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Identifying agroforestry characteristics for enhanced nutrient cycling potential in Brazil

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ABSTRACT

Tropical soils are prone to rapid degradation if not managed well, and agroforestry systems have the potential to restore degraded soils and support agricultural production together with other ecosystem services. In Brazil, an increasing number of pioneering farmers are establishing agroforestry systems on previously cleared farmland. However, while there are a wide range of agroforestry systems, this diversity has hardly been quantified, and it is not clear how these systems differ in their capacity for nutrient cycling to reverse soil degradation. The objectives of the study were to assess innovative agroforestry systems in terms of taxonomic and functional diversity, spatial structure and management, and to assess how these systems differ in terms of structural complexity and their potential for nutrient cycling. We assessed a LiDAR-derived stand structural complexity index (SSCI), interrow spacing, stem density, tree species richness and diversity, community weighted means (CWM) of foliar nitrogen and wood density, livestock density, pruning and mowing regimes in 30 agroforestry systems in the state of São Paulo, Brazil. We used N, P, K, Ca and Mg stocks in litter as a proxy for nutrient cycling. The agroforestry systems could be broadly categorized into silvopastures, multistrata and successional agroforestry systems. These types spanned a gradient of structural complexity, and this complexity was positively associated with tree species richness and planting density. Litter nutrient stocks were positively associated with pruning and mulching, and negatively associated with CWM of wood density, indicating the importance of pioneer trees. Overall, our results suggest that densely planted, pruned agroforestry systems that contain high species richness, including pioneer trees, contain relatively high amounts of N, P, K, Ca and Mg in their litter. These findings provide insight in the key characteristics of agroforestry systems to support nutrient cycling, and can inform the design of agroforestry systems for the regeneration of degraded agricultural land.

1. Introduction

Agroforestry systems are ancient production systems which are traditionally developed by integrating desired plant species into forests (Nogué et al., 2017; Maezumi et al., 2018). However, agroforestry systems may also help to restore degraded land, which requires the design of systems suitable for cleared farmland without existing tree cover (FAO, 2017; Wolz et al., 2018). The restoration of agricultural land is particularly urgent in the tropics, as tropical soils are often susceptible to rapid degradation if not managed appropriately (Lehmann et al., 2012; Lal, 2015), and agroforestry systems are well-suited for these environments (Muchane et al., 2020). Agroforestry is an umbrella term for the deliberate integration of crops and woody perennials in the same management unit, and encompasses a wide variety of systems (Nair, 1987). This integration of plant species can enhance biomass production and increase nutrient flows via litter (Fonte and Six, 2010). However, the capacity of agroforestry systems to enhance *in situ* nutrient cycling can be variable and context dependent (Barrios et al., 2017; Sauvadet et al., 2019; Veldkamp et al., 2023). This is particularly the case for phosphorus (P) (Nesper et al., 2018; Muchane et al., 2020), the most critical

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nutrient in tropical agriculture (Roy et al., 2016). Countries such as Brazil face immense economic and environmental costs to restore degraded and P deficient agricultural soils (Withers et al., 2018). Therefore, there is a need for a better understanding of the key characteristics of agroforestry systems that moderate their capacity to provide *in situ* nutrient inputs via litter (Veldkamp et al., 2023).

Agroforestry systems are managed according to farmers' needs and preferences, and therefore vary in species composition and tree density among others (Valencia et al., 2015). This variation can be captured by classifying agroforestry systems into distinct types (Atangana et al., 2013) or by quantifying key properties, such as stand structural complexity (Seidel et al., 2021), which is defined as the heterogeneity of biomass distribution in a three-dimensional space (Ehbrecht et al., 2021). In forests, structural complexity can be quantified by LiDAR (Newnham et al., 2015), and is strongly related to net primary productivity ((Stark et al., 2012); Ali et al., 2016; Gough et al., 2019), microclimate (Ehbrecht et al., 2019) and habitat for biodiversity (Ishii et al., 2004). In agroforestry systems, structural complexity has been associated with carbon storage (Ali and Mattsson, 2017; Cardozo et al., 2022), habitat for biodiversity (Ibarra et al., 2021) and productivity (Jagoret et al., 2017). Due to the tight association of structural complexity and the provision of several ecosystem services, there is a need for a better understanding of what agroforestry design characteristics influence the structural complexity of agroforestry systems.

In Brazil, there is a wide variety of agroforestry systems, ranging from silvopastoral systems where timber trees are planted into pastures to increasingly biodiverse fruit and vegetable agroforestry systems (Schuler et al., 2022). While traditional agroforestry systems can be found in cocoa producing regions in north-east Brazil, there has recently been an increase in newly planted, innovative agroforestry systems in the south-eastern state of São Paulo (Agroicone, 2022; MapSAF, 2022). Here, farmers are combining a range of crops and tree species at varying densities (Guerreiro et al., 2013; Vinholis et al., 2020), and some farmers also apply management practices to generate *in situ* mulch by mowing cover crops and intensively pruning trees (Martinelli et al., 2017; Miccolis et al., 2017). Such practices can enrich soils with nutrients (Froufe et al., 2019) and improve the availability of beneficial soil microbial populations (Chaudhary et al., 2023). Most research on these agroforestry systems focusses on the Atlantic Forest biome, whereas other biomes, such as the Cerrado, have received less attention (Schuler et al., 2022). The meta-analysis by Santos et al. (2019) suggested a relationship between the type of agroforestry system and the provision of ecosystem services in the Atlantic Forest biome. While this relationship holds promise for designing and managing agroforestry systems for particular desired ecosystem services, this relationship still requires further exploration.

The objectives of this study were to explore and describe the types of innovative agroforestry systems in the Cerrado and Atlantic Forest/Cerrado ecotone of São Paulo state, and to assess the capacity of these systems to support nutrient cycling via litter. Specific objectives were to (i) describe agroforestry systems in terms of taxonomic and functional diversity, spatial structure and management, (ii) assess how these agroforestry characteristics influence their structural complexity, and (iii) assess the relationship between and agroforestry characteristics and nutrient stocks in litter.

2. Methods

2.1. Study region

The study area was located in the central-east part of the São Paulo state, Brazil, in a transition zone between the Atlantic Forest and the Cerrado biomes. The predominant soil types in the region are highly weathered Ferralsols (*Latossolos* in Brazilian soil classification) and Acrisols, spanning a gradient in soil texture from very sandy to very clayey (Rossi, 2017). The climate is classified as Cwa according to Köppen criteria with humid summers and dry winters, and an average annual precipitation ranging from 1350 to 1550 mm. The dominant crops in the region include sugarcane, grains, citrus fruits, pastures and eucalypt plantations. Unlike other regions of Brazil, agroforestry systems are not part of the traditional agricultural landscape. However, in recent years a growing number of newly implemented agroforestry systems have been registered (Agroicone, 2022).

2.2. Selection of agroforestry systems

We selected agroforestry farmers in the Cerrado/Atlantic Forest ecotone in the state of São Paulo that have implemented innovative agroforestry on previously agricultural land with the help of local experts, researchers and farmer networks (Fig. 1). Here, agroforestry systems are deemed innovative if they were purposefully and systematically designed to meet multiple objectives (Smith et al., 2012; Wolz et al., 2018). In practice, this entailed systems with cash crops, as well as trees or grasses that fulfil complementary functions, such as producing in situ green manure. This approach deviates from more traditional agroforestry where often remnants of secondary or primary vegetation are left to fulfil functions that are deemed important and only the crop of commercial interest is planted (e.g. leaving scattered trees in planted pastures or planting coffee under native forest canopy).

