Chapter 4
Litter Decomposition and Soil Carbon Stocks in Mixed Plantations of *Eucalyptus* spp. and Nitrogen-Fixing Trees

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4.1   Introduction

Increased demand for forest products around the world has contributed to the growth of planted forest areas over the last few decades (FAO 2015). The annual growth rate of planted forests in the tropics has been 2.5% per year, corresponding to an increase of around 20 million hectares from 1990 to 2015 (Payn et al. 2015). In Brazil, the planted forest generates and offers a huge diversity of products, especially pulp, paper, charcoal, sawn wood, and plywood, among others. Brazil currently has 7.84 million hectares of planted trees and its planted tree industry is responsible for 91% of the wood produced for industrial purposes in the country and 6.2% of the Brazilian gross domestic product; it is one of the industries with the greatest potential to help build a green economy (IBA 2017). Most of these planted forests are monocultures of *Eucalyptus* spp. (72%) and *Pinus* spp. (20%), but other species can also attend the internal and external market, such as *Acacia mangium* and *Acacia mearnsii* that together occupy 2.0% of the planted forest area. Other species include *Hevea brasiliensis* (2.9%), *Schizolobium amazonicun* (1.1%), and *Tectona grandis* (1.1%) (IBA 2017).

Despite the success of the Brazilian forestry agribusiness, most of these forest plantations occupy extensive areas of marginal soils, previously managed soils with low fertility or at some stage of degradation (Gonçalves et al. 2013). The sus-

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tainability of these plantations could be compromised in the medium and long terms, because they have been managed under short rotations and a fertilization regime, often far from high nutrient exports due to timber harvests, especially for P, K, and N (Santana et al. 2008; Laclau et al. 2010; Bouillet et al. 2013; Gonçalves et al. 2013).

Soil organic matter (SOM) in tropical planted or native forests has many functions that affect soil properties and processes. It plays a role of the nutrient reserve, and energy source for animals, plants, and microorganisms since its soil minerals are not great suppliers of mineral nutrients due to the high degree of weathering (Sanchez 1979; Maquere et al. 2008; Quesada et al. 2010). In addition, SOM features the greatest cation exchange capacity (CEC) of these soils (Senesi and Loffredo 1999; Oorts et al. 2000; Motta et al. 2002), which prevents essential nutrients from being easily lost by leaching and, consequently, not utilized by forests. Instead, the SOM allows such nutrients to be exchanged easily with the soil solution and to be taken up by plants. SOM participates in soil aggregation and consequently in soil pore space formation (Tisdall and Oades 1982; Denef et al. 2001; Denef and Six 2005). With an expressive and balanced pore space (i.e., macro- and micropores) the roots exploit the soil profile much better, water infiltration is facilitated, and plants get benefit from increased soil water storage (Doran and Parkin 1994; Franzluebbers 2002).

Poorly managed planted forests stimulate decomposition of SOM and C loss. This poor management includes excessive use of machines, with high traffic intensity in soil preparation or harvesting, in addition to removing or burning crop residues from the harvested area and excessive soil disturbance during preparation, which comprises the provision of numerous soil ecosystem services and the sustainability of these forests (Chaer and Tótola 2007; Dominati et al. 2010; Gonçalves et al. 2013; Jesus et al. 2015; and Chap. 10).

The rates of SOM and litter decomposition are clearly influenced by many factors, including temperature, air humidity, soil moisture content, soil microbial community, and litter quality. The last one may be described by lignin, polyphenols, carbon, and nutrient concentrations (especially N and P) or ratios of these (Attiwill and Adams 1993; Hättenschwiler et al. 2011). The N_2-fixing species often have higher N concentrations and decompose more rapidly. Thus, mixtures of *Eucalyptus* litter with more readily decomposable and more nutrient-rich litter may enhance the litter decomposition rates (Briones and Ineson 1996). Gartner and Cardon (2004) in a meta-analysis found synergistic effects in the majority of mixed-litter decomposition studies (47.5%), while antagonistic effects (19.1%) were less frequent. However, some expected improvements due to the introduction of N_2-fixing trees in litter decomposition, such as microbial activity and nutrient release (especially N), seem to be conditioned by the structural quality of the residues, the N:P ratio of litter, and the integration with microorganisms, driven by the increase in diversity of the plant community (Forrester et al. 2006; Rachid et al. 2015; Santos et al. 2018).

This chapter presents and discusses some data about changes in key soil processes, litter decomposition, and C stabilization (i.e., humification) arising from the

introduction of N_2-fixing legumes in mixed *Eucalyptus* spp. plantations. We must emphasize the dynamics of C in tropical soils, especially Brazilian soils, and of the understanding of the main drivers of C stock in mixed-forest soil. Many researchers believe that one of the legacies of mixed plantations is the increase of soil C stocks, and at the end of this chapter, some of the practices and challenges to overcome obstacles of C storage will be introduced.

4.2 Carbon Assimilation and Partitioning in Forest Plantation

Understandings of carbon dynamics in forests involve knowledge of the biotic and abiotic factors that interfere in the growth of species that colonize a particular site, as well as where assimilated C is allocated (Cannell 1989; Davidson and Hirsch 2001). According to Cannell (1989), the CO_2 conversion efficiency in forest biomass is variable and associated with factors such as earth geometry, geographic location of the plantations, CO_2 diffusion rate for chloroplasts, canopy interception capacity (I_o), respiration rate, and proportion of the different aboveground tree compartments.

Carbon accumulation in a forest occurs in several aboveground and belowground compartments. In the case of woody tissues such as stem, thick roots, and branches, this accumulation may last for years or decades. On the other hand, in labile tissues such as leaves, flowers, and fine roots, after the senescence C will return to the atmosphere in days or weeks via decomposition (Landsberg and Gower 1997; Fearnside 2000; Schlesinger and Lichter 2001; Nouvellon et al. 2012; Bachega et al. 2016).

In general, about half of all CO_2 annually fixed in terrestrial biomass via photosynthesis (~120 Pg C y^{-1}) is respired by plants (~60 Pg C y^{-1}) and the other half is respired heterotrophically (Janzen 2004). In other words, if not disturbed, the C reservoirs shall remain constant in these environments, including the soil compartment. Because soil is the largest active C compartment of the terrestrial ecosystem (~1500–2000 Pg) and is in direct connection with other environmental components (i.e., atmosphere, hydrosphere, pedosphere, and biosphere), land use and climate changes have led to the loss of soil capacity to provide varied ecosystem services associated to SOM loss.

The net primary production (NPP) of forests increases with the reduction of latitude because there is a higher incidence of global radiation, higher evapotranspiration, and, consequently, higher cloud formation and rainfall in tropical regions (Ometto 1981). Reducing the vapor saturation deficit in these regions increases stomatal conductance and rate of carbon fixation of plant species (Sands and Mulligan 1990; Novais and Barros 1997; Whitehead 1998). Recent papers with *Eucalyptus* in Brazil have shown that NPP of the genus is determined preferentially by local water

availability and, to a lesser extent, by soil fertility (Reis et al. 1985; Stape et al. 2004, 2010; Rigatto et al. 2005; Balieiro et al. 2008). The importance of water supply for *Eucalyptus grandis* and *E. urophylla* was highlighted by Stape et al. (2004), when evaluating 14 sites with a significant productivity gradient (9.7–39.1 Mg ha^{-1} year^{-1}). According to the authors, the NPP of the sites with intermediate productivity (i.e., average of 16 Mg ha^{-1} year^{-1}) was 46% higher than NPP of the sites with low productivity (i.e., average of 11.9 Mg ha^{-1} year^{-1}), where 32% of this variation was related to the site of water supply. Although the productivity difference between the high and medium productivity sites was 72%, one-third of this difference was related to the availability of soil water.

Similarly, when measured by the average monthly increment of the stem, the productivity of eucalypt was directly related to precipitation in the Rio Doce Basin, in Minas Gerais (Souza et al. 2006). According to the authors, for each increase of 100 mm in the total precipitation within a year, there was an average increase of 0.45 m^3 ha^{-1} month^{-1}, while 100 mm reduction affects this increase in 0.64 m^3 ha^{-1} month^{-1}. Rigatto et al. (2005) also found very high correlations between the height of *Pinus taeda* plants and the available water in eight different forest sites. Stape et al. (2010) across a large edaphoclimatic gradient (~1000 km) and eight regions found that fertilization beyond the current operational rates did not increase the growth of clonal *Eucalyptus* plantations, whereas irrigation raised growth about 30% (to 30.6 Mg ha^{-1} year^{-1}).

At mixed-forest plantations in Brazilian and Congolese conditions, where the set of trials with *Eucalyptus* and *Acacia mangium* (*Acacia*) were developed, the complementary interactions in the mixed stands of acacia and eucalypt led to significant biomass production. However, the NPP was higher than in monocultures without N fertilization only where appropriate climate conditions (i.e., temperature, high humidity, and rainfall) for *Acacia* and poor soil occur (Bouillet et al. 2013; Santos et al. 2016; Voigtlaender et al. 2019). Under milder and drier climate, *Acacia* cannot compete with *Eucalyptus*. For E50:A50 arrangement, and comparing six different sites (five in Brazil and one in Congo), Santos et al. (2016) after Bouillet et al. (2013) found that stemwood production only exceeded E100 ones at the Congo and Seropédica sites, although the differences in both studies were not significant at the 5% level (Santos et al. 2016).

Using the C budget approach to quantify growth, C uptake, and C partitioning in pure and mixed plantations with the same stocking density of *E. grandis* and *A. mangium* plantations, Nouvellon et al. (2012) developed an interesting work with C allocation of mixed plantation in São Paulo state. According to the results, the production in mixed plantation is lower than in *Eucalyptus* due to the lower gross primary production and net primary production values, as well as shifts in C allocation from above- to belowground and from growth to litter production. However, the pattern seems to be site specific due to the two contrasting tropical site environments (i.e., Brazilian and Congolese). Epron et al. (2013) compared Brazilian and Congolese site, and found that mixed-species plantations at the Brazilian site had a lower stand of wood biomass and aboveground net primary production (ANPP) without change in total belowground C fluxes (TBCF). In contrast, the mixed-species

plantations overyielded the monocultures at the Congolese site, which led to higher standing wood biomass at the harvest. The NPP partitioning of the mixed plantations shifted towards aboveground growth at Kissoko (Congo site) and towards belowground growth at Itatinga (Brazil).

## 4.3 Litterfall and Nutrient Deposition in Pure and Mixed-Forest Plantations

As Chap. 3 explores this subject, we briefly discuss the main nutrient cycling alterations during the presence of N_2-fixing trees in *Eucalyptus* plantations.

