forests

Article

Forest Structure, Wood Standing Stock, and Tree Biomass in Different Restoration Systems in the Brazilian Atlantic Forest

Danila Morena Fidéles Pontes [1,*], Vera Lex Engel [1] and John A. Parrotta [2]

[1] Forest Science Department, School of Agriculture/FCA, São Paulo State University/UNESP, 18610-034 Botucatu, Brazil
[2] USDA Forest Service, Research and Development, Washington, DC 20250-0003, USA
* Correspondence: fideles.danila@gmail.com; Tel.: +55-014-99759-1779

Received: 15 June 2019; Accepted: 8 July 2019; Published: 15 July 2019

Abstract: Reliable estimates of tree growth and wood yield are fundamental to support the management of restored forests and better reconcile the objectives of recovering biodiversity with the provision of ecosystem services. In this study, wood standing volumes and tree biomass stocks were estimated in different ecological restoration systems and at two sites with contrasting soil fertility, in order to evaluate the potential trade-offs between biodiversity and forest production. At each site, a complete randomized block design, with three replications of six treatments, was established in 1997–1998: direct seeding (DIRS), high-diversity tree plantation (HDIV), modified "Taungya" agroforestry system (AFS), mixed plantation with timber and firewood species (MIX), managed agroforestry system (AFSm) and managed mixed plantation (MIXm). We inventoried all trees with diameter at breast height (DBH) ≥ 5 cm in 450 m^2 per treatment per plot, 19–20 years after establishment, using site-specific allometric models. Significant site effects were found for tree height, tree density and wood volume. Restoration systems (treatments) affected forest structure and forest productivity. Higher wood stock and biomass tree were observed in the less complex system (DIRS), while AFSm and HDIV reconciled higher species richness and diversity with good wood volume yields and tree biomass.

Keywords: tropical semideciduous seasonal forest; ecological restoration; agroforestry; ecosystem services; Legal Reserve

1. Introduction

Ecological restoration is an important strategy to reverse forest loss and degradation as well as the predatory exploitation of the remaining natural forests [1], particularly in the Tropics, where socioeconomic aspects also need to be considered. To be effective, however, forest restoration should be able to reconcile the objectives of biodiversity recovery and the provision of services and goods. In Brazil, since 2012, the Federal Law 12.651 [2] has required that at least 20% of the total area of each rural property, over a certain size (depending on regional parameters), be protected as a "legal reserve (LR)", where native vegetation should be maintained or restored. The LRs aim to achieve sustainable use of natural resources, as well as the recovery and conservation of ecological processes and biodiversity. Within this legislative context, a recent governmental plan has aimed [3,4] to increase forest cover in 12 million hectares by 2030, in order to meet the country's international commitments to reduce greenhouse gases (GHG) and mitigate climate change, in compliance with the Paris Agreement targets [5].

In Brazil, wood consumption has decreased when compared to previous years (6.4 million m^3 in 2016, compared to 7.2 million m^3 in 2015) for sawn wood and by 4.5 m^3 for firewood in 2016 [6], due to a more restrictive legislation regarding native forest logging. One of the alternatives for meeting the demand of tropical timber might be wood extraction from restored, sustainably managed, legal reserves in Brazil, which could provide timber and firewood, while realizing the positive impacts on biodiversity recovery and conservation. This could involve at least part of the 12 million hectares across the country planned for LR restoration, with the Atlantic Forest Biome accounting for 38% of the total recovery target [3]. In the State of São Paulo alone, an estimated 1.5 million hectares should be restored [7].

However, it is still challenging to reconcile the environmental, social, and economic benefits of tropical forest restoration [8,9]. Important limitations for wood production in restoration plantations are the high establishment costs and longer time spans required for positive cash flow in comparison to commercial plantations [10]. Furthermore, there is still a lack of knowledge on the expected growth and biomass production rates of potential species for wood production, as well as their behavior in different ecological restoration models, which impedes the development of viable management plans for restored forests.

Forest landscape restoration (FLR), or the recovery and restoration of native vegetation at the landscape scale, has emerged as an approach seeking to restore both ecological and human wellbeing [11], focusing on the capacity of ecosystems to provide goods and services for humans [12]. In this context, there is increasing societal recognition of the climate regulation service provided by forests, both by the avoidance of greenhouse gas (GHG) emission and by enhancing atmospheric carbon sequestration. This role of forests is an important justification for the restoration of degraded areas or areas with low agricultural suitability. Carbon stocks can be partitioned into different compartments: Above- and below-ground living biomass, necromass, and soil organic matter [13], with above-ground biomass representing the major compartment in tropical forests ecosystems [14]. Considering the high primary productivity rates of tropical forests, compared to other ecosystems [15] and their significant carbon storage capacity, tropical forest landscape restoration might play an increasing role in climate change mitigation [16]. Tropical forests are also hotspots of global biodiversity [17], and a positive relationship between productivity and biodiversity indicates that conserving high-carbon forests can provide co-benefits for biodiversity conservation [18,19]. However, this relationship is scale-dependent and weaker at the site level [17], which means that tropical forests can have any combination of tree diversity and productivity, the same being expected for restored tropical forests.

Furthermore, in tropical regions, where socioeconomic issues are often limiting factors for restoration success [20], forest restoration initiatives must be able to, not only accomplish biodiversity conservation objectives, but also meet the landholder's expectations of providing income in the form of wood or non-wood products [9,21]. Recent studies have evaluated the role of restored tropical forests in meeting the goals of recovering plant biodiversity and forest structure [22–24], while others have focused on biomass recovery and carbon sequestration [25–27]. To date, the value of restored tropical forests in accomplishing multiple goals is still subject of debate. Thus, besides generating data on forest structure and diversity, more accurate estimates of biomass and wood yields from alternative restoration approaches can contribute to the refinement of FLR initiatives seeking to attain multiple objectives. Specifically, such studies can provide practical guidance related to the tree species to be planted and managed, forest production potential, and, above all, impacts of forest management on the biodiversity of restored forests and their capacity to provide ecosystem services.

In this study, we evaluated the forest structure and estimated wood and total aboveground biomass in six forest restoration plantation systems, with contrasting species richness and complexity, to verify their potential role in reconciling wood production and biodiversity values. Our specific research objectives were as follows: 1) to assess the effects of site conditions and restoration system design on current species richness and forest structure after 19–20 years; 2) to assess wood production potential, biomass, and carbon stocks among these restoration systems and examine the trade-offs between wood production, biomass accumulation, and biodiversity recovery.

2. Materials and Methods

2.1. Study Area

The study area (Figure 1) is located at Botucatu, in the south-central region of São Paulo State, Brazil (22°52′32″S and 48°26′46″W). According to Köeppen's classification, the climate is Cfa [28], moist subtropical climate. Annual rainfall averages 1,494 mm, with the rainy season from October to March. Annual mean temperature is 20.3 °C (±2.8), with the minimum average occurring in July and the maximum in February. The original natural vegetation cover is tropical semideciduous seasonal forest within the Atlantic Forest biome range [29].

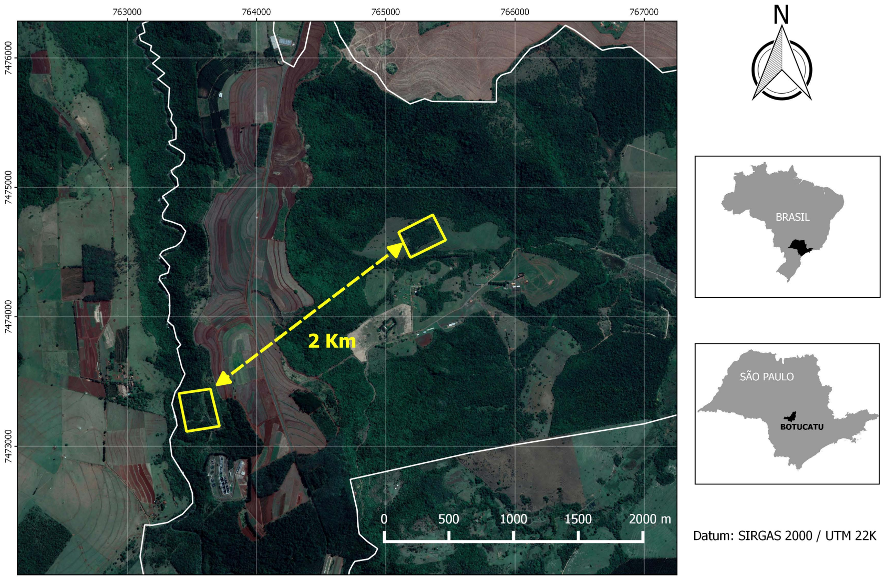


Figure 1. Aerial view of the study area in the state of São Paulo, Brazil, showing the two experimental sites: Ultisol (U) left side and Alfisol (A) right side.