Thirty agroforestry systems were selected on both small- and large-scale farms (farm size range 1 - >2000 ha). The mean age of the systems at the time of sampling was 5.2 ± 0.6 years (range 3 – 14). The agroforestry systems hosted a diversity of crops such as fruits, e.g. coffee (*Coffea arabica*), lime (*Citrus latifolia*), and avocado (*Persea americana*), timber species, such as lemon eucalyptus (*Cambria citriodora*) and mahogany (*Khaya senegalensis*), a range of vegetables and beef cattle (Fig. 2, Suppl. Table 1). Besides crops, in some systems 'support species' were planted, such as leguminous gliricidia trees (*Gliricidia sepium*) or fast-growing guinea grass (*Panicum maximum cv* Mombaça). In 28 out of 30 agroforestry systems organic fertilizers (e.g., compost and rock meal) were used at generally low levels, and in two silvopastoral systems on an experimental farm chemical fertilizers were applied to maintain base saturation at recommended levels.

2.3. Classification of agroforestry systems into types

The selected agroforestry systems were classified into broad agroforestry system types and further distinguished into more specific types based on literature and the consultation of a local agroforestry expert (Table 1). In one case of doubt we used expert judgement to make the final decision.

2.4. Sampling design and methodology

In each of the 30 agroforestry systems, a sampling plot was established at the centre of the field to minimize edge effects. Twenty-nine out of 30 systems were planted in linear rows and in these systems interrows were defined as the spaces between tree rows where no woody vegetation was present. Hence, sampling plots were divided into 'row' and 'interrow' areas. Sampling plots were 30 m long and three adjacent rows and interrows wide. The plot width was variable and ranged from 15 to 64 m. In the only system where trees were not planted in linear rows, a representative 30 ×30 m sampling plot was established at the centre of the field. Areas with steep slopes were avoided, and sampling plots were visually assessed to ensure that these were representative of the system. Farmers were consulted to verify that sampling plots had a representative management history of the agroforestry system.

We assessed a selection of metrics to characterize the agroforestry systems in terms of spatial structure, taxonomic diversity, functional diversity and management (Table 1). These metrics were chosen to allow for a holistic assessment of the complexity of the agroforestry systems. Data were collected by conducting field measurements between

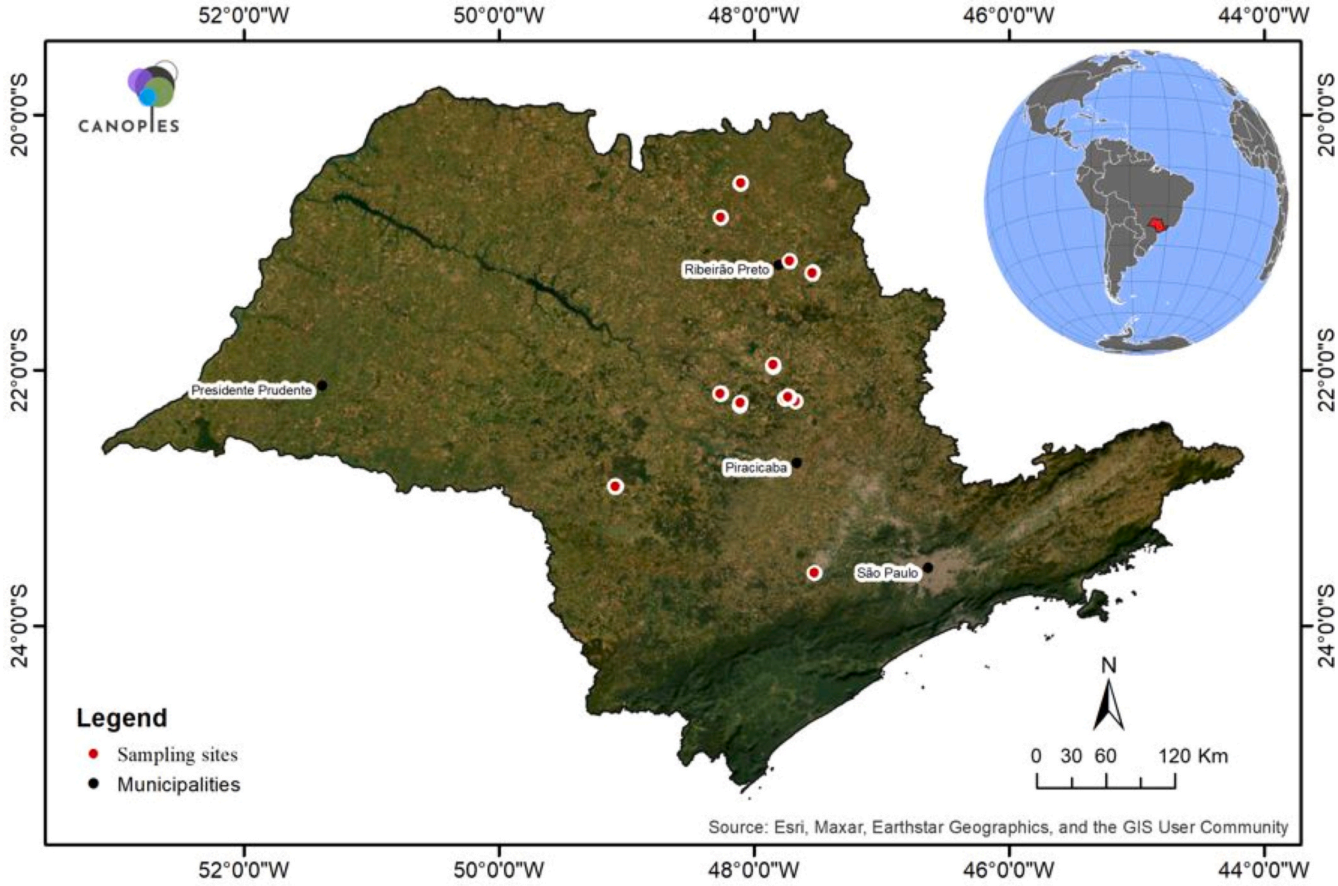


Fig. 1. Location of the study area in the state of São Paulo, south-eastern Brazil. The distribution of sampling sites is indicated by red dots (some dots contain multiple sites).

January-February 2021, by conducting interviews with farmers, and using the TRY database, which contains a large set of plant functional trait data (Kattge et al., 2020; Mariano et al., 2021).

