing or deliberate retention of trees with crops and/or animals in interacting combinations for multiple products or benefits from the same management unit" (Nair et al., 2021). Diversified agroforestry systems, may be especially suitable due to their multifunctionality, i. e providing multiple goods and services (Jose, 2009; Mortimer et al., 2018).

As of 2019, more than 7.3 million households are involved in social forestry in SEA (RECOFTC, 2020a) and between 2010 and 2020, the area of land under social forestry schemes has more than doubled (RECOFTC, 2020b). 13.9 Mha are currently designated community forestry, 46% of the accumulative target for each country, totalling 30 Mha (RECOFTC, 2020b). Once achieved, this will account for 15% of the region's forest area.

The goals of social forestry in SEA are ambitious and therefore multifunctionality is a must if designated areas are to simultaneously provide economic, social and environmental benefits. Contrastingly, in Indonesia's Jambi Province for example, smallholder agroforestry systems are often simplified into rubber and oil palm monocultures to maximize economic benefits (Clough et al., 2016). This is often accompanied by an increased reliance on external inputs, a reduction in ecosystem service provision and negative environmental impacts such as soil carbon loss and nutrient leeching (Clough et al., 2016; Liu et al., 2018). For an agroforest to be sustainable and multifunctional -thereby appropriate for the goals of social forestry-it should be established in a way that ensures internal ecological functions, allowing for self-regulation without reliance on external inputs. This requires diversification, since different species will have to fulfil different functions, be that nutrient generation and recycling, microclimate regulation, ensuring adequate pollination and pest control, etc. One way to promote the provision of these functions is by basing diversification on functional diversity and niche complementarity which will be outlined in box 1.

Given the potential of diversification to meet the goals of social forestry in SEA as well as sustainable agroecological and silvicultural systems elsewhere, this paper aims to critically review the benefits and challenges associated with the diversification of agroforestry while considering ecological and socioeconomic factors in sections 1.2 and 1.3. In the methods and results (section 2), drawing from on-site data from agroforests in Central Kalimantan, Borneo, this paper will present and apply two tools, one based on functional traits and the other phylogeny, that may aid in effective diversification by promoting complementarity and functional diversity before assessing the potential of these tools in the discussion (section 3).

### *1.1. Benefits of diversification*

In a recent global meta-analysis on the effects of diversification in agriculture, Tamburini et al. (2020) showed that diversification promotes a wide range of ecosystem services without necessarily compromising crop yields. Indeed, another meta-analysis demonstrates that diversity mediated improvements in pollination and pest control can lead to improved yields (Dainese et al., 2019).

Generally, the provision of multiple ecosystem services in a system (multifunctionality) increases with increasing biodiversity (Meyer et al., 2018), especially when considering differing spatial and temporal scales, in which case there may be very little redundancy (Isbell et al., 2011). Additionally, more species become necessary for multifunctionality as the number of ecosystem services considered increases (Lefcheck et al., 2015; Meyer et al., 2018). In agroforests and perennial agriculture, the provision of various ecosystem services varies widely depending on species selection and management, with co-benefits and trade-offs, but generally increases when functionally distinct species are cultivated (Tschora and Cherubini, 2020; Rapidel et al., 2015).

When the conservation of biodiversity is an important outcome for a given agroforest, increasing the species richness of trees, if associated with increased functional and structural diversity, is likely to lead to increases in the diversity and abundance of at least arthropods at multiple trophic levels (Schuldt et al., 2019). It is reasonable to assume that this would be the case with other taxa as well since these factors are related to habitat provision.

Diversification, while potentially reducing single crop yields, often results in higher system yields. As will be discussed in box 1, cultivating complementary species can improve resource capture efficiency, meaning less resources are unutilized and biomass production is enhanced. Expressed as land equivalent ratios (LERs), this reflects values higher than 1, where 1 is the yield of a comparable monoculture. For example, simply cultivating cocoa alongside oil palm can result in LERs of 1.4 (Khasanah et al., 2020). Examples of diversified agroforests having higher system yields are numerous (Armengot et al., 2016; Pérez-Neira et al., 2020; Schneider et al., 2017; Niether et al., 2019).

When diversification is based on the cultivation of a range of products (i.e. cash crops, staple foods, fruits and timber) that are harvestable at different times of year and in short and long time-frames, it may also confer socioeconomic benefits. These include food security, improved and diversified income generation and resilience in both the short and long term (especially if timber is integrated), a broader and more nutritious diet, and fodder for livestock (Pratiwi and Suzuki, 2019; Simien and Penot, 2011; Armengot et al., 2016;

Rosenstock et al., 2019; Altieri et al., 2012; Roshetko et al., 2013).

In addition to this, diversification may enable farmers to gain access to certifications that have diversity-based criteria (e.g., Naturland, Sustainable Forest Management, PEFC, Smithsonian Bird Friendly, BioSuisse). This can provide access to additional high paying markets and therefore allow them to obtain more income from their diversified plot which may have otherwise been less financially viable (Tscharntke et al., 2014). However, care must be taken to avoid situations in which the cost of certification is higher than the improved revenues, as is the case with RSPO palm oil certification (Hutabarat et al., 2018).

Diversified agroforestry systems may also be more resilient to climate change (Nguyen et al., 2013), a factor that will become increasingly important given that, in Brazil for example, the area suitable for sun grown coffee is expected to decline by 60% while shaded agroforestry coffee will remain suitable for 75% of the current coffee growing area (Gomes et al., 2020). This is due to improved microclimatic conditions shade can provide (Lin, 2007).

Given the array of global policy objectives associated with climate change mitigation, the conservation of biodiversity, and sustainable development; diversified agroforestry is a form of agriculture that would allow SEA to comply with international frameworks such as REDD+, the IPBES, and the United Nation's sustainable development goals, etc. (Buttoud, 2013; Van Noordwijk, 2019; Waldron et al., 2017). Indeed, the ASEAN guidelines for the implementation of agroforestry specifically adhere to all conventions, agreements and treaties committed to be ASEAN members (Catacutan et al., 2019). And, should payments for ecosystem services proliferate in the future, agroforesters could be well-placed to receive this income given the number of ecosystem services they can provide.