The experiment was undertaken at two sites (Figure 1) with contrasting soil fertility (Table 1): Site 1, Ultisol (U), with clay texture with a tendency to compaction and high fertility, with an undulated relief, at an elevation of 700 m. Former use was based on agriculture (coffee and beans) and pastures of *Pennisetum purpureum* Shum.; Site 2, Alfisol (A), with sandy texture and lower fertility in comparison to Site 1 [30–32], with a soft undulated relief, at an elevation of 574 m. Previously, the area contained a *Citrus* sp. orchard and pastures of *Urochloa decumbens* Stapf.

Table 1. Fertility and granulometry of soils at different experimental sites at depths of 0–5, 5–10, 10–20, and 20–40 cm, in Botucatu, São Paulo, Brazil. Data correspond to the site conditions at the establishment time. Adapted from [30–32].

Soil	**pH**	**OM**^{a}	**P**$_{resin}$	**K**	**Ca**	**Mg**	**H + Al**	**V**^{b}	**N**	**CEC**^{c}	**Sand**	**Silt**	**Clay**
	CaCl$_2$	**g·dm**$^{-3}$	**mg·dm**$^{-3}$		**cmol**$_c$**·dm**$^{-3}$			**%**		**mmol**$_c$**·dm**$^{-3}$	**g·kg**$^{-1}$		
Ultisol				0–5 cm					0–20 cm				
	5.8	51	40	4.7	84	26	26.1	82	0.155	97.1			
				5–10 cm								0–10 cm	
	5.7	44	22	4.8	59	22	28.4	76			300	170	530
				10–20 cm								10–20 cm	
	5.7	37	16	3.6	77	18	32.5	77			210	120	670
				20–40 cm								20–40 cm	
	5.6	26	13	1.8	64	15	30.4	72			223	127	650

Table 1. *Cont.*

Soil	pH	OM^a	P_{resin}	K	Ca	Mg	H + Al	V^b	N	CEC^c	Sand	Silt	Clay
	$CaCl_2$	g·dm^{-3}	mg·dm^{-3}		cmol$_c$·dm^{-3}			%		mmol$_c$·dm^{-3}		g·kg^{-1}	
Alfisol				0–5 cm					0–20 cm				
	5.6	16	27	2.3	18	12	13.1	67	0.06	36.8			
				5–10 cm								0–10 cm	
	5.1	14	19	1.7	14	8.4	16.6	56			920	0	80
				10–20 cm								10–20 cm	
	4.6	11	12	1.3	12	5.8	19.6	47			899	0	101
				20–40 cm								20–40 cm	
	4.4	6.5	10	1.3	10	4.8	22.5	38			852	27	121

^{a} OM: Organic matter; ^{b} V: Base saturation; ^{c} CEC: Cation Exchange Capacity $_{K+Ca+Mg+H+Al}$.

2.2. Description of the Restoration Systems, Site Preparation, and Maintenance

The restoration systems (experimental treatments), with different tree species compositions and arrangements, were as follows [31–33]:

a. Direct seeding (DIRS), sowing of five fast-growing heliophyllous tree species (Supplementary Appendices Table S1, Group A), at a spacing of 1.0 × 1.0 m spacing and a depth of 5 cm, with two to four seeds per spot. This system was implemented 1 year prior to the others.

b. Agroforestry system (AFS), modified "Taungya" system. Mixed plantation with seedlings of 10 fast-growing tree species (1332 ind·ha^{-1}) and 10 slow- to medium-growing tree species (660 ind·ha^{-1}), each group allocated in the same planting line. Trees were arranged in triple lines (fast-slow-fast growth), interspaced with 5-m-wide alleys, where annual crops (beans, maize, cassava, pumpkin, sweet potato) were cultivated during the first 3 years. After 9 to 10 years, 14 fruit tree species were introduced at the Ultisol site and three medicinal tree species at the Alfisol site (Supplementary Appendices Table S2). After 14 years, one exotic tree species (*Mimosa caesalpiniifolia* Benth, Fabaceae) was removed from half of each experimental plot [34] using a split-plot design. Thus, the AFS treatment was subdivided into AFSm (managed) and AFS (control).

c. Commercial mixed plantation (MIX). Consortium of 15 commercial timber, slow-growing species (Groups C–D) and 10 firewood (Groups A–B) (Supplementary Appendices Table SA), fast-growing species, each group allocated in the same planting line at a density of 2500 individuals per hectare. After 14 years, one exotic tree species (*Mimosa caesalpiniifolia* Benth, Fabaceae) was removed from half of each experimental plot [34], using a split-plot design. Thus, the MIX treatment was subdivided into MIXm (managed) and MIX (control).

d. High-diversity tree plantation (HDIV). Mixed plantation of 40 tree species (Supplementary Appendices Table S1) per plot of different ecological groups; planting density was 2500 individuals per hectare.

Species chosen for planting considered their natural ranges as well as their potential uses for timber, firewood or non-timber forest product (NTFP), since an important part of the experimental design was to evaluate the income generation potential for landholders who may adopt these restoration models. Most of the species were native to the region, but some exotic species were used as multipurpose tree species (Supplementary Appendices Table S1). Species were classified into different successional/silvicultural groups as A—short-lived pioneers, B—long-lived pioneers, firewood trees, C—non-pioneer (mid- or late-successional species) canopy species, timber trees; D—non-pioneer (late-successional) mid-canopy or understory trees, fleshed-fruited, and NTFP trees.

Prior to planting in 1997–1998, all sites were mechanically mowed and sprayed with post-emergence herbicide (glyphosate). In all treatments, the sites were prepared using conventional plowing and harrowing, except for the direct seeding system, where minimal tillage was used, with line ripping. All seedlings (for systems AFS, MIX, and HDIV) were grown in the nursery, using root-trainer containers, and were about 30 cm high at the time of planting. Weeds (invasive grasses only) were controlled twice a year in the first 4–5 years using manual mowing and/or herbicide spraying, as necessary. All naturally regenerated trees and forbs were not weeded. No fertilizer was added, except for the annual crops that were fertilized according to specific agronomic recommendations.

2.3. Experimental Design and Data Collection

A complete randomized block design with three replicates and six treatments (restoration systems) was installed at each experimental site (Figure 2). Each 50 × 50 m (0.25 ha) experimental plot, included an effective sampling area of 30 × 30 m (disregarding a 10 m border), subdivided into four subplots of 15 × 15 m (Figure 2). In this study two of these 15 × 15 m subplots were randomly selected for data collection, totaling 450 m^2 for each treatment per block per site.

Figure 2. Experimental design at the Alfisol site: plots by treatment (50 × 50 m) and sampled subplots (15 × 15 m). Labels: MIXm ('managed' commercial mixed plantation), MIX (commercial mixed plantation), HDIV (high-diversity tree plantation), AFSm ('managed' agroforestry system), AFS (agroforestry system), DIRS (direct seeding). For HDIV and DIRS, two subplots were sampled, while in the (split) AFS and MIX plots, all four 15 × 15 subplots were sampled.

Within these 15 × 15 m subplots, all trees with a diameter at breast height (DBH) ≥ 5 cm were included in this study. The DBH was measured with a diametric tape and the total height with a Haglöf Vertex IV hypsometer. Voucher specimens were collected for botanical identification, and all sampled individuals were identified to the species level, when possible. Species names, origin, and geographical distribution were classified according to the Species List of the Brazilian Flora [35].

2.4. Data Analysis

Wood volume and tree biomass were estimated by the indirect (non-destructive) method, using allometric models developed for the same restoration plantations [36,37].

To estimate the total wood volume (Equation (1)), we used the Spurr logarithmized model [36]:

$$\ln V_i = \beta_0 + \beta_1 * \ln\left(DBH_i^2 * H_i\right) + \ln_{\varepsilon_i}, \tag{1}$$

where: V_i is the individual volume, DBH_i is the diameter at breast height, H_i is the total height, β_0 (−9.88231) and β_1 (0.94569) are the adjusted parameters for the same local treatments, and ε_i is the random error (i = 1... N).

Tree biomass was estimated from the sum of the above-ground biomass ($\mathrm{B^aG}$) and the below-ground biomass ($\mathrm{B_bG}$) [37], using Equations (2) and (3), respectively:

$$\ln(B^aG) = -1,305 + 1,055 * \ln\left(DBH^2\right) + 0,34 * \ln(H) + 1,077 * \ln(WD) \tag{2}$$

$$\ln(B_bG) = -2,086 + 1,086 * \ln\left(DBH^2 * WD\right), \tag{3}$$

where B^aG is the above-ground biomass, B_bG is the below-ground biomass, DBH is the diameter at breast height, H is the total height, WD is the species wood density [37].

Wood density for the 19 most abundant species in the restoration system was estimated by the gravimetric method, at the same time, the trees were felled for biomass estimation [37]. For the other species sampled, we used the average of all species for which wood density had been estimated, i.e., 0.43.

