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Identifying indigenous tree species for land reforestation, forest restoration, and plantation transformation on Hainan Island, China

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Abstract: Selecting suitable species is the most important issue for bare land reforestation, degraded secondary forest restoration, and single-species plantation transformation. However, little information has been documented related to tree species selection for these silvicultural endeavors on tropical Hainan Island of Southern China. The present study employed Baisha County, the ecological core area of Hainan Island, as a case study area. We initially inventoried a slightly disturbed primary forest and attempted to produce diameter distribution curves for each tree species. Second, the tree species were classified into shade intolerant, opportunist, and shade tolerant species based on shape of their diameter distribution curves. Third, market value was determined for each tree species based on published literature and on-site investigations at local wood trading companies. Totally 118 tree species were encountered in the inventoried forest and 13 tree species present were finally identified as potential tree species for our silvicultural endeavor on Hainan Island, of which 3 species are shade intolerant, 5 species are opportunist and 5 species are shade tolerant. Additionally, we also selected 12 tree species that were not in the inventoried forest but were extremely economically valuable and ecologically important. This study should contribute to the formulation of a sustainable forest management strategy on Hainan Island and the methodology might be replicated in other tropical region where suitable species also need to be identified for silvicultural endeavor.

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Introduction

The State Forestry Administration of China has accomplished the afforestation of 241 million ha in the past 60 years in an unprecedented effort to increase forest cover in China from 8.6% in 1949 to 21.6% in 2013 (Zeng et al. 2015; Song and Zhang 2009). The initial goal of the afforestation was only timber production and this stage lasted from 1949 to the late nineteen seventies. Facing worsening environmental problems and increasing demands for ecological benefits from forest ecosystems, the objective of afforestation has gradually started to focus on ecological functions (e.g., carbon sequestration, soil and water conservation and watershed protection) rather than only on timber production (Shao 2003; Li 2004; Meng et al. 2014). However, these recently established forests are mainly pure plantations and only a very few tree species have been planted. For instance, China Fir (*Cunninghamia lanceolata*) now covers 9.215 million ha and accounts for 28.53% of all forested area in China (Liao and Zhao 1999). The planting of these monocultures has been criticized because they are often not ecologically stable forests, provide a low level of ecological services, and they are highly susceptible to disturbance (Gärtner and Reif 2004; Felton et al. 2010; Meng et al. 2014; Forrester et al. 2006a; Richards et al. 2010). Correspondingly, reforestation with mixed tree species has more recently been widely proposed and adopted. Many authors have documented the advantages of mixed-species plantations from both ecological and economic perspectives (Piotto et al. 2010; Petit and Montagnini 2006; Redondo-Brenes and Montagnini 2006; Forrester et al. 2006b). For instance, Piotto et al. (2010) compared the growth and economic viability of 15–16 year-old trees of native species in pure and mixed-species plantations on degraded pasturelands and found that the mixed-species plantations outperformed pure plantations in terms of growth and economic benefits. Forrester et al. (2006b) reported that mixed-species plantations of *Eucalyptus* with a nitrogen-fixing species had the potential to increase productivity while maintaining soil fertility, when compared with *Eucalyptus* monocultures.

Additionally, transforming existing single-species plantations into more irregular uneven-aged stand structures of multiple species has also been widely adopted as a promising approach to multi-function forest management (Seeling 2001; Harmer et al. 2012; Adams et al. 2011; Gärtner and Reif 2004). The successful transformation effects of multi-species plantations have been reported worldwide in terms of improved economic and ecological conditions in forest stands (Gärtner and Reif 2004; Haywood 2002; Yang et al. 2009; Meng et al. 2014). One notable example in China was the transformation of *C. lanceolata* plantations into irregular mixed-species forests by introducing seedlings of more than 20 indigenous hardwoods into the Tropical Forest Research Center, in Southern China. The encouraging transformation effect was reported by Stone (2009).