In general, the amount of litter deposited by a given species or forest follows the same pattern of NPP (Fraser et al. 2015). Studies of litterfall are essential for the sustainability of planted forests since litter management significantly changes the biogeochemistry of these ecosystems and has already known consequences on plant growth, soil quality, and climate (Bowen and Nambiar 1984; Bonan 2008; Ponge 2013; Berg 2018). The C accumulation pattern and partitioning in the different tissues of plants, including the litterfall per unit area, depend on the density, arrangement, and interaction between the species (Reis et al. 1985; Leite et al. 1998; Nouvellon et al. 2012; Epron et al. 2013; Laclau et al. 2013).

The amount and quality of the material deposited on forest soils are related to not only genetics (i.e., planted species), structural, and aging factors of the plantation, but also climatic variables and soil type (Bernhard Reversat 1996; Landsberg and Gower 1997; Laclau et al. 2010; Voigtlaender et al. 2019). Soil fertility and climate significantly shape these two variables (i.e., quantity and quality of leaf litter) (Reis and Barros 1990; Negi and Sharma 1996; Stape et al. 2010). In soils with low fertility, it is natural for species to use nutrients more efficiently than nutrient-richer areas (Novais and Barros 1997; Malhi et al. 2006; Laclau et al. 2010). Therefore, it is common to find more nutrients being recycled in litter in soils of better fertility or without nutritional limitation. However, if there is water deficit during forest development, the water deficit induces stomata closure and, consequently, reduction in carbon fixation; that is, the plant will not succeed to express its potential and efficiency of nutrient use (Novais and Barros 1997; Epron et al. 2009; Stape et al. 2010).

Based on some studies about N deposition via litterfall in pure and mixed plantations, it was found that the litterfall in N_2-fixing leguminous plantation is 65% higher (in average) than that in the monocultures of *Eucalyptus* (without N). In addition, combining such legumes with *Eucalyptus* can promote significant increase, even 42% higher, which evidences the N input increase with the introduction of a leguminous in a mixed plantation (Fig. 4.1).

The presence of *A. mangium* in adult mixed plantations (i.e., >5 years) of five sites in Brazil also intensified the contribution of N via litterfall (Table 4.1), although the deposition pattern was different in the sites analyzed. In four sites, *Acacia* showed higher deposition in comparison to *Eucalyptus* without N fertilization,
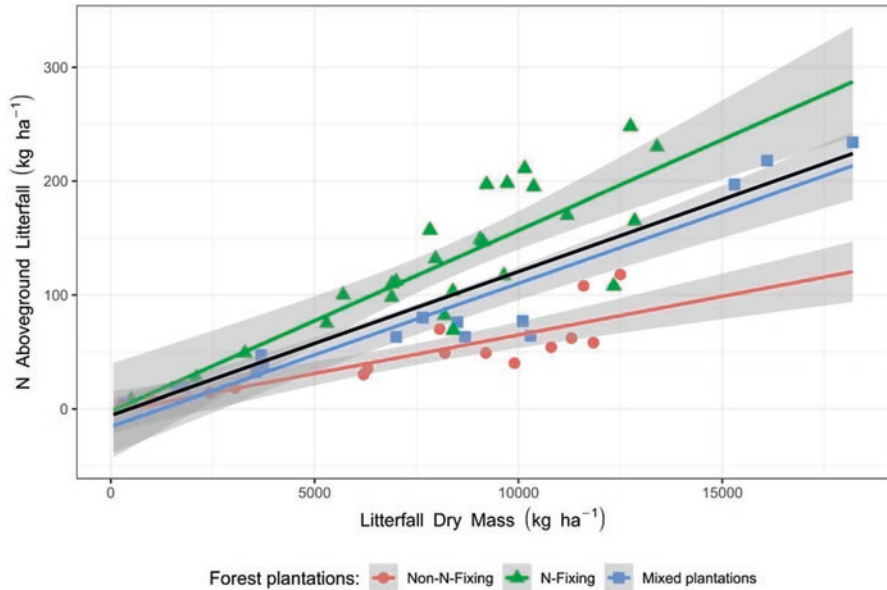
Fig. 4.1 Scatterplot between litterfall dry mass and N aboveground litterfall (Kg ha^{-1}) among N$_2$-fixing, non-N$_2$-fixing, and mixed plantations. Data from $n = 53$ selected studies (see Tables 4.1 and 4.2). The black line represents the mean regression line independent of plantations, that is, the overall regression line ($R^2 = 0.60$, $p < 0.001$). The regression line for red (circle) for non-N$_2$-fixing species, blue (square) for mixed plantations (E50:A50), and green (triangle) for N$_2$-fixing species are given. The shadows represent the standard error around lines for non-N$_2$-fixing, N$_2$-fixing, and mixed plantations only

while the other one showed similar deposition. This trend correlated with the climatic adaptation of the *A. mangium*.

In Brazilian sandy soils, the addition of 120 kg ha^{-1} of N via fertilizer in the *Eucalyptus* monoculture increased the N via litterfall around 10 kg ha^{-1} above the monoculture without N fertilization (final phase of the first rotation). On the other hand, in mixed plantations with half of the plant density replaced by *Acacia mangium* (E50:A50) and double density (E100:A100), the contributions were 110 and 79 kg ha^{-1} higher than in the monocultures without N fertilization, respectively. In younger plantations, the contribution of N inputs via litterfall was lower. But in the first and second rotations and up to 33 months, the contributions for pure *Acacia* or mixed plantations are significantly higher than in the *Eucalyptus* monocultures (without N fertilization) (Santos et al. 2016; Tchichelle et al. 2017).

Most studies referred in Table 4.1 do not provide information about deposition of other nutrients, so it is not possible to imply whether mixed plantations improve the contributions of these elements. On the other hand, since litterfall in mixed plantations is superior to monocultures, it is believed that the overall contribution is higher, as observed for N (Fig. 4.2a). The variability of P and N deposition data (Fig. 4.2)

Table 4.1 Litterfall mass and nutrient deposition associated (kg ha⁻¹ ano⁻¹) under pure and mixed-forest plantations of N_2-fixing and non-N_2-fixing trees in different countries around the world[*]

Species (proportion)	Country State	Rainfall mm	Temp. °C	Soil (texture) or substrate	Age years	Mass kg ha⁻¹ year⁻¹	N	P	K	Ca	Mg	Reference
Pseudosamanea guachapele	Brazil (RJ)	1500	25	Planosol (sandy)	5	7,968	132	7	34	119	51	Froufe (1999)
P. guachapele + E. grandis	Brazil (RJ)	1500	25	Planosol (sandy)	5	7,653	80	5	20	71	20	Froufe (1999)
A. mangium	Brazil (RJ)	1500	25	Planosol (sandy)	5	12,854	165	6	57	96	23	Froufe (1999)
Eucalyptus grandis	Brazil (RJ)	1500	25	Planosol (sandy)	5	9,903	40	6	29	84	21	Froufe (1999)
E. urograndis-	Brazil (RJ)	1370	24	Planosol (sandy)	2.5	500	4	0.3	2	5	1	Santos et al. (2016)
E. urograndis + N	Brazil (RJ)	1370	24	Planosol (sandy)	2.5	1,000	8	0.6	4	9	2	Santos et al. (2016)
A. mangium + E. urograndis (100:100)	Brazil (RJ)	1370	24	Planosol (sandy)	2.5	1,800	19	0.6	6	13	3	Santos et al. (2016)
A. mangium + E. urograndis (50:50)	Brazil (RJ)	1370	24	Planosol (sandy)	2.5	1,620	19	0.6	5	12	3	Santos et al. (2016)
A. mangium	Brazil (RJ)	1370	24	Planosol (sandy)	2.5	2,100	27	0.4	7	13	3	Santos et al. (2016)
E. urograndis	Brazil (RJ)	1370	24	Planosol (sandy)	5	11,600	108	4	37	69	0	Santos et al. (2016)
E. urograndis + N	Brazil (RJ)	1370	24	Planosol (sandy)	5	12,500	118	4	38	74	21	Santos et al. (2016)
A. mangium + E. urograndis (100:100)	Brazil (RJ)	1370	24	Planosol (sandy)	5	16,100	218	5	51	89	24	Santos et al. (2016)

(continued)

Table 4.1 (continued)

Species (proportion)	Country (State)	Rainfall (mm)	Temp. (°C)	Soil (texture) or substrate	Age (years)	Mass (kg ha⁻¹ year⁻¹)	N	P	K	Ca	Mg	Reference
A. mangium + E. urograndis (50:50)	Brazil (RJ)	1370	24	Planosol (sandy)	5	15,300	197	4	47	83	22	Santos et al. (2016)
A. mangium	Brazil (SP)	1390	24	Planosol (sandy)	5	13,400	230	3	52	61	15	Santos et al. (2016)
A. mangium	Brazil (SP)	1390	19	Ferralsol (loam)	6	6,890	98		–	–	–	Voigtlaender et al. (2019)
A. mangium + E. grandis (50:50)	Brazil (SP)	1390	19	Ferralsol (loam)	6	8,693	63		–	–	–	Voigtlaender et al. (2019)
E. grandis	Brazil (SP)	1390	19	Ferralsol (loam)	6	9,201	49		–	–	–	Voigtlaender et al. (2019)
A. mangium	Brazil (SP)	1420	21	Ferralsol (loam)	6.3	8,394	103		–	–	–	Voigtlaender et al. (2019)
A. mangium + E. grandis (50:50)	Brazil (SP)	1420	21	Ferralsol (loam)	6.3	10,107	77		–	–	–	Voigtlaender et al. (2019)
E. grandis	Brazil (SP)	1420	21	Ferralsol (loam)	6.3	11,302	62		–	–	–	Voigtlaender et al. (2019)
A. mangium	Brazil (SP)	1420	23	Arenosol (sandy)	6.1	5,297	75		–	–	–	Voigtlaender et al. (2019)
A. mangium + E. urograndis (50:50)	Brazil (SP)	1420	23	Arenosol (sandy)	6.1	10,296	64		–	–	–	Voigtlaender et al. (2019)
E. urograndis	Brazil (SP)	1420	23	Arenosol (sandy)	6.1	10,804	54		–	–	–	Voigtlaender et al. (2019)
A. mangium	Brazil (SP)	1240	24	Ferralsol (clayed)	6.3	8,185	82		–	–	–	Voigtlaender et al. (2019)
A. mangium + E. urograndis (50:50)	Brazil (SP)	1240	24	Ferralsol (clayed)	6.3	8,504	76		–	–	–	Voigtlaender et al. (2019)