2.5. Spatial structure: Interrow width, stem density and stand structural complexity index (SSCI)

Distances between rows were measured to determine interrow width (m) and trees in rows were counted and converted to stem density (ha^{-1}). Stand structural complexity was assessed by single terrestrial laser scans at nine locations in each system according to the sampling design (Fig. 2) using a Faro Focus 3D laser scanner (Faro Technologies Inc., Lake Marry, Florida, USA) mounted on a tripod at 1.3 m height. Scans were converted into xyz files using Faro Scene software and the resulting point cloud was processed into the Stand Structural Complexity Index (SSCI) (R-code available here: https://github.com/ehbrechtetal/Stand-structural-complexity-index—SSCI). The SSCI is based on the fractal dimension of cross-sectional polygons derived from the 3D point cloud. The fractal dimension is a scale-invariant, mathematical measure of shape complexity (Mandelbrot, 1975), that does not take the stand's vertical structure into account. Therefore, fractal dimension values for each scan are scaled by using the effective number of layers (ENL, Ehbrecht et al., 2016). ENL quantifies the number of canopy layers that are effectively occupied by foliage and woody components. Based on these two components of fractal dimension and ENL, the SSCI quantifies the heterogeneity of biomass distribution in a 3D space. SSCI values increase with increasing stand density and vertical stratification (for further details see Ehbrecht et al., 2017; Ehbrecht et al., 2021). The index has been used in numerous studies to investigate impacts of management and species composition on 3D vegetation structure (e.g. Juchheim et al., 2019; Asbeck and Frey, 2021; Willim et al., 2022) and to study effects of 3D forest structure on ecosystem functions and services (e.g. Röll et al., 2019; Donfack et al., 2021).

2.6. Taxonomic diversity: Species richness and exponential Shannon-Wiener index

Tree species within plots (25 per row, total 75 per plot; Fig. 2) were identified to species level and the number of trees per species counted. Herbaceous crop plants, including cover crops, were identified to species level and their soil cover (as percentage) in the interrow area was visually estimated. The density of spontaneous herbaceous vegetation in interrows was generally low and was therefore not assessed. Species data was used to calculate richness and the exponential Shannon-Wiener index (exp H') (Hill, 1973; Jost, 2006).

2.7. Functional traits: Leaf N concentration, wood density and successional groups

Leaf N concentration ($g\ kg^{-1}$) and wood density ($g\ cm^{-3}$) data per tree species were sourced from the TRY database (Kattge et al., 2020), and community weighted means (CWM) per system were derived by weighting trait values by the relative abundance of each species (De Bello et al., 2021). Foliar N trait data were obtained from the Brazilian database of Mariano et al. (2021) and TRY. As these databases contained multiple values per species, a stepwise strategy was used to select datapoints that were most representative for the study region (supplementary method).

The recorded tree species were allocated to four successional groups (pioneer, early secondary, late secondary or climax species) and

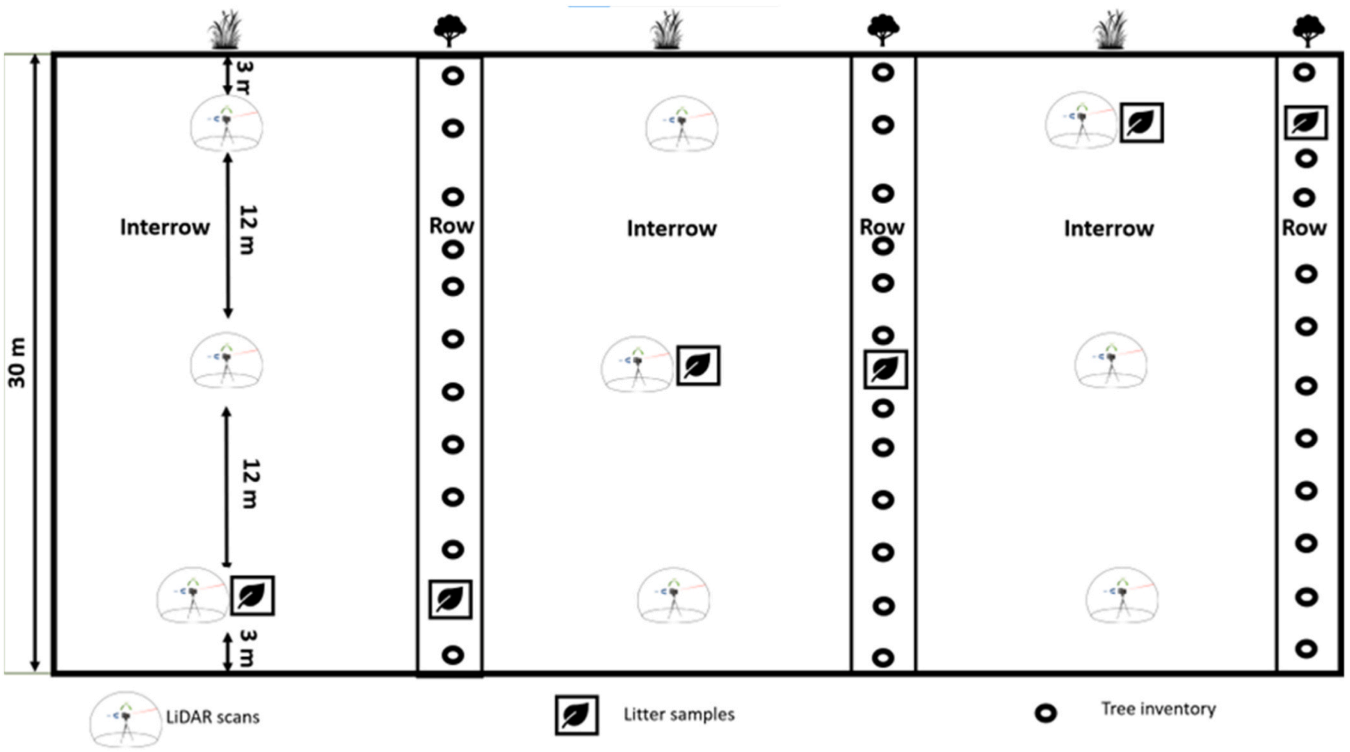


Fig. 2. Sampling design used in the agroforestry systems. Plots were 30 m long and three adjacent rows and interrows wide. LiDAR scans were performed at nine locations within each plot (LiDAR symbol); litter samples (leaf symbol) were taken from each row and interrow following a transect at the centre of the row/interrow. Per row, 25 trees (circles) were identified and their diameter at breast height (DBH) measured.

Table 1
Description of three agroforestry types and six agroforestry sub-types used for the classification of 30 agroforestry systems.

Agroforestry system type	Description	References	Sub-type	References
Silvopastures	Integration of trees and livestock, mainly in grazing systems	(Jose and Jeanne, 2019)	Integrated Livestock-Forestry (iLF)	(Guerreiro et al., 2013)
			Intensive Silvopastoral Systems (SSPi)	(Calle et al., 2013)
Multistrata	Integration of two or more strata of trees or shrubs, no animals	Schroth and do Socorro Souza da Mota (2014)	Simple multistrata	Schroth and do Socorro Souza da Mota (2014)
			Complex multistrata	Schroth and do Socorro Souza da Mota (2014)
Successional	Integration of two or more strata of trees or shrubs, plant species selection based on ecological succession, and dynamic management	Götsch (1994); Miccolis et al. (2016); Andrade et al. (2020)	Successional horticulture	Miccolis et al. (2017); Padovan et al. (2021)
			Successional perennial	(Young, 2017)

herbaceous plants in five successional groups (based on time until harvest: <45 days, <90 days, <120 days, <12 months, perennial) (Chacel, 2018). The validity and consistency of the grouping was checked by triangulating the data with a local agroforestry expert and with (grey) literature (Götsch, 1994; Yana and Weinert, 2001; Miccolis et al., 2016). We used the number of successional groups in plots for further analyses.