In addition to plantations, the natural forests of China cover 122 million ha and account for 58.65% of the total forest area, according to the 8th Chinese National Forest Inventory (SFA 2014). Intensive forest exploitation, which includes local harvesting, unregulated logging and even illegal logging, in the past several decades means most of these natural forests are now secondary forests. For example, Zaizhi (2001) documented that secondary forests occupied 86.1% of all natural forests and 31.5% of the forestland in tropical China. These degraded forests are of extremely poor quality and productivity. Moreover, they have also lost much of their ability to serve ecological functions, e.g., wildlife habitat (Li 2004; Liu et al. 2001; Yin 1998), watershed protection (Lu et al. 2001; Weyerhaeuser et al. 2005), and carbon sequestration (Zhang and Xu 2003). Therefore, restoration of such forests is another important issue facing Chinese foresters. Many reports have documented technical efforts that have been made to restore the poor structure of secondary forests (Holl et al. 2000; Aide et al. 2000; Parrotta et al. 1997; Corbin and Holl 2012; Reid et al. 2012; Meng et al. 2011). Among them, enrichment planting has generally been regarded to be a promising pathway to accelerating the natural process of succession for restoration purposes (Aide et al. 2000; Ashton et al. 2001; Shono et al. 2007; Mansourian et al. 2005).

Indigenous tree species are frequently identified as the most natural solution for establishing new mixed-species plantations, transforming single-species plantations into mixed irregular forests, and restoration of degraded secondary forests(Larsen 1995; Haggar et al. 1997; Lamb et al. 2005); however, considerable knowledge gaps remain with respect to the most appropriate silvicultural characteristics for most indigenous tree species. A great amount of research and most practical experiences, not only in China, have focused on a few fast growing non-native species such as *Eucalyptus*, *Acacia* and *Pinus* species. However, knowledge of indigenous tree species remains limited and insufficient information related to proper silvicultural planning is lacking. Two basic approaches exist to research the silvicultural characteristics of tree species, namely, (1) the experimental approach through species trials, and (2) the observational approach by inventorying and analyzing the structure of natural forests (McLeod 2000). The experimental approach allows for directly testing the effect of specific treatments and is a long-term and costly endeavor. In the observational approach, the currently observed forest structure is interpreted as a result of manifold natural processes and the researcher strives to understand those processes by observing and analyzing the current forest structure (Bonino and Araujo 2005). Primary forests, otherwise known as old-growth forests, are climax communities and are frequently investigated and analyzed to provide basic and applied information related to conservation biology and forest restoration (Foster et al. 1996; Meng et al. 2011; Zhao et al. 2012). For instance, based on the species composition and structure of old-growth forests, Meng et al. (2011) formulated detailed and concrete management strategies for restoring two degraded secondary forests in different successional stages. In spruce-fir mixed primary forest, Zhao et al. (2012) examined tree species interactions to determine the optimal enrichment plantings needed in each one.

In this present study, we employed Baisha County, the ecological core area on Hainan Island in Southern China, as a case study area. The objective of this study is to 1) identify light requirement-based characteristics for a number of indigenous tree species by inventorying and analyzing slightly disturbed old-growth forests; 2) select suitable indigenous tree species and formulate the relevant management strategies for bare land reforestation, degraded secondary forest restoration, and single-species plantation transformation, based on market value and light demand characteristics of each tree species.

1 Materials and Methods

1.1 Study area

The study area, located in Baisha County (18°56'–19°29'N, 109°02'–42'E) in the center of Hainan Island, South China (Figure 1), experiences a tropical monsoon climate that provides an annual average air temperature of 17°C to 36°C (mean 23.6°C). The annual precipitation ranges between 1500 and 2000 mm (mean 1750 mm). The research was conducted in the mountainous northern part of the county, where elevations range between 800 and 900 m and on slopes between 8.7° and 26.8°. Granite and sandstone dominate the parent rocks with primarily a lateritic mountain soil supporting