E. urograndis	Brazil (SP)	1240	24	Ferralsol (clayed)	6.3	8,195	49	–	–	–	–	Voigtlaender et al. (2019)
P. guachapele	Brazil (SP)	1250	24	Planosol (sandy)	7	12,750	248	–	–	–	–	Balieiro et al. (2004)
E. grandis	Brazil (RJ)	1250	24	Planosol (sandy)	7	11,840	58	–	–	–	–	Balieiro et al. (2004)
E. globulus	Australia	1009	16	Acrisol (sandy loam)	8.8	2,430	14	0.5	–	–	–	Forrester et al. (2013)
A. mearnsii	Australia	1009	16	Acrisol (sandy loam)	8.8	3,290	49	1	–	–	–	Forrester et al. (2013)
E. globulus + A. mearnsii	Australia	1009	16	Acrisol (sandy loam)	8.8	3,560	32	1	–	–	–	Forrester et al. (2013)
E. globulus + A. mearnsii	Australia	1009	16	Acrisol (sandy loam)	8.8	3,740	39	1	–	–	–	Forrester et al. (2013)
E. globulus + A. mearnsii	Australia	1009	16	Acrisol (sandy loam)	8.8	3,690	47	1	–	–	–	Forrester et al. (2013)
E. globulus + N	Australia	1009	16	Acrisol (sandy loam)	8.8	3,050	18	1	–	–	–	Forrester et al. (2013)
E. saligna	Hawaii	4600	21	Andosol	4	8,070	70	5	4	61	10	Binkley et al. (1992)
Albizia falcataria	Hawaii	4600	21	Andosol	4	12,340	108	6	6	86	14	Binkley et al. (1992)
E. saligna + A. falcataria (50:50)	Hawaii	4600	21	Andosol	4	18,200	234	9	7	72	19	Binkley et al. (1992)
A. mangium	Congo	1200	25	Arenosol (sandy)	7	7,000	112	10	–	–	–	Koutika et al. (2014)
A. mangium + E. urograndis (50:50)	Congo	1200	25	Arenosol (sandy)	7	7,000	63	11	–	–	–	Koutika et al. (2014)
E. urograndis	Congo	1200	25	Arenosol (sandy)	7	6,200	30	9	–	–	–	Koutika et al. (2014)

(continued)

Table 4.1 (continued)

Species (proportion)	Country State	Rainfall mm	Temp. °C	Soil (texture) or substrate	Age years	Mass	N	P	K	Ca	Mg	Reference
						kg ha^{-1} year^{-1}						
A. mangium (2nd rotation)	Congo	1200	25	Arenosol (sandy)	2	5,000	388					Tchichelle et al. (2017)
A. mangium + E. urograndis (50:50) (2sd rotation)	Congo	1200	25	Arenosol (sandy)	2	3,300	306					Tchichelle et al. (2017)
E. urograndis (2nd rotation)	Congo	1200	25	Arenosol (sandy)	2	2,700	89					Tchichelle et al. (2017)
P. guachapele + E. grandis – M (50:50)	Brazil (RJ)	1250	24	Planosol (sandy)	7	66	–	–	–	–	–	Balieiro et al. (2004)
Leguminous tree plantations												
A. mangium	Brazil (RJ)	1005	25	Planosol (sandy)	4	10,155	211	12	28	80	24	Andrade et al. (2000)
A. holosericea	Brazil (RJ)	1005	25	Planosol (sandy)	4	9,062	149	6	20	83	17	Andrade et al. (2000)
Mimosa caesalpiniaefolia	Brazil (RJ)	1005	25	Planosol (sandy)	4	9,132	147	4	21	60	11	Andrade et al. (2000)
Sclerolobium paniculatum–P	Brazil (AP)	2100	27	Ferralsol (sandy loam)	9	9,646	117	3	6	26	10	Mochiutti et al. (2006)
M. caesalpiniaefolia	Brazil (PE)	1300	26	Acrisol (sandy loam)	10	7,830	157	10	55	115	26	Ferreira et al. (2007)
Degraded lands												
Mimosa caesalpiniaefolia	Brazil (RJ)	1005	25	Gravel extraction pit	10	11,200	170	7	31	190	40	Costa et al. (1998)
M. caesalpiniaefolia + Gliricidia sepium	Brazil (RJ)	1005	25	Gravel extraction pit	10		100	4	18	110	25	Costa et al. (1998)
Gliricidia sepium	Brazil (RJ)	1005	25	Gravel extraction pit	10	5,700	100	4	18	100	32	Costa et al. (1998)

Species	Country			Land use								Reference
Acacia auriculiformis	Brazil (RJ)	1005	25	Gravel extraction pit	10	6,900	110	5	19	120	29	Costa et al. (1998)
M. caesalpiniaefolia/A. auriculiformis	Brazil (RJ)	1005	25	Gravel extraction pit	10		130	5	24	150	29	Costa et al. (1998)
M. caesalpiniaefolia	Brazil (MA)	1900	27	Red mud deposits	3	9,727	198	–	–	–	–	Fortes (2000)
M. acutistipula	Brazil (MA)	1900	27	Red mud deposits	3	9,221	197	–	–	–	–	Fortes (2000)
A. mangium	Brazil (MA)	1900	27	Red mud deposits	3	10,376	195	–	–	–	–	Fortes (2000)
E. camaldulensis	Brazil (RJ)	1020	24	Clay extraction pit	4	6,300	35	3	19	45	10	Silva et al. (2015)
A. mangium	Brazil (RJ)	1020	24	Clay extraction pit	4	8,400	69	4	18	31	9	Silva et al. (2015)

*Most of the information in the table is short rotation (1 year). When data were not available in tables or supplementary materials within the papers, the "web plot digitizer program" was used to extract the graphical data (https://automeris.io/WebPlotDigitizer/)
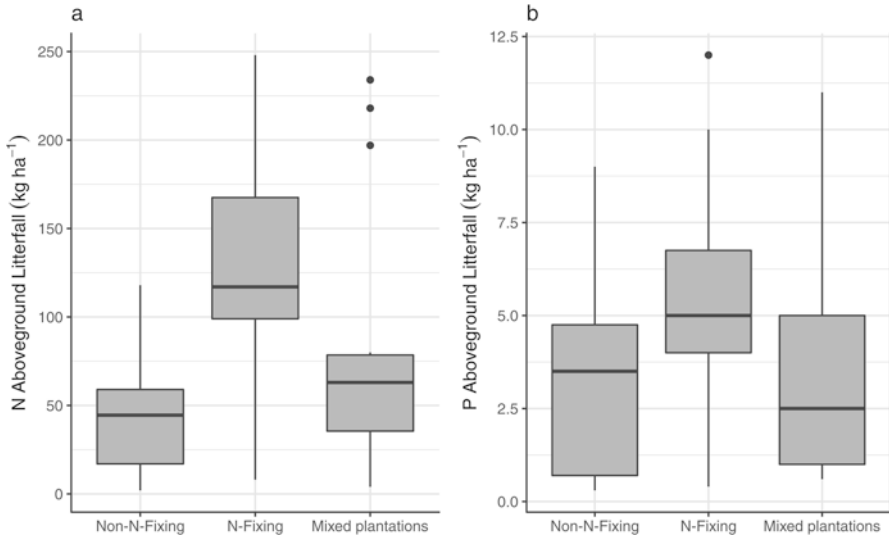
Fig. 4.2 Box plots of N (**a**) and P (**b**) in aboveground litterfall (Kg ha^{-1}) under N$_2$-fixing and non-N$_2$-fixing monocultures and mixed plantations of both. Data from $n = 58$ selected studies (see Tables 4.1 and 4.2). Black points represent outliers

is mostly due to the evaluated species, age of plantations, and variations in the soil types studied that present different mineralogy and fertility, as well as different patterns of growth and accumulation in plants.

4.4 Litter Decomposition Under Pure and Mixed-Forest Plantation

The logic of non-N$_2$-fixing and N$_2$-fixing species' mixed plantations is to promote forest sustainability through complementarity and competitive reduction interactions among species. The "extra" supply of N provided by legume trees via biological nitrogen fixation and its redistribution offer throughout the system an intensification of leaf litter decomposition, N mineralization, and transferring between fixing and non-fixing species. Collectively, they are key processes to improve the growth and yield of the mixed forests, eliminating or using less N fertilizers (Forrester et al. 2006; Kaye et al. 2000; Koutika and Richardson 2019).

In general, decomposition of forest residues is driven by the litter chemical attributes, environmental conditions, and surface area/volume ratio of the residue (Landsberg and Gower 1997; Gholz et al. 2000; Laclau et al. 2010). Although the N deposition is high in pure and mixed plantations with N$_2$-fixing trees (Fig. 4.1), this chemical characteristic is not a guarantee of higher litter decomposition, especially under tropical conditions. For instance, *A. mangium* in sandy and loamy textured

Table 4.2 Changes in soil C stocks (Mg ha^{-1}) under plantations of *Eucalyptus* spp. in comparison to native vegetation as a function of rotation, soil texture, and biome evaluated

Depth	n observations; comments	Max	Min	Median	SD	Mean[*]
		Carbon stock budget in pure stands of *Eucalyptus* related to natural vegetation Mg ha^{-1}				
0–20 cm	50	20.0	−20.9	−1.8	10.0	−1.5
20–40 cm	39	42.0	−25.0	−1.9	15.9	0.3
		Carbon stock change induced by time rotations Mg ha^{-1}				
0–20 cm	13; 1st rotation	19.0	−20.7	1.2	11.6	−2.3
	15; 2nd rotation	20.0	−20.9	3.0	11.5	2.3
	21; not reported	14.0	−18.2	−4.0	7.3	−3.8
20–40 cm	9; 1st rotation	24.0	−21.2	5.0	16.3	−1.0
	14; 2nd rotation	42.0	−25.0	−0.6	20.6	3.1
	14; not reported	20.0	−21.0	−1.8	10.0	−1.5
		Carbon stock change induced by soil texture Mg ha^{-1}				
0–20 cm	10; sandy	7.8	−10.0	−1.6	6.9	−1.0
	17; clayed	19.0	−18.2	0.0	11.5	1.2
	22; not reported	20.0	−20.9	−2.2	9.9	−3.9
20–40 cm	12; sandy	24.0	−12.0	−1.5	10.7	2.5
	13; clayed	32.8	−21.0	1.0	15.5	2.6
	12; not reported	42.0	−25.0	−9.1	20.3	−4.4
		Carbon stock change induced by biome Mg ha^{-1}				
0–20 cm	13; Cerrado	19.0	−10.0	1.0	8.7	3.5
	22; Atlantic rainforest	15.0	−21.0	−6.5	10.3	−5.2
	12; Pampa	20.0	−13.0	−3.5	9.4	−0.3
20–40 cm	10; Cerrado	33.0	−12.0	2.5	13.6	6.4
	18; Atlantic rainforest	14.0	−23.0	−4.5	12.1	−5.3
	9; Pampa	42.0	−25.0	10.0	21.6	5.6

Adapted from Fialho and Zinn (2012); * In average, *Eucalyptus* spp. plantations do not affect the soil organic carbon stocks in Brazil (t-test at p < 0.05 were used in all comparasions)

soils shows lower leaf and fine root decomposition in comparison to *Eucalyptus*, although it has high N leaf concentration (Balieiro et al. 2004; Bachega et al. 2016; Doughty et al. 2018). Besides, *A. mangium* has high internal cycling of P (Balieiro et al. 2004; Bachega et al. 2016; Doughty et al. 2018), providing a litter with low P concentration. Furthermore, *A. mangium* has a more recalcitrant leaf litter, lignin rich with low contents of nonstructural carbohydrates or low-molecular-weight phenols and P concentration (Santos et al. 2017). Thus, the microbiota faces a harsh condition to decompose its residues. The concept of "decomposer starvation," proposed by Hättenschwiler et al. (2011), reveals a syndrome of poor C litter in tropical rainforests which could be applied to pure *A. mangium* plantations in oligotrophic

soils (e.g., Arenosol). According to these authors "*in the neotropical rainforest, natural selection favored a leaf litter trait that leads to starvation-inhibition of decomposers, thereby increasing the tree ability to compete for the uptake of highly limiting nutrients, P in particular, via mycorrhizal associations*." Other authors who have also observed a decrease of P in the soil in areas in mixed plantations claim that this decrease comes from the P uptake by *Eucalyptus* to maintain the N:P stoichiometry of their leaves (Koutika et al. 2014).

