Facilitation of Forest Landscape Restoration on Abandoned Swidden Fallows in Laos Using Mixed-Species Planting and Biochar Application

Sovu, Mulualem Tigabu, Patrice Savadogo and Per Christer Odén

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The cessation of swidden cultivation and the increasing trend of abandonment of swidden fallows have created an opportunity for forest landscape restoration. However, ways need to be found to improve the poor soil fertility at these sites with affordable materials and to generate short-term socio-economic benefits for small-scale swidden fallow holders. This study assessed the feasibility of using mixed-planting of eight native species and application of rice husk biochar as soil amendment measure at a site in Laos. The effect of biochar application was compared against addition of inorganic (NPK) fertilizer and the control. The establishment and growth of the planted seedlings was then monitored for four years. The addition of rice husk biochar and NPK fertilizer did not significantly ($p = 0.578$) improve the survival rate of planted seedlings, which ranged from 72% to 91% (depending on the species) compared to the control. No significant growth responses to the soil amendments were observed for most of the species during the first year after planting compared to the control. The biochar effect was, however, more evident at the fourth year for diameter ($p < 0.01$) and height ($p < 0.01$) of sapling for all species; particularly its effect was more vivid on the diameter of slow-growing species. The results indicate that the species tested in the mixed-planting showed marked growth variation while application of rice husk biochar boosted their growth. Thus, planting mixed-species in swidden fallows has potential to provide continuous supplies of wood from different species to diversify the livelihood of swidden field owners, while maintaining ecosystem services.

Keywords black carbon, charcoal, rice husk biochar, secondary forest, shifting cultivation
Addresses Swedish University of Agricultural Sciences, Southern Swedish Forest Research Centre, Alnarp, Sweden
E-mail mulualem.tigabu@slu.se
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1 Introduction

Forest landscape restoration, defined as 'a process that aims to regain ecological integrity and enhance human well-being in deforested or degraded forest landscapes', is being promoted by The World Conservation Union (IUCN), The World Wildlife Fund (WWF) and other partners as an approach to meet the challenges of ecosystem conservation and livelihood improvement (Pfund and Stadtmüller 2005). Unlike ecological restoration that primarily focuses on biodiversity conservation (Wangpakapattanawong et al. 2011), forest landscape restoration seeks to put in place forest-based assets that are beneficial for both people and nature simultaneously. The approach encompasses a flexible package of site-based techniques; ranging from management of secondary forests to establishment of plantations and management of on-farm trees, which together bring significant landscape-level impacts. The growing interests in forest landscape restoration in the Lao People's Democratic Republic (Laos) has been in large part due to the increasing abandonment of swidden (also known as slash-and-burn or shifting agriculture) fallows as a result of strict government policy to end damaging practices associated with swidden cultivation since the 1980s (Kingsada 1998) as well as the national forest policy that envisaged to increase the national forest cover to 70% by the year 2020 through establishment of plantations and natural regeneration of degraded lands including fallows.

Secondary succession generally proceeds relatively quickly during fallow periods (Sovu et al. 2009, Wangpakapattanawong et al. 2011), but it is unlikely that primary forest species will re-establish and the species composition will return to pre-disturbance states due to paucity of propagules (Nepstad et al. 1991, Schmidt-Vogt 2001) and depletion of soil nutrients in swidden fields (Lawrence et al. 2005). To achieve goals stipulated by the Laos Forestry Act, including meeting local populations' short-term needs for wood and the diversification of rural livelihoods, converting some of the small-scale swidden fallows to mixed-species plantations of native species may be a more viable (and reliable) option than simply relying on the natural regeneration of secondary forests, which is a common restoration practice today, and whose species composition fails to meet economic objectives (Sovu et al. 2009). Such an approach enables rapid capture and/or efficient use of the resources to produce biomass (Kelty 2006), and fosters the establishment of additional native plant species in the plantation understory (Kanowski et al. 2003, McNamara et al. 2006, Basu et al. 2007). It allows harvesting products from different species on different rotations, reduces risk of market shifts or insect or disease impacts, risks of climate uncertainty, or achieves some combination of these. Ideally, species used in mixed-planting programs should exploit resources in a complementary manner and/or have good ecological combining ability (Harper 1977, Haggar and Ewel 1997) in order to minimize inter-specific competition – a common constraint of this approach. Thus, before mixed planting is applied on a wide scale it is essential to evaluate the performance of any mixtures that may be used, and preferably to assess a wide range of species.

The low soil fertility in swidden fallows can be addressed by using readily available and affordable organic residues, such as charred bark (Yamato et al. 2006), wood ash and sawdust (Brunner et al. 2004, Solla-Gullon et al. 2008) or agricultural residues (Moyin-Jesu 2007), all of which have proven utility for amending problematic soils. Rice husk is a readily available bio-resource in Southeast Asia, where rice production is the dominant farming system. For instance, the estimated annual rice husk production is 500 000 tons in Laos alone (our own estimation; annual rice yield × 20% rice husk production by the mills). Much of the husk produced from processing rice is either burnt or dumped as waste. However, carbonized rice husks (also called rice husk biochar, rice husk charcoal), produced by the partial combustion of rice husks, contain high proportions of plant nutrients (carbon, silicon, nitrogen, phosphorus, potassium, calcium, magnesium, iron, and zinc) with a pH of 8.6 (Haefele et al. 2011) that can be used for amending problematic soils, such as fallows. The application of biochar has been shown to improve soil chemical properties by neutralizing its pH and increasing its total nitrogen, available phosphorous and exchangeable cation contents, cation exchange capacity and base saturation,