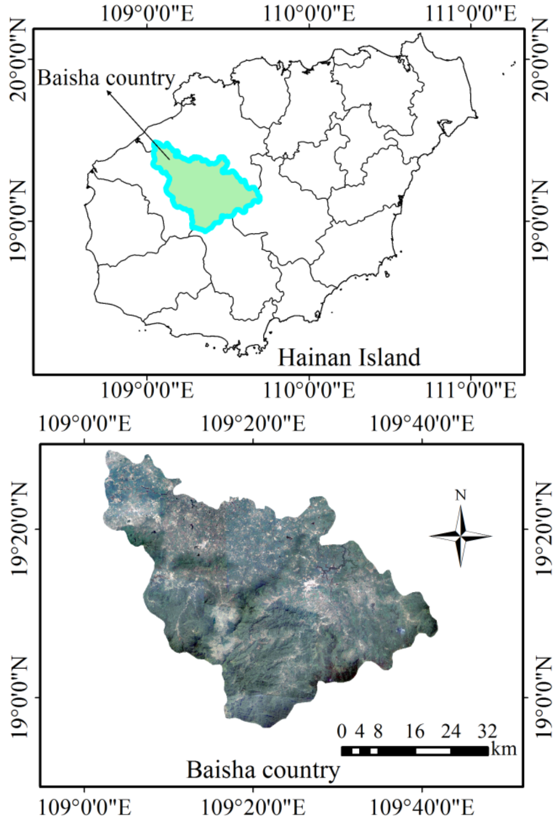

Figure 1 The location of the research area in Baisha County, Hainan Island, South China.

the forest (Meng et al. 2011). The tropical mountain rain forest we inventoried lies far away from human settlements and historically it has not experienced major human interventions. In 1994, the Hainan provincial government banned all logging in natural forests (Zhang et al. 2000). Since then, this forest was under particularly strict protection and so it could represent the zonal vegetation and could be regarded as "primary forest."

1.2 Plot establishment and data collection

In the primary forests, we established ten 10 m × 100 m transects that were each subdivided into ten 10 m × 10 m subplots in representative areas of the slightly disturbed primary forests. The representative area, which have a 2-3 km buffer zone from the forest edges, lies in the central part of the slightly disturbed primary forests. This area was determined and investigated with the help of the local villagers. All free standing trees with diameter at breast height (dbh, 1.3 m above the ground) ≥ 5 cm were considered sample trees and identified to species level. The dbh, height, and location of each tree was recorded. It was noteworthy that the potential limitations of capturing each of this plots in a single point in time would be important because our forests was not static and there is likely much variation through time in a given plot due to tree mortality, blowdown, etc. However, we assumed a constant equilibrium and a predictable climax state in each site.

1.3 Tree species classification according to light demand characteristics

Following Swaine and Hall (1983), Lamprecht (1989), Richards (1996) and Quoc (2008), we used a diameter distribution curve to classify tree species into shade intolerant, shade tolerant, and opportunist species. The descriptions of the three types of tree species were as follows:

Shade intolerant species are usually pioneer species that easily regenerate and become established in larger stand gaps or on open areas with an abundance of sunlight. These species are well suited for planting in sufficiently large gaps or in open areas and therefore are potential candidates for bare land reforestation. The typical form of a diameter distribution is bell-shaped (Figure 2).

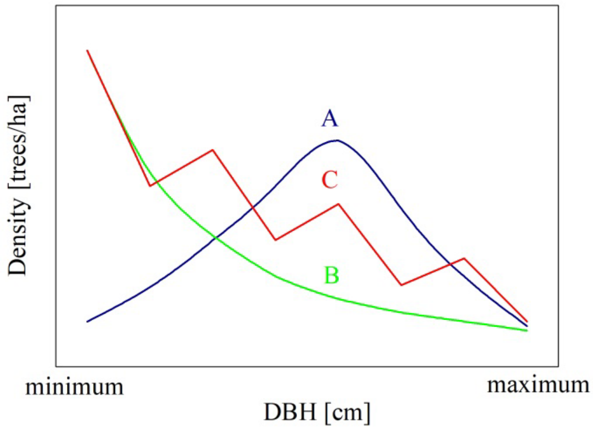

Figure 2 Diameter distribution of the typical shade intolerant (A), shade tolerant (B), and opportunist species (C).

Shade tolerant tree species can regenerate in moderate shade, usually occur in larger numbers in the understory of forests than shade intolerant species, and survive many decades in the interior of stands with virtually no growth whatsoever; both young and older shade tolerant species are frequently found in the shaded understory of forests (Poorter 2004). The diameter distribution of this group generally exhibits an inverse J-shape (Figure 2). Shade tolerant species are particularly suited for planting under the canopy during the restoration of degraded natural forests.