It is worth noting that legume trees have a different demand for P as a function of symbiosis with diazotrophic bacteria (Giller and Cadisch 1995; Vadez et al. 1995). Therefore, different strategies are required for capturing this element, such as acidification of the rhizosphere that improves the solubilization of less soluble forms of P (Raven et al. 1990) and root exudation of acid phosphatases and organic acids that leads to PO_4 desorption from the soil matrix and improves P availability (Vance 2001; Venterink 2011). These strategies are paramount in tropical soils since they are mainly able to fix P by ligand exchange and occupation of P sorption sites (Bhatti et al. 1998; de Campos et al. 2016). This is possibly due to the high content of aluminum and iron oxides in the Oxisols and Ultisols typically found in moist tropical sites (Leal and Velloso 1973; Lloyd et al. 2001).

Land-use history may also affect the litter decomposition. Under Ferralsols, previously managed with *Eucalyptus* (for 60 years), Bachega et al. (2016) detected that early decomposition of leaves and fine roots of *Acacia mangium* was markedly slower than that of *Eucalyptus* residues, despite higher N and P concentrations in both tissues of *Acacia* (respectively, 1.9 and 1.5 times higher for leaves and 2.9 and 3.3 times for roots). The lower values of C:N and C:P ratios were associated to litter decomposition rates of *Acacia*, but the authors did not confirm the home field advantage (HFA) that states which plants create a specialization of local decomposer communities of their litter. For *Acacia*, authors claim that the time since the start of the first rotation was not long enough to allow the decomposers to become specialized for its residues. In contrast, several researches have demonstrated that in the short term the litter and soil bacterial and fungi communities are very specific for both (Rachid 2013; Rachid et al. 2015; Bini et al. 2013).

As was pointed out in the perspective of the HFA theory, our research group studied the litter leaf decomposition of both species (i.e., *Acacia* and *Eucalyptus*) in a sandy soil. Our team observed a distinct HFA for decomposition litter from *Acacia* and *Eucalyptus*, with *Acacia* decomposing in the home stands faster than under *Eucalyptus* stands. In contrast, litter from *Eucalyptus* decomposed faster under *Acacia* stands. Additionally, the litter of each material showed very distinct fungal communities and did not change in function of time, and the local of incubation did not influence the microbial community (Rachid 2013). Higher diversity and lower dominance of fungi were reported in litter from *Acacia* and mixed plantations during the decomposition period (180d), regardless of the place at which they were established (Rachid 2013). By using infrared spectroscopy, it was found that *Eucalyptus* litter during the decomposition under *Acacia* stands remain more proteinaceous material than the initial residue, and the migration of N to *Eucalyptus* litter may be considered. On the other hand, the *Acacia* litter did not change its

chemical composition during the incubation (Novotny et al. 2013). These results demonstrate the importance of biological N_2 fixed for the *Eucalyptus* litter decomposition, and suggests that the most diverse fungi community is essential for mixed litter decomposition allowing N mobility. Nonetheless, it is interesting to note that the higher P concentration in *Eucalyptus* litter acts simultaneously and synergistically with the decomposition process in the mixed plantation (Santos et al. 2017). In addition, the C:N ratio alone seems not to be the main predictor of soil organic and litter decomposition (Cotrufo et al. 2013; Lehmann and Kleber 2015; Berg 2018). Some predictors such as N:P, lignin:N, and lignin:P, when possible, should be analyzed collectively.

The N:P ratio of the litter trait is often cited as an essential drive of litter decomposition (Güsewell 2004; Bakker et al. 2011). However, differences in the N:P ratio observed in aboveground biomass and leaf litter usually reflect even more significant changes in the available N:P ratio of soil (Güsewell 2004). Figure 4.3 demonstrates the broad range of the N:P ratio (mass) of the litter in the papers analyzed and, consequently, about edaphic conditions of the studies. Also, there is a trend towards increasing this relation in mixed plantations: non-N_2-fixing (N:P–14) < N_2 fixing (N:P–25) < mixed (N:P–32). Although the contribution of N via litterfall is higher for leguminous plantations, followed by mixed plantings compared to *Eucalyptus* plantations, for P there is a lower
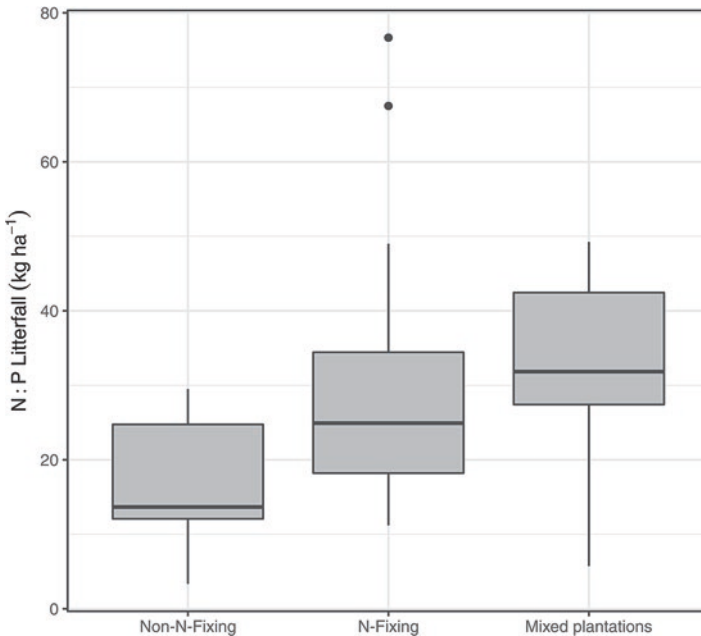
Fig. 4.3 Box plots of N:P relationship in aboveground litterfall (Kg ha^{-1}) among N_2-fixing, non-N_2-fixing, and mixed plantations. Data from *n* = 58 selected studies (see Tables 4.1 and 4.2). Black points represent outliers

recycling trend in mixed planting conditions (Fig. 4.2b). This finding corroborates the productivity of these plantations and the accumulation of P in the aboveground biomass of the species, besides the edaphic limitations in the P supply. In other words, although P is being absorbed more efficiently in these plantations, the plants begin to drain this P for internal use. This process decreases the availability of P for the soil in the medium and long terms (Sanchez 1979; Binkley et al. 2000) and requires attentive management with phosphate fertilization in future rotations.

Climate change and especially temperature rise may also affect the chemical characteristics of leaf litter with effects on decomposition. Trees growing in high-temperature environments have a reduction in the N content of the leaves and an increase in the rate of carboxylation, which results in increased structural and nonstructural carbon levels in the leaves (e.g., glucose, sucrose, fructose) (Güsewell 2004; Pandey et al. 2015) and a recalcitrant leaf litter. These effects can be intensified in the tropics, where the soils are acidic and poor (i.e., with minerals with high adsorption capacity of P). In addition, the presence of leguminous species with high internal P recycling, such as *A. mangium* (Balieiro et al. 2005; Inagaki et al. 2011; Santos et al. 2017), may impair the decomposition process with unfavorable stoichiometric ratios in the leaf litter (e.g., C:N, C:P, or N:P) (Güsewell 2004). Therefore, changes in leaf litter quality may be reflected by changes in soil enzymatic activity (Fanin and Bertrand 2016; Santos et al. 2017), stabilization of C stocks (Fisk et al. 2015; Castellano et al. 2015), emission of CO_2 through microbial respiration (Zhou et al. 2013, 2015), and nutrient mineralization rates (e.g., P, N, and S) (Marklein et al. 2016; van Huysen et al. 2016). All these aspects are feedbacks of climate change and productivity of forest systems (i.e., plantations or natural forests) (Bonan 2008).

4.5 Are Soil Carbon Stocks Really Higher in Mixed Plantations than in Monocultures?

In general, soils present several mechanisms related to the protection of organic matter that is associated with chemical complexation (e.g., polymerization, humification, organic synthesis, and organo-mineral interaction) and physical protection (e.g., complexation with mineral fractions and degree of aggregation) (Feller and Beare 1997; Sollins et al. 1996; Roscoe and Machado 2002). In planted forests, crop residue management, machine traffic, planting structure, climate, and planted and understory species all were identified as determinants for nutrient dynamics and degree of C storage in soils (Bernhard Reversat 1996; Binkley et al. 2000; Kaye et al. 2000; Resh et al. 2002; Qiao et al. 2014; Jesus et al. 2015). With the possibility of managing the communities of soil bacteria and fungi in mixed *Eucalyptus* and *A. mangium* plantations (Rachid et al. 2013, 2015; Bini et al. 2013), it is also reasonable to think about changes in belowground interactions (i.e., belowground competition for nutrients and water). These consequences are still poorly studied in soil C dynamics, although Sokol and Bradford (2019) have claimed that belowground
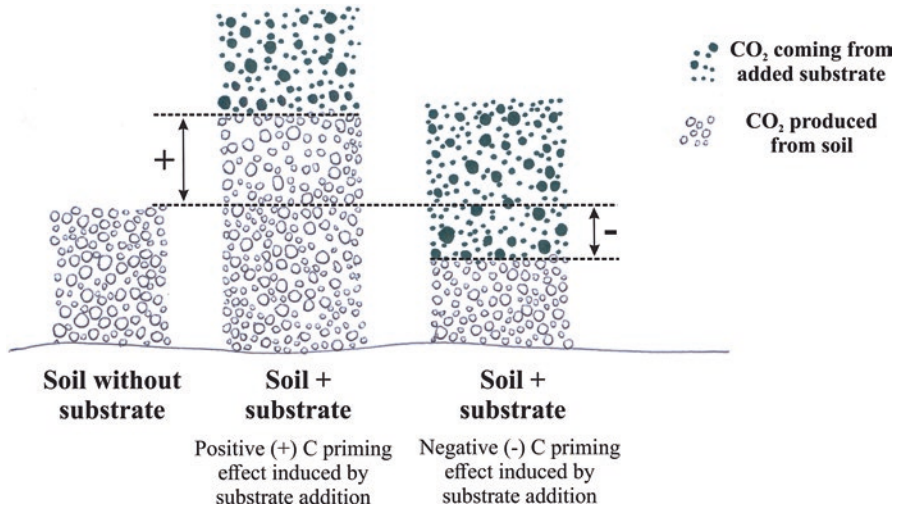
Fig. 4.4 Schematization of the priming effect—nonadditive interactions between decomposition of the added substrate and of soil organic matter (SOM): (+) acceleration of SOM decomposition—positive effect; (−) retardation of SOM decomposition—negative priming effect (adapted from Kuzyakov et al. (2000))

inputs provided by the microbial formation pathway form mineral-stabilized soil C are more effective than aboveground inputs, partly due to the higher efficiency of formation by the rhizosphere microbial community relative to the bulk soil community. In mixed plantations of *A. mangium* and *Eucalyptus*, there might be a more favorable environment for soil C stabilization, because we observed a complementarity in terms of nutrient deposition (e.g., N and P deposition) (Santos et al. 2017, 2018), soil bacterial and fungi communities (Rachid et al. 2013, 2015), and fine root growth (segregated) in soil profile (Silva et al. 2009; Laclau et al. 2013).