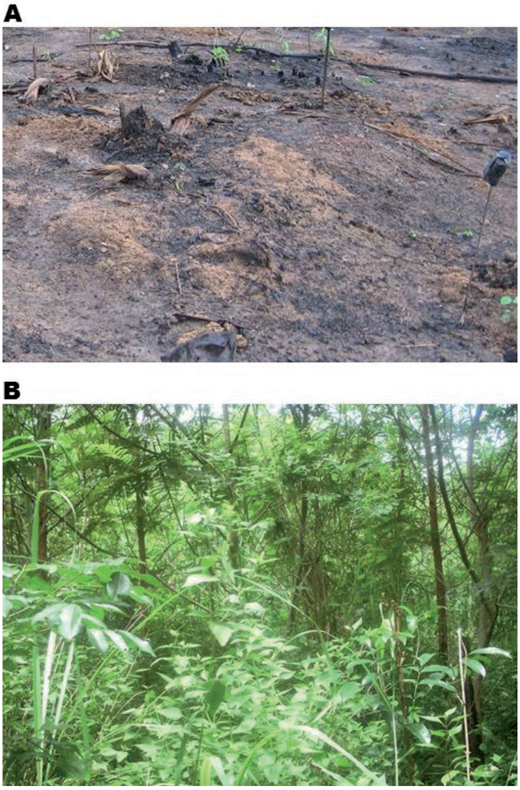

Fig. 1. Typical view of abandoned swidden fallow after burning (A) and establishment of mixed-species forest where *P. dasyrachis* appeared as emergent (B).

while inducing reductions in levels of exchangeable Al ions, which impair root growth (Ogawa and Okimori 2010). Biochar also enhances the physical properties of soil, e.g. by raising its porosity and water holding capacity, as well as the inoculation efficacy of root nodule bacteria and mycorrhizae (Warnock et al. 2007).

Application of biochar has also been shown to improve the growth and yield of various crops, and to provide (together with other organic residues) a suitable rooting medium for woody seedlings (Annapurna et al. 2005, Basu et al. 2007, Agele et al. 2010). It can also induce increases in carbon sequestration in the soil (Lehmann et al. 2006, Ogawa et al. 2006). However, despite its extensive application in crop production (Food and Fertilizer Technology Centre, 2010), its application in forestry practices is very limited. Here we report the effects of adding rice husk biochar to the soil on the establishment and growth of eight native species with contrasting ecological characteristics in a mixed-planting trial established on abandoned swidden fallow in Laos. Inorganic fertilizer (NPK) was used as an additional treatment in the trial to evaluate the comparative advantages of using rice husk biochar (if any) for improving the establishment and subsequent growth of planted seedlings. The main objective of the study was to generate knowledge that supports forest recovery on degraded lands to enhance ecosystem services and goods accrued from restored forests. The specific objective was to assess the effects of rice husk biochar on survival and growth of seedlings of eight species in mixed-planting.

2 Materials and Methods

2.1 Study Area

The experiment was established at a site close to Napo village, Sang Thong District, about 70 km north-west of Vientiane, the capital of Laos (18°16′26″N and 102°10′31″E). The experimental site, located at an altitude of 205 m above sea level, was a swidden fallow that had been abandoned 8–10 years ago, mainly covered by bamboos and shrubs. The area has a typical tropical monsoon climate, with distinct rainy (May to November) and dry seasons (December to April). The mean (± SD) annual rainfall amounts to 1647.1 ± 16.4 mm during the rainy season, the mean (± SD) daily temperature during the year is 26.74°C ± 0.66, and the average daily relative air humidity ranges from 63% (March and April) to ca. 72% (June to September), based on data collected by the Department of Meteorology in Vientiane from 1995 to 2005. The bedrock consists mainly of sandstone, and alisol (highly acidic, poorly drained soil, prone to aluminum toxicity and erosion) is the dominant soil type (MAF 2005). The experimental plot was prepared by completely clearing and burning bamboos and shrubs on the site before planting (Fig. 1).