Opportunist or non-pioneer shade intolerant species are species with intermediate light demand and can regenerate in or even require shade for germinating seedlings but require more light when mature (Hill and Curran 2003). The diameter distribution typically exhibits an inverse J-shape in general but with fluctuations as the dbh increases (Figure 2). Opportunist species are suited for all types of restoration of degraded secondary forests and single-species plantation transformation.

The distributions of the diameters of various tree species can only be reasonably evaluated when a minimum number of observations are provided for each species. Therefore, in the present study we set ten as the minimum number, meaning that diameter distributions were not provided for tree species with fewer than ten individuals. Diameter distributions of the eligible species were then graphed and visually classified into the three distribution types to determine the light demand characteristics of each type: bell-shaped, inversely J-shaped, and inversely J-shaped with fluctuations patterns.

1.4 Structure of this study

From the structure of the slightly disturbed primary forests we wished to infer the light demand characteristics of each tree species. Additionally, the market value of each tree species should also be considered during the final determination of species suitable for silvicultural endeavor. We grouped the tree species into five economic categories base on the typical sale prices at the local woodlots and following Liang (1999) and Wang (2006), who determined the economic value of the tree species by carefully evaluating the physical characteristics and the potential usage at markets. These five categories range from the highest economic value (superfine) to moderate economic value (third category) to very low or little economic value (fifth category). The nomenclature of Latin names for all tree species follows a regional flora (http://gjk.scib.ac.cn/hnzwz/result.asp?keyword; accessed July 2017).

Consequently, our study included:

1. An inventory of a natural undisturbed forest or slightly disturbed forest (study area);

2. An analysis of the diameter distribution per species in order to assign each species to one of the three classes based on light demand characteristics; this could only be done for species where ten or more trees of a particular species were observed;

3. Identification of the market value of each tree species;

4. Identification of suitable species and formulation of suggestions for their application to bare land reforestation, degraded secondary forest restoration, and single-species plantation transformation.

2 Results

2.1 Stand structure and identification of species light characteristics

A total of 1499 live stems (dbh ≥ 5.0 cm) were recorded representing 118 tree species of 41 families in the slightly disturbed primary forest study area. The diameter distribution of all trees when lumped together showed an "inverse J-shape" (Figure 3). For each tree species, we tried to group each tree species into 5-cm diameter classes to produce a diameter distribution, and attempted to identify the light demand characteristics of each species. However, the light characteristics for some species could not be identified because an insufficient number of trees were available (less than 10 individual trees) or the trees of a particular species only fell into a few dhh classes (e.g., 1 or 2 dbh classes). The diameter distribution and relevant light demand characteristics for each tree species are listed in the Appendix.

The ten most frequently encountered species, making up 59.6% of the total basal area, are depicted in (Figure 4). From a silviculturists' perspective, these ten species could be good candidates for our silvicultural endeavor and should be given priority, though they might not be necessarily the most promising ones with different objectives. Of these ten most important species, three were identified as shade intolerant species (*Engelhardia roxburghiana*, *Castanopsis fabri* and *Commersonia bartramia*), three as opportunist species (*Cyclobalanopsis nemoralis, Castanopsis hystrix* and *Artocarpus styracifolius*), and four as shade tolerant species (*Castanopsis hainanensis, Garcinia multiflora, Cleyera japonica* and *Castanopsis carlesii*).

2.2 Identification of potential restoration candidate tree species

Each tree species was also assigned to an economic category based on its economic value (Appendix). Among the first ten most frequently encountered species, six tree species belonged to the first three economic categories as follows: *E. roxburghiana* and *C. hystrix* (first economic class),

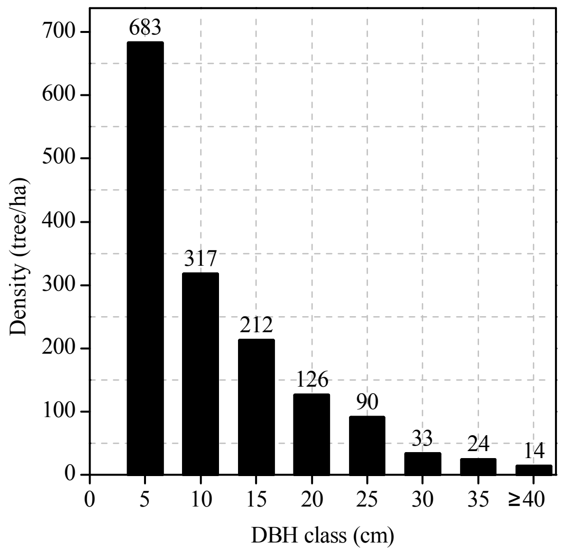

Figure 3 Diameter distribution of the inventoried primary forests in Baisha County, Hainan, China