The dynamics of soil organic matter from natural and planted forests, including mixed plantations, have been studied from the viewpoint of the "priming effect" by several authors (Resh et al. 2002; Balieiro et al. 2008; Hoosbeek and Scarascia-Mugnozza 2009; Forrester et al. 2013; Koutika et al. 2014). The priming effects were defined by Kuzyakov et al. (2000) as the "*strong short-term changes in the turnover of soil organic matter caused by comparatively moderate treatments of the soil.*" Such changes might be the input of organic or mineral fertilizer to the soil, exudation of the organic substances by roots, and simple mechanical treatment of soil or its dry and wet cycles. Figure 4.4 presents the schematic representation of the priming effect. Under an ecological point of view, the negative priming effects have a much greater significance than positive ones, but the direction of these changes depends mostly on the nutrient status of the soil and the C:N ratio of the active SOM pool (i.e., labile organic matter) (Kuzyakov et al. 2000).

4.5.1 Soil Carbon Stocks in Pure Plantations of Eucalyptus

The impacts of *Eucalyptus* on soil carbon stocks vary according to many factors, including the land-use history, previous crop, post-logging residue management, climate, and spatial variability of soil attributes (Forrester et al. 2006; Chaer and Tótola 2007; Balieiro et al. 2008; Gonçalves et al. 2013). Under a broader point of view, in a recent meta-analysis, Fialho and Zinn (2014) compiled data on the organic soil C stocks using 50 observations for depths between 0 and 20 cm and 39 between 0 and 40 cm of studies in Brazil in paired plots (i.e., plantations and natural forests) aiming to evaluate the impact of native vegetation conversion on plantations of *Eucalyptus*. The authors verified that, on average, the net effect of the conversion is null; that is, it does not damage the original C stocks of the soil, although losses and gains are related to local site conditions (Table 4.2). The authors conclude that this null effect, even after considering the rotation time, texture, and biome, suggests that other factors may control the direction and intensity of changes in soil C stocks in Eucalyptus plantations and point to the productivity, techniques of soil preparation, soil type, and management as essential factors in this evaluation.

Cook et al. (2016) studied the effects of *Eucalyptus* plantations on soil carbon stocks, 0–30 cm deep, over two decades, in 306 operational eucalypt plantations across a 1200 km gradient in Brazil. The study included two tropical states (Bahia and Espírito Santo) and one subtropical state (São Paulo), and resulted in the findings that the size and rates of change in soil C stocks were due to different factors. These factors include the history of the site, soil order, clay content, seasonal precipitation (especially dry season), and mean annual temperature. In general, across all sites, the soil C showed a slight decrease (-0.22 ± 0.05 Mg ha^{-1} year^{-1}) from the original sampling that ranged in approximately 3–4 rotations, but in subtropical regions the stocks remained the same (0.06 Mg ha^{-1} year^{-1}).

Maquere et al. (2008) studied the impact of different land uses (i.e., savanna, pasture, and *Eucalyptus saligna* plantations) and a management (i.e., 60 years under short rotation vs. 60 years under continuous growth) on soil carbon and nitrogen stocks. The authors found significant soil carbon increases (approximately 25%) with *Eucalyptus* under short rotation management when compared to Cerrado native vegetation, whereas soil carbon stocks in the continuous forest plantation increased by 15% in relation to Cerrado vegetation. In the same biome and in degraded pastures Lima et al. (2006) reported that afforestation of former degraded pasture land leads to increased C storage in the soil in the short term (30 years). They observed carbon sequestration rates up to 0.57 Mg C ha^{-1} year^{-1} by *Eucalyptus* afforestation.

Finally, it is evident in the studies that pure *Eucalyptus* plantations present a potential for soil C increase, especially if preceded by degraded pastures. However, local abiotic conditions and forest management seem to be the significant constraints to the effective increase of C in soil. On the other hand, the introduction of legume trees associated with diazotrophic bacteria to *Eucalyptus* monocultures has gained expression in recent years. The increase of soil C stocks so far had always been related to these plantations but, as will be seen below, this phenomenon cannot be generalized, mainly for the Brazilian tropics.

4.5.2   Soil C Stocks Under Mixed Plantations of N_2-Fixing and Non-N_2-Fixing Plantations

Several authors reported higher soil C accumulation of N_2-fixing species over non-N_2-fixing ones (Binkley et al. 1992; Kaye et al. 2000; Resh et al. 2002). However, when a small or no variation is detected in soil C stocks, changes in soil morphological and molecular levels of soil organic matter have also been observed (Kindel et al. 2003; Voigtlaender 2012; Koutika et al. 2014; Santana et al. 2015; Voigtlaender et al. 2019), and this may have consequences for the nutrient cycling in these plantations.

Resh et al. (2002), using isotopic techniques, detected that 55% of the soil C enriching the N_2-fixing plantations came from the retention of native C, in a comparison between the C soil stocks of N_2-fixing species, as *Albizia falcataria, Leucaena leucocephala*, and *Casuarina equisetifolia*, and the soil C stocks of *Eucalyptus saligna* in four tropical soils, two Andisols and one Vertisol and Entisol. They reported that the native C stock was derived from old sugarcane plantations and pastures with metabolic assimilation of C_4, while the other 45% came from C stabilized and derived from recently allocated C_3 from the trees, showing a clear negative priming effect. In addition, 62% of the explanation of the stabilization of native C (C_4) occurred due to the accumulation of N in the soil of the legume trees and *Casuarina* plantations. Very similar results were reported by Kaye et al. (2000) in Andisols from Hawaii, where *Albizia* monocultures had 2.3 Mg ha^{-1} more N and 20 Mg ha^{-1} more C than Eucalyptus monocultures in the 50 cm topsoil. In Acrisols (Brown Dermasols) from Australia, Forrester et al. (2013) reported a difference greater than 15 Mg ha^{-1} between N_2-fixing and non-N_2-fixing trees in the first 30 cm topsoil. However, in Arenosols from Congo and Brazil, a lower gain in soil carbon storage was detected in the N_2-fixing *Acacia mangium* plantations at 7 and 5 years after planting in comparison to monocultive of *Eucalyptus*, respectively (Koutika et al. 2014; Rocha et al. 2019). In the *Pseudosamanea guachapele* plantations, the C storage was even much lower than that found under *Eucalyptus grandis* plantations in southeastern Brazil, in the same soils (Balieiro et al. 2008), a fact that was justified by the authors by high contribution of N (~250 kg ha^{-1} y^{-1}) and other nutrients cycled through litterfall, resulting in a rapid decomposition of the litter and SOM. In is worth mentioning here that the pure legume tree stands studied in Brazil (*Acacia mangium* and *Pseudosamanea guachapele*) had no similar growth in comparison to *Eucalyptus*, contrary to the plantations of *Falcataria moluccana* (*Albizia falcataria*) in Hawaii that present higher aboveground biomass than Eucalyptus saligna (Kaye et al. 2000).

Climate and soil characteristics can control soil C stocks, but the aboveground biomass and NPP are also drivers of C stocks in various environments (Lal 2005; Cornwell et al. 2008; Qiao et al. 2014; Nottingham et al. 2015; Lange et al. 2015). With the literature data consulted, it is not possible to state that C stocks are a function of aboveground biomass production since the soil C augmentation pattern is not very different between monocultures and mixed ones.

Under mixed plantations and Brazilian conditions, mixed plantations presented aboveground biomass higher than monocultures only in sites with poor soils (for

Acacia mangium and *Pseudosamanea guachapele*) (Santos et al. 2017; Balieiro et al. 2010). However, despite the soil C stocks in N_2-fixing plantations did not differ statistically from *Eucalyptus* monocultures (without N) (Balieiro et al. 2008; Rocha et al. 2019), under mixed plantations were detected higher rates of C sequestration (up to 1.44 Mg ha^{-1} y^{-1}), in comparison to *Eucalyptus* monocultives (without N fertilization), demonstrating that for oligotrophic soils the mixed plantation is an great alternative to improve soil quality.

In Australia, Forrester et al. (2013) studied mixed plantations of *Eucalyptus globulus* and *Acacia mearnsii*. They detected a linear relationship between aboveground production and soil C, but not at an N_2-fixing proportion, as found by Kaye et al. (2000), who observed higher aboveground biomass production in mixed plantations and lower in monocultures. In both papers, the increase in C soil stocks in mixed plantations is justified by the negative priming effect of the mixed litter, that is, the maintenance of the C originated from previous crops (sugarcane) and by the addition and stabilization of C derivatives from the trees.

A significant contrast found among these plantations seems to be the pattern of C allocation in the belowground biomass, because Hawaiian monocultures accumulated more C in the belowground than mixed plantations, contrary to what was observed in Australia (Forrester et al. 2013; Binkley and Ryan 1998). In Hawaii, intraspecific competition intensified the use of soil resources, while interspecific competition in Australia further pressured soil resources, culminating in belowground investments to compensate for distinct constraints. In monocultures, the accumulation patterns of the species can lead to the storage for the aboveground biomass of critical elements for soil C storage; in contrast, and because of the complementarity of niches and facilitation (in both directions), mixed plantations can more efficiently cycle nutrients and better use available water. As previously mentioned (Sokol and Bradford 2019) and pointed out by other authors (Schmidt et al. 2011; Nouvellon et al. 2012), the change in the pattern of C allocation in plantations may be due to the large C stock drive to the soil.