A further benefit of agroforestry is its suitability to favourably alter landscape dynamics, especially when integrated into planned multifunctional landscapes that integrate both land sparing and land sharing. Previous research has shown that a planned combination of land sharing and land sparing may optimize food production and biodiversity (Butsic and Kuemmerle, 2015). Diversified agroforests are an effective means of land sharing due their ability to provide ecosystem services, retain biodiversity and provide yields of nutritious and valuable food and goods, enabling them to achieve multiple landscape level management targets (Jose, 2009; Mortimer et al., 2018; Buck et al., 2020). Agroforests can also be suitable as transition or buffer zones between conservation areas and more intensive agriculture (Barrios et al., 2018). A land sharing transition zone can help to reduce edge effects by attenuating the contrast between habitat and non-habitat (Santos-Barrera and Urbina-Cardona, 2011), and may similarly reduce unfavourable source sink dynamics. Agroforestry around conservation areas may also help to attenuate invasive species pressure on them. Agroforests can act as an invasion barrier to invasive species, whereas monoculture plantations can act as invasion gateways (Lee et al., 2020; de Almeida et al., 2018; Ramos et al., 2015). The ecosystem services provided by agroforestry may also benefit surrounding agroecosystems. For example, Hass et al. (2018) found that rice fields support a low functional diversity of bees which may impair pollination, while agroforests support a high functional diversity of bees which surrounding rice fields can benefit from up to a few hundred meters away.

Diverse agroforests also have the potential to increase habitat connectivity (Ocampo et al., 2019; Haggar et al., 2019) which is increasingly important as forest habitats in SEA become increasingly fragmented (Savini et al., 2021; Hughes, 2017). However, the effectiveness of increasing connectivity via agroforestry varies among species (Oliveira et al., 2019) and agroforest type, but evidence suggests that intensive agroforestry is less effective for connectivity than traditional diverse agroforests (Ferreira et al., 2020) although species specific requirements should be evaluated.

In spite of the numerous benefits mentioned above extensive adoption of agroforestry in SEA remains low (Catacutan et al., 2017) and several studies have reported a decline in agroforestry in some parts of the region (Parikesit et al., 2005; Pham et al., 2016; Watanabe et al., 2014). The following section will look at why this is the case and what can be done to promote diversified agroforestry.

### 1.2. *Difficulties and trade-offs in diversifying agroforestry*

The primary roadblock for extensive agroforestry adoption is profitability. In the current economic system it is unlikely that multifunctional agroforests with high biodiversity will achieve the profitability of monoculture plantations (Grass et al., 2020). This is reflected in small holder's preferences to transition from diverse agroforests to more profitable monocultures over time (Feintrenie et al., 2010; Clough et al., 2016). However, there may be exceptions, such as cases where the incorporation of management practices that promote biodiversity and ecosystem services lead to decreased yields but increased product quality, resulting in equal or greater economic return (Jezeer et al., 2017). Zheng et al. (2019) also found that effective diversification is able to reconcile economic interests and ecosystem service provision in rubber plantations.

To overcome this economic roadblock, diverse agroforests need improved product commercialization and better integration into rural value chains (Snelder et al., 2007). Currently, even if farmers have higher whole system yields it may be impossible to sell all their produce because the quantity of each individual crop may be too low for traders, limiting farmers to selling their by-crops cheaply in local markets. Thus, farmers are penalized for diversification in spite of the increased land use efficiency. Additionally, in cases where product quality is increased at the expense of yield, as is often the case with shaded coffee, cocoa and tea, rural smallholder farmers need access to traders that will give them fair prices for the quality of their crops.

Further roadblocks which discourage farmers from implementing diversified agroforestry across SEA are land tenure insecurity (Zimmer et al., 2018), lack of financial incentives (Simelton et al., 2017), and limited access to planting material and technical assistance (Baynes et al., 2009; Lasco et al., 2016; Roshetko et al., 2013). Additionally, smallholders often lack the financial means to invest in their agroforests in order to improve their crop diversity or production capacity, resulting in declining yields due to ageing trees, diseases and pests, and soil degradation (Mithöfer et al., 2017; Praseptiangga et al., 2020). Another constraint is that diversified agroforestry systems require a higher workload, although the return on labour is higher (Armengot et al., 2016; Pérez-Neira et al., 2020).

A promising solution to many aforementioned problems may be the formation of cooperatives. Extensive research from a long running cooperative in Bolivia has shown their ability to: improve market access via collective marketing, provide education, training and technical assistance, reduce certification costs for individuals, provide seed bank and nursery access, provide microcredit for investments, and improve local infrastructure for the processing and transport of goods (Jacobi et al., 2017). The cooperative also promotes and facilitates diversification, resulting in member farms having a higher species richness than non-members (Jacobi et al., 2014). However, this cooperative focuses on cocoa production, and therefore many of the associated benefits may not apply to other marketable goods produced in diverse systems. While this cooperative inspired the creation of a similar one for organic bananas (Garming et al., 2011), instead of forming cooperatives for each individual product, it may be more reasonable to aim for the formation of single regional cooperatives for agroforestry in general rather than many for individual products.

Even if cooperatives allow agroforest farmers to overcome issues in producing and trading diverse products with prices that match their quality and production methods, further economic incentives such as certifications (Tscharntke et al., 2014) and payments for ecosystem services (Middendorp et al., 2018) may still be necessary for smallholders in SEA to break out of subsistence farming in a sustainable manner.