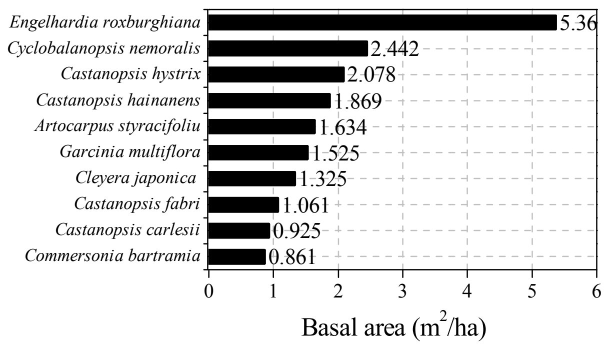

Figure 4 Basal area for the ten main species in the inventoried primary forests in Baisha County, Hainan, China.

C. nemoralis, *C. hainanensis*, and *A. styracifolius* (second economic class), and *C. japonica* (third economic class). These six species were hence given to first priority for the identification of species suitable for restoration work in the present study. Furthermore, based on the results presented (Appendix 1), we also identified seven other species, although they did not constitute a large amount of the basal area in the forest.

3 Discussion

In the present study, based on sampling data we identified the light demand characteristics for certain tree species, which have at least ten individuals, i.e., the minimum number, in our plots. However, more than 70% of tree species did not have sufficient individuals to infer light characteristics requirements. Moreover, even for the tree species with individuals more than the minimum number, this low simple size might naturally lend itself to the appearance of "opportunist"-shaped curves over smooth, inverse-j distributions. Additionally, in our sampling data low number of tree species with high economic value and no nitrogen fixing species were found. However, based on sampling data we found potential good candidates although not in a considerable number.

Additionally, based on published research and the experience of local foresters, we selected another set of species that were not in this inventoried forest but were extremely economically valuable and ecologically important for bare land reforestation, degraded secondary forest restoration, and single-species plantation transformation in this region. *Dalbergia hainanensis*, *Homalium hainanense*, *Hopea hainanensis, Madhuca hainanensis* and *Litchi chinensis* represent the five superfine commercial wood tree species on Hainan Island. In addition, *Acacia dealbata*, *Albizia odoratissima*, *Gleditsia microcarpa*, and *Pithecellobium lucidum* are indigenous nitrogen-fixing species, which have the potential to improve soil fertility. *Acacia mangium*, *Eucalyptus robusta*, and *Pinus caribaea* are the currently commonly used tree species for plantation establishment. Although these tree species were not found in the primary forests during the present study, their light characteristics and economic value were identified based on published literature as well as the on-site investigation at local wood trading companies. All of the selected species are listed in (Table 1).

3.1 Tree species selection for plantation establishment

Forest plantations are artificially established stands in which wood is produced as a raw material with methods that are more closely related to agricultural systems of cultivation than to traditional silvicultural methods (Lamprecht 1989). Initially, the objective of creating a plantation is primarily timber production by using mostly fast-growing tree species. Therefore, the rapid growth of tree species is given top priority regardless of whether it is native or exotic tree species. The typical fast-growing tree species, which are exotic tree species for most countries, e.g., E. robusta, A. mangium, and P. caribaea, are widely used worldwide to establish single-species plantations.