2.8. *Management*

Information on management, age and previous land use of the agroforestry plots was obtained by interviews with farmers. A large share of farmers applied *in situ* mulching, e.g. by mowing interrows and applying the cut material as mulch and/or by intensively pruning service trees and applying the residue as mulch. Here, the frequencies (number of times) of mowing & mulching and pruning & mulching per year are reported. Silvopastoral systems were the only systems containing livestock, and also had generally low taxonomic and functional diversity of plants. Due to the high collinearity between livestock density and diversity indices we used the diversity indices for further analysis and did not further explore relationships of livestock density and litter nutrient stocks.

2.9. *Nutrient cycling: Litter nutrient stocks*

Litter was sampled within a 0.5 ×0.5 m quadrant in each of the three tree rows and each of the three interrows along a transect in the plot (Fig. 2). Leaf litter and woody branches < 2 cm in diameter were collected, dried at 70° C for 48 h, weighed and finely ground in the laboratory for further chemical analysis. Subsamples from this ground material were then used to determine N concentration via the Kjeldahl method and P concentrations using the Vanadomolybdate method with determination via spectroscopy. K was analysed via flame photometry and Ca and Mg were extracted with HCl and determined via atomic absorption spectroscopy. All nutrient analyses were carried out at the

University of São Paulo and followed standard procedures (MAPA, 2017). Nutrient concentrations were multiplied by the dry weight of the sample and converted to kg ha^{-1}. The reported nutrient stocks are averages of rows and interrows, which were weighted based on their area proportions in the sampling plots.

2.10. Statistical analyses

Principal component analysis (PCA) was used to explore relationships between indicators for spatial structure, taxonomic diversity, functional diversity and management (Table 2). Data were centered around their mean and the PCA was performed using the *FactoMineR* package, and extracted and visualized using the *factoextra* R package (Kassambara, 2020). Metrics between agroforestry types were tested using non-parametric Kruskal-Wallis and Dunn post-hoc tests. Relationships between litter nutrient stocks (response variables) and SSCI, stem density (log10-transformed), interrow width, tree species richness and Shannon diversity in rows and interrows, leaf N, wood density, pruning & mulching, and mowing & mulching (explanatory variables) were explored using simple and multiple linear regression models. Full models contained all explanatory variables and the *dredge* function of the *MuMIn* package (Bartoń, 2022) was used for model selection based on the AICc criterion. Models within ΔAICc<2 were considered and interactions were tested between variables in the most parsimonious models. Variance Inflation Factors (VIF) were checked for all models to assess collinearity and all reported models had VIF values <2.5 (Witten and James, 2013). All analyses were carried out in R (R Core Team, 2022).

3. Results

3.1. Spatial structure, taxonomic and functional diversity and management of agroforestry system types

PCA indicated a separation between silvopastoral systems on the one hand and multistrata and successional systems on the other along PC1 (40% of variation; Fig. 3). Silvopastoral systems were associated with larger interrow widths and higher wood density CWM, while multistrata and successional systems were associated with tree species richness, stem density and pruning frequency. PC2 (18% of variation) was largely defined by the mowing regime of the interrows and to a lesser extent by the taxonomic plant species richness of the interrows (Fig. 3).

Table 2
Overview of the metrics used for the characterization of agroforestry systems in terms of spatial structure, taxonomic diversity, functional diversity and management. For each metric the unit and collection method is indicated.

	Metrics	Unit	Data collection method
Spatial structure	Stand Structural Complexity Index (SSCI)	dimensionless	Single terrestrial laser scans
	Stem density	Woody stems ha^{-1}	In-field measurements
	Interrow width	m	
Taxonomic diversity	Species richness in rows and interrows	Number of species plot^{-1}	Vegetation survey
	Exponential Shannon-Wiener index (H')	dimensionless	
Functional diversity	Leaf N community weighted mean (CWM)	N g kg^{-1}	TRY database and Mariano et al. (2021)
	Wood density community weighted mean (CWM)	g cm^{-3}	TRY database
	Successional groups	Number of successional groups plot^{-1}	Literature
Management	Livestock density	Heads ha^{-1}	Farmer interview
	Pruning & mulching	Frequency year^{-1}	Farmer interview
	Mowing & mulching	Frequency year^{-1}	Farmer interview

The 30 agroforestry systems spanned a gradient in spatial structure and taxonomic diversity whereby silvopastures were the most simple, followed by multistrata agroforestry systems, and successional agroforestry systems were generally the most complex (Table 3). Silvopastoral systems had a significantly lower stem density and tree species diversity (exp H') than successional systems. Differences in interrow width, tree species richness and wood density CWM between multistrata and successional systems were not statistically significant (Table 3). Wood density CWM was significantly higher in silvopastoral than in the other two agroforestry types, while Leaf N concentrations CWM were not statistically different between the three types. Silvopastoral systems were the only systems with livestock, but applied almost no mowing & mulching or pruning & mulching management. Mowing & mulching was most frequently applied in multistrata systems, and pruning & mulching was most frequently applied in successional systems.

When focussing on sub-types of agroforestry systems, there was a general pattern for tree species richness and functional diversity (successional group richness) of integrated Livestock-Forestry (iLF) < intensive Silvopastoral Systems (SSPi) < simple multistrata < complex multistrata < successional horticulture < successional perennial systems (Table 3). Stem density and SSCI also tended to increase in that order, whereas interrow width decreased in that order. SSPi tended to have a higher tree species richness and diversity than iLF, both in rows and interrows. Complex multistrata systems tended to have a higher species diversity and tree density than simple multistrata systems. Successional horticulture systems had a higher interrow species diversity (mostly vegetables) and similar tree species richness and diversity than successional perennial systems. Pruning & mulching frequency was slightly higher in horticultural than perennial successional systems.

3.2. Explaining variation in stand structural complexity

Successional agroforestry systems had significantly higher SSCI values than silvopastures (Fig. 4.1). There was substantial variation in SSCI in the 30 agroforestry systems, with the highest SSCI (6.5 ± 0.3) in a successional perennial system and the lowest in an iLF with few scattered trees (1.9 ± 0.5; Fig. 5).

The most parsimonious model for SSCI indicated that SSCI was positively associated with tree species richness, stem density and their interaction (R^2=0.71, $p<0.001$; Suppl. Table 2). The combination of high tree species richness and stem density was most prevalent in successional systems, and less so in multistrata and silvopastoral systems (Fig. 5).

3.3. Variation in litter nutrient stocks and best explanatory metrics

Successional systems had consistently higher N, P, Ca and Mg nutrient stocks in litter than silvopastoral and multistrata systems (Fig. 6). For P, mean values show a ranking of silvopastures < multistrata < successional, but differences were only significant between successional and silvopasture systems (Fig. 6). Also for N, Ca and Mg, successional systems had higher litter nutrient stocks than silvopastures, but for Ca and Mg these differences were not statistically significant between multistrata and successional systems. For N, however, successional systems had significantly higher litter stocks than multistrata systems.