A final issue is how to diversify, with which species, and what additional goals? Diversifying simply according to market orientation (i.e currently profitable species) may compromise the growth and yields of other cultivated species as well as reduce the ability of an agroforest to provide additional ecosystem services. Optimally, alongside economic considerations and traditional ecological knowledge, species should be selected according to the principles niche complementarity (see box 1) in order to reduce competition and provide a range of ecosystem services. Tools that facilitate this selection will be presented in the following section.

## 2. Box 1 ecological theory behind effective diversification

A major concern with diversification is that the crops grown together may compete for resources and therefore suffer from reduced yields. This is a valid concern that has been demonstrated in Nicodemo et al. (2016) and Nyaga et al. (2019) for example; but has the potential to be overcome by basing diversification around niche complementarity. In order to do so, one must consider a species' functional traits which are indicative of its niche (McGill et al., 2006; Sterck et al., 2011). By characterising species by their functional traits and then selecting appropriately to avoid niche overlap, niche complementarity can be enhanced, potentially leading to reduced competition and enhanced resource use efficiency (Wood et al., 2015; Flombaum et al., 2014; Hildebrand et al., 2021). Given this, a system with high functional diversity would be expected to have a high niche complementarity, as the species in question would have distinct trait syndromes that allow them to exploit different niches. By identifying species that are functionally distinct from one another, one can design agroforests around the principles of niche complementarity and enhance functional diversity.

This may have the additional benefit of enhancing multifunctionality. Functional traits and their diversity within a system are directly related to ecosystem functioning and services (Lavorel, 2013; Cadotte et al., 2011; Schuldt et al., 2018) and indices of functional diversity are able to better predict ecosystem services compared to taxonomic approaches (Finney and Kaye, 2017; Cadotte et al., 2011; Mouillot et al., 2011). However, diversity mediated increases in multifunctionality may plateau. This was demonstrated by Storkey et al. (2015) who tested the ability of all possible combinations of 12 species to optimize the provision of six ecosystem services. They found that multifunctionality was optimized with up to four species that were functionally distinct, i.e. complementary to each other. Zhang et al. (2012) also showed that forest productivity plateaus at a species richness of six, which is likely due to increases in redundancy rather than complementarity as additional species are added. Further studies also show that functional distinctness in species mixtures is a key factor in enhancing multifunctionality (Sauvadet et al., 2020; Somarriba et al., 2013; Blesh, 2018; Schuler et al., 2017; Mouillot et al., 2011).

Initial results from recently established agroforests with varying levels of functional diversity confirm that both ecosystem service provision and yields can be enhanced by designing agroforests around functional diversity and niche complementarity (Santos et al., 2021), although more time is needed to see if this holds as the agroforests mature. Further support comes from Nesper et al. (2017) who found that coffee yield and quality increased with increasing shade tree diversity. This was due to decreased pest incidence and potentially due to increased pollination as well as soil improvements.

Phylogenetic distance may also be a suitable alternative to identify species that exhibit complementary resource exploitation and ecosystem service provision. In principle, a larger evolutionary distance between species should reflect greater niche differentiation and therefore the exploitation of different niches. Communities with higher phylogenetic diversity (equivalent to the sum of phylogenetic distances) are more stable due to complementarity (Cadotte et al., 2012) and are correlated with higher biomass production (Flynn et al., 2011). Additionally, woody species phylogenetic diversity -in part, likely due to evolutionary dependencies-mediates arthropod biomass and plant herbivore networks (Schuldt et al., 2014; Wang et al., 2020). Indeed, a global meta-analysis by Molina-Venegas (2021) demonstrated that plant phylogenetic diversity is vital to ecosystem service provision worldwide and that few species and genera are capable of being multi-beneficial. Applying this to agroforestry, Sauvadet et al. (2020) demonstrated that the phylogenetic distance of shade tree species to cocoa was correlated with their desirability for cultivation alongside it; where desirability was related to shade quality, regulation of pests and disease, soil health enhancement and resource use complementarity.

Thus, basing diversification on functional diversity and phylogenetic distance may greatly aid with establishing systems with niche complementarity and high multifunctionality and thus these form the basis of the tools presented in this paper.

## 3. Methods and results

### 3.1. *Functional group delineation*

A method with great potential for the diversification of agroforests is to delineate a given set of species into functionally distinct groups that are likely to be complementary to each other. This would enable agroforesters to improve the complementarity and potentially multifunctionality of their systems by cultivating species from different groups.

Such an approach will be illustrated below using data from coffee agroforests in Indonesia. The data characterise 159 agroforests by the woody species cultivated and their abundance, as well as each tree's diameter at breast height (DBH). The total number of species was 66. Functional trait data for each species was obtained from TRY database (Kattge et al., 2020) and the Bien trait database (Maitner et al., 2018). The traits obtained were height, specific leaf area (SLA), leaf nitrogen content, wood density, nitrogen fixing ability and leaf phenology. Missing data for nitrogen fixing ability and leaf phenology were extracted, when available, from online encyclopaedic databases, including ICRAF's agroforestree database (World Agroforestry Center, 2009), the useful tropical plants database (© Ken Fern, 2014), the plants for a future database (PFAF, 2019) and the Monaco nature encyclopaedia (© Giuseppe Mazza). Each species was assigned its mean trait value from TRY or Bien aside from DBH which was the mean value trait for a given species across all sites.