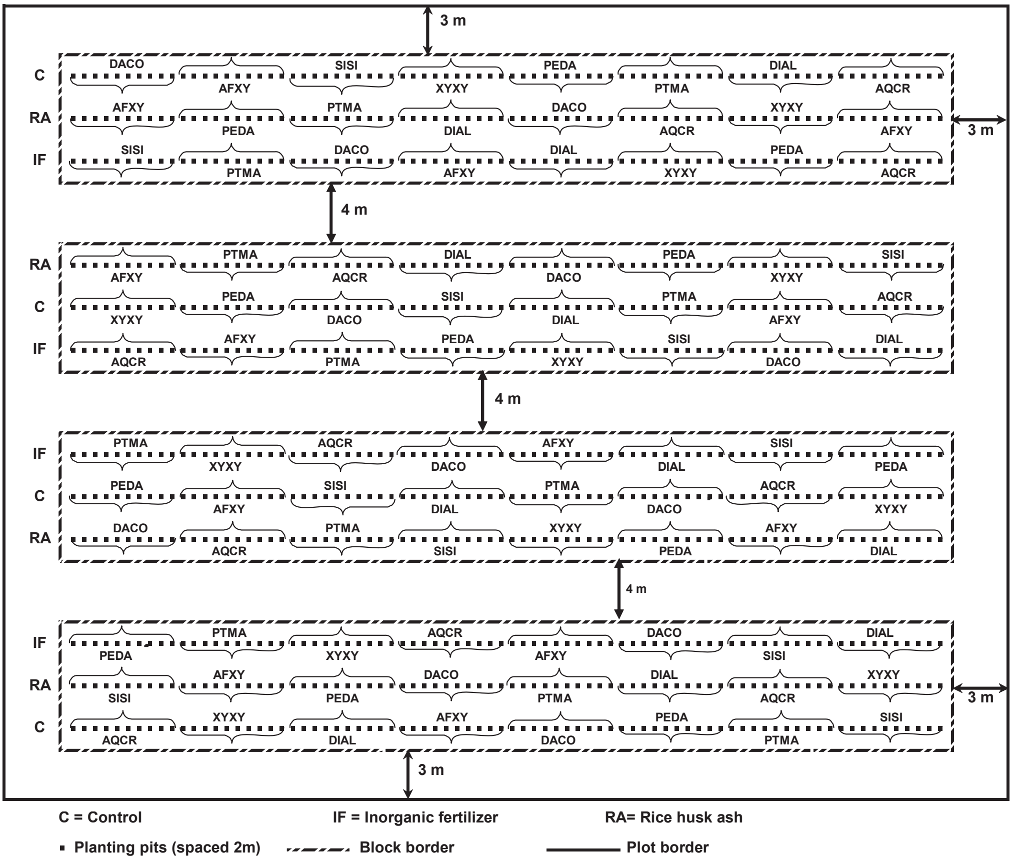

Fig. 2. Layout of the experimental set-up involving three soil amendment measures and eight tree species (AFXY = *A. xylocarpa*, AQCR = *A. crassna*, DACO = *D. cochinchinensis*, DIAL = *D. alatus*, PEDA = *P. dasyrachis*, PTMA = *P. macrocarpus*, SISI = *S. siamensis*, XYXY = *X. xylocarpa).*

2.2 Species Description

Six legumes (*Afzelia xylocarpa* Craib, *Dalbergia chochinchinensis* Pierre, *Peltophorum dasyrachis* Kurz ex Baker, *Pterocarpus macrocarpus* Kurz, *Sindora siamensis* Teijsm. ex Miq., and *Xylia xylocarpa* (Roxb.) W.Theob), a dipterocarp (*Dipterocarpus alatus* Roxb) and *Aquilaria crassna* Pierre ex Lecomte of the Thymelaeaceae were used in mixed-planting, with and without rice husk biochar or inorganic fertilizer applications, to test the feasibility of using these measures for forest landscape restoration on abandoned fallows. The selected species have wide ranges of ecological adaptations, for instance most dipterocarps (species belonging to Dipterocarpaceae) are shade tolerant while the legumes are light-demanding; and the species planted in the trial are also highly esteemed for their high quality timber and non-timber products (Table 1).

2.3 Experimental Layout and Planting

In 2006, a split-plot experiment was established in which two soil amendment treatments (NPK fertilizer or rice husk biochar) were applied, with non-amendment control, and eight native tree species were planted. The experimental site (1 ha) was divided into four 0.19-ha blocks and within each block three planting rows (160 m long) were established, with 4 m gaps both between rows and between blocks (Fig. 2). The soil amendment and control (no soil amendment) treatments were

Table 1. Ecological distribution, growth habits and economic importance of the species included in the study.

Family	Species	Ecological distribution	Growth habit	Uses
Dipterocarpaceae	*Dipterocarpus alatus*	Native to evergreen & deciduous forests of Cambodia, Laos, Myanmar, Philippines, Thailand, Vietnam, Bangladesh, Andaman islands; occurs gregariously along rivers at altitudes up to 500 m	Large tree up to 40 m tall and 150 cm in diameter; shade-tolerant and fast growing; endangered species	Timber, oleoresins, medicine, soil improvement
Leguminoseae	*Afzelia xylocarpa*	Native to Cambodia, Laos, Myanmar, Thailand, Vietnam; occurs in evergreen and deciduous forests at 100–650 m altitudes	Tree up to 30 m tall & 150 cm in diameter; light-demanding; deciduous; endangered species	Timber, food, tanning, soil improvement
Leguminosea	*Dalbergia cochinchinensis*	Occurs in dry evergreen forests of Cambodia, Laos, Thailand, Vietnam at altitudes up to 1000 m	Evergreen tree up to 30 m tall, 60–80 cm in diameter; drought-tolerant but slow growing; shade-tolerant when young; vulnerable species	Timber, soil improvement,
Leguminoseae	*Pterocarpus macrocarpus*	Native to dry evergreen, mixed deciduous and deciduous forests of Cambodia, Laos, Vietnam, Thailand and Myanmar; introduced to India and the Caribbean; altitudes up to 800 m	Medium to large tree (up to 35 m tall and 120 cm in diameter); light-demanding; deciduous, endangered species	Timber, medicine, soil improvement
Leguminoseae	*Sindora siamensis*	Native to Cambodia, Laos, Vietnam, Thailand, Myanmar and Malaysia; occurs in dry dipterocarp, mixed deciduous and dry evergreen forests	Tree up to 30 m tall and 80 c m in diameter; light-demanding; deciduous; grows in poor and rocky sites; endangered species	Timber, medicine, soil improvement
Leguminoseae	*Peltophorum dasyrachis*	Native to Cambodia, Laos, Vietnam, Thailand and Myanmar; occurs at altitudes up to 800 in secondary mixed deciduous and dry dipterocarp forests	Tree up to 30 m tall and 80 cm in diameter; light-demanding; deciduous, good colonizer as fast growing species; pioneer species with drought tolerance.	Timber, soil nutrient improvement, young leaves used as fodder for cattle
Thymelaeaceae	*Aquilaria crassna*	Native to Tonkin and other countries of Southeast Asia; occurs in wide range of forest types, primary and secondary forests and in the understory at altitudes up to 1200 m	Tree up to 30 m tall and 80 cm in diameter; light-demanding; fast growing tree; endangered species	Aroma industry: perfume; medicine
Leguminoseae	*Xylia xylocarpa*	Native to Oceania and S.E. Asia (Burma, Cambodia, China, India, Laos, Myanmar, Philippines, Thailand, Vietnam); grows in mixed deciduous, dry dipterocarp and dry evergreen forests	Tree up to 40 m tall and 150 cm in diameter; light-demanding; deciduous, endangered species	Timber, medicine, soil improvement