For each subplot, vegetation structure parameters (stand basal area, tree density, species richness, and species diversity) were estimated. Structural parameters were estimated using the Mata Nativa 4® software (https://www.matanativa.com.br). Species diversity indices (Fisher's alpha—α, using Equation (4) by iteration procedures) were estimated by plot, treatment (within site and pooled), and site, using the software package PAST® [38]. Fisher's alpha index was chosen because it is the last sensitive one to bias due to differences in sample sizes [39]. Rarefaction analysis was performed by the bootstrap method with a confidence interval of 95%, using the Estimate-S 8.20® Software (http://viceroy.eeb.uconn.edu/estimates/). All diversity and richness analyses were based in [39].

$$S = a * \ln\left(1 + \frac{n}{a}\right) \tag{4}$$

where S is number of taxa, n is number of sampled individuals and a is the Fisher's alpha.

All statistical analyses were performed in the R environment [40], using the *car* package, *lm* function. The factorial models were initially composed of all factors under study (sites, blocks, and restoration systems) and their interactions, i.e., by all the explanatory variables, and by the response variables (tree density, stand basal area, species richness and diversity, wood volume, and tree biomass). In the variance analysis, factors that did not show a significant effect ($p \geq 0.05$) were removed from the model, and thus, we used the most parsimonious one.

For each model, the assumptions of the variance analysis were first tested (Shapiro-Wilk normality test and homogeneity of variances Bartlett's test). We used logarithmic data transformation, as necessary, in case of non-normality (wood volume). Multiple comparisons of means were performed using the Tukey test, considering the probability level of $p \leq 0.05$.

3. Results

Significant differences between sites were found for mean tree height, tree density, wood volume, and tree biomass; however, there were no differences for stand basal area and species diversity (Table 2).

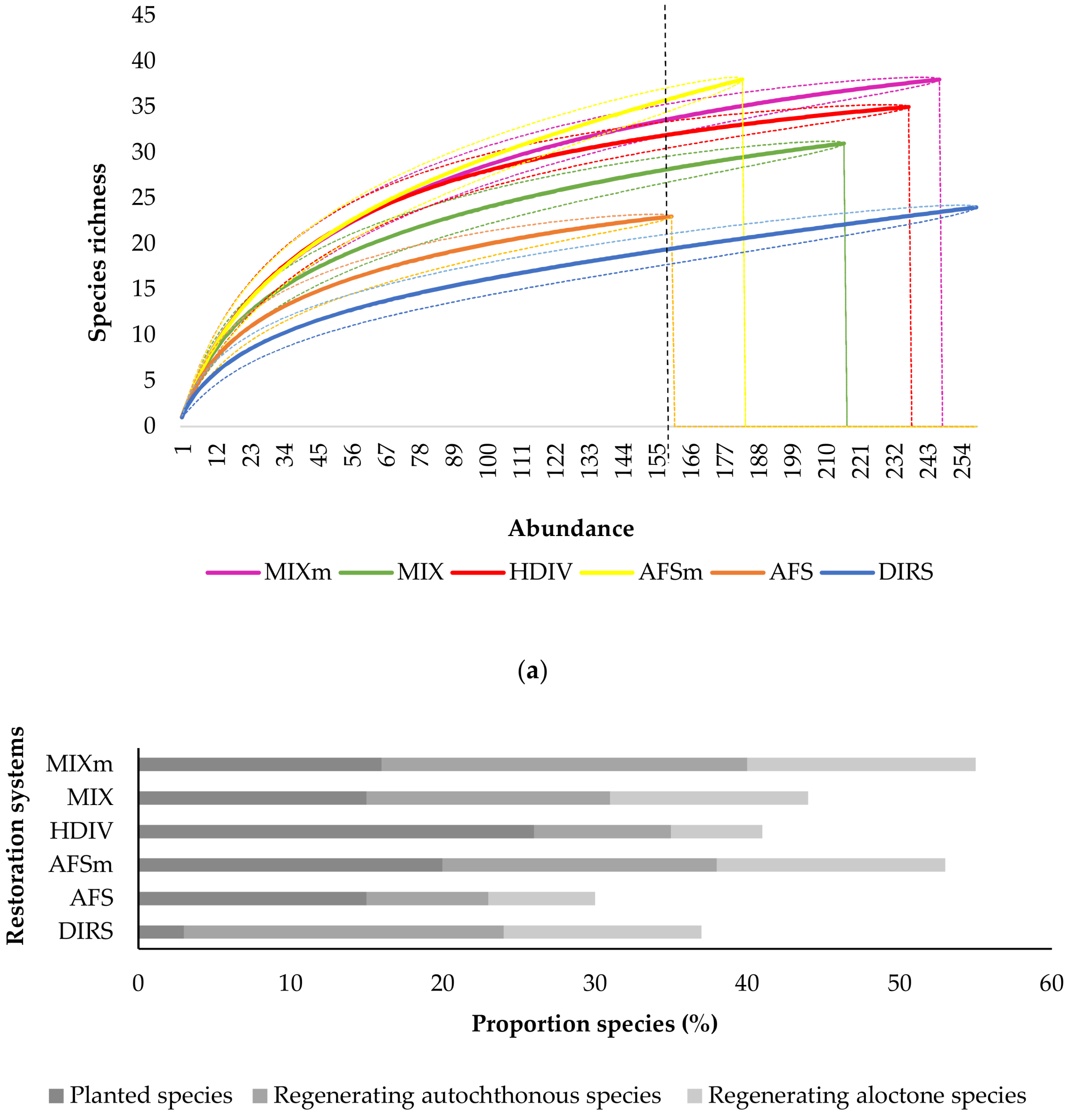
Table 2. Differences between experimental sites in stand structure and wood productivity after 19–20 years of implementation. The different restoration systems were pooled.

	Forest Structure Variables (means ± S.E.)				Forest Productivity Variables (means ± S.E.)	
Site	**Total Height (m)**	**Tree Density (individuals·ha^{-1})**	**Stand Basal Area (m^2·ha^{-1})**	**Diversity Index (α)**	**Wood Volume (m^3·ha^{-1})**	**Tree Biomass (t·ha^{-1})**
Ultisol (U)	11.61 ± 4.61 ^{a}	702 ± 148 ^{b}	22.779 ^{a}	8.67 ± 4.93 ^{a}	142.31 ± 50.98 ^{a}	130.87 ± 32.17 ^{a}
Alfisol (A)	9.19 ± 4.10 ^{b}	906 ± 393 ^{a}	22.543 ^{a}	6.86 ± 4.10 ^{a}	121.61 ± 83.62 ^{b}	113.28 ± 50.14 ^{a}
p-value	<0.0001	0.0182	0.9196	0.0579	0.0215	0.1631
F-value	34.97	6.3225	0.0104	3.9230	5.9531	2.0561

Means followed by the same letter in the same column do not differ at the 5% probability level. (Tukey's test, $p < 0.05$).

At the Ultisol site, forest production was higher than at the Alfisol site (Table 2), as the more fertile soil resulted in taller individuals which contributed to a greater timber stock and tree biomass in that site. Nevertheless, tree density was higher in the Alfisol site, resulting in comparable stand basal areas between sites.

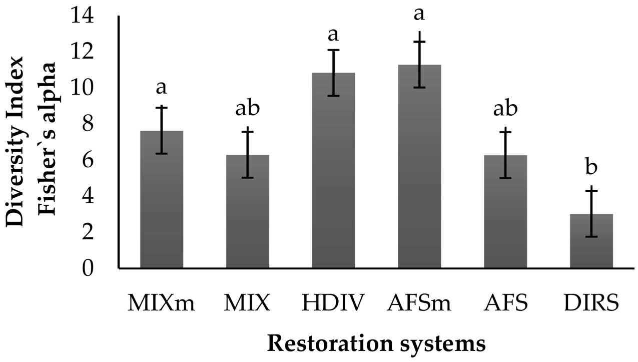
The rarefaction curves (Figure 3a) indicated three main patterns of species diversity and heterogeneity among restoration systems, considering the interpolation line for a sample size of 160 individuals (the AFS curve). The AFSm and MIXm systems exhibited the highest species richness and heterogeneity, in both cases, these stands had been managed by harvesting the exotic species *Mimosa caesalpiniifolia* Benth for firewood. Neither differed from the HDIV system. The MIX and AFS systems (without exotic species removal) were intermediate, and DIRS had the lowest species richness and diversity.



(**a**)

(**b**)

Figure 3. *Cont.*



(**c**)

Figure 3. Effects of different restoration systems for tropical semi-deciduous forest on species richness and diversity, 19–20 years after planting (pooled for sites). (**a**) Rarefaction curves for each restoration system, using the bootstrap method. The curves indicate the number of accumulated species as a function of the number of sampled individuals, by interpolation, with a confidence interval of 95%. The dotted lines indicate the error and the straight lines the interpolation points of rarefaction curves. (**b**) Total number of sampled species per system and the proportion of planted species, regenerating autochthonous and allochthonous species. (**c**) Effect of restoration system on the Fisher's Alpha diversity index. Labels: MIXm ('managed' commercial mixed plantation), MIX (commercial mixed plantation), HDIV (high-diversity tree plantation), AFSm ('managed' agroforestry system), AFS (agroforestry system), DIRS (direct seeding). Bars represent average and standard error. Results for pooled sites data. Treatment means labelled with the same letters are not statistically different at 5% probability level (Tukey's test).