When shifting from comparing agroforestry types to employing the full range of metrics as explanatory variables, the model selection procedure indicated that pruning & mulching frequency was contained in the selection of most parsimonious models (ΔAIC<2) and was positively associated with all litter nutrient stocks (Table 4). However, the most parsimonious model for P stocks in litter indicated that there was a significant interaction between pruning & mulching and stem density

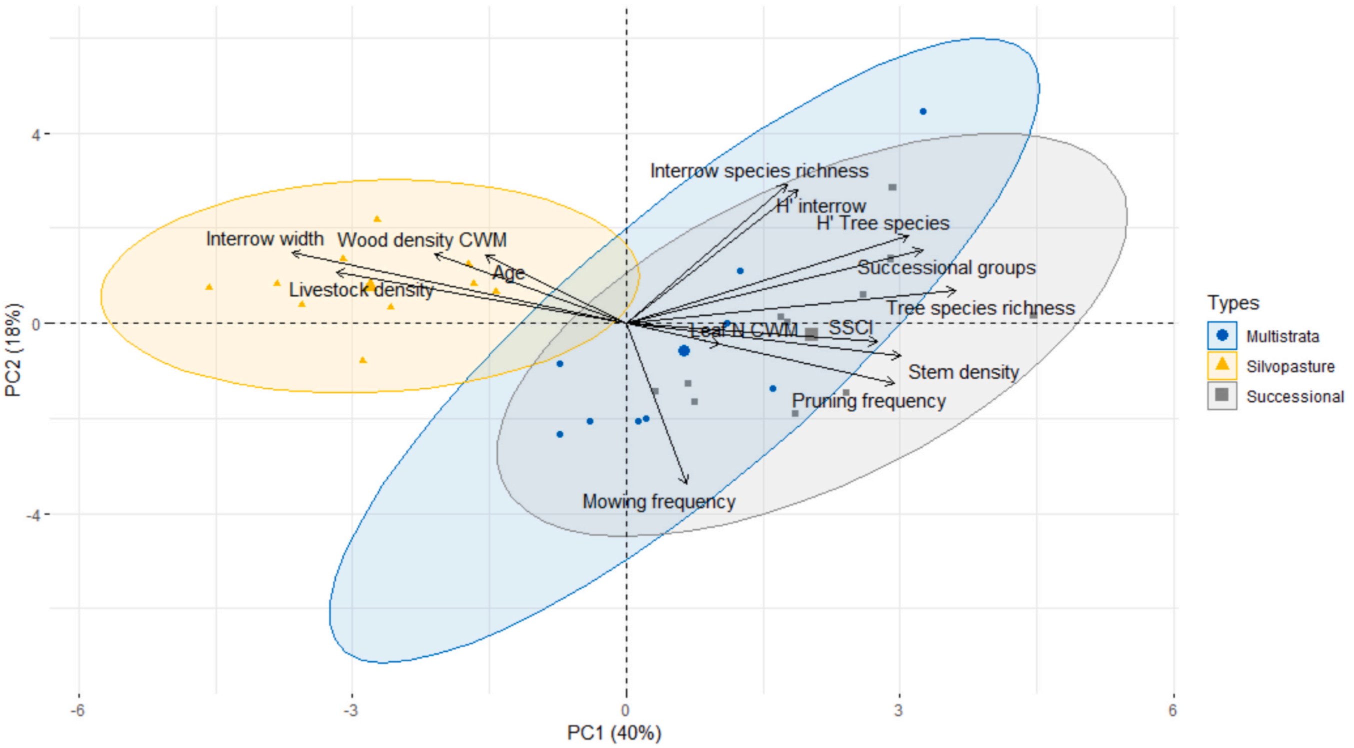


Fig. 3. Principal component analysis of the data collected in silvopastures (yellow), multistrata agroforestry systems (blue), and successional agroforestry systems (grey). The proportion of explained variance is indicated on the axes.

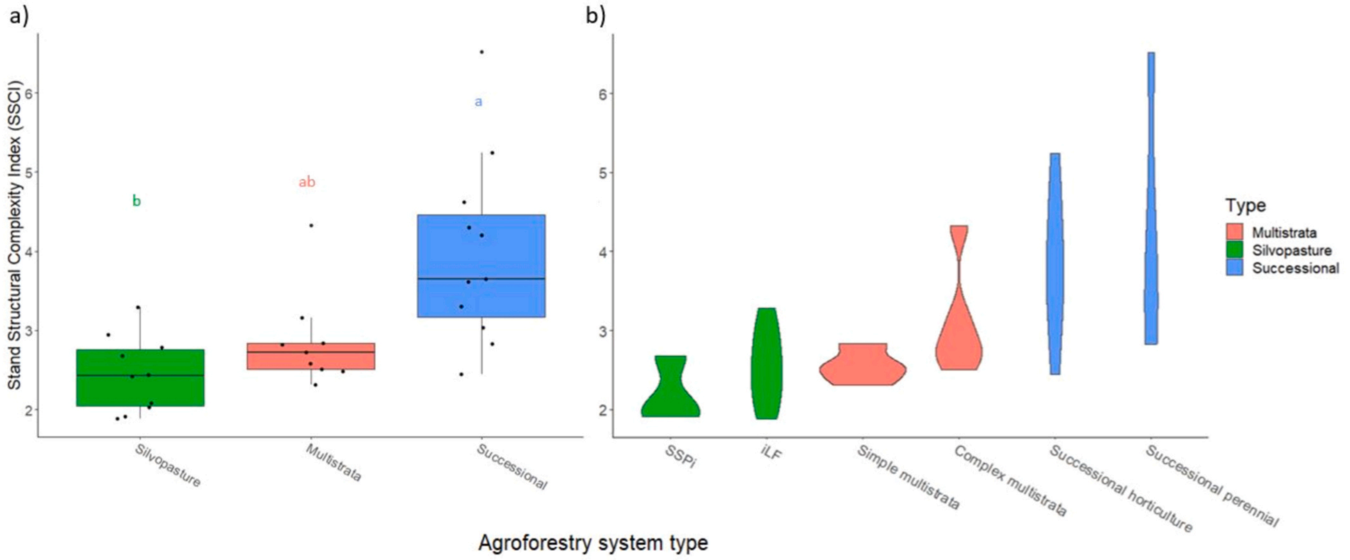


Fig. 4. Stand structural complexity index of silvopastures, multistrata and successional agroforestry systems. Letters indicate significant differences ($p<0.05$; Kruskal-Wallis and Dunn's posthoc test) (a). Differences between the six sub-types were not tested statistically due to low levels of replication and their distribution is visualized in a violin plot (b). SSPi: intensive silvopastoral systems (Spanish acronym), iLF: integrated Livestock-Forestry.

(log) (R^2=0.46, $p<0.01$). Wood density CWM was negatively associated with N, K, Ca and Mg litter stocks. Tree species richness was positively associated with P, K and Ca stocks in litter, while SSCI was positively associated with litter Ca stocks.

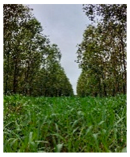
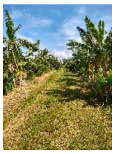
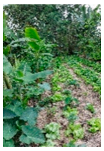
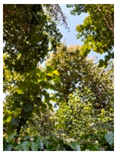
4. Discussion

4.1. General findings

Soil degradation is estimated to affect 40% of agricultural land and 50% of people globally (UNCCD, 2022). Agroforestry systems can contribute to soil regeneration through *in situ* nutrient cycling, but this potential may be system specific (Barrios et al., 2017). Based on the analysis of 30 innovative agroforestry systems which were established

Table 3

Mean values (± standard errors) of the variables reflecting spatial structure, taxonomic diversity, functional diversity and management of the agroforestry types that the 30 sampled systems were assigned to. Differences between silvopastures, multistrata and successional agroforestry systems were tested using the Kruskal-Wallis and Dunn post-hoc test ($p_{Holm-adj.} < 0.05$) and are indicated by letters. Differences between sub-types were not statistically tested due to low levels of replication.