Sources: Ankarfjard and Kegl (1998); Bräutigam (1996); McCombe (1977)

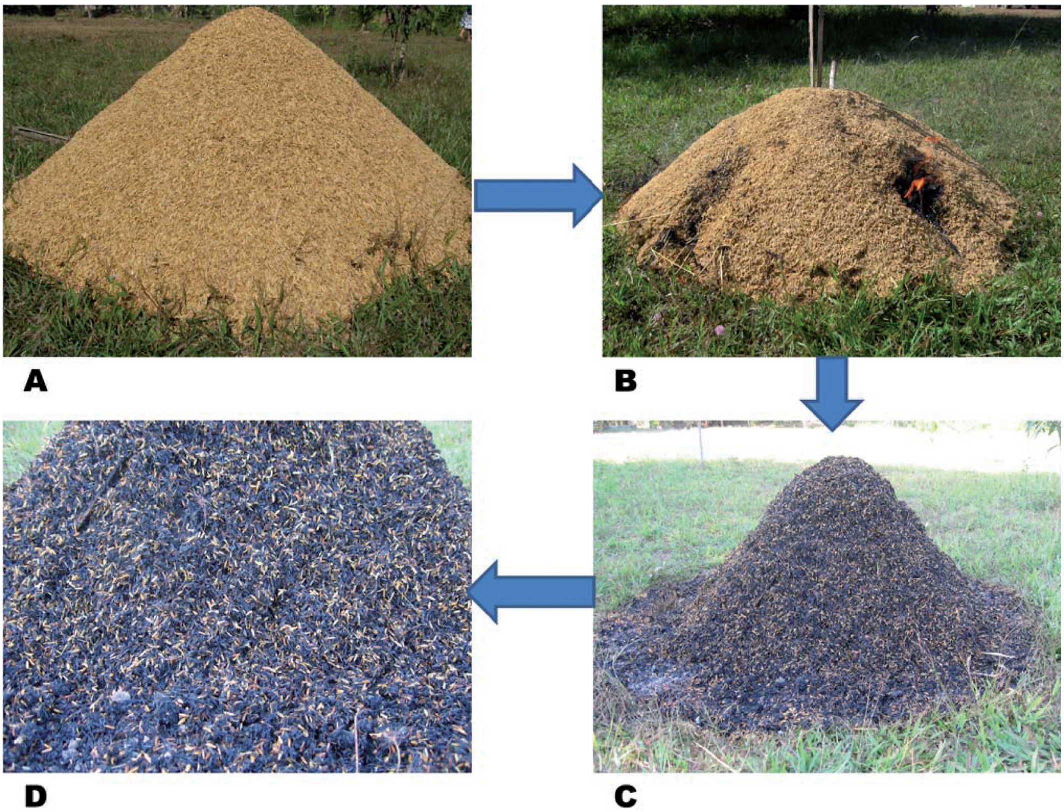

Fig. 3. Production of biochar from rice husks (A) by igniting a heap of the material at several points around the circumference with burning bamboo sticks (B), then letting the rice husk burn slowly for 8 hours (C) before cooling the carbonized rice husks with water to prevent them from turning into ashes (D).

each randomly assigned to a planting row in each block, and species were randomly assigned to positions within each planting row at 2 m spacing. The NPK fertilizer (15:15:15) was applied at a rate of 100 g per seedling during the planting time, followed by 200 g per seedling three months after planting; doses based (according to our experience) on those commonly used in forest plantations in Laos. The rice husk biochar was applied (mixed with soil excavated from the planting holes) two weeks before planting at a rate of 200 g per seedling, followed by addition of the same amount three months after planting, giving a total biochar application equivalent to 4 Mg ha^{-1}. As this study is the first attempt to apply rice husk biochar directly on planting sites, we considered an application rate lower than the rate recommended for crops (10–20 Mg ha^{-1}) by the Food and Fertilizer Technology Center (www.fftc.agnet.org). Rice husk biochar was produced by incomplete combustion of rice husks (60–70% by volume) using the traditional charcoal-making practice (Fig. 3).