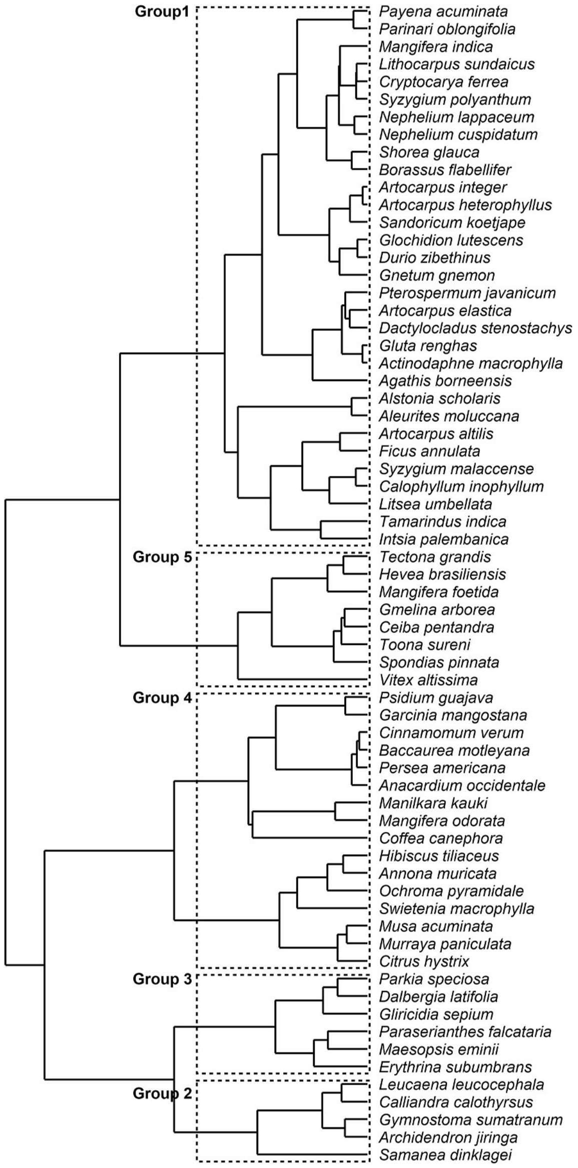

**Fig. 1.** Dendrogram dividing species into optimal number of groups based on trait dissimilarity and hierarchical cluster analysis. The grouping maximises the dissimilarity between groups and minimizes the dissimilarity within groups.

Functionally distinct groups can be identified from species' functional trait data using consensus hierarchical clustering constructed with various functions and packages within R (R Core Team, 2022) that will be detailed below.

First the continuous traits were log transformed due to positive skew, and improved robustness to missing data (Májeková et al., 2016), and because comparisons between species are best made by the ratios between traits rather than absolute differences (Westoby, 1998; Cornelissen et al., 2003). Differences in species' trait values were assessed with Gower dissimilarity using the Gawer package (Bello et al., 2021) which calculates the optimum weighting for each trait so that every trait has a more uniform contribution to the dissimilarity value. Gower dissimilarity rather than euclidean distance is necessary when including categorical traits. The dissimilarity matrix was then used to construct a hierarchical cluster dendrogram. The suitability of the data for such a purpose was tested with the Hopkins statistic. The test yielded a result of 0.75, suggesting intermediate clusterability (above 0.5 suggests the data is clusterable, with a value of 1 suggesting the data are highly clustered). Various clustering algorithms exist, each giving a slightly different dendrogram for the same data, and there is little consensus over which algorithm to use in which circumstance (Mouchet et al., 2008; Rodriguez et al., 2019). To solve this problem without arbitrarily choosing an algorithm, the mergeTrees package was used (Hulot et al., 2020). Mergetrees enables consensus hierarchical clustering by aggregating the trees produced by various algorithms into a consensus tree. All algorithms available in the hclust R function were used to produce eight trees which were subsequently merged into a consensus tree. In order to group branches of the consensus dendrogram the NbClust package was used (Charrad et al., 2014). The NbClust package uses multiple indices of clustering validity to assess the best number of clusters (in this case groups) in a dendrogram resulting in maximised dissimilarity between groups and minimized dissimilarity within groups. The dendrogram was plotted using ggplot2 (Wickham, 2016).

### 3.1.1. Results

Five groups of species were identified (Fig. 1) with one large group containing 31 out of 66 species suggesting that many species grown in these agroforests may be functionally redundant. The mean functional group richness across sites was 3.1 while the mean species richness was 6.8, demonstrating the potential to further integrate complementary species, potentially at the expense of functionally redundant ones.

Table 1 presents the average traits of each group. No significant differences between groups were detected for SLA and wood density suggesting that these traits may have had less influence on the divisions into functionally distinct groups and were relatively similar across most species in the data. Meanwhile, two groups had significantly lower heights, two had significantly higher leaf nitrogen contents, and one had especially large DBH while another had especially small DBH. Leaf phenology and nitrogen fixing ability were also distinctly divided across groups.

The functional group divisions often correspond to management uses, product types as well as ecosystem service provision, which will be detailed in the discussion.

### 3.1.2. Phylogenetic distance

As discussed in Box 1, phylogenetic distance (PD) is another measure that may enable effective diversification within agroforestry. To illustrate this, the suitability of woody species for cultivation with rubber and/or cocoa in Indonesia was analyzed according to phylogenetic distance, replicating the study by Sauvadet et al. (2020) for cocoa in Sub-Saharan Africa.

The phylogenetic distances between (1) 45 shade tree genera and cocoa and (2) 40 secondary tree genera and rubber trees across Indonesia were measured. The hypothesis is that shade trees/secondary trees classified as 'desirable' (via farmers experiences, peer-reviewed literature and research institutions) will have a greater phylogenetic distance from cocoa/rubber than those classified as 'undesirable'. Given that rubber and cocoa systems function well (Zeng et al., 2021), additional species which are classified 'desirable' for both, cocoa and rubber, can also be identified with this method.