		Silvopastures (*n=10*)		Multistrata (*n=9*)		Successional (*n=11*)	
		Integrated Livestock-Forestry (*n=7*)	Intensive silvopastoral systems (*n=3*)	Simple multistrata (*n=4*)	Complex multistrata (*n=5*)	Successional horticulture (*n=7*)	Successional perennial (*n=4*)
							
Spatial structure	Stand Structural Complexity Index (SSCI)	2.49 ± 0.15 b		2.87 ± 0.20 ab		3.98 ± 0.35 a	
		2.64 ± 0.19	2.19 ± 0.24	2.53 ± 0.11	3.12 ± 0.32	3.83 ± 0.36	4.24 ± 0.82
	Stem density (ha^{-1})	283 ± 45 b		1255 ± 247 ab		3533 ± 710 a	
		240 ± 55	381 ± 50	1550 ± 540	1019 ± 118	3694 ± 969	3251 ± 1141
	Interrow width (m)	23.10 ± 1.89 a		5.39 ± 0.33 b		4.32 ± 0.39 b	
		24.43 ± 2.58	20 ± 0	5.25 ± 0.75	5.5 ± 0.22	4.5 ± 0.54	4 ± 0.57
Taxonomic diversity	Tree species richness	2.80 ± 0.75 a		7.78 ± 1.80 b		10.45 ± 0.86 b	
		2 ± 0.84	4.67 ± 0.88	4.5 ± 1.55	10.4 ± 2.50	10.14 ± 1.01	11 ± 1.73
	H' tree species	2.04 ± 0.42 b		3.79 ± 1.12 ab		4.87 ± 0.38 a	
		1.62 ± 0.52	3.01 ± 0.54	2.19 ± 0.25	5.07 ± 1.88	5.51 ± 0.39	3.75 ± 0.40
	Interrow species richness	1.70 ± 0.39 a		3.56 ± 1.95 a		2.64 ± 0.59 a	
		1.71 ± 0.56	1.67 ± 0.33	2 ± 0.71	4.8 ± 3.55	3.29 ± 0.81	4 ± 0.50
	H' interrow species	1.38 ± 0.19 a		1.71 ± 0.34 a		2.10 ± 0.47 a	
		1.39 ± 0.26	1.35 ± 0.22	1.75 ± 0.47	1.68 ± 0.53	2.52 ± 0.67	1.36 ± 0.36
Functional diversity	Successional group richness	2.70 ± 0.42 b		3.89 ± 0.51 ab		4.91 ± 0.44 a	
		2.29 ± 0.52	3.67 ± 0.33	3.75 ± 1.1	4 ± 0.45	5.29 ± 0.56	4.25 ± 0.63
	Leaf N (g kg^{-1}) CWM	25.67 ± 2.60 a		29.86 ± 0.83 a		26.55 ± 1.90 a	
		22.22 ± 2.77	33.72 ± 0.77	29.94 ± 1.62	29.79 ± 0.95	27.42 ± 1.52	25.04 ± 4.84
	Wood density (g cm^{-3}) CWM	0.69 ± 0.04 a		0.44 ± 0.07 b		0.44 ± 0.05 b	
		0.72 ± 0.04	0.63 ± 0.13	0.35 ± 0.11	0.51 ± 0.10	0.46 ± 0.06	0.39 ± 0.11
Management	Livestock density (ha^{-1})	1.52 ± 0.24 a		0 b		0 b	
		1.49 (0.31)	1.6 (0.38)	0	0	0	0
	Mowing & mulching frequency ($year^{-1}$)	0.30 ± 0.30 b		3.94 ± 0.97 a		2.64 ± 0.88 ab	
		0.43 ± 0.43	0	3.75 ± 1.64	4.1 ± 1.33	2 ± 1.15	3.75 ± 1.31
	Pruning & mulching frequency ($year^{-1}$)	0 b		0.81 ± 0.27 a		1.58 ± 0.18 a	
		0	0	0.5 ± 0.29	1.05 ± 0.42	1.86 ± 0.14	1.1 ± 0.33

on previously agricultural land we report three key findings. First, we found that silvopastoral systems represented a clearly different agro-ecological context than multistrata and successional agroforestry systems. Silvopastoral systems were associated with relatively large interrow widths and higher wood density, reflecting management recommendations for interrow spacing (Vieira Junior et al., 2022) and economically motivated choices of planting high value timber trees. Multistrata and successional systems were associated with relatively high tree species richness, stem density, successional groups and pruning & mulching frequency. Secondly, variation in the LiDAR-derived SSCI was best explained by the combination of tree species richness and stem density. This explains the highest structural complexity in successional systems, as these systems typically had both high species richness and tree density. Third, stocks of N, P, K, Ca and Mg in litter were the lowest in silvopastures, followed by multistrata, and the highest in successional agroforestry systems. Variations in litter stocks of N, K, and Mg were explained by the frequency of pruning & mulching and wood density CWM. P litter stocks were associated with the interaction between pruning frequency and stem density, while Ca litter stocks were associated with wood density CWM and SSCI.

4.2. Agroforestry types

Our study highlights the diversity of agroforestry systems established on previous agricultural land (mostly pastures) in south-eastern Brazil, which range from relatively simple to highly complex systems. Integrated livestock-forestry systems were developed by Brazilian research institute EMBRAPA (EMBRAPA, 2022) and their adoption in São Paulo state depended on the innovative capacity of farmers (de Souza Filho et al., 2020). The concepts behind intensive silvopastoral systems with high densities of fodder shrubs originate from Colombia and central America where their adoption has been fostered by innovation networks between farmers and researchers (Calle et al., 2013). Simple multistrata systems, which typically consist of combinations of two to three tree crops, are representative of experimental alley cropping systems in the global tropics, whereas the complex multistrata systems in this study had considerably higher species diversity than average tropical alley cropping systems (Wolz and DeLucia, 2018). Both horticultural and perennial successional systems are unique to Brazil as they were developed by local farmers, most notably by Ernst Götsch (Götsch, 1994; Andrade et al., 2020). While successional systems partly resemble tropical homegardens (Kumar and Nair, 2006), their commercial orientation and size, linear design in rows and intensive pruning and mulching regime set them apart from typical homegardens (Miccolis et al., 2017). The three types and six sub-types described here showcase pioneering examples of agroforestry systems which can serve both further research as well as real examples for farmers interested in transitioning towards agroforestry (Valencia et al., 2022).