Seedlings of *A. crassna*, *A. xylocarpa*, *P. dasyrachis*, *P. macrocarpus*, *S. siamensis* and *X. xylocarpa* were raised in the Faculty of Forestry, National University of Lao, nursery at Dong Dok for seven months, while those of *D. alatus* and *D. chochichinensis* were bought from nurseries near to the planting sites. Seedlings (30 cm mean height, 7 mm mean root collar diameter) were planted. These sizes are commonly used standards for containerized seedling production in Laos. For each treatment, 10 seedlings per species and a total of 30 seedlings per block were planted along each planting row in May 2006 using the same planting hole-size, 30 cm in diameter and 30 cm in depth, for all treatments. The plots were manually weeded twice per year, in July and October during the rainy season, partly because weeds usually grow well in this season and partly to reduce risks of wildfire.

2.4 Data Collection and Statistical Analyses

Survival rates, root collar diameter and height of the planted seedlings were assessed at the beginning of the rainy season in the following two years, while the diameter at 1.3 m (dbh) and height of the saplings that developed from them were measured four years after planting. Mean survival rates and growth parameters of each species, in rows subjected to each soil amendment treatment were computed per block (the blocks being considered as replicates during the statistical analyses). The survival rates were arcsin-transformed and root collar diameter and seedling shoot height were log-transformed to meet homogeneity of variance and normality assumptions for analysis of variance, ANOVA (Zar 1996). The analysis of variance was performed for each variable using the split-plot design model:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_{ij} + \varepsilon_{ij} + \varepsilon_{ijk}$$

Y_{ijk} was the response variable, μ was the overall mean, α_i was the effect of the between-subject factor, i (soil amendment measures), β_j was the effect of the within-subject factor, j (species), γ_{ij} was the interaction of the between- and within-subject factors. The parameters ε_{ij} and ε_{ijk} are random errors of the between- and the within-subjects factor, respectively with k number of blocks. When the homogeneity of variance assumption was violated, according to Mauchly's test of sphericity, the degrees of freedom for testing the significance of the within-subject factors were adjusted using Huynh-Feldt correction factor, which is less biased than other correction factors (Davis 2002). The Bonferonni adjustment for multiple comparisons was employed to control the inflation of Type I error. Results of the statistical analyses were considered significant if Bonferonni-adjusted p values were ≤ 0.02. The SPSS 17 software package (SPSS Inc., 2008, Chicago, IL, U.S.A.) was used for all statistical analyses.

Table 2. Survival rate of planted seedlings of the eight species during the first two years in relation to the soil amendment treatments (mean ± SE). For each factor and time of assessment, means followed by different letters across rows are significantly different.

Factors	Survival rate (%) Year-1	Year-2
Soil amendment treatments		
Control	83 ± 2 a	82 ± 2 a
NPK fertilizer	86 ± 2 a	85 ± 2 a
Rice husk Biochar	84 ± 2 a	82 ± 2 a
Species		
A. xylocarpa	91 ± 2 a	91 ± 2 a
A. crassna	73 ± 3 b	71 ± 3 b
D. chochichinensis	90 ± 2 a	87 ± 3 a
D. alatus	73 ± 3 b	72 ± 3 b
P. dasyrachis	86 ± 3 a	86 ± 3 a
P. macrocarpus	87 ± 2 a	87 ± 2 a
S. siamensis	86 ± 3 a	84 ± 4 a
X. xylocarpa	88 ± 3 a	87 ± 3 a

3 Results

3.1 Survival Rate

Neither rice husk biochar nor NPK fertilizer application resulted in significant differences in survival rates of the planted seedlings during the two years after planting, relative to the control ($F_{[2, 6]} = 1.68$; $p = 0.761$ for the first year; $F_{[2, 6]} = 0.66$; $p = 0.541$ for the second year), but survival rates varied significantly among species ($F_{[7, 63]} = 4.38$; $p = 0.001$ for the first year ; ($F_{[7, 63]} = 5.06$; $p < 0.001$ for the second year). There was no significant interaction effect of the between-within factors ($F_{[14, 63]} = 0.76$; $p = 0.712$ for the first year; ($F_{[14, 63]} = 0.86$; $p = 0.607$ for the second year). The overall mean survival rate exceeded 80% in rows subjected to all soil amendment treatments during the two years following planting (Table 2), but it was significantly lower for *A. crassna* and *D. alatus* than for the other species, all of which had similar survival rates (Table 2).

Table 3. Root collar diameter of planted seedlings of the eight species during the first two years in relation to the soil amendment treatments (mean ± SE). For each factor, means followed by different letters in each column are significantly different.