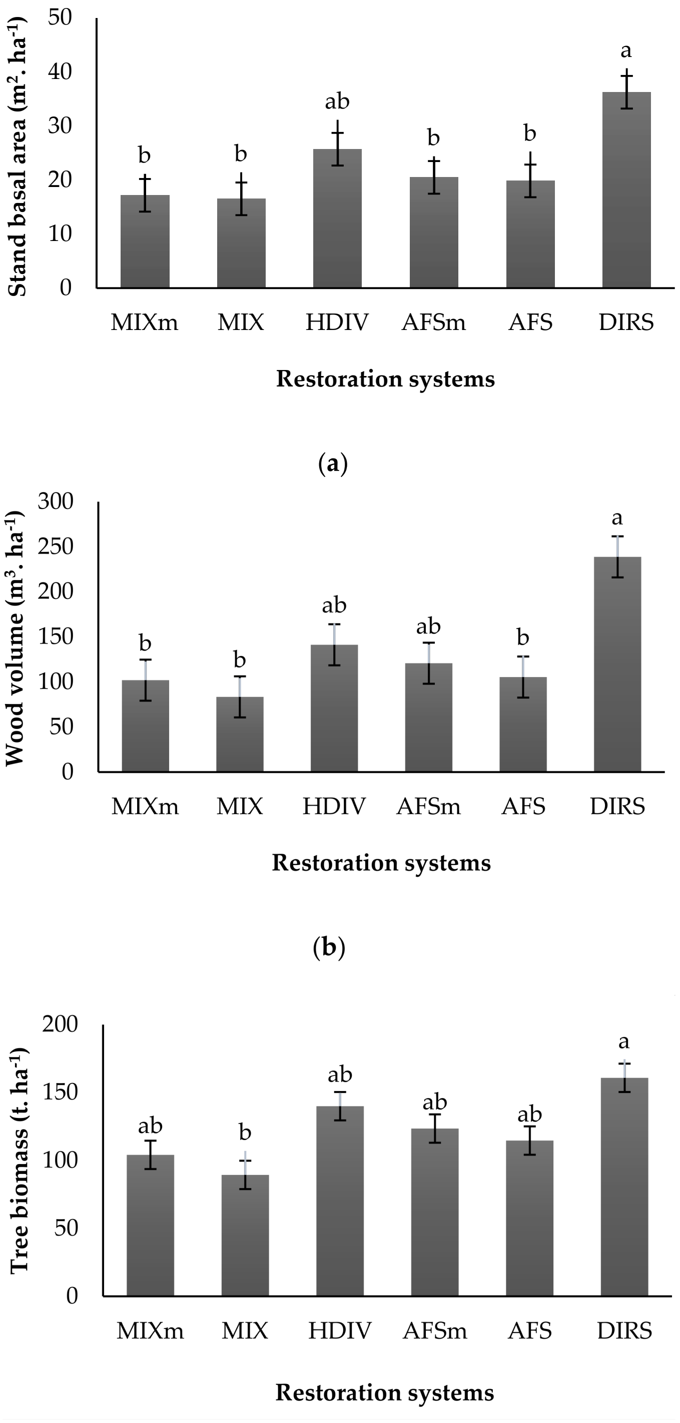
XThe total number of species with individuals ≥ 5 cm of DBH varied from 30 in the agroforestry system (AFS) to 54–55 in the 'managed' commercial mixed plantation (MIXm) and 'managed' agroforestry system (AFSm), respectively; the latter was higher than in the direct seeding (DIRS) system (37 spp.), high-diversity (HDIV) tree plantation system (41 spp.), and in the commercial mixed (MIX) plantation (44 sp) (Figure 3b). Considering the originally planted species, only 8%, 50%, 38%, 34%, 29%, and 63% were sampled, respectively, in the restoration systems DIRS, AFS, AFSm, MIX, MIXm, and HDIV after 20 years, all other species surveyed were colonizers from the surrounding landscape. The majority of the regenerating species were already present in some of the planting systems (autochthonous species), accounting for 57% (DIRS), 27% (AFS), 34% (AFSm), 36% (MIX), 44% (MIXm), and 22% (HDIV), compared to regenerating species coming from the neighboring landscape (allochthonous species) (Supplementary Appendices Table S3 and Figure 3b).

The treatments differed in species diversity ($F_{(5)} = 8.1459$ and $p = 0.00009$). Following the same pattern of rarefaction curves, the mean values of the Fisher Alpha diversity index (Figure 3c) of HDIV, AFSm, and MIXm treatments were higher, followed by those for MIX and AFS at intermediate diversity levels and those for DIRS with the lowest diversity.

The same pattern was observed for stand basal area (Figure 4a), wood stock (Figure 4b) and tree biomass (Figure 4c) for treatments considering the pooled effects of sites.

The stand basal area (Figure 4a) of restoration systems was higher in the DIRS (36.23 $m^2 \cdot ha^{-1}$), represented mostly by individuals of *Schizolobium parahyba* (Vell.). Blake, being lower in the AFS, MIX, AFSm, and MIXm. The HDIV system showed an intermediate stand basal area (25.70 $m^2 \cdot ha^{-1}$), not differing from the other systems evaluated.

The highest wood volume (238.81 $m^3 \cdot ha^{-1}$) was observed in the less complex system (DIRS) too (Figure 4b). In the HDIV and AFSm systems, we observed intermediate wood volume averages, i.e., 141.25, and 120.80 $m^3 \cdot ha^{-1}$, respectively. In contrast, in the other restoration systems, AFS, MIXm, and MIX, the wood values were lowest (115.16, 102.00, and 83.45 $m^3 \cdot ha^{-1}$, respectively).



(**a**)

(**b**)

(**c**)

Figure 4. Stand basal area (**a**), wood volume (**b**), tree biomass (**c**) in different ecological restoration systems of the tropical semideciduous seasonal forest in Botucatu, São Paulo, at 19–20 years after planting. Labels: MIXm ('managed' commercial mixed plantation), MIX (commercial mixed plantation), HDIV (high-diversity tree plantation), AFSm ('managed' agroforestry system), AFS (agroforestry system), DIRS (direct seeding). Bars represent average and standard error. Results for pooled sites data. Treatment means labelled with the same letters are not statistically different at 5% probability level (Tukey's test).

The tree biomass was highest (160.83 t·ha^{-1}) in DIRS, and MIX had the lowest value (89.38 t·ha^{-1}). The other restoration systems had intermediate tree biomass averages, i.e., 139.95, 123.50, 114.66, 104.12 t·ha^{-1}, respectively, for HDIV, AFSm, AFS and MIXm.

The stem diameter structure within the restoration systems, independent of site, followed a negative exponential distribution ("inverted J"), with an exponential decrease in numbers (tree density) with increasing diameter class. Most individuals (90%) were include in the class with the lowest DBH (5.0 to 25.0 cm) (Figure 5).