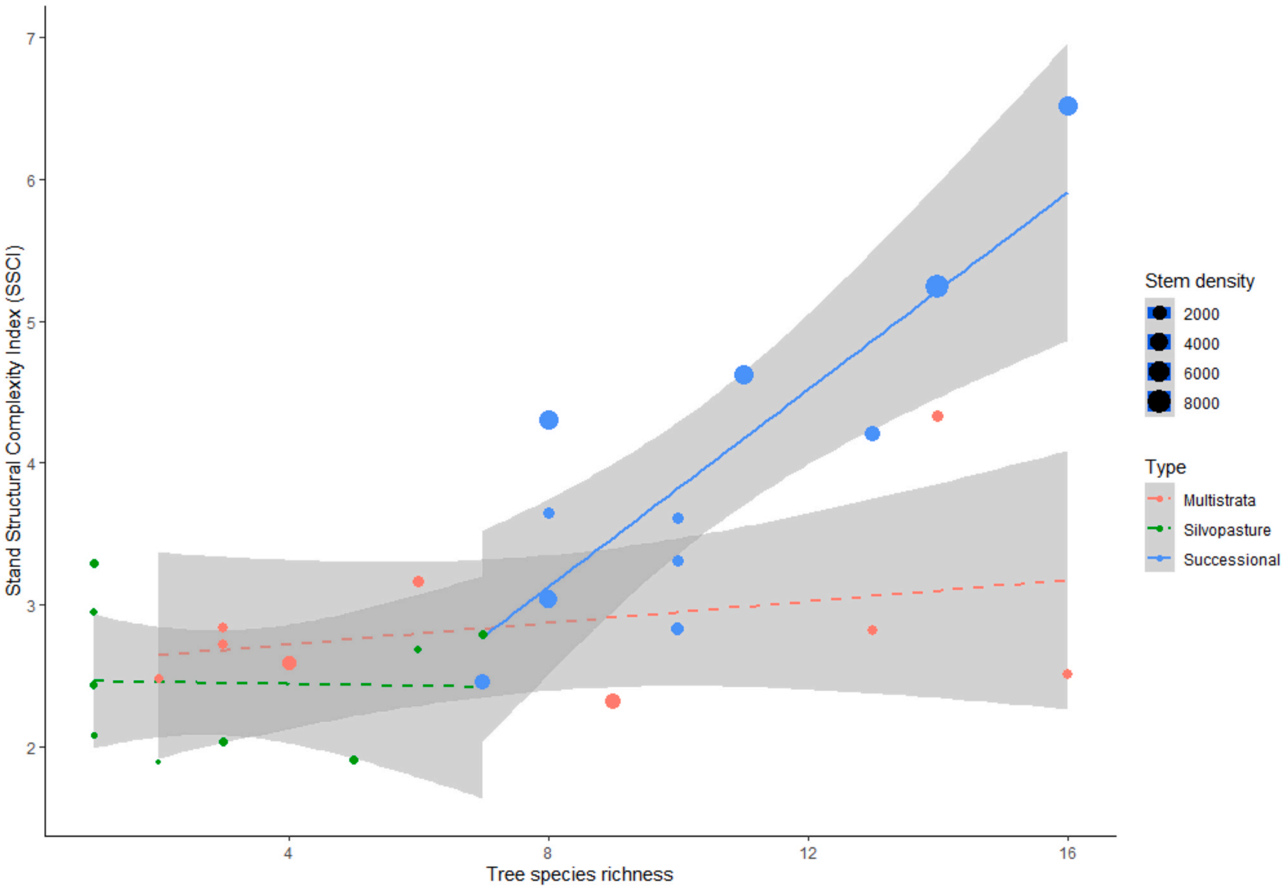


Fig. 5. Relationship between stand structural complexity index (SSCI), tree species richness and stem density. Successional systems are designed to combine high species diversity with high stem density (bubble size), which results in a relatively high structural complexity. In silvopastoral and multistrata systems, increasing tree species richness does not increase SSCI as they tend to be planted at lower densities.

4.3. *Stand structural complexity*

The combination of high species diversity and high planting density resulted in high structural complexity, as evidenced by the LiDAR-derived SSCI. This finding offers farmers practical guidelines for the design of systems with high structural complexity, and also explains why successional systems were structurally more complex than silvopastoral systems. SSCI values of the studied successional agroforestry systems were similar to those from a biodiversity enrichment experiment in Indonesia where up to six native species were added to oil palm monocultures (Zemp et al., 2019). The highest SSCI value in this study (6.5 ± 0.3) was a 15 year old successional agroforest with SSCI values comparable to native woodlands in the Neotropics (Ehbrecht et al., 2021). SSCI values of silvopastoral and multistrata systems were in a similar range as in German silvopastoral systems which were older and had a lower tree density than most of the agroforestry systems presented here (Seidel et al., 2021). However, in this study, the association between SSCI and age was not significant. SSCI can be used as an indicator for microclimate or habitat suitability of a wide range of biota (Zemp et al., 2019). However, further research is needed to underpin the relationship of the SSCI and productivity as well as other ecosystem services in agroforestry systems.

4.4. *Litter nutrient stocks*

High litter nutrient stocks were associated with the practice of pruning & mulching, which is in line with previous studies from southern São Paulo state (Froufe et al., 2019) and experimental agroforestry systems in Bolivia (Schneidewind et al., 2018) and Costa Rica (Russo and Budowski, 1986). Particularly for litter P stocks, the recycling of this critical nutrient will become ever more important for farmers as global P fertilizer stocks are finite (Withers et al., 2018). While the bioavailability of P for crops was not tested in this study, other studies suggest that organic P inputs can stimulate the formation of long-term slow release P sources for plants (Malik et al., 2012) through soil microbial processing (Tang et al., 2014; Gao et al., 2019; Maranguit and Kuzyakov, 2019). Soil organic P stocks were also the main source of plant extractable P when no chemical fertilizers were used (Soltangheisi et al., 2018), and in native tropical forests, P was suggested to cycle directly from litter to plants (Sayer and Tanner, 2010). Litter nutrient stocks in our successional agroforestry systems were in the same range as those in a canopy pruning experiment in a tropical forest where pruning also lead to significant increases in litter N and P concentrations (Silver et al., 2014). Pruned leaf and twig material has not gone through a process of senescence and associated nutrient withdrawal, and has therefore relatively high nutrient concentrations (Noodén and Leopold, 1988).

Besides pruning, wood density CWM, tree species richness and tree stem density were positively associated with litter nutrient stocks. Wood density CWM was negatively associated with litter N, K, Ca and Mg stocks, indicating that agroforestry systems that are dominated by trees with low wood density benefitted from relatively high litter nutrient enrichment. Wood density CWM was associated with the proportion of pioneer species (R^2=0.47, p<0.001, Suppl. Fig. 1), suggesting a relationship between the growth strategy of trees and litter nutrient stocks. Elevated levels of N, P and Ca in litterfall from pioneer trees have been reported in tropical forests and attributed to the ability of pioneers to mobilize nutrients from degraded soil (Aidar et al., 2003; Vasconcelos