Factors / Levels	Root collar diameter (mm) First year	Second year
Soil amendment treatments		
Control	20.76 ± 1.4 a	30.49 ± 1.5 a
Rice husk biochar	22.02 ± 1.2 a	33.32 ± 2.2 b
NPK fertilizer	23.89 ± 1.5 b	34.90 ± 2.5 b
Species		
D. alatus	12.96 ± 0.8 a	18.57 ± 1.0 a
S. siamensis	15.54 ± 0.5 a	24.16 ± 1.0 b
P. macrocarpus	20.34 ± 0.8 b	28.27 ± 0.9 bc
A. crassna	21.15 ± 0.7 b	32.67 ± 0.8 de
D. chochichinensis	21.62 ± 0.8 b	28.18 ± 1.3 bc
A. xylocarpa	23.15 ± 1.5 bc	31.96 ± 1.0 cd
X. xylocarpa	25.84 ± 1.4 c	36.49 ± 1.4 e
P. dasyrachis	37.17 ± 1.5 d	62.93 ± 2.1 f

Table 4. Height of planted seedlings of the eight species during the first two years in relation to the soil amendment treatments (mean ± SE). For each factor, means followed by different letter(s) across each column are significantly different.

Factors / Levels	Height (cm) First year	Second year
Soil amendment treatments		
Control	111.13 ± 6.2 a	214.67 ± 15.3 a
Rice husk biochar	115.36 ± 5.7 a	225.42 ± 12.5 a
NPK fertilizer	118.88 ± 6.3 a	245.00 ± 15.3 b
Species		
D. alatus	64.73 ± 4.4 a	127.08 ± 5.2 a
S. siamensis	100.20 ± 2.8 b	185.25 ± 8.8 b
P. macrocarpus	105.39 ± 4.5 b	182.95 ± 7.2 b
A. crassna	107.50 ± 4.5 b	223.75 ± 7.9 cd
D. chochichinensis	114.35 ± 4.9 b	205.50 ± 4.7 bc
X. xylocarpa	119.88 ± 8.0 bc	263.75 ± 11.2 e
A. xylocarpa	136.48 ± 4.7 c	234.45 ± 6.2 d
P. dasyrachis	172.43 ± 7.1 d	404.17 ± 12.1 f

3.2 Seedling Diameter and Height

The root collar diameter of seedlings one year after planting was significantly influenced by the soil amendment treatments ($F_{[2,6]}=7.76$; $p=0.011$), species ($F_{[7,63]}=68.46$; $p<0.001$), and the interaction between them ($F_{[14,63]}=2.83$; $p= 0.002$). This variable was significantly enhanced by the application of NPK fertilizer compared to the control, but not by rice husk biochar application relative to either the control or NPK fertilizer treatments (Table 3). The smallest root collar diameters were recorded for *D. alatus* and *S. siamensis* and the largest for *P. dasyrachis*, regardless of soil treatment. When each species was examined separately, the soil treatments had significant effects on only two species; *A. xylocarpa* and *X. xylocarpa*. For *A. xylocarpa*, root collar diameter was significantly greater following the NPK fertilizer (28.08 ± 1.0 mm) and rice husk biochar (24.03 ± 1.9 mm) treatments than the control (17.35 ± 1.1 mm), while for *X. xylocarpa* the application of NPK fertilizer significantly increased the root collar diameter (30.31 ± 2.2 mm) compared to both the control (21.46 ± 1.1 mm) and the addition of rice husk biochar (25.74 ± 1.4 mm). Two years after planting, root collar diameter of seedlings still showed significant variations among the soil amendment treatments ($F_{[2,6]}=9.95$; $p=0.005$) and species ($F_{[7,63]}=162.65$; $p<0.001$), but not for their interaction effect ($F_{[14,63]}=1.80$; $p=0.06$). The addition of NPK fertilizer and rice husk biochar resulted in greater root collar diameter than the control, and *P. dasyrachis* seedlings had significantly greater root collar diameters than those of the other species, while *D. alatus* seedlings had the smallest root collar diameters (Table 3).

One year after planting seedling height varied significantly among species ($F_{[7,63]}=35.23$; $p<0.001$), but was not significantly influenced by either the soil amendment treatments ($F_{[2,6]}=1.37$; $p=0.303$) or the species × soil treatment interaction ($F_{[14,63]}=1.22$; $p=0.286$). The mean height was greatest for *P. dasyrachis*, and lowest for *D. alatus* (Table 4). During the second year after planting, the seedlings were significantly taller ($F_{[2,6]}=15.75$; $p= 0.001$) following NPK fertilizer application than following both the rice husk biochar and control treatments (Table 4). There were also significant between-species differences in seedling height ($F_{[7,63]}=25.14$; $p<0.001$); the three tallest species were *P. dasyrachis*, *X. xylocarpa* and *A. xylocarpa*, while the shortest were *D. alatus*, *P. macrocarpus* and *S. siamensis* (Table 4). There was no significant soil amend-

Table 5. Diameter (cm) of saplings of the eight species in relation to the soil amendment treatments (mean ± SE). For each species, means followed by different lowercase letter(s) across rows are significantly different; upper case letter(s) denote significant differences among species (S) and treatments (T).