Shade tree taxa from Indonesian cocoa farms, and secondary tree taxa from Indonesian rubber plantations were collated and their

**Table 1**

Functional trait characteristics of each functional group, including mean and 1 standard deviation for continuous traits.

| Trait (unit) | Group* (number of species included) | | | | |
|---|---|---|---|---|---|
| | 1 (31) | 2 (5) | 3 (6) | 4 (16) | 5 (8) |
| **SLA ($mm^2$/mg)** | 11.98 (3.71) | 15.43 (4.08) | 16.86 (3.36) | 11.63 (5.98) | 11.51 (5.46) |
| **Leaf Nitrogen Content (mg/g)** | 18.97 (3.93)a | 31.69 (7.26)b | 32.88 (4.84)b | 22.36 (8.33)a | 19.77 (4.84)a |
| **Height (m)** | 25.50 (11.45)a | 8.26 (2.16)bc | 24.15 (4.93)a | 8.13 (4.00)b | 20.12 (7.47)ac |
| **Wood Density (g/$cm^3$)** | 0.564 (0.147) | 0.660 (0.153) | 0.441 (0.189) | 0.561 (0.185) | 0.475 (0.155) |
| **DBH (cm)** | 23.63 (13.11)a | 17.46 (7.92)ab | 17.43 (6.09)ab | 12.33 (4.31)b | 20.36 (8.95)ab |
| **Phenology** | Evergreen | 4 Evergreen, 1 Deciduous | 2 Evergreen,<br>1 Deciduous,<br>3 Semi- deciduous | Evergreen | Deciduous |
| **Nitrogen Fixing (%N fixers (n))** | 6 (2) | 100 (5) | 83 (5) | 0 | 0 |

*Significant differences ($p < 0.05$) between groups for each trait are indicated by different letters. Group differences in SLA, Leaf Nitrogen Content and Wood density were tested with analysis of variance (ANOVA) and a post-hoc Tukey HSD test. As Height and Diameter at Breast Height (DBH) did not meet the assumptions of ANOVA, they were tested with the Kruskal-Wallace test and the post-hoc *kruskalmc* function from the pgirmess package (Giraudoux, 2021) that determines which groups from a positive Kruskal-Wallace test are different via pairwise comparison adjusted for multiple comparisons.

phylogenetic distance was determined. Commonly used shade tree genera were extracted from datasets received by ICRAF from on-site agroforest data and a literature review on commonly used trees in Indonesian agroforestry.

To classify shade and secondary trees as ‘desirable’ or ‘undesirable’, recommendations from research institutes were compiled (Indonesian Coffee and Cocoa Research Institute (ICCRI); Indonesian Rubber Research Institute; World Agroforestry (ICRAF), UTZ, 2017), and the literature on multispecies agroforesty was reviewed. The analysis was conducted at genus level to avoid over-representation of some genera. Only genera commonly used in agroforestry were included, so, while many more genera may be present in Indonesian agroforests these are often relics from forest conversion and are not common enough to be considered in this study.

The phylogeny of the included genera was obtained from the V. PhyloMaker R package (Jin and Qian, 2019) which creates user specified phylogenies extracted from a combination of the two megatrees presented by Zanne et al. (2014) and Smith and Brown (2018). The phylogenetic distance between *Theobroma cacao* and *Hevea brasiliensis* (rubber) to all other species for which a desirability status is known was calculated using the cophentic function. Average distances between desirable and undesirable species were assessed via analysis of variance with type 3 error using the car R package (Fox and Weisberg, 2018) because a direction of difference was not assumed, making a two-tailed significance test more reliable. Faith’s index, the total length of all branches in the phylogeny, was calculated using the Adephylo R package (Jombart et al., 2010). The phylogenetic tree was plotted using the dendextend and circlize R packages (Galili, 2015; Gu et al., 2014) and phylogenetic distance comparisons were plotted using ggplot2 (Wickham, 2016).

### 3.1.3. *Results*

A phylogenetic tree was produced for all genera with classification of their desirability status with cocoa and rubber (Fig. 2). Faith’s index of phylogenetic diversity was 6252 for the entire tree. From the 46 genera included, 20 were desirable cultivation alongside Cocoa and Rubber, one, *Blighia* spp., was undesirable for both, 16 had mixed desirability and 7 had an unknown desirability status for either Cocoa or Rubber. The phylogenetic distance between shade tree genera and cocoa was significantly higher for the desirable shade tree genera (F-value = 11.52, p-value = 0.0015) than for the undesirable shade tree genera (Fig. 3). The phylogenetic distance between rubber and its desirable secondary tree genera was not significantly higher than to those classified as undesirable (F-value = 3.342, p-value = 0.076; Fig. 3).

## 3.2. *Discussion*

Initially, in response to land degradation and forest loss many countries across SEA adopted a land sparing type policy contrasting to the land sharing policy of social forestry (Vongvisouk et al., 2016; Fox et al., 2009). This involved government demarcation of land into agricultural areas and forest or restoration areas, with associated village resettlement and land allocation. Promotion of the privatization of land at the expense of communal and traditional systems often resulted in increased state authority over land rights (Fox et al., 2009). By allocating land and giving tenure, states hoped to promote a shift to permanent and commercial agriculture (Castella et al., 2013). In forested land, tenure is seen as a strategy to incentivize the sustainable management of forests, with some evidence suggesting that deforestation is reduced in communities that have land tenure (Kusters and Graaf, 2019). However, a lack of

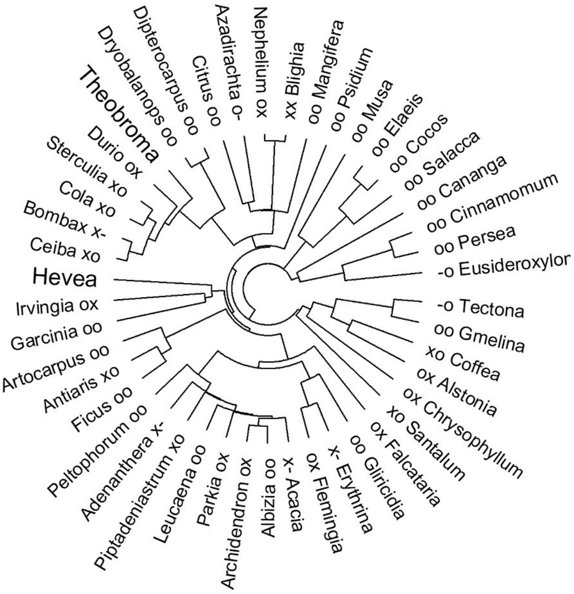

**Fig. 2.** Phylogenetic tree of 46 tree genera found in or recommended for cocoa and rubber agroforestry systems in Indonesia. Symbols represent co-cultivation status where: o = desirable, x = not desirable, - = unknown. Following text directionality, *Theobroma cocoa* is positioned first and *Hevea brasiliensis* second.