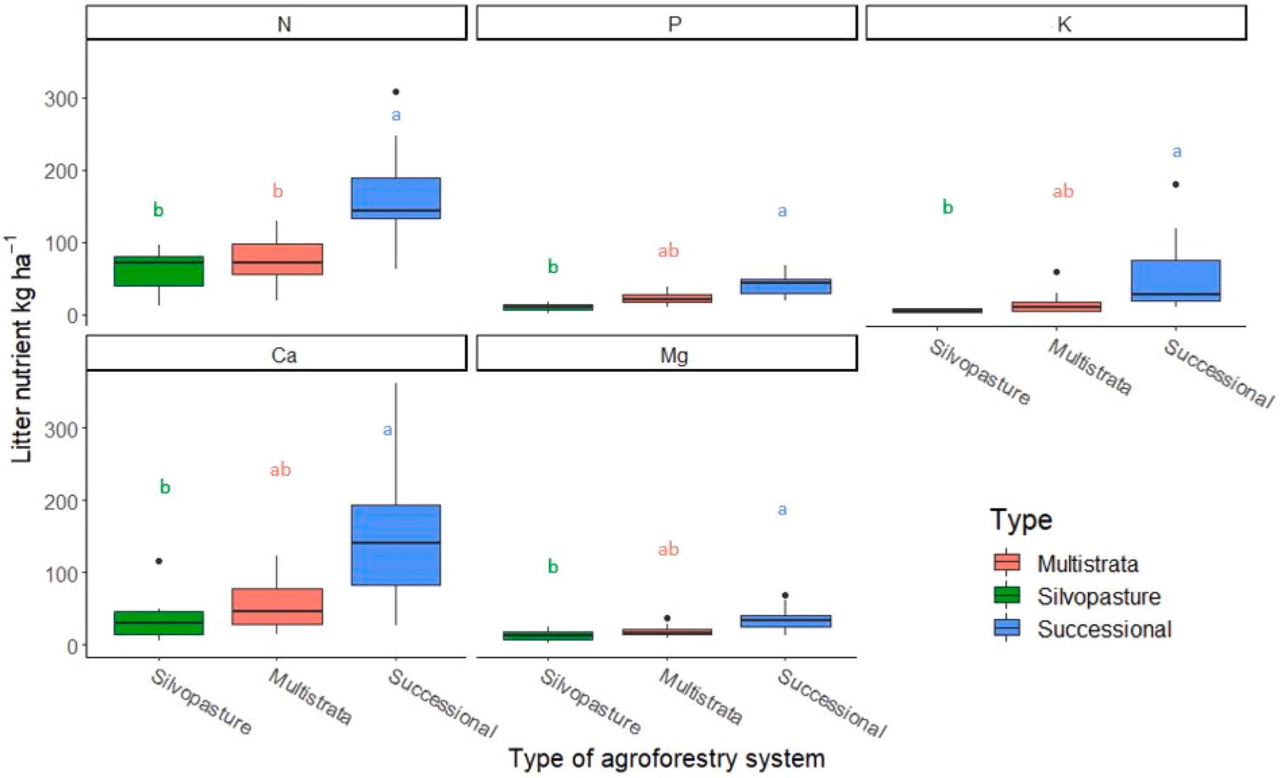


Fig. 6. Litter nutrient stocks of N, P, K, Ca and Mg (kg ha^{-1}) in 30 agroforestry systems. Differences between silvopastures, multistrata and successional systems were tested using the Dunn posthoc test ($p<0.05$) and significant differences are indicated by different letters.

and Luizão, 2004; Santiago, 2010). The positive association between tree species richness and nutrient cycling is also in line with studies which showed the interactive effects of the resulting litter diversity and soil biodiversity on the provision of multiple ecosystem services (Gaitanis et al., 2023; Liu et al., 2023). The association between stem density and litter nutrient input is likely related to higher aboveground biomass in dense stands, as has also been shown in Brazilian secondary forests (Teixeira et al., 2020).

4.5. *Insights for agroforestry system design*

Globally, 74% of scientific agroforestry experiments only included a single tree species (Wolz and DeLucia, 2018), while the farmers managing successional agroforests presented here included on average 10 tree species and two herbaceous species in the interrows. Based on our metrics of functional diversity, results indicate that a substantial share of pioneer trees can enhance nutrient cycling. Pioneer trees are fast-growing and, if managed well (e.g. by periodic pruning), can also provide adequate shade for slower-growing, late successional fruit or high value timber trees (Brancalion et al., 2019). Integration of species with different life cycles also allows for denser plantations, as fast-growing species can be harvested or thinned out over time. Systems with the highest litter nutrient stocks in this study had about 3500 trees ha^{-1}, which is substantially more than in most agroforestry studies (Ma et al., 2020). While coffee and cocoa are the most prominent agroforestry crops globally (Jezeer et al., 2017), our observations suggest that a wide range of crops (including limes, avocados and vegetables) can be grown under shade, especially if pruning management of service trees is used to regulate light interception and to support in situ nutrient cycling (Tscharntke et al., 2011). Pruning and mulching of functionally diverse and dense agroforests also enhanced tree crop productivity in Bolivia, but requires substantial labour input (Armengot et al., 2016; Esche et al., 2022). Agroforestry design should therefore also take into account implications for labour demand.

5. Conclusions

Our findings indicate that more complex agroforestry systems have higher nutrient cycling potential, and that the design of such systems should take into account the taxonomic and functional diversity, spatial structure and management of trees. The establishment of species-enriched agroforestry systems with a high tree density and a high proportion of pioneer tree species, in combination with intense pruning & mulching, can increase litter nutrient stocks, and potentially stimulate nutrient cycling to reverse soil degradation. As all systems in this study were established on previous agricultural land without tree cover, the results show promise for the restoration of degraded farmland. Moving forward, agroforestry research should focus on how to complexify agroforestry systems to increase the provision ecosystem services, while keeping the required labour input manageable (Lovell et al., 2017; Wolz et al., 2018).

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Declaration of Competing Interest

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

Table 4
Results of model selection procedure to determine the most parsimonious models for N, P, K, Ca and Mg stocks in litter based on full models that contained all explanatory variables listed in Table 1. Models with ΔAIC<2 are reported and all models were tested for collinearity using the Variance Inflation Factor (VIF). All reported variables had VIF of below 2.5. Asterisks indicate significance levels: * p <0.05; ** p < 0.01.

Response variable	Explanatory variable	Estimate	R^2	p	Δ AICc
Litter N stock	Pruning frequency + Wood density CWM	4.233e-01 * -3.836e-01 *	0.33	0.001	0
Litter P stock	Pruning frequency + Stem density (log) + Pruning: Stem density	3.1397 * 0.2208 -0.3997 *	0.46	0.006	0
	Pruning frequency + Tree species richness	4.225e-01 * 3.534e-01 *	0.38	<0.001	1.90
Litter K stock	Wood density CWM	-4.212e-01 *	0.18	0.02	0
	Wood density CWM + Pruning frequency	-3.845e-01 * 2.197e-01	0.16	0.03	1.0
	Tree species richness	3.780e-01 *	0.14	0.04	1.19
Litter Ca stock	SSCI + Wood density CWM	3.935e-01 * -3.099e-01	0.29	0.005	0
	SSCI	5.025e-01 **	0.25	0.005	0.76
	Pruning frequency + Wood density CWM	3.460e-01 * -3.906e-01 *	0.26	0.007	0.83
	Tree species richness	4.940e-01 **	0.24	0.006	1.09
Litter Mg stock	Pruning frequency + Wood density CWM	3.408e-01 -3.345e-01	0.21	0.01	0
	Stem density (log)	0.3480 *	0.19	0.01	0
	Pruning frequency	3.967e-01 *	0.16	0.03	1.30

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108828.

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