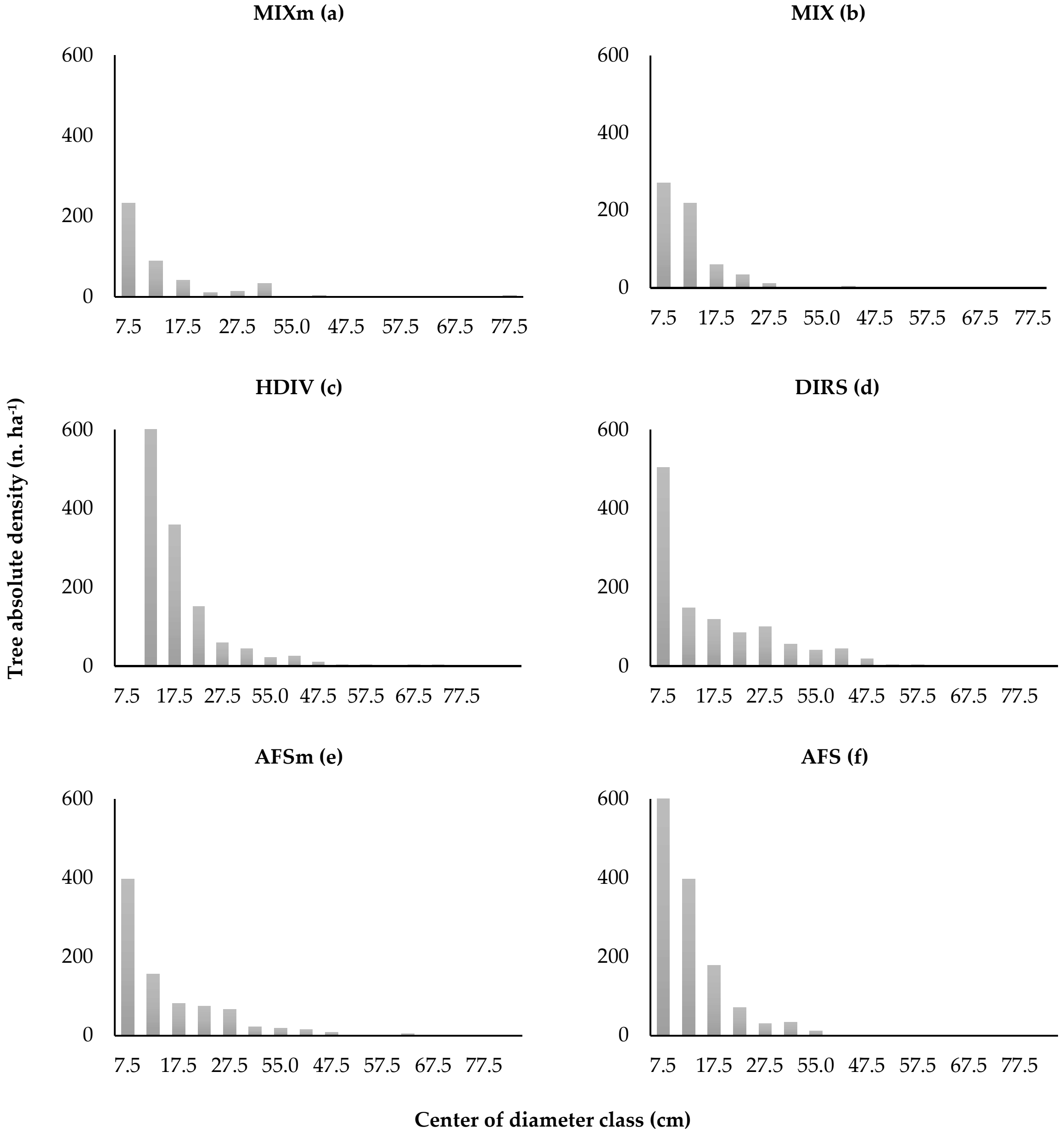


Figure 5. Tree absolute density (n·ha^{-1}) as a function of DBH (diameter at breast height) classes of different restoration systems of the tropical semi-deciduous seasonal forest after 19–20 years of plantation at Botucatu, São Paulo. Labels: (**a**) MIXm ('managed' commercial mixed plantation), (**b**) MIX (commercial mixed plantation), (**c**) HDIV (high-diversity tree plantation), (**d**) DIRS (direct seeding, (**e**) AFSm ('managed' agroforestry system), (**f**) AFS (agroforestry system),). Analyses were performed for pooled sites data.

For the distribution of wood volume as a function of stem diameter class (Figure 6), the curve showed a normal distribution pattern for all restoration systems, with a higher volume concentration in the DBH classes of 25 to 45 cm. Restoration systems differed in their size distribution structure, with non-managed AFS and MIX having smaller tress than their managed counterparts. The largest trees and highest volumes were found for DIRS, the system with the lowest species diversity.

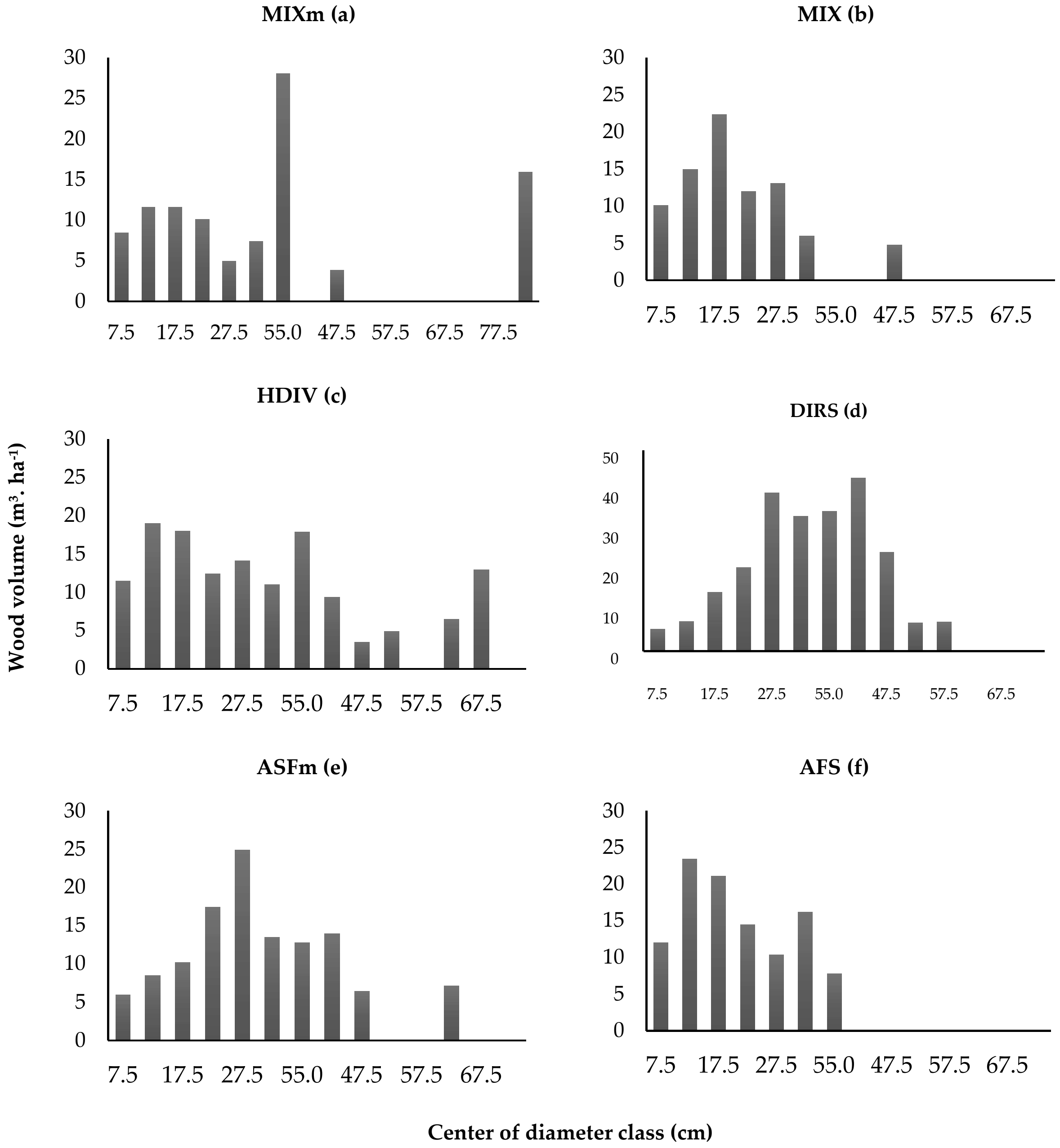


Figure 6. Wood volume ($m^3 \cdot ha^{-1}$) as a function of DBH (diameter at breast height) classes of different restoration systems of the tropical semi-deciduous seasonal forest after 19–20 years of plantation at Botucatu, São Paulo. Labels: (**a**) MIXm ('managed' commercial mixed plantation), (**b**) MIX (commercial mixed plantation), (**c**) HDIV (high-diversity tree plantation), (**d**) DIRS (direct seeding), (**e**) AFSm ('managed' agroforestry system), (**f**) AFS (agroforestry system). Analyses were performed for pooled sites data.

4. Discussion

The observed differences between sites were largely expected [41], as the two sites showed contrasting conditions for plant growth. Nevertheless, while the site was affected forest structure, it did not affect species diversity and composition. Although floristic differences were observed between sites for the natural regeneration community (individuals under 5 cm of DBH) [42], we would expect a higher similarity for the forest canopy because of the strong influence of the planted species in this stratum. The degree of contribution of the surrounding landscape in providing propagules for new colonizers might be expected to increase over time [43].

The term "site" is used in forestry to express the sum of factors such as climate, soil characteristics, topography, and biotic factors that affect tree growth [44]. When comparing the two sites studied, since they belong to the same climatic domain and have a similar topography, the more striking the differences are due to soil characteristics (texture, structure, soil moisture, and fertility). Since the site quality index is defined as the average height of dominating trees in a fully stocked, even-aged stand [41], tree height is the variable, which correlates better with site quality and is most strongly affected by site quality and soil fertility [45–47]. This explains the higher wood volume at the Ultisol site, which favored tree growth.