However, the establishment of mixed-species plantation has been receiving a greater amount of attention over time worldwide. Additionally, instead of fast-growing exotic tree species, recently more attention is being given to indigenous tree species, that are expected to be better adapted to local site conditions and offer a broader diversity of valuable forest products (Leopold et al. 2001; Paquette et al. 2009). In this case, we recommended the local indigenous shade intolerant species as the potential candidates for reforestation on bare land. These include *D. hainanensis* and *M. hainanensis* (superfine economic class), *C. nemoralis* (first economic class), as well as *E. roxburghiana*, and *Adinandra hainanensis* (third economic class). Additionally, some of opportunists such as *H. hainanense* and *L. chinensis* (superfine economic class), *C. hystrix* (first economic class), and *A. styracifolius* (second economic class), may also be considered because some of these species have high plasticity and can regenerate in large open areas (Quoc 2008).

With the species mentioned above, we can either establish single- or mix-species plantations. Successful cases of establishing single-species plantations using indigenous tree species such as *Vatica astrotricha* (Xing 2004; Hao et al. 2011), *H.*

Table 1 Species identified as most promising for bare land reforestation, degraded secondary forest restoration, and single-species plantation transformation

Species	Light characteristics	Economic class	Rank of basal area	Nitrogen fixing
Tree species present in the forest inventoried				
Engelhardia roxburghiana	SI	third	1	no
Cyclobalanopsis nemoralis	SI	first	2	no
Castanopsis hystrix	OP	first	3	no
Castanopsis hainanensis	ST	second	4	no
Artocarpus styracifolius	OP	second	5	no
Cleyera japonica	ST	third	7	no
Cinnamomum parthenoxylon	OP	third	15	no
Adinandra hainanensis	SI	third	19	no
Syzygium chunianum	ST	third	26	no
Castanopsis kerrii	ST	second	28	no
Sarcosperma laurinum	ST	third	31	no
Phoebe tavoyana	OP	third	34	no
Eurya nitida	OP	third	38	no
Tree species not present in the forest inventoried				
Dalbergia hainanensis	SI	superfine	-	no
Homalium hainanense	OP	superfine	-	no
Hopea hainanensis	ST	superfine	-	no
Madhuca hainanensis	SI	superfine	-	no
Litchi chinensis	OP	superfine	-	no
Acacia dealbata	SI	fifth	-	yes
Albizia odoratissima	SI	fifth	-	yes
Gleditsia microcarpa	SI	fifth	-	yes
Pithecellobium lucidum	SI	fifth	-	yes
Liquidambar formosana	SI	fifth	-	no
Acacia mangium	SI	-	-	yes
Pinus caribaea	SI	-	-	no

Notes: SI: shade intolerant species; ST: shade tolerant species; OP: opportunist species; -: data not available.

hainanense (Li et al. 1999; Song et al. 1980) and *Gmelina hainanensis* (Li et al. 1999) have been documented on Hainan Island. However, mixed-indigenous plantations have unfortunately not been reported on this Island, even though a large body of relevant studies have been documented in other areas of South China (Bauhus et al. 2004; He et al. 2013; Wang et al. 2008; Wang et al. 2011). Therefore, exploring reasonable species combinations of indigenous tree and silvicultural techniques will require further study on Hainan Island.

When compared with the original definition, the concept of plantation forestry is now seen in a much broader context. For instance, Parrotta et al. (1997) argued that plantations can be considered as a 'catalytic technique' to 'jump-start' succession towards climax forests. In other words, plantations can be employed to modify both physical and biological site conditions and hence facilitate forest succession. Actually, many authors had advised using a small number of fast-growing but short-lived tree species to create a canopy cover that shades out grasses and weeds, diminishes fire hazards, and facilitates the colonization of a site by a wide range of species from nearby intact forest (Lugo 1997; Parrotta et al. 1997; Leopold et al. 2001; Lamb et al. 2005). In this present study, however, rather than being colonized by the species from nearby intact forest, the created canopy covers are suggested to be transformed into mixed-species irregular forest by admixing indigenous tree species. In this case, the rapid establishment of a forest environment is undoubtedly given the first priority. *Engelhardia roxburghiana* and *Liquidambar formosana*, the native and relatively fast-growing tree species, is therefore a good choice to develop a forest environment. When the canopy closes, the conversion into a mixed-species forest may be tackled.

3.2 Tree species selection for plantation transformation

The first step in single-species plantation transformation is to regenerate a new age class or cohort of trees (O'Hara 2014). The shelterwood system has been widely adopted as a promising approach that can be used to generate new stand layers (Wetzel and Burgess 2001; Malcolm et al. 2001). Additionally, O'Hara (2014) documented the creation of gaps or openings as another simple approach to transforming single-species plantations into stands with a more complex structure.