The differential input of N by N_2-fixing species appears not to be the major reason for increasing soil C storage (Forrester et al. 2013). The complementarity of niches (above- and belowground) (Tilman 1999; Tilman et al. 2001; Forrester et al. 2006), soil microbial sharing and increased fungal richness (Rachid et al. 2013, 2015), and stimulus to grow and microbial activity (Bini et al. 2013; Pereira et al. 2017; Santos et al. 2017) seem to prove that belowground dynamics commands soil C storage (Sokol and Bradford 2019), but studies in this sense need to be performed for mixed plantations.

The difference in the magnitude of C stocks of soils has a great association with mineralogy and texture (Feller and Beare 1997; Hassink 1997), hence the variations presented in Table 4.3. In general, Andisols from Hawaii have high specific surface phyllosilicate clays and naturally higher SOM contents due to the complexes formed with Al (i.e., noncrystalline Al hydroxide and Al-insoluble organic complexes) and allophanes (Feller and Beare 1997). Even in soils with a recognized SOM stability, the biologically fixed N input was responsible for a significant increase of the C and N stocks, showing the benefit of the N_2-fixing species in that environment, which presents a nonexistent water deficit (i.e., 4500 mm of annual precipitation).

Table 4.3 Soil C stocks (Mg ha⁻¹) in pure and mixed plantations of eucalyptus and N-fixing trees

Species	Country	Age years	Non-N-fixing Proportion	N-fixing	Soil layer cm	Carbon stock Mg ha⁻¹	N:P	Soil classification	Reference
Eucalyptus saligna	Hawaii	16	100	0	0–50	123.4[a]		Andosol	Kaye et al. (2000)
E. saligna + Albizia falcataria	Hawaii	16	75	25	0–50	129.7[a]		Andosol	Kaye et al. (2000)
E. saligna + Albizia falcataria	Hawaii	16	66	34	0–50	132[a]		Andosol	Kaye et al. (2000)
E. saligna + Albizia falcataria	Hawaii	16	50	50	0–50	136.1[a]		Andosol	Kaye et al. (2000)
E. saligna + Albizia falcataria	Hawaii	15	34	66	0–50	140.1[a]		Andosol	Kaye et al. (2000)
Albizia falcataria	Hawaii	15	0	100	0–50	148.8[a]		Andosol	Kaye et al. (2000)
E. globulus	Australia	8.8	100	0	0–30	66.3	30[b]	Acrisol	Forrester et al. (2013)
E. globulus + Acacia mearnsii	Australia	8.8	75	25	0–30	77.9	46[b]	Acrisol	Forrester et al. (2013)
E. globulus + Acacia mearnsii	Australia	8.8	50	50	0–30	84.5	49[b]	Acrisol	Forrester et al. (2013)
E. globulus + Acacia mearnsii	Australia		25	75	0–30	86.1	57[b]	Acrisol	Forrester et al. (2013)
Acacia mearnsii	Australia		0	100	0–30	82.8	66[b]	Acrisol	Forrester et al. (2013)
E. urograndis	Brazil	5	100	0	0–40	20.0	27[b]	Planosol	Rocha et al. (2019)); Santos et al. (2017)
A. mangium + E. urograndis	Brazil	5	50	50	0–40	22.4	49[b]	Planosol	Rocha et al. (2019); Santos et al. (2017)
A. mangium	Brazil	5	0	100	0–40	22.1	77[b]	Planosol	Rocha et al. (2019); Santos et al. (2017)
E. grandis	Brazil	7	100	0	0–40	17.2	7[c]	Planosol	Balieiro et al. (2008); Froufe (1999)
A. mangium + E. grandis	Brazil	7	50	50	0–40	23.8	16[c]	Planosol	Balieiro et al. (2008); Froufe (1999)
A. mangium	Brazil	7	0	100	0–40	14.2	19[c]	Planosol	Balieiro et al. (2008); Froufe (1999)
E. urograndis	Congo	7	100	0	0–25	15.9	62[d]	Arenosol	Koutika et al. (2014)
A. mangium + E. urograndis	Congo	7	50	50	0–25	17.8	75[d]	Arenosol	Koutika et al. (2014)

(continued)

Table 4.3 (continued)

Species	Country	Age years	Non-N-fixing Proportion	N-fixing Proportion	Soil layer cm	Carbon stock Mg ha⁻¹	N:P	Soil classification	Reference
A. mangium	Congo	7	0	100	0–25	16.7	59[d]	Arenosol	Koutika et al. (2014)
E. grandis (Bofete)	Brazil	5	100	0	0–15	27.6	—	Ferralsol	Voigtlaender et al. (2019)
A. mangium + E. grandis (Bofete)	Brazil	5	50	50	0–15	29.6	—	Ferralsol	Voigtlaender et al. (2019)
A. mangium (Bofete)	Brazil	5	0	100	0–15	26.7	—	Ferralsol	Voigtlaender et al. (2019)
E. urograndis (Luiz Antônio)	Brazil	6	100	0	0–15	22.2	—	Ferralic Arenosol	Voigtlaender et al. (2019)
A. mangium + E. urograndis (Luiz Antônio)	Brazil	6	50	50	0–15	24.1	—	Ferralic Arenosol	Voigtlaender et al. (2019)
A. mangium (Luiz Antônio)	Brazil	6	0	100	0–15	21.6	—	Ferralic Arenosol	Voigtlaender et al. (2019)
E. urograndis (Santana do Paraíso)	Brazil	6	100	0	0–15	35.1	—	Ferralsol	Voigtlaender et al. (2019)
A. mangium + E. urograndis (Santana do Paraíso)	Brazil	6	50	50	0–15	34.5	—	Ferralsol	Voigtlaender et al. (2019)
A. mangium (Santana do Paraíso)	Brazil	6	0	100	0–15	38.7	—	Ferralsol	Voigtlaender et al. (2019)
Casuarina equisetifolia	Porto Rico	4	0	100	0–40	65.1	191	Andosol	Parrota (1999)
Eucalyptus robusta	Porto Rico	4	100	0	0–40	75.7	124	Andosol	Parrota (1999)
Leucaena leucocephala	Porto Rico	4	0	100	0–40	75.6	150	Andosol	Parrota (1999)
C. equisetifolia + E. robusta	Porto Rico	4	50	50	0–40	65.9	133	Andosol	Parrota (1999)
C. equisetifolia + L. leucocephala	Porto Rico	4	50	50	0–40	56.6	179	Andosol	Parrota (1999)
E. robusta L. leucocephala	Porto Rico	4	50	50	0–40	61.7	146	Andosol	Parrota (1999)

[a]Values estimated from models adjusted by authors for monocultures and mixed stands

[b]N:P ratio estimated using the total of N and P (kg ha⁻¹ y⁻¹) deposited by litterfall under each plantation

[c]N:P ratio estimated using N and P stocked (kg ha⁻¹) in soil (0–40 cm)

[d]N:P ratio calculated from N and P stocks cited by authors

[e]We classified isohyperthmeric typic troposamments as Andosol, with reservations

Thus, the feedback effect of the N input and NPP (Kaye et al. 2000), associated with the fact that N favors, in consonance with high fertility and humification of soil organic matter (Kirkby et al. 2011) justifies such results for Hawaii. On the other hand, the Ferralsols, in which the Brazilian plantations were established, are highly weathered and acidic and have low fertility, which contrast with the high physical aggregate stability that confers protection of soil C (Feller and Beare 1997; Silva et al. 2013). Thus, even under tropical conditions, plantings associated with N_2-fixing species can store significant amounts of C in the soil. It is interesting to note that even under a single soil class (Ferralsols), large variations in soil C stocks occur in plantations, due to variations in soil clay content and climate (Voigtlaender 2012; Bouillet et al. 2013; Voigtlaender et al. 2019). The Arenosols of Brazil and Congo, from which the main results of this class originated, are in turn naturally lower in amounts of C due to accelerated biochemical dynamics and reduced SOM protection, as well as poor structure and aggregation (Feller and Beare 1997; Zinn et al. 2002). However, it is a fact that even among the Arenosols, small variations in the clay contents of these soils can confer significant changes in the C stocks, as well as capping of the quartz grains by kaolinite and hematite or goethite type clays that increase the formation possibilities of organo-mineral complexes and C storage of these soils (Scheidegger et al. 1993; Donagemma et al. 2008).

The storage of C in the soil of mixed plantations is also due to the rate of decomposition of the deposited residues, which determines how fast the C is incorporated into the mineral phase. By comparing monocultures, Kaye et al. (2000), Resh et al. (2002), Forrester et al. (2013), Koutika et al. (2014), and Pereira et al. (2017) detected greater incorporation of C in soil under N_2-fixing species. However, considering the literature on mixed plantations the C stock in soil was higher but do not show differences in relation to monocultures of Eucalyptus and legume trees (Fig. 4.5) due to higher variability of data. In addition, C stocks occur preferentially in the more labile compartments of SOM fractions (Bini et al. 2013; Koutika and Mareschal 2017; Pereira et al. 2017).

These authors compared the C content of the microbial biomass as well as C and N of the soil organic fraction (physically fractionated between 2000 and 75 μm) and found that, in the four treatments, Eucalyptus without N fertilization, Eucalyptus + N fertilization, Eucalyptus + *Acacia mangium* (E50:A50), or pure *A. mangium* plantations, they differed and were significantly higher in plantings of *Acacia* or in mixed plantations, confirming positive changes in microbial indicators and increases in concentration and nutrient cycling in Ferralsols. When analyzing Table 4.3, it is possible to detect that, with the exception of allophanic soils, the storage of C in poor soils follows the N:P ratio up to a certain limit. This implies that the management of these plantations in oxidic soils with high P adsorption capacity (Lloyd et al. 2001) or sandy soil with low SOM and P reserves should require, in the short and medium terms, a special attention to the management of P fertilizer.
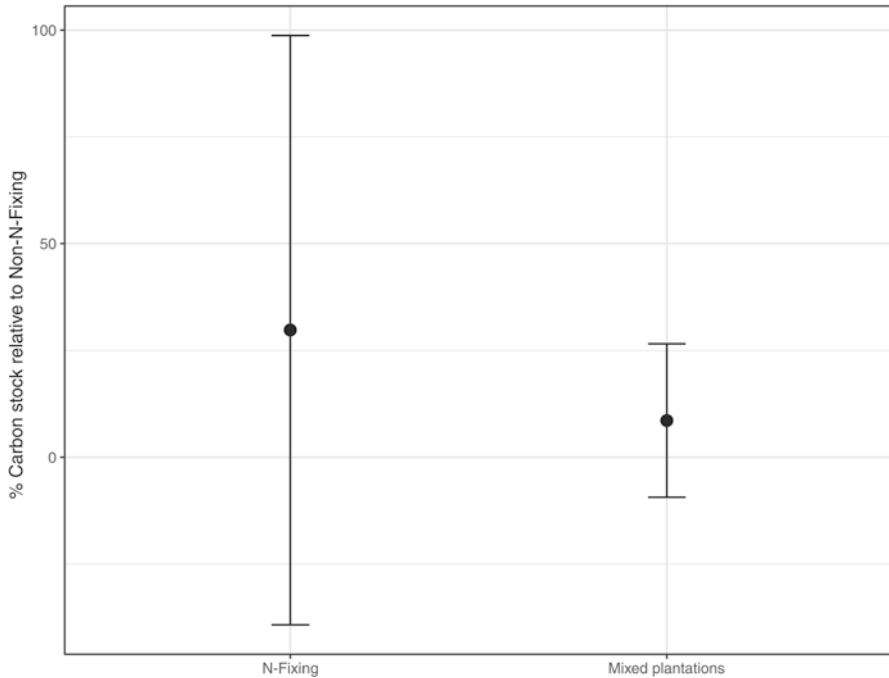
Fig. 4.5 Mean (●) and SD (whiskers) of carbon stock differences (%) of N_2-fixing and mixed plantations relative to non-N_2-fixing species plantations (Eucalyptus) ($n = 29$)

4.6 How to Improve the Soil C Stocks in Mixed-Species Plantations Under Tropical Conditions?

Based on the reviewed literature and data collected, it can be suggested that soil C stocks in planted forests can be increased with improved management practices to overcome environmental restraints and with a broader logic of available biological resources.