Species	Control	NPK fertilizer	Rice husk biochar	Main effect (S)
A. xylocarpa	3.63 ± 0.4a	4.28 ± 0.5a	3.50 ± 0.2a	3.81 ± 0.2**C**
A. crassna	3.74 ± 0.4a	3.58 ± 0.4a	4.69 ± 0.2a	4.01 ± 0.2**C**
D. chochichinensis	2.34 ± 0.2a	3.51 ± 0.1b	3.48 ± 0.6b	3.11 ± 0.3**B**
D. alatus	1.61 ± 0.1a	2.03 ± 0.1ab	2.63 ± 0.3b	2.09 ± 0.2**A**
P. dasyrachis	9.34 ± 0.5a	9.78 ± 0.4a	9.73 ± 0.3a	9.62 ± 0.2**E**
P. macrocarpus	2.23 ± 0.1a	2.74 ± 0.2ab	3.46 ± 0.5b	2.81 ± 0.2**B**
S. siamensis	3.12 ± 0.2a	3.73 ± 0.5a	3.28 ± 0.1a	3.37 ± 0.2**BC**
X. xylocarpa	4.80 ± 0.6a	5.89 ± 0.4a	5.21 ± 0.4a	5.30 ± 0.3**D**
Main effect (T)	3.85 ± 0.4**A**	4.44 ± 0.4**B**	4.50 ± 0.4**B**	

Table 6. Height (m) of saplings of the eight species in relation to the soil amendment treatments (mean ± SE). Means followed by different letter(s) are significantly different for the main effects of treatments (T) and species (S).

Species	Control	NPK fertilizer	Rice husk biochar	Main effect (S)
A. xylocarpa	4.38 ± 0.2	4.66 ± 0.5	4.04 ± 0.5	4.36 ± 0.3**c**
A. crassna	3.76 ± 0.3	3.97 ± 0.1	4.74 ± 0.2	4.15 ± 0.2**bc**
D. chochichinensis	3.12 ± 0.1	3.57 ± 0.2	4.49 ± 0.4	3.73 ± 0.2**bc**
D. alatus	2.43 ± 0.1	2.84 ± 0.2	3.36 ± 0.6	2.88 ± 0.2**a**
P. dasyrachis	9.32 ± 1.4	8.82 ± 0.8	10.79 ± 0.8	9.65 ± 0.6**e**
P. macrocarpus	2.94 ± 0.2	3.25 ± 0.1	4.12 ± 0.3	3.44 ± 0.2**b**
S. siamensis	3.77 ± 0.2	4.39 ± 0.2	4.20 ± 0.3	4.12 ± 0.1**bc**
X. xylocarpa	5.16 ± 0.6	5.84 ± 0.5	5.54 ± 0.5	5.52 ± 0.3**d**
Main effect (T)	4.36 ± 0.4**A**	4.67 ± 0.3**AB**	5.16 ± 0.4**B**	

ment treatment and species interaction effect on seedling height ($F_{[14, 63]} = 1.41$; $p = 0.176$).

3.3 Sapling Diameter and Height

Sapling growth was assessed four years after planting, and significant differences in diameter were observed among soil amendment measures ($F_{[2, 6]} = 6.64$, $p = 0.017$), species ($F_{[7, 63]} = 101.22$, $p < 0.001$), and interaction between factors ($F_{[14, 63]} = 2.24$, $p = 0.016$). The NPK fertilizer and rice husk biochar applications resulted in greater diameter than the control (Table 5). The mean diameter was greatest for *P. dasyrachis* followed by *X. xylocarpa*, and smallest for *D. alatus* followed by *P. macrocarpus* and *D. cochichinensis*; for these latter species the application of rice husk biochar resulted in larger diameter compared to the control but comparably the same effect as the application of inorganic fertilizer (Table 5). The height of the saplings was also significantly affected by the soil amendment treatments ($F_{[2, 6]} = 10.47$, $p = 0.004$), and varied significantly among species ($F_{[7, 63]} = 53.12$, $p < 0.001$), but not due to interaction effect ($F_{[14, 63]} = 1.11$, $p = 0.364$). This variable was significantly enhanced by the application of rice husk biochar, relative to the control, but not by NPK application relative to either the control or biochar treatments (Table 6). The mean sapling height was greatest for *P. dasyrachi*, which appeared as emergent (Fig. 1), followed by *X. xylocarpa*, and the smallest for *D. alatus* followed by *P. macrocarpus* (Table 6).

4 Discussion

Application of rice husk biochar reduces the bulk density, and enhances both the aeration and water-holding capacity of soil (Ogawa and Okimori 2010), thus encouraging lateral root formation and expanding the rhizosphere zones that can be exploited by plant roots. In addition, it improves soil chemical properties and increases the abundance of free-living and symbiotic microorganisms that are beneficial for plant growth, as well as supplying macro- and micro-nutrients. Thus, we hypothesized that addition of rice husk biochar to swidden fallows would improve the soil and enhance seedling establishment and growth. However, the use of rice husk biochar in the present study did not increase the survival rate of planted seedlings relative to the control or application of NPK fertilizer (which exceeded 80% for most species, irrespective of the treatments). This could be related to our use of container-grown seedlings, since the root systems of such seedlings are disturbed much less during lifting, transportation and planting than those of bare-rooted seedlings. Hence, resistance to water flow through the soil–plant–atmosphere continuum is reduced (Grossnickle 2005), the seedlings are less prone to water stress after transplantation, and they have higher survival rates in the field. However, non-drought stressors, such as herbivores and competition, can also cause seedling mortality (Zida et al. 2008). This may explain why seedling mortality rates as high as 30% (depending on the species) were observed, although field survival rates were generally high.