The Ultisol site had taller trees than the Alfisol site (Table 2), a lower stem density, but higher wood volumes, although the basal areas were similar. Site conditions, such as higher natural fertility, higher clay content [30,31], and a higher water retention capacity [48,49] might initially have favored some individuals of species with a high competitive capacity, which dominated early in the process of stand development [50], suppressing the growth of other individuals. In contrast, in the Alfisol site, individuals might have grown up more evenly, since the soil conditions did not favor individual species with a higher competitive capacity. In addition to the higher natural soil fertility, the higher water holding capacity allowed trees to grow for a longer period of time during the dry season, which explains also the higher wood stock in the Ultisol site. This has been found, for example, in *Pinus taeda* L. in clayey soils, which had a higher average annual increment in comparison with trees in soils with equal clay and sand fractions [51].

The restoration systems examined in this study differed in their biodiversity levels after 20 years. The initial composition of the plantings might have played a role in the current vegetation composition and heterogeneity, although a high level of floristic turnover was observed in most plots, as less than half of the present species in all treatments were those that were originally planted (Figure 3b). A convergence in species richness and diversity levels was observed between the restoration planting that originally had the highest complexity (40 species of different ecological groups on 2500 m^2) and those with half the number of planted species, i.e., treatments that focused on commercial tree species designed to be managed for timber and firewood (the managed agroforestry system, AFSm, and the managed commercial mixed planting- MIXm). Both AFS and MIX treatments were intermediate, and the direct seeding system (DIRS) showed lower levels of species richness and diversity.

The differences between AFSm and AFS, and between MIXm and MIX can be attributed to the harvest and removal of all *Mimosa caesalpiniaefolia* trees in the AFSm and MIXm 5 years earlier [34]. This species is not native to this region and was introduced in this experiment as a nitrogen-fixing, multipurpose tree, to suppress grasses and to establish a litter layer. Nevertheless, because of its fast growth and wide-canopy architecture, after some years, it started to suppress the growth of the other tree species and was thus removed. One year after removal of *M. caesalpiniaefolia*, the growth of the remaining trees had recovered the stand basal area and species diversity to levels existing just prior this harvest [34]. Our results confirm that this intervention provoked positive responses in those stands, only 5 to 6 years later, and that the application of further silvicultural techniques could improve the forest yield and income potential of restored forests. The AFSm had also an outstanding standing wood volume, comparable with the DIRS and the HDIV.

The DIRS system had lower species richness and diversity, although it did not differ in basal area from the HDIV system, which had greater species richness and diversity. This indicates that richness and diversity of species were not preponderant factors for stand basal area development in these systems.

Comparing managed and unmanaged systems (AFS and MIX systems), the species diversity was higher for managed systems (AFSm and MIXm), indicating that the removal of the exotic tree species, *M. caesalpiniifolia* for firewood at 14 years contributed to the recruitment of new species, resulting in stands that were comparable in species diversity to those that were initially more species-rich (HDIV treatment). In contrast, non-managed systems (AFS and MIX) had a tree species diversity comparable to that of the less complex system (DIRS), indicating a possible suppressive effect of this exotic species on the recruitment of regenerating individuals.

The direct seeding treatment (DIRS) had higher averages of stand basal area, wood volume, and tree biomass because it is dominated by individuals of *S. parahyba.* This species had the highest tree density, mean DBH, and height values.

The DIRS had the lowest species richness and diversity of all treatments, although it was planted one year earlier than the others. This system showed a five-fold increase in the original number of species planted, showing a potential of the sown species in catalyzing native vegetation regeneration, with a lower implantation cost [32]. These plots also showed a complex dynamic over time. Two years after sowing, only two species had succeeded out of the five that were originally sown (*Enterolobium contorstisiliquum* (Vell.) Morong and *Schizolobium parahyba* (Vell.) Blake, Fabaceae) [32,33,36,52], with a strong dominance of the first one after 7 years [33] and 13 years [52]. After 12–13 years, *E. contorstisiliquum* trees started to decay and die. Nowadays, the upper canopies of these stands are almost exclusively dominated by *S. parahyba* trees, a fast-growing softwood species. This dominance explains the significantly higher basal area and standing wood volume in DIRS system plots, in comparison with all the other systems, differing in tree biomass only from MIX system, because *S. parahyba* had a lower wood density (0.29) compared to the higher wood density of other species (mid- or late-successional species, groups C and D) in other systems that increase tree biomass. *Schizolobium parahyba* had a high average wood yield (10.52 $m^3 \cdot ha^{-1} \cdot yr^{-1}$), even without genetic or mass selection, or thinning. Because of this species high suitability for plywood [53], these stands could also be subjected to management for commercial and ecological purposes. While these trees represent a source of economic income, the reduction of *S. parahyba* standing stocks by selective thinning creates gaps that other native species could colonize, thereby increasing biodiversity.

Although differences were observed in basal area and wood volume among treatments, as a general pattern, we found no evidence for a general positive relationship between carbon stocks per unit area (calculated as 50% of all phytomass [37]) and tree species richness. Although this relationship can exist at larger spatial scales, at the plot level, tropical forests can have any combination of tree diversity and carbon stocks [17]. This indicates that diversity is not a key structural factor that leads to a high biomass in some tropical forest stands [17].

Tree biomass differences were found among restoration systems, when the analysis considered the site pooled data. The DIRS could be used for wood production and tree biomass for the first 20 years and managed for increasing biodiversity benefits over time [21], recruiting species to increase tree biomass again. Indeed, the carbon–biodiversity relationship is strongly dependent on disturbance intensity and successional stage [54]. These findings reveal that different management strategies may be needed to ensure that carbon conservation schemes return biodiversity co-benefits across forests with different successional trajectories. Forest restoration initiatives that seek to protect and enhance carbon stocks in restored forests are, therefore, likely to protect significant proportions of their biodiversity, especially in more severely degraded areas.

The diameter-class structure is already characteristic of the general pattern of natural tropical forests [55], showing a "reverse-J" shape for all treatments. While this structure is desirable for biodiversity conservation, indicating a higher canopy stratification, it creates a strong limitation for wood production and exploitation, since most trees are concentrated in the smaller diameter classes. Thus, to be able to reconcile biodiversity conservation and wood production, restored forests must be monitored and adequately managed. For example, individual species' diameter distribution can be used to inform restoration system choice and exploitation intensity, as well as the silvi-cultural methods to be adopted, in a way that can be managed without provoking major ecological disturbances [56]. Although foresters have succeeded in managing plantations for wood production and ecologists have succeeded in restoring the biodiversity of tropical forests, we have, so far, been unable to reconcile both approaches in a win-win strategy.

In natural forest fragments, the differences observed between sites in wood, biomass, and carbon stocks in the tree component can be attributed to differences in floristic composition, diameter structure, and successional stage [25–27,37,57]. Moreover, the specific characteristics of each vegetation type can contribute to the different biomass stocks at each site, as the previous land use history of each site might also affect the biomass accumulation rates [27]. At least for tree biomass, our data support the idea that site characteristics are more important than restoration design, a finding that is highly relevant for the design and management of climate mitigation schemes involving forest restoration approaches.

The lowest diversity system (DIRS) showed the highest wood volume and tree biomass yield. Nevertheless, the more complex systems, with a higher number of species planted (HDIV), did not differ in yield from it. Less complex systems, composed of shorter-lived species, can be managed to promote higher biomass accumulation in the future, by the recruitment and regeneration of species with longer life spans. Nevertheless, the system that shows the best potential to reconcile ecological restoration of multiple services is the AFSm, because of its high carbon sequestration potential, with a better balance between short, medium, and long-cycle species [58]. Agroforestry has been considered a leading agricultural practice for mitigating and adapting to climate change impacts, as it can increase carbon sequestration and improve soil quality [31,59]; such systems also provide more flexible options to reconcile economic and social aspects [59]. In addition, utilizing such systems in restoration can offer multiple economic, social, and environmental benefits by: a) enhancing forest provisioning services, such as firewood, timber, fruits and medicinal plants, plant oils, seeds, and honey; b) supporting services such as nutrient cycling and carbon sequestration; and, c) having the highest chance of being adopted by farmers because of their high capacity for food production.

5. Conclusions

Considering our main research question, there are trade-offs between wood production, biomass accumulation, and biodiversity recovery when using different active restoration strategies, namely a combination of wood volume, biomass, tree size distribution, species richness, and diversity. Wood standing stocks and tree biomass in ecological restoration plantation systems depend on species combinations, management practices, and site conditions. A trade-off between species diversity and forest production was observed in species-poor and less complex plantations (DIRS), especially in the lower-quality site. The AFSm and HDIV were the restoration systems more capable to reconcile higher species richness and diversity, while still permitting good forest yield and good potential for multiple services.

Considering the objectives set out in the Brazilian environmental policies regarding the aims of restoring the Legal Reserves [2,3], our results indicate that these goals can be fully accomplished with any of the restoration strategies studied, as all of them are capable of restoring biodiversity, while permitting a certain direct income at varying degrees of management, as these forests develop. Nevertheless, AFSm showed the best balance between the variables analyzed and the best potential to reconcile forest and food production with biodiversity conservation. However, the outcomes can still be improved by improving adaptive management strategies.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/10/7/588/s1, Table S1: List of the composition of the floristic families and species that were originally planted during the installation of different ecological restoration systems (1997–1998) of the Semideciduous Seasonal Forest in Botucatu, São Paulo; Table S2: List of families and species introduced eight years after establishment as enrichment planting at agroforest system (AFS) plots with fruit species at Ultisol and medicinal species at Alfisol; Table S3: List of the floristic composition of the families and species sampled 20 years after establishment in the ecological restoration systems of the Semideciduous Seasonal Forest in Botucatu, São Paulo.