Planted forests in the tropics and mainly in Brazil occupy marginal soils, with a history of intense use. Thus, these soils present low fertility, high acidity, Al saturation, and adsorption capacity of P and S (Leal and Velloso 1973; Motta et al. 2002). However, huge differences in these attributes occur within the tropical climatic zone (Sanche 1997), and may partially justify changes in species responses under monoculture and mixed conditions described in this chapter. Although the responses of the forest plantations to liming and fertilization of the soil are small, the non-replacement of the exported nutrients leads to a decrease in the nutritional capital of the soil and the future commitment of these forests. The focus of foresters shall be on the construction of soil fertility under planted forests, with the adoption of practices and technologies that potentiate the above- and belowground growth of

species. For the P case specifically, although most are in the non-labile form in soil, considered reserves exist in labile and moderately labile fractions (up to 7.7 and 15.5 Tg, respectively) (Withers et al. 2018) in areas under higher fertilizer regimes. Especially when combined with no till, correction of acidity, and adoption of the 4R principles of nutrient management (right rate, right time, right place, and right form) (INPI 2012) the stocks of soil natural capital related migth be at least maintained.

In Brazilian Eucalyptus plantations, accumulation in the aboveground biomass of N, P, K, Ca, and Mg in 100 Mg is in the range of 238–298 kg for N, 16–29 kg for P, 123–236 kg for K, 176–590 kg for Ca, and 40–92 kg for Mg. From these totals, 35% of N, 29% of P, 36% of K, and 21% of Ca and Mg are potentially exportable by wood (Santana et al. 2008). In the average 7-year rotations for Eucalyptus, Gonçalves et al. (2013) recommend up to 2 Mg ha^{-1} of lime, 60–80 kg ha^{-1} of N, 60–80 kg ha^{-1} of P$_2$O$_5$, and 140–160 kg ha^{-1} of K$_2$O. For trace elements around 1–5 kg ha^{-1} of B are applied, depending on the local water deficit, and 1 kg ha^{-1} of Cu and Zn. Roughly, the natural nutritional capital of the soil (Sanche 1997; Dominati et al. 2010) seems to be compromised, with detrimental consequences to the organic and inorganic nutrient reserves of these forests.

Managing mixed plantings or rotations with legumes that associate with bacteria that fix N$_2$ from the atmosphere will lead to substantial changes in fertilizer management given the changes in biogeochemical cycles of nutrients and differentiated nutrient exports (Chap. 3). Legumes have a differentiated demand for P in relation to non-N$_2$-fixing species (Vadez et al. 1995; Inagaki et al. 2009, Venterink 2011). *Acacia mangium*, the species most studied under Brazilian conditions, presents high absorption of P in the seedling and adult phase (Inagaki et al. 2011; Santos et al. 2017), and it is very efficient in recycling internally this absorbed P, so that it deposits litter with a high N:P ratio (Inagaki et al. 2010; Santos et al. 2018). Since plants and microorganisms compete strongly for soil P, affecting key soil biological processes and growth of tropical forests (Wieder et al. 2009; Hättenschwiler et al. 2011), strategies to reduce species competition for soil P or to increase complementarity in recycling due to P deposition should be pursued jointly with the adoption of management practices that favor the permanence of crop residues on the soil and SOM.

The recommendations of crop fertilization in Brazil are based on response curves of crop production (shoot biomass or stem in the case of Eucalyptus or its productivity) in relation to the applied fertilizer dose or its availability (i.e., concentration) in the soil (Cantarutti et al. 2007). Little or no attention has been given to changes in the C allocated to roots by planted forests and their relationship to fertility management and soil C stocks. Based on current hypotheses that the belowground inputs provided by the microbial formation pathway form mineral-stabilized soil C more efficiently than aboveground inputs partly due to the greater efficiency of formation by the rhizosphere microbial community relative to the bulk soil community (Sokol and Bradford 2019), it can be considered that, by managing the soil chemical limitations (i.e., acidity, P, N, S, Zn concentration, among others), there will be higher plant growth and consequently root growth, which together will increase soil C

stocks. Recent works (Kirkby et al. 2011, 2014) also demonstrate the possibility of altering the potential for soil C accumulation and sequestration of soils from the introduction of nutrients to the soil, correcting the stoichiometry among C, N, P, and S of the heavy fraction of organic matter (i.e., humidified). The formation of a "new-fine fraction of soil organic matter," the most stable C component in soil, increased threefold by increasing the residues with supplementary nutrients, which in other words implies to say that we can manipulate the nutrients in favor of C sequestration and restoration of the fertility. In other words, although *Eucalyptus* or *Acacia* (or other leguminous species) is tolerant to acidity and high saturation of Al, it does not mean that the practice of soil fertilizing and correction shall not be stimulated. On the other hand, gains in productivity in oxidic soils under the correct management of soil fertility are always accompanied by increased biomass and microbial activity (i.e., basal respiration and enzymatic activity) and, consequently, increases in SOM levels.

4.7   Final Considerations

As shown in this chapter, it seems clear that the establishment of mixed plantations of *Eucalyptus* and *Acacia mangium* represents an alternative to increase soil C stocks in marginal lands. However, the success of these plantations is not the guarantee to increase C stocks. It is necessary to take into account the climatic and soil conditions of the site for the intercropped species, to perform conservationist practices of soil preparation, residue management, and conservative harvesting practices. Better results were obtained where exist appropriated climate condition for Acacia and oligotrophic soils (e.g. sandy soils).

Finding a new set of other species (including N_2-fixing and non-N_2-fixing) that have ecological and economic interest seems to be the main future challenge, although this is not such a simple task. It could begin through a list of priority legume tree species with litter traits that, together with eucalypt, can promote the increase of the global stand biomass production (and also belowground) and improvements in soil properties and functions. It is interesting to note that C sequestration is only an ecosystem service that the soil can provide and that the mix of non-N_2-fixing with N_2-fixing trees may provide many other ecosystem services, such as flood mitigation; greenhouse gas regulation; filtration and recycling of nutrients; and biodiversity preservation among others. In Chap. 10, these services are presented and discussed.

New researches should also elucidate under which arrangements and trees density could provide positive ecological interactions (complementarity and competitive reduction) that can increase the biomass production (above- and belowground) and accelerate litter decomposition and soil C sequestration.

Finally, due to the close relationship between the N and C cycle, it has been reported that as a result of the presence of N_2-fixing trees in *Eucalyptus* plantations positive changes in soil N stocks are more pronounced than for C (Bernhard Reversat 1996; Voigtlaender 2012; Rachid et al. 2013; Voigtlaender et al. 2019; Rocha et al.

2019). These general results confirm that the presence of legumes in *Eucalyptus* plantation might contribute to reducing the need for mineral N fertilization in the long term and increasing the soil nutritional capital. New mixtures of species and arrangements of mixed plantations in combination with nutrient management could enhance C sequestration and produce a more stable organic matter (humus).

References

Andrade AG, Costa GS, Faria SM (2000) Deposição e decomposição da serapilheira em povoamentos de Mimosa caesalpiniifolia, Acacia mangium e Acacia holosericea com quatro anos de idade em planossolo. Revista Brasileira de Ciência do Solo 24(4):777–785

Assis PCR, Stone LF, Medeiros JC et al (2015) Atributos físicos do solo em sistemas de integração lavoura-pecuária-floresta. Rev Bras Eng Agr Amb 19:309–316

Attiwill PM, Adams MA (1993) Nutrient cycling in forests. New Phytol 124:561–582

Bachega LR, Bouillet J-P, de Cássia Piccolo M et al (2016) Decomposition of Eucalyptus grandis and Acacia mangium leaves and fine roots in tropical conditions did not meet the Home Field Advantage hypothesis. Forest Ecol Manag 359:33–43

Bakker MA, Carreño-Rocabado G, Poorter L (2011) Leaf economics traits predict litter decomposition of tropical plants and differ among land use types. Funct Ecol 25:473–483

Balieiro F d C, Dias LE, Franco AA et al (2005) Acúmulo de nutrientes na parte aérea, na serapilheira acumulada sobre o solo e decomposição de filódios de *Acacia mangium* Willd. Cienc Florest 14:59–65

Balieiro F d C, Franco AA, Pereira MG et al (2004) Contribution of litter and nitrogen to soil under *Pseudosamanea guachapele* and *Eucalyptus grandis* plantations. Pesqui Agropecu Bras 39:597–601

Balieiro F d C, Pereira MG, Alves BJR et al (2008) Soil carbon and nitrogen in pasture soil reforested with eucalyptus and guachapele. Rev Bras Cienc Solo 32:1253–1260

Balieiro FC, Franco AA, Pereira MG, Campello EF, Faria SM, Dias LE (2010) Alves BJR Acúmulo e distribuição de biomassa e nutrientes na parte aérea de *Pseudosamanea guachapele* e *Eucalyptus grandis* em consórcio e monocultivos. Embrapa Solos, Rio de Janeiro. Boletim de Pesquisa

Berg B (2018) Decomposing litter, limit values, humus accumulation, locally and regionally. Appl Soil Ecol 123:494–508

Bernhard Reversat F (1996) Nitrogen cycling in tree plantations grown on a poor sandy savanna soil in Congo. Appl Soil Ecol 4:161–172

Bhatti JS, Comerford NB, Johnston CT (1998) Influence of oxalate and soil organic matter on sorption and desorption of phosphate onto a spodic horizon. Soil Sci Soc Am J 62:1089–1095

Bini D, Figueiredo AF, da Silva MCP et al (2013) Microbial biomass and activity in litter during the initial development of pure and mixed plantations of *Eucalyptus grandis* and *Acacia mangium*. Rev Bras Cienc Solo 37:76–85