The positive effects of rice husk biochar on plant growth (which seem to be strongest in infertile tropical soils) are believed to be related to boosting soil fertility and the abundance of free-living and symbiotic micro-organisms (Ogawa and Okimori 2010). Although our planting site has highly acidic and poorly drained alisols, the addition of rice husk biochar did not significantly enhance the growth of seedlings of most species compared to the control during the first year. There are two plausible explanations for this. First, the planting site was a swidden fallow that was abandoned 8–10 years prior to the start of the experiment, and the soil fertility might have replenished to some extent during these years. Second, we slashed and burned the existing vegetation (including the bamboos) while preparing the land for planting, and the ash from the burning might have temporarily boosted the availability of soil nutrients (Wan et al. 2001), thereby enhancing post-burn re-growth. This hypothesis is supported by the observation that the biochar had a significantly greater effect on the root collar diameter of seedlings during the second year than during the first year. In this context it should be noted that interactions between biochar, soil, microbes and plant roots are generally biochar- and site-specific, hence the potential of biochar as a soil amendment is highly dependent on the combination of biochar types and soil conditions at specific sites (Joseph et al. 2010).

The effect of biochar was most clearly manifested in the fourth year by increasing the diameter and height of saplings (of all tested species) relative to those subjected to the other treatments. The marked increases in diameter and height of the saplings in response to biochar application can be attributed to the replenishment of the soil fertility resulting from gradual releases of nutrients from the biochar over time; it should be noted that rice husks decompose slowly in the soil due to high silica content (Ogawa and Okimori 2010). Similar positive, prolonged effects have been observed up to the tenth rotation for maize, for example (Ogawa and Okimori 2010). The marked increase in diameter of slow-growing species (*D. alatus*, *P. macrocarpus* and *D. cochichinensis*) in response to the application of biochar (so also inorganic fertilizer) is also consistent with the ‘‘resource optimization hypothesis’’ (Ågren and Franklin 2003). According to this hypothesis, plants allocate higher proportions of resources to above-ground biomass than to their root systems when the availability of soil nutrients and water increases, and variations in nutrient availability induce stronger changes in allocation patterns than variations in water availability (Poorter and Nagel 2000). The increase in wood biomass, indicated by the greater diameter of saplings in the biochar-treated soil, is of course a highly desirable response for tree growers aiming to maximize productivity.

The substantial variations in growth observed among species might be related to complementary resource use, which may arise from use of different resources by different species, or through partitioning of resource use in space or time (Haggar and Ewel 1997). Variations in the growth rates, rates of resource acquisition and utilization efficiency of roots and leaves, all of which are generally high for fast-growing pioneer species, can lead to complementary spatial use of resources. Similarly, variations in leaf phenology (e.g. among the species used here *A. xylocarpa*, *X. xylocarpa*, *P. dasyrachis*, *S. siamensis* and *P. macrocarpus* are deciduous, while *D. alatus* and *D. cochinchinensis* are evergreen) may promote complementary temporal use of resources. Complementary resource use may also arise from differences in the forms of resources used by different species, for example in the trial reported here the legumes might have relied on diatomic nitrogen fixed by their roots while the non-legumes used inorganic N present in the soil. Our finding is consistent with the mixed-species trial in Vietnam where *P. dasyrachis* has been reported as fast-growing species (McNamara et al. 2006).

5 Conclusions and Recommendations

In this study, the feasibility of mixed species planting together with soil amendment using rice husk biochar was investigated as a way to expedite forest recovery on small-scale abandoned swidden fallows so as to meet short-term needs of the local people while maintaining ecosystem services in the long run. The following conclusions can be drawn:

1. For all species studied, the use of rice husk biochar was not advantageous relative to either the control or application of inorganic fertilizer in terms of seedling survival rates, probably because of the use of container-grown seedlings with intact root systems, which reduce resistance to water flow through the soil–plant–atmosphere continuum.
2. No enhancement of growth in response to the application of rice husk biochar (or inorganic fertilizer) was observed for most of the species during the first year, probably because the soil in all of the plots received a temporary fertility boost when we burned the vegetation while preparing the land for planting.
3. The addition of biochar had marked positive effects on subsequent diameter and height growth of saplings, particularly the slow-growing species (*D. alatus*, *P. macrocarpus* and *D. cochichinensis*). The findings highlight the possible utility of biochar applications in attempts to enhance tree growth at degraded sites, potentially including numerous sites in Southeast Asia, where rice husk is a readily available and affordable bio-resource.
4. The divergence in growth rates among species indicates that planting a mixture of fast-growing pioneer and later successional native tree species could provide a continuous supply of wood from different species to diversify the livelihood of swidden field owners, while maintaining ecosystem services.

This study is the first attempt to assess the applicability of rice husk biochar in amending reforestation sites to foster forest landscape restoration, but the application rate of biochar in the present study (4 Mg ha^{-1}) is lower than the rate recommended for crops (10–20 Mg ha^{-1}) by the Food and Fertilizer Technology Center (www.fftc.agnet.org). Hence, further study is required to optimize the doses for fallows with different ages and rotations, for permutations of other site variables, and for biochar from other sources, in order to maximize its applicability in reforestation. In addition, time and frequency of application as well as chemical analysis of the biochar itself and the amended soils need to be further studied to standardize the technique.

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