In a shelterwood system, the first option using shade tolerant species and opportunists that can survive and tolerate shaded conditions, might be the optimal choice for enrichment planting, whereas shade intolerant species should be excluded because of their poor performance in low light conditions. Therefore, the following shade tolerant species and opportunists are recommended: *H. hainanense*, *H. hainanensis*, and *L. chinensis* (superfine economic class), *C. hystrix* (first economic class), *A. styracifolius*, *C. hainanensis*, and *Castanopsis kerrii* (second economic class), *C. japonica*, *Cinnamomum parthenoxylon*, *Eurya nitida*, *Phoebe tavoyana*, *Sarcosperma laurinum*, and *Syzygium chunianum* (third economic class). Of course, after a shelterwood cut, when sufficient light is available, shade intolerant species could also be considered for enrichment planting.

In the second option involving the creation of gaps or openings, because the understory is exposed to adequate light, O'Hara (2014) thought the creation of gaps may be particularly useful with shade-intolerant species. Because opportunists might require shade in a young stand (Hill and Curran 2003), we do not recommend them for enrichment planting as part of this approach. Therefore, the following shade intolerant species are recommended: *D. hainanensis* and *M. hainanensis* (superfine economic class), *C. nemoralis* (first economic class), and *E. roxburghiana* as well as *A. hainanensis* (third economic class). Note that in this option if the objective of transformation is only to achieve structural complexity, the creation of small numbers of gaps can be a promising option. However, if a consistent timber production is also demanded, then a regulated approach to the entire stand would require half of the stand be harvested in group cuts (O'Hara 2014).

3.3 Tree species selection for restoration of degraded secondary forests

A degraded secondary forest has an intact but degraded main canopy. In early or middle successional stages this kind of forest usually does not have many valuable tree species but is comprised of low-value, fast-growing species. Furthermore, fragmentation of the forest landscape and site degradation often causes seed dispersal to become problematic, especially for high-valuable tree species of late successional stages. Correspondingly, the rate of natural regeneration, which mostly consists of low-value, fast-growing species, could be also disappointing (Chazdon 2014; Aide et al. 2000). Enrichment planting with high-value, later-successional trees are therefore widely used to accelerate natural succession and hence finally reconstruct the degraded forest ecosystem.

The restoration of degraded forests may draw upon all valuable indigenous tree species because these forests have a wide span of canopy structure and a continuum of small gaps as well as extremely large openings. In other words, only for ecological goals, almost any tree species from our inventory plots could be a good candidate. However, we also want to increase the economic value when restoring the degraded secondary forests. Therefore, economic value is also given priority when selecting tree species. For large openings and forest gaps, similar to reforestation on bare land, we recommended the following indigenous shade intolerant species to fill the gaps or openings: *D. hainanensis* and *M. hainanensis* (superfine economic class), *C. nemoralis* (first economic class), *E. roxburghiana*, and *A. hainanensis* (third economic class). Hill and Curran (2003) documented that these shade intolerant species regenerated only under canopy gaps and hence thrived in secondary forests.

In contrast, in the understory, shade tolerant species and opportunists, that are able to survive and develop in shaded conditions, are recommended for planting in support of the economic and ecological improvement of degraded stands. The recommended tree species are: *C. hystrix* (first economic class), *C. hainanensis*, *A. styracifolius*, and *C. kerrii* (second economic class), *C. japonica*, *C. parthenoxylon*, *S. chunianum*, S. *laurinum*, *P. tavoyana*, and *E. nitida* (third economic class). Although opportunists can survive in or even require shade in young stands, they require intermediate light to survive beyond the early parts of their life cycle (Hill and Curran 2003). Canopy gaps should be created to promote the development of opportunists. Therefore, it seems necessary to purposely plant opportunists in the understory where selection cuttings are scheduled to generate canopy gaps at the same time when the opportunists need light. In contrast, since both young and older shade tolerant species are frequently found in shaded forest understory (Poorter 2004), so that canopy gap creation might not be a mandatory management treatment.