Author Contributions: D.M.F.P. contributed with the research design, collected and processed all data and wrote the manuscript. V.L.E. contributed to the design of the original experiment, the research, and revision of the manuscript. J.A.P. contributed to the design of the original experiment, writing and revision of the manuscript.

Funding: This research was funded by CNPq (Brazilian National Council for Scientific and Technological Development) grant number 133132/2016-1 and 455327/2013-0.

Acknowledgments: We are grateful to Bruna Trentin and Leonardo Martins for their valuable field assistance and to Deivid Machado for statistical analysis assistance. D.M.F. Pontes received a scholarship from CNPq (Brazilian National Council for Scientific and Technological Development). V.L. Engel received a Research Productivity Fellowship Grant from CNPq. We also appreciate very useful contributions from three anonymous reviewers.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Paquette, A.; Messier, C. The role of plantations in managing the world's forests in the Anthropocene. *Front. Ecol. Environ.* **2009**, *8*, 27–34. [CrossRef]
2. BRASIL. Lei Federal nº 12.651, de 25 de Maio 2012. Dispõe Sobre a Proteção da Vegetação Nativa. Available online: http://www.planalto.gov.br/ccivil_03/_Ato2011-2014/2012/Lei/L12651.htm (accessed on 21 August 2016).
3. Planaveg. *Plano Nacional de Recuperação da Vegetação Nativa*; Ministério do Meio Ambiente, Ministério da Agricultura, Pecuária e Abastecimento, Ministério da Educação: Brasília, Brazil, 2017; p. 73. Available online: http://www.mma.gov.br/images/arquivos/florestas/Planaveg_ingl%C3%AAs.pdf (accessed on 28 May 2019).
4. Brasil. Decreto nº 8972, de 23 de Janeiro de 2017. Institui a Política Nacional de Recuperação da Vegetação Nativa. Available online: http://www.planalto.gov.br/ccivil_03/_ato2015-2018/2017/decreto/D8972.htm (accessed on 13 July 2018).
5. United Nations Climate Change. Paris Agreement Targets. Adopted on 12 December 2015. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed on 15 May 2018).
6. IBA, Indústria Brasileira de Árvores. *Relatório 2017*; IBA: Brasília, Brazil, 2017; p. 80. Available online: https://iba.org/images/shared/Biblioteca/IBA_RelatorioAnual2017.pdf (accessed on 5 April 2017).
7. CAR, Cadastro Ambiental Rural. Consulta Pública. Available online: http://www.car.gov.br/publico/imoveis/index (accessed on 23 April 2018).
8. Engel, V.L. Princípios silviculturais aplicados à restauração ecológica. *Ação Ambiental* **2011**, *45*, 7–9.
9. Engel, V.L. Manejo sustentável e restauração florestal. In *Seminário Temático Sobre Recuperação de Áreas Degradadas: A Resolução SMA 21 de 21/11/2001 como Recurso Gerencial para a Recuperação de Áreas Degradadas: Avanços Obtidos e Perspectivas Futuras*; Instituto de Botânica: São Paulo, Brasil, 2003; pp. 21–31.
10. Brancalion, P.H.S.; Viani, R.A.G.; Strassburg, B.B.N.; Rodrigues, R.R. Finding the money for tropical forest restoration. *Unasylva* **2012**, *63*, 25–34.
11. Mansourian, S.; Stanturf, J.; Derkyi, M.A.A.; Engel, V.L. Forest landscape restoration: Increasing the positive impacts of forest restoration or simply the area under tree cover? *Restor. Ecol.* **2017**, *25*, 178–183. [CrossRef]
12. Engel, V.L. Restoring tropical forests. *Rev. Opin.* **2016**, *13*, 34–35.
13. FRA. *Terms and Definitions*; Forest Resources and Assessment Working Paper 180 FAO Forestry Department: Rome, Italy, 2015; p. 36. Available online: http://www.fao.org/3/a-ap862e.pdf (accessed on 25 April 2017).
14. Vieira, S.A.; Alves, L.F.; Aidar, M.; Araújo, L.S.; Baker, T.; Batista, J.L.F.; Campos, M.C.; Camargo, P.B.; Chave, J.; Delitti, W.B.C.; et al. Estimation of biomass and carbon stocks: The case of the Atlantic Forest. *Biota Neotrop.* **2008**, *8*, 21–29. [CrossRef]
15. Clark, D.A.; Brown, S.; Kicklighter, D.W.; Chambers, J.Q.; Thomlinson, J.R.; Ni, J.; Holland, E.A. Net primary production in tropical forests: An evaluation and synthesis of existing field data. *Ecol. Appl.* **2001**, *11*, 371–384. [CrossRef]

16. Malhi, Y.; Doughty, C.; Galbraith, D. The allocation of ecosystem net primary productivity in tropical forests. *Philos. Trans. R Soc. Lond B Biol. Sci.* **2011**, *366*, 3225–3245. [CrossRef]
17. Sullivan, M.J.P.; Talbot, J.; Lewis, S.L.; Phillips, O.L.; Qie, L.; Begne, S.K.; Chave, J.; Cuni-Sanchez, A.; Hubau, W.; Lopez-Gonzalez; et al. Diversity and carbon storage across the tropical forest biome. *Sci. Rep. Nat.* **2017**, *7*, 39102. Available online: https://www.nature.com/articles/srep39102 (accessed on 20 April 2017). [CrossRef]
18. Sullivan, M.J.P.; Deere, N.J.; Guillera-Arroita, G.; Baking, E.L.; Bernard, H.; Pfeifer, M.; Reynolds, G.; Wearn, O.R.; Davies, Z.G.; Struebig, M.J. High Carbon Stock forests provide co- benefits for tropical biodiversity. *J. Appl. Ecol.* **2018**, *55*, 997–1008.
19. Parrotta, J.A.; Wildburger, C.; Mansourian, S. *Understanding Relationships between Biodiversity, Carbon, Forests and People: The Key to Achieving REDD+ Objectives. A Global Assessment Report Prepared by the Global Forest Expert Panel on Biodiversity, Forest Management, and REDD+*; World Series; IUFRO: Vienna, Austria, 2012; Volume 31, p. 161. Available online: https://www.iufro.org/science/gfep/biodiv-forman-redd-panel/report/ (accessed on 30 June 2019).
20. Brancalion, P.H.S.; Schweizer, D.; Gaudare, U.; Mangueira, J.R.; Lamonato, F.; Farah, F.T.; Nave, A.G.; Rodrigues, R.R. Balancing economic costs and ecological outcomes of passive and active restoration in agricultural landscapes: The case of Brazil. *Biotropica* **2016**, *48*, 856–867. [CrossRef]
21. Lamb, D.; Erskine, P.; Parrotta, J. Restoration of degraded tropical forest landscapes. *Science* **2005**, *310*, 1628–1632. [CrossRef] [PubMed]
22. Suganuma, M.; Durigan, G. Indicators of restoration success in riparian tropical forests using multiple reference ecosystems. *Restor. Ecol.* **2015**, *23*, 238–251. [CrossRef]
23. Campoe, O.C.; Stape, J.L.; Mendes, J.C.T. Can intensive management accelerate the restoration of Brazil's Atlantic forests? *Forest Ecol. Manag.* **2010**, *59*, 1808–1814. [CrossRef]
24. Kanowski, J.; Catterall, C. Carbon stocks in above-ground biomass of monoculture plantations, mixed species plantations and environmental restoration plantings in north-east Australia. *Ecol. Manag. Restor.* **2010**, *11*, 119–126. [CrossRef]
25. Ferez, A.P.C.; Campoe, O.C.; Mendes, J.C.T.; Stape, J.L. Silvicultural opportunities for increasing carbon stock in restoration of Atlantic forests in Brazil. *Forest Ecol. Manag.* **2015**, *350*, 40–45. [CrossRef]
26. Souza, A.L.; Boina, A.; Soares, C.P.B.; Vital, B.R.; De Oliveira Gaspar, R.; De Lana, J.M. Estoque e crescimento em volume, biomassa, carbono e dióxido de carbono em Floresta Estacional Semidecidual. *Revista Árvore* **2011**, *35*, 1277–1285. [CrossRef]
27. Ribeiro, S.C.; Jacovine, L.A.G.; Soares, C.P.B.; Martins, S.V.; Nardelli, A.M.B.; Souza, A.L. Quantificação de biomassa e estimativa de estoque de carbono em uma capoeira da zona da mata mineira. *Revista Árvore* **2010**, *34*, 495–504. [CrossRef]
28. Alvares, C.A.; Stape, J.L.; Sentelhas, P.C.; De Moraes, G.; Leonardo, J.; Sparovek, G. Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift* **2013**, *22*, 711–728. [CrossRef]
29. IBGE. *Manual Técnico da Vegetação Brasileira*; Instituto Brasileiro de Geografia e Estatística: Rio de Janeiro, Brazil, 2012; p. 271. Available online: https://biblioteca.ibge.gov.br/visualizacao/livros/liv63011.pdf (accessed on 4 April 2017).
30. Nogueira Junior, L.R. Caracterização de Solos Degradados Pela Atividade Agrícola e Alterações Biológicas Após Reflorestamentos com Diferentes Associações de Espécies da Mata Atlântica. Master's Thesis, São Paulo University, São Paulo, Brazil, 2000.
31. Nogueira Junior, L.R.; De Moraes Gonçalves, J.L.; Engel, V.L.; Parrotta, J. Soil dynamics and carbon stocks 10 years after restoration of degraded land using Atlantic Forest tree species. *Forest Syst.* **2011**, *20*, 536–545. [CrossRef]
32. Engel, V.L.; Parrotta, J. An evaluation of direct seeding for reforestation of degraded lands in central São Paulo state, Brazil. *Forest Ecol. Manag.* **2001**, *152*, 169–181. [CrossRef]
33. Siddique, I.; Engel, V.L.; Parrotta, J.A.; Lamb, D.; Nardoto, G.B.; Ometto, J.P.; Martinelli, L.A.; Schmidt, S. Dominance of legume trees alters nutrient relations in mixed species forest restoration planting within seven years. *Biogeochemistry* **2008**, *88*, 89–101. [CrossRef]
34. Podadera, D.S.; Engel, V.L.; Parrotta, J.A.; Machado, D.L.; Sato, L.M.; Durigan, G. Influence of removal of a non-native tree species *Mimosa caesalpiniifolia* Benth. on the regenerating plant communities in a tropical semideciduous forest under restoration in Brazil. *Environ. Manag.* **2015**, *56*, 1148–1158. [CrossRef] [PubMed]