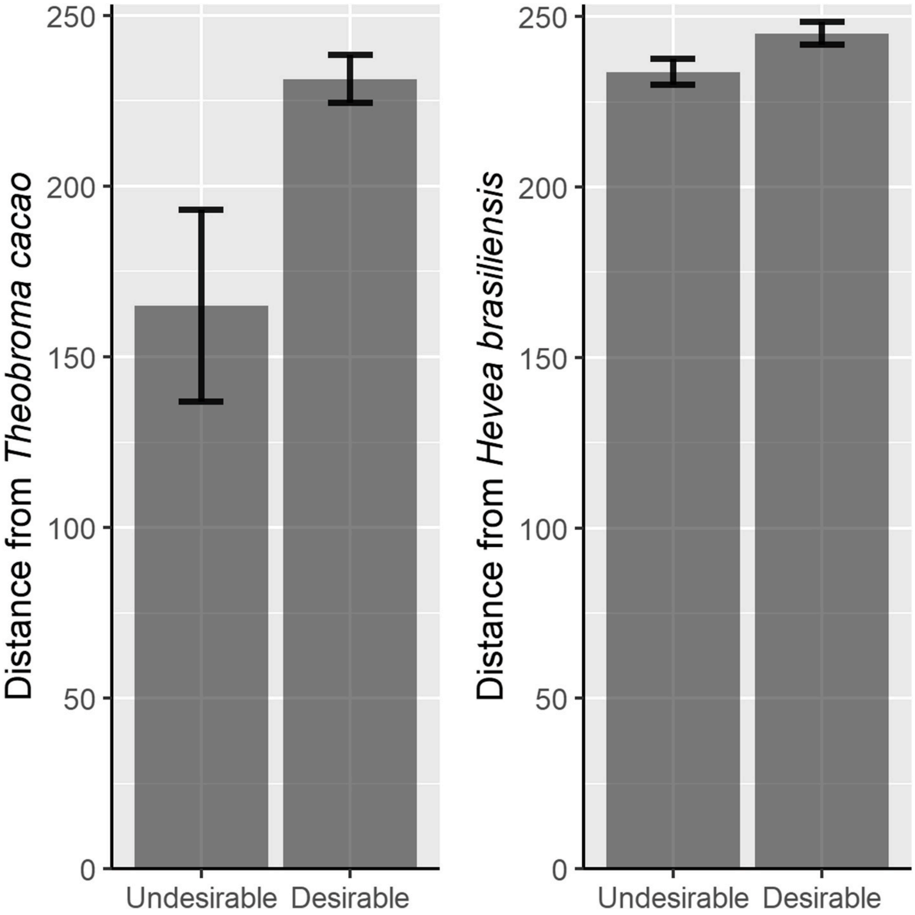

**Fig. 3.** The mean ± SE phylogenetic distance of potentially cultivated genera from *Theobroma cacao* and *Hevea* brasiliensis by desirability status. The mean phylogenetic distance of desirable genera was significantly higher than undesirable genera for cocoa (F = 11.52 p = 0.0015) but not for rubber (F = 3.342, p = 0.076).

support in establishing permanent agriculture, sustainable forest management or the provision of economic alternatives means communities were often unsuccessful in this transition and reverted back to unsustainable slash and burn practices (Castella et al., 2013; Cramb et al., 2009). Additionally, the conservation aspect of land sparing was sometimes forgotten (Vongvisouk et al., 2016).

Social forestry represents a progression that addresses many of the shortcomings of these previous policies, one with communities at the heart of a sustainable transition. Yet, success for both the communities and the environment still depends on developing effective land use strategies within the social forestry framework. This paper argues for diversified agroforestry as a desirable way forward due to its potential for multifunctionality, resilience and growing economic prospects.

While there remain significant issues with diversified agroforestry, particularly economic ones relating to marketing and value chains, through strategies such as the formation of cooperatives, these are not insurmountable. One of the issues, how to diversify in a way that does not overly decrease yields while also promoting a range of ecosystem services, is tackled in this paper. Two methods are presented, one based on delineating functionally distinct groups via trait dissimilarity, and the other based on phylogenetic distance, both of which act as proxies for identifying niche complementarity between species. Each will be discussed in turn in the following sections.

### 3.3. Discussion of functional group delineation

By enhancing functional diversity and niche complementarity via the incorporation of more complementary species selected according to their functional group, an agroforests multifunctionality may be enhanced. Using consensus hierarchical clustering based on trait dissimilarities, the species found in 159 current agroforests in Indonesia were delineated into functional groups that may aid in informing management decisions.

From the 66 species in this study, five functionally distinct groups were identified, with group 1 containing the majority of species (31, see Table 1; Fig. 1) suggesting substantial redundancy within the given species pool. The traits that were most important in the group divisions were leaf nitrogen content (and associated nitrogen fixing ability), height, and DBH, with leaf phenology likely having a weaker but notable influence (Table 1). The fact that SLA and wood density did not influence functional group placement is interesting considering the results of Kunstler et al. (2016) where dissimilarities in these traits did not influence competitive interactions amongst a large number of trees. However, as wood density is related to carbon sequestration (Thanh Nam et al., 2018), selecting species with high wood density wood be advisable if this goal is targeted.

The functional groups delineated often correspond to management uses, product types as well as the provision of specific ecosystem services. Group 4, which includes coffee, is characterised by small, evergreen trees, with many being shade tolerant -according to online encyclopaedias (see section 2.1.1)- and bearing edible fruits (Fig. 1). This contrasts to group 5 with larger deciduous trees -including rubber-many of which are used for timber. Groups 2 and 3 contain the majority of nitrogen fixing species with high leaf nitrogen content. Group 3 contains the taller species that may be suitable as nitrogen fixing shade trees while group 2 contains the smaller trees, often fast growing, that may be useful for the production of green manure, restoration or potential fallow periods. Due to the large number, group 1 is hard to generalize but contained many tall evergreen trees.