3.4 Application of nitrogen-fixing species and identification of optimal species combinations

In any type of landscape modification discussed here (bare land reforestation, degraded secondary forest restoration, and single species plantation transformation), introducing nitrogen-fixing tree species provide a promising pathway that can be used to improve soil fertility and possibly foster stand production. Actually, the promising effects of admixed nitrogen-fixing species has been reported by many authors (Forrester et al. 2006b;Kelty 2006;Rothe and Binkley 2001;Bouillet et al. 2008). For instance, Rothe and Binkley (2001) found that soil nitrogen pools were increased relative to those of monocultures when the mixtures included a nitrogen-fixing species, but generally no improvement was observed with non-nitrogen-fixing speciesForrester (2004). Forrester et al. (2006b) further argued that the admixture of nitrogen-fixing species not only improved soil fertility but also increased site productivity. Therefore, these nitrogen-fixing species are also given top priority, although they have very low economic value. In the present study, unfortunately no nitrogen fixing species were found in our sampling data. However, Huang et al. (2016) have recommended the following four indigenous nitrogen-fixing tree species, i.e., *A. dealbata*, *A. odoratissima*, *G. microcarpa*, and *P. lucidum*, which are shade intolerant, to improve soil quality on Hainan Island. They can be mixed with other shade intolerant species to reforest bare land or fill the openings or canopy gaps in degraded secondary forests. They could be also employed to transform single-tree plantations into mixed-species forests using the shelterwood system. However, these light demanding nitrogen-fixing species should only be planted at a certain stage of shelterwood cutting, when sufficient light is available to them to thrive. Although we did not find any nitrogen-fixing tree species with our sampling data, many authors have found nitrogen-fixing tree species with similar sampling technique (Roggy and Prevost 1999; Liao and Menge 2016; Menge et al. 2014). We therefore conclude that our technique could be useful in other areas to find nitrogen-fixing tree species.

The present study recommends suitable tree species for bare land reforestation, degraded secondary forest restoration, and single-species plantation transformation and discusses relevant silviculture treatments. However, the optimal combination of the recommended tree species has not been tackled in this study. Many studies have been reported investigating optimal species arrangements. For instance, using the O-ring function, Hao et al. (2007) examined the intra-species spatial relationships between adult and juvenile trees of different species, based on which optimal species arrangements were determined for enrichment plantings. Long et al. (2013) used size-distance regression to investigate the competition and facilitation between tree individuals of different tree species, in a way that could help to determine the optimal species assemblage. Meng et al. (2014) examined the transformation effects of a *Pinus massoniana* plantation using different enrichment planting alternatives, and found that the species combination of *Erythrophleum fordii*, *C. hystrix*, and *Magnoliaceae glance* showed a significant advantage over three other alternatives in terms of mortality rate. The knowledge obtained from these studies could provide significant information that could be used to formulate a *forest* management strategy. Therefore, the optimal species combinations of indigenous tree species and relevant silvicultural techniques will require further exploration, testing, and evaluation on Hainan Island.

In the present study, only the shape of the diameter distribution of each species and its economic value were involved during the identification of species useful in forest restoration. The two variables might be not sufficient for the best decision when selecting this type of suitable species. Other variables such as mode of seed dispersal, tree root characteristics, as well as sexual and asexual regeneration strategy could be studied in support of successful restoration species identification. For instance, Schroth (1995) reviewed the role of tree root systems for the functioning of agroforestry associations and rotations; then he formulated root-related criteria for the selection of agroforestry tree species and the design of agroforestry systems. Additionally, studies related to other factors such as landscape scale forest fragmentation should be also encouraged. Many previous works have shown the potential of many native species to grow successfully in altered environments. For example, Leopold et al. (2001) reported that planting mixed stands of native species was a good effort to stimulate the restoration of degraded forests which were idle or are coming up in scrub in Costa Rica.

4 Conclusion

In the present study, we reported the criteria and procedure of species selection and 25 native tree species were finally identified as potential candidates for bare land reforestation, degraded secondary forest restoration, and single-species plantation transformation. Furthermore, silvicultral techniques for these selected tree species were also proposed. We hope this study could contribute to the formulation of solid forest management regimes on Hainan Island. Additionally, we also hope that this research could be reproduced in other places where information about suitable species are also unknown.

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