35. Forzza, R.C.; Costa, A.F.; Walter, B.M.T.; Bicudo, C.; Moura, C.W.N.; Peralta, D.F.; Costa, D.P.; Barros, F.; Lima, H.C.; Prado, J. Flora do Brasil 2020 em Construção. Jardim Botânico do Rio de Janeiro. 2013. Available online: http://floradobrasil.jbrj.gov.br/ (accessed on 20 April 2017).
36. Ré, D.S. Equações Volumétricas e Produção de Madeira em Plantios Mistos Visando à Restauração da Floresta Estacional Semidecidual. Master's Thesis, São Paulo State University, São Paulo, Brazil, 2011.
37. Nogueira Junior, L.R.; Rodrigues, L.; Engel, V.L.; Parrotta, J.A.; Melo, A.C.G.D.; Ré, D.S. Allometric equations for estimation of tree biomass in mixed plantations with native species in the restoration of the Atlantic Forest. *Biota Neotrop.* **2014**, *14*, 1–9. [CrossRef]
38. Hammer, O.; Harper, D.A.T.; Ryan, P.D. PAST: Paleontological statistics software package for education and data analysis. *Palaeontol. Electron.* **2001**, *4*, 9.
39. Magurran, A.E. *Measuring Biological Diversity Malden*; Blackwell Publishing: Hoboken, NJ, USA, 2004; p. 256.
40. R Development Core Team. *R: A Language and Environment for Statistical Computing*; Versão 3.1.4; R Foundation for Statistical Computing: Vienna, Austria, 2017.
41. Stuble, K.; Fick, S.; Young, T. Every restoration is unique: Testing year effects and site effects as drivers of initial restoration trajectories. *J. Appl. Ecol.* **2017**, *54*, 1051–1057. [CrossRef]
42. Figueiredo, L.P.I. A comunidade regenerante em diferentes sistemas de restauração ecológica na floresta estacional semidecidual. Master's Thesis, São Paulo State University, São Paulo, Brazil, 2018.
43. Villota Céron, D.E. Chuva de sementes do solo em diferentes sistemas de restauração ecológica da floresta estacional semidecidual. Master's Thesis, São Paulo State University, São Paulo, Brazil, 2015.
44. Geyer, W.; Lynch, K. Use of site index as a forestry management tool. *Trans. Kans. Acad. Sci.* **1987**, *90*, 45–51. [CrossRef]
45. Batista, J.L.F.; Couto, H.T.Z. O estéreo. *METRVM* **2002**, *2*, 1–18. Available online: http://cmq.esalq.usp.br/Philodendros/lib/exe/fetch.php?media=metrvm:metrvm:metrvm-2002-n02.pdf (accessed on 10 July 2019).
46. Barnes, B.V.; Zak, D.R.; Denton, S.R.; Spurr, S.H. *Forest Ecology*, 4th ed.; John Wiley and Sons Inc.: New York, NY, USA, 1998; p. 774.
47. Taylor, P. *Growing Up: Forestry in Queensland*; Allen & Unwin: St. Leonards, NSW, Australia, 1994; p. 242.
48. Oliveira, R.M. Desempenho ecofisiológico de mudas de *Euterpe edulis* Martius de diferentes estádios de desenvolvimento e implicações para a restauração ecológica. Master's Thesis, São Paulo State University, São Paulo, Brazil, 2015.
49. Fideles-Pontes, D.M. Effects of restoration systems on water retention capacity of accumulated litter and soil moisture at two sites with contrasting soil properties. In *Book of Abstracts of the World Conference on Ecological Restoration, Foz do Iguassu, Brazil, 27 August–1 September 2017*; Society for Ecological Restoration: Washington, DC, USA, 2017; p. 422. Available online: http://ser2017.org/ser2017_livroresumos-site.pdf (accessed on 3 July 2018).
50. Von Guillhaussen, P.; Rascher, U.; Jablonowski, N.D.; Plückers, C.; Beierkuhnlein, C.; Temperton, V.M. Priority effects of time of arrival of plant functional groups override sowing interval or density effects: A grassland experiment. *PLoS ONE* **2014**, *9*, 1–11. [CrossRef]
51. Bognola, I.A.; Dedecek, R.A.; Lavoranti, O.J.; Higa, A.R. Influência das propriedades físico-hídricas do solo no crescimento de *Pinus taeda*. *Pesqui Florest Bras.* **2010**, *30*, 37–49. [CrossRef]
52. Nogueira Junior, L.R. Estoque de carbono na fitomassa e mudanças nos atributos do solo em diferentes modelos de restauração da Mata Atlântica. Ph.D. Thesis, São Paulo University, São Paulo, Brazil, 2010.
53. Palma, H.A.L.; Moreno, J.S.; Ballarin, A.W. Compensados de Guapuruvu (*Schizolobium parahyba* (Vell.) S. F. Blake). In Proceedings of the Anais Congresso Brasileiro de Ciência e Tecnologia da Madeira, Madeira, Portugal, 4–6 September 2017; Available online: https://proceedings.science/cbctem/papers/compensados-de-guapuruvu-%28schizolobium-parahyba-%28vell.%29-s.-f.-blake%29 (accessed on 24 May 2019).
54. Ferreira, J.; Lennox, G.D.; Gardner, T.A.; Thomson, J.R.; Berenguer, E.; Lees, A.C.; Mac Nally, R.; Aragão, L.E.; Ferraz, S.F.; Louzada, J.; et al. Carbon-focused conservation may fail to protect the most biodiverse tropical forests. *Nat. Clim. Change* **2018**, *8*, 744–749. [CrossRef]
55. Lima, J.P.C.; Leão, J.R.A. Dinâmica de crescimento e distribuição diamétrica de fragmentos de florestas nativa e plantada na Amazônia Sul Ocidental. *Floresta e Ambiente* **2013**, *20*, 70–79. [CrossRef]
56. Souza, A.L.; Jesus, R.M. *Distribuição diamétrica de espécies arbóreas da Floresta Atlântica: Análise de agrupamento*; Serviço do Instituto de Florestas (Boletim Técnico, 10): Viçosa, Brazil, 1994; p. 30.

57. Ré, D.S.; Engel, V.L.; Ota, L.M.S.; Blanco Jorge, L.A. Equações alométricas em plantios mistos visando à restauração da Floresta Estacional Semidecidual. *Cerne* **2015**, *21*, 133–140. [CrossRef]
58. Oliveira, R.E.; Carvalhaes, M. Agroforestry as a tool for restoration in Atlantic Forest: Can we find multi-purpose species? *Oecologia Aust.* **2016**, *20*, 425–435. [CrossRef]
59. Vieira, D.L.M.; Holl, K.D.; Peneireiro, F.M. Agro-successional restoration as a strategy to facilitate tropical forest recovery. *Restor. Ecol.* **2009**, *17*, 451–459. [CrossRef]