Clearly species from each group must be matched to local environmental conditions, but given the number of species in each group, managers have sufficient options for achieving high functional group richness in each site. The number of groups identified in this study also corresponds well to previous studies showing diminishing returns to ecosystem service provision with increasing species richness. Storkey et al. (2015) found a plateau at four species and Zhang et al. (2012) at six species. Therefore, aiming to incorporate a species from the five functional groups identified could potentially increase the complementarity effects necessary for improved multifunctionality. Further, evenness between functional groups should be considered since, at least in ecosystem services related to leaf litter mixtures, the evenness between functionally distinct species was identified as a key facet explaining multifunctionality (Bagousse-Pinguet et al., 2021).

Since the functional groups identified correspond to different commodities and services, by basing diversification on these functional groups, farmers would at least benefit via diversified income or improved environmental conditions (soil or microclimate improvements, for example). While in theory species selected from different functional groups should grow well together due to complementarity, the statistical rather than mechanistic nature of the results means they cannot supplant local expertise and traditional ecological knowledge. Indeed, if this framework is implemented, the aforementioned expertise and knowledge should feedback into the framework if possible. However, in spite of these further considerations, priority is still placed on species' use value and thus does little to attenuate the dichotomy between winner and loser plants identified by Kress and Krupnick (2022). While species without direct use value could easily be incorporated into this tool, facilitating social and political conditions need to be in place to promote the "losers".

Evidence for a link between functional diversity, ecosystem services and multifunctionality is well established (Santos et al., 2021; Mouillot et al., 2011, Schuldt et al., 2018; also see box 1). That being said, whether delineating and optimizing the number and perhaps evenness of functional groups relates to increased yields from multiple commodities and multifunctionality should specifically be assessed. Multifunctionality and niche complementarity are also likely to depend on agroforest management, such as pruning and planting density as well (Niether et al., 2018; Tscharntke et al., 2011; Hosseini Bai et al., 2017). Therefore, the interaction with management variations should be modelled along with manipulations of functional group richness in order to optimize yield and multifunctionality outcomes. Trade-offs between ecosystem services also occur (Tschora and Cherubini, 2020) and the tools in this paper are unable to give any indication of these trade-offs, l*et al*one reconcile them. However, the traits selected for use with the framework should be based on resource capture as well as traits that relate to the set of ecosystem services that wish to be promoted in any given situation.

While highlighting the importance of trait selection it is important to acknowledge that the selection of traits used in this study was limited by data availability. In order to accurately assess complementarity and functional distinctness, a species' niche has to be precisely identified using an appropriate selection of traits (McGill et al., 2006). A crucial omission was the absence of any root-associated traits which are critical for complementarity in agroforests (Isaac and Borden, 2019) and for the provision of many ecosystem services (Bakker et al., 2019). Also, leaf and branch traits other than those used in this study are crucial for determining competition for light and its influence on complementarity (Yachi and Loreau, 2007). In this study each species' niche was only approximated by the limited selection of traits, and with more trait data many of the outcomes may have differed. For example, the optimal number of functional groups identified may have increased as species become more functionally distinct by the inclusion of root traits.

### 3.4. *Discussion of phylogenetic distance*

Assessing species based on their phylogenetic distance is comparable to functional group delineation in that it enables the identification of complementary species for cultivation.

Like with the functional groups identified, species suitable for cultivation alongside rubber and/or cocoa according to phylogenetic distance had specific additional uses and functions in agroforestry. Amongst the 20 tree genera that were identified as 'desirable' for both species, 10 were food crops such as *Cocos* spp*, Musa* spp. Timber trees, such as *Dryobalanops and Peltophorum* spp. Were also among the genera that were classified as desirable for both as well as Nitrogen fixing trees such as trees of the genera *Albizia* and *Gliricidia*.

As initially hypothesized, phylogenetic distance between the shade tree genera and cocoa was significantly higher for the shade tree genera classified as 'desirable' (Fig. 3). These results add to the evidence recommending phylogenetic distance as a useful tool for complementary diversification (Sauvadet et al., 2020). Nevertheless, the original hypothesis was rejected for rubber, as the phylogenetic distance between rubber and its secondary trees classified as 'desirable' was not significantly higher (Fig. 3). A follow-up analysis based on differences in species functional traits might help to gain further insight as to why this is the case. One possible explanation for the mixed results found in this study is that this assessment tool may be more suitable for shade trees for understory tree crops such as cocoa or coffee, rather than overstory trees such as rubber. Further research is needed to confirm this, but initially it seems that additional shade tree genera recommendations could be made based on their evolutionary distance to cocoa. However, further assessments of desirability for co-cultivation are also necessary to confirm the use of such an approach as just in this study's selection seven species had an unknown desirability status.

An advantage of this tool is that it may account for unmeasured trait and feature variation (Owen et al., 2019), and requires only information on the phylogeny of species in question. However, it does not directly account for the precise properties of a species that make it desirable or undesirable, as functional trait information could. Also this analysis depended on the pre-classification of genera's desirability and further studies on a broad array of agroforestry genera must be made before recommendations can be made without pre-classification. Finally, a tool based on phylogenies may not be intuitively comprehensible and/or meaningful to all agroforest managers.

### 3.5. *Potential of the tools for diversification*

The tools presented above, while useful for identifying potential species for diversification, are theory-based. Before actively cultivating additional species based on these tools, it would be prudent to use modelling software to assure the potential of co-cultivation, especially given variation that may occur due to site specific conditions. Many modelling software exist for such a purpose, including WaNuLCAS, Hi-sAFE, SCUAF, APSIM and Epic (see Kraft et al., 2021 for information and further examples). Generally these models dynamically represent the aboveground and belowground interactions between intercropped species such that competition and complementarity can be predicted based on outcomes of resource capture. In doing so, predictions of yields can be made. Further modelling software, in addition to a few of the above, focus more on modelling ecosystem service provision given set species combinations, which may also be useful if ecosystem services are a focus. Models such as ModEST, developed and applied by Fiedler et al. (2021) are especially suitable for such a purpose given its use of plant functional traits (see box 1).

While the example in this paper focused on woody species in the context of agroforestry, these tools could separately or additionally incorporate other crops and weeds. Indeed, these tools could be applied to any agroecosystem or silvicultural system, as well as to ecological restoration efforts where similar approaches to those in this paper have already proven useful (Ostertag et al., 2015). In spite of this, further discussion will still focus primarily on agroforestry.

As seen in 1.2,diversification can be very beneficial within agroforestry and the broader landscape context. However, planned diversification is important, which is where the tools in these paper prove useful. In linking plant community diversity with insect diversity, Schuldt et al. (2019) demonstrated that increases in insect diversity are strongly mediated by increasing functional and structural diversity. From this it can inferred that diversification without increases in functional and structural diversity could have poorer diversity outcomes at higher trophic levels. Consequently, delineating functional groups may be especially useful for two reasons: by increasing the number of functional groups in a given system, functional diversity is almost assuredly increased; and, given that many functional traits are linked to structural characteristics (e.g. height, crown traits, diameter at breast height) concomitant increases in structural diversity can be expected. This highlights the need to include such traits in order to increase the effectiveness of implementing this method, as well to further investigate which functional traits correlate with structural diversity.

Diversification cannot optimize all factors however, and trade-offs are unavoidable (Tschora and Cherubini, 2020). This may also be the case with habitat provision. For example, teak agroforests are capable of supporting some ungulates and primates but not others (Oliveira et al., 2019). Perhaps other types of agroforests would be capable of supporting those species not supported by teak agroforests, but landscape scale planning and cooperation would be necessary to ensure this. Therefore, when planning diversification a set ecosystem services and conservation targets should be defined so that the specifics of diversification can be designed to optimize these goals at the expense of others in a given landscape. At a landscape scale, benefits are likely to accrue if agroforests are diversified in different ways with different species, although further research is needed to determine appropriate ways of doing this. If farmers' coopertives are initiated that encompass farmers from entire landscapes, planning on this scale could be feasible but should then be compensated and promoted by landscape scale certifications such as those proposed by Ghazoul et al. (2009) and Tscharntke et al. (2014).

Studies assessing the relationship between yield and biodiversity and/or ecosystem service provision in agroforests and other agroecosystems have occasionally found no relationship and often include sites with high yields and high diversity/provision and lower yields with low diversity/provision (Clough et al., 2011; Andreotti et al., 2018; Tamburini et al., 2020). Thus, assessing the differences between sites with different yield and diversity outcomes may provide valuable insights into how to maintain high yields in high diversity systems. The difference between high yield and low yield sites that have high biodiversity could be attributed to management as well as niche complementarity, and the tools detailed in this paper should be applied to studies including yields (also in a broad sense by incorporating secondary products and non-commodity goods as well as quality differences) in an attempt to disentangle these contrasting observations.

Regarding applicability, it would be feasible to use the tools from this paper to create regional recommendations that could be dispersed by extension officers, cooperatives and organizations that operate in SEA such as ICRAF, CIFOR and RECOFTC. Given a regional species pool, adequate trait data and/or a phylogenetic tree, one could delineate each species into a functional group or ranking based on phylogenetic distance. With a preprepared R script, anyone with intermediate ability in R statistical programming (R Core Team, 2022) would be able to perform the necessary analysis. This increases the potential for wider use of these tools compared to more complex models that would be limited by expertise and computational capacity. If these results are combined with information on species commodity and non-commodity values, farmers could diversify their farms in a way that improves complementarity and multifunctionality by selecting species from each functional group in combinations that suite them. Ideally, broad habitat suitability information would be included with each species so selections can be based on individual local conditions. Traditional ecological knowledge should also feed into this system to ensure legitimacy and increase adoption.

## 4. Conclusions

Depending on future management scenarios the economic value of ecosystem services is estimated to decline by 51 trillion USD/year or increase by 30 trillion USD/year (Kubiszewski et al., 2017), and SEA is well positioned to capitalize on the latter. The latter scenario can be achieved if policies like social forestry that enable the success of the UN sustainable development goals are followed with effective implementation. Agroforestry has been identified as a suitable agricultural system for progress towards the UN sustainable development goals (Waldron et al., 2017), but, as identified in this paper, must be facilitated with appropriate market mechanisms so diversification is not at the expense of livelihoods. This paper presents tools that can aid in simply and reliably enabling the diversification of agroforests without necessarily compromising yields while also having the potential to improve multifunctionality. Additionally, these tools may aid in the disentanglement of variability in yield, biodiversity and/or ecosystem service provision relationships. If foundation projects in agroforestry, like that presented in Santos et al. (2021), continue to experimentally demonstrate a link between functional diversity and complementarity with sufficient yield and multifunctionality, then simply assessing the functional diversity of an agroforest is likely to be the quickest and most feasible way to evaluate the multifunctional value of an agroforest. If these tools were already established, the simplest evaluation would be to assess the number of functionally distinct groups or the phylogenetic diversity in a given agroforest as an indicator for its potential ecosystem service provision. This would be implementable by all involved stakeholders and the subsequent management recommendations could be as simple as increasing the evenness of functional groups or adding species from additional groups or that are phylogenetically distant. Crude tools such as this, if widely applied, have the potential to greatly increase the multifunctionality of agroforests and therefore aid in progress towards the UN sustainable development goals and SEAs social forestry initiatives.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The authors do not have permission to share data.

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