Binkley D, Dunkin KA, DeBell D, Ryan MG (1992) Production and nutrient cycling in mixed plantations of eucalyptus and albizia in Hawaii. For Sci 38:393–408

Binkley D, Ryan MG (1998) Net primary production and nutrient cycling in replicated stands of *Eucalyptus saligna* and *Albizia falcataria*. For Ecol Manag 112:79–85

Binkley D, Giardina C, Bashkin MA (2000) Soil phosphorus pools and supply under the influence of *Eucalyptus saligna* and nitrogen-fixing *Albizia facaltaria*. For Ecol Manag 128:241–247

Bonan GB (2008) Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320:1444–1449. https://doi.org/10.1126/science.1155121

Bouillet J-P, Laclau J-P, Gonçalves JL de M et al (2013) Eucalyptus and Acacia tree growth over entire rotation in single- and mixed-species plantations across five sites in Brazil and Congo. For Ecol Manag 301:89–101. https://doi.org/10.1016/j.foreco.2012.09.019

Bowen GD, Nambiar ES (1984) Nutrition of plantation forests. Academic, London

Briones MJI, Ineson P (1996) Decomposition of eucalyptus leaves in litter mixtures. Soil Biol Biochem 28:1381–1388

Cannell MGR (1989) Physiological basis of wood production: A review. Scand J Forest Res 4:459–490. https://doi.org/10.1080/02827588909382582

Cantarutti RB, Barros ND, Martinez HEP, Novais RF (2007) Avaliação da fertilidade do solo e recomendação de fertilizantes. Fertilidade do solo. Sociedade Brasileira de Ciência do Solo, Viçosa, pp 769–850

Castellano MJ, Mueller KE, Olk DC et al (2015) Integrating plant litter quality, soil organic matter stabilization, and the carbon saturation concept. Glob Change Biol 21:3200–3209. https://doi.org/10.1111/gcb.12982

Chaer GM, Tótola MR (2007) Impact of organic residue management on soil quality indicators during replanting of eucalypt stands. Rev Bras Cienc Solo 31:1381–1396. https://doi.org/10.1590/S0100-06832007000600016

Cook RL, Binkley D, Stape JL (2016) *Eucalyptus* plantation effects on soil carbon after 20 years and three rotations in Brazil. For Ecol Manag 359:92–98

Cornwell WK, Cornelissen JHC, Amatangelo K et al (2008) Plant species traits are the predominant control on litter decomposition rates within biomes worldwide. Ecol Lett 11:1065–1071. https://doi.org/10.1111/j.1461-0248.2008.01219.x

Costa GS, de Andrade AG, de Faria SM (1998) Aporte de nutrientes pela serapilheira de Mimosa caesalpiniifolia (Sabiá) com seis anos de idade. In: 3 Simpósio Nacional de Recuperação de Áreas Degradadas

Costa GS, da Gama-Rodrigues AC, Cunha GdM (2005) Decomposição e liberação de nutrientes da serapilheira foliar em povoamentos de Eucalyptus grandis no norte fluminense. Revista Árvore 29(4):563–570

Cotrufo MF, Wallenstein MD, Boot CM et al (2013) The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? Glob Change Biol 19:988–995. https://doi.org/10.1111/gcb.12113

de Campos M, Antonangelo JA, Alleoni LRF (2016) Phosphorus sorption index in humid tropical soils. Soil Till Res 156:110–118. https://doi.org/10.1016/j.still.2015.09.020

Davidson EA, Hirsch AI (2001) Fertile forest experiments. Nature 411:431–433

Denef K, Six J (2005) Clay mineralogy determines the importance of biological versus abiotic processes for macroaggregate formation and stabilization. Eur J Soil Sci 56:469–479

Denef K, Six J, Paustian K, Merckx R (2001) Importance of macroaggregate dynamics in controlling soil carbon stabilization: short-term effects of physical disturbance induced by dry-wet cycles. Soil Biol Biochem 33:2145–2153

Dominati E, Patterson M, Mackay A (2010) A framework for classifying and quantifying the natural capital and ecosystem services of soils. Ecol Econ 69:1858–1868. https://doi.org/10.1016/j.ecolecon.2010.05.002

Donagemma GK, Ruiz HA, Alvarez VVH et al (2008) Fósforo remanescente em argila e silte retirados de Latossolos após pré-tratamentos na análise textural. Rev Bras Cienc Solo 32:1785–1791. https://doi.org/10.1590/S0100-06832008000400043

Doran JW, Parkin TB (1994) Defining and assessing soil quality. In: Doran JW, Coleman DC, Bezdicek DF, Stewart BA (eds) Defining soil quality for a sustainable environment, SSSA

Special Publication, vol 35. Soil Science Society of America/The American Society of Agronomy, Madison, pp 1–21

Doughty CE, Santos-Andrade PE, Shenkin A et al (2018) Tropical forest leaves may darken in response to climate change. Nature Ecol Evol 2(12):1918. https://doi.org/10.1038/s41559-018-0716-y

Epron D, Marsden C, ThongoM'Bou A et al (2009) Soil carbon dynamics following afforestation of a tropical savannah with Eucalyptus in Congo. Plant Soil 323:309–322. https://doi.org/10.1007/s11104-009-9939-7

Epron D, Nouvellon Y, Mareschal L et al (2013) Partitioning of net primary production in Eucalyptus and Acacia stands and in mixed-species plantations: Two case-studies in contrasting tropical environments. Forest Ecol Manag 301:102–111. https://doi.org/10.1016/j.foreco.2012.10.034

Fanin N, Bertrand I (2016) Aboveground litter quality is a better predictor than belowground microbial communities when estimating carbon mineralization along a land-use gradient. Soil Biol Biochem 94:48–60. https://doi.org/10.1016/j.soilbio.2015.11.007

Food and Agriculture Organization – FAO (2015) Global forest resources assessment 2015: How have the world's forests changed? FAO, Rome, p 253

Fearnside PM (2000) Global warming and tropical land-use change: greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. Clim Chang 46:115–158. https://doi.org/10.1023/A:1005569915357

Feller C, Beare MH (1997) Physical control of soil organic matter dynamics in the tropics. Geoderma 79:69–116. https://doi.org/10.1016/S0016-7061(97)00039-6

Ferreira RLC, Lira Junior M d A, da Rocha MS, dos Santos MVF, Lira M d A, Barreto LP (2007) Deposição e acúmulo de matéria seca e nutrientes em serapilheira em um bosque de sabiá (Mimosa caesalpiniifolia Benth.). Revista Árvore 31(1):7–12

Fialho RC, Zinn YL (2014) Changes in soil organic carbon under eucalyptus plantations in Brazil: a comparative analysis. Land Degrad Develop 25:428–437. https://doi.org/10.1002/ldr.2158

Fisk M, Santangelo S, Minick K (2015) Carbon mineralization is promoted by phosphorus and reduced by nitrogen addition in the organic horizon of northern hardwood forests. Soil Biol Biochem 81:212–218. https://doi.org/10.1016/j.soilbio.2014.11.022

Forrester DI, Cowie AL, Bauhus J et al (2006) Effects of changing the supply of nitrogen and phosphorus on growth and interactions between *Eucalyptus globulus* and *Acacia mearnsii* in a Pot trial. Plant Soil 280:267–277. https://doi.org/10.1007/s11104-005-3228-x

Forrester DI, Pares A, O'Hara C et al (2013) Soil organic carbon is increased in mixed-species plantations of eucalyptus and nitrogen-fixing acacia. Ecosystems 16:123–132. https://doi.org/10.1007/s10021-012-9600-9

Fortes JLO (2000) Reabilitação de depósito de rejeito do refino de bauxita com o uso de resíduos industriais e leguminosas arbóreas. Tese, Universidade Federal do Rural do Rio de Janeiro

Franzluebbers AJ (2002) Water infiltration and soil structure related to organic matter and its stratification with depth. Soil Till Res 66:197–205. https://doi.org/10.1016/S0167-1987(02)00027-2

Fraser LH, Pither J, Jentsch A et al (2015) Worldwide evidence of a unimodal relationship between productivity and plant species richness. Science 349:302–305. https://doi.org/10.1126/science.aab3916

Froufe LCM (1999) Decomposição de serapilheira e aporte de nutrientes em plantios puros e consorciados de eucalyptus grandis maiden, pseudosamanea guachapele dugand e acacia mangium willd. Tese, Universidade Federal Rural do Rio de Janeiro

Gartner TB, Cardon ZG (2004) Decomposition dynamics in mixed-species leaf litter. Oikos 104:230–246

Gholz HL, Wedin DA, Smitherman SM et al (2000) Long-term dynamics of pine and hardwood litter in contrasting environments: toward a global model of decomposition. Glob Change Biol 6:751–765. https://doi.org/10.1046/j.1365-2486.2000.00349.x

Giller KE, Cadisch G (1995) Future benefits from biological nitrogen fixation: An ecological approach to agriculture. Plant Soil 174(1–2):255–277

Gonçalves JL d M, Alvares CA, Higa AR et al (2013) Integrating genetic and silvicultural strategies to minimize abiotic and biotic constraints in Brazilian eucalypt plantations. Forest Ecol and Manag 301:6–27. https://doi.org/10.1016/j.foreco.2012.12.030

Güsewell S (2004) N: P ratios in terrestrial plants: variation and functional significance. New Phytol 164:243–266. https://doi.org/10.1111/j.1469-8137.2004.01192.x

Hassink J (1997) The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant Soil 191:77–87. https://doi.org/10.1023/A:1004213929699

Hättenschwiler S, Coq S, Barantal S, Handa IT (2011) Leaf traits and decomposition in tropical rainforests: revisiting some commonly held views and towards a new hypothesis. New Phytol 189:950–965. https://doi.org/10.1111/j.1469-8137.2010.03483.x

Hoosbeek MR, Scarascia-Mugnozza GE (2009) Increased litter build up and soil organic matter stabilization in a poplar plantation after 6 years of atmospheric CO_2 enrichment (FACE): final results of POP-EuroFACE compared to other forest FACE experiments. Ecosystems 12:220–239. https://doi.org/10.1007/s10021-008-9219-z

van Huysen TL, Perakis SS, Harmon ME (2016) Decomposition drives convergence of forest litter nutrient stoichiometry following phosphorus addition. Plant Soil 406:1–14. https://doi.org/10.1007/s11104-016-2857-6

IBA (2017). Relatório Ibá 2017

Inagaki M, Kamo K, Miyamoto K et al (2011) Nitrogen and phosphorus retranslocation and N:P ratios of litterfall in three tropical plantations: luxurious N and efficient P use by *Acacia mangium*. Plant Soil 341:295–307. https://doi.org/10.1007/s11104-010-0644-3

Inagaki M, Kamo K, Titin J et al (2010) Nutrient dynamics through fine litterfall in three plantations in Sabah, Malaysia, in relation to nutrient supply to surface soil. Nutr Cycl Agroecosyst 88:381–395. https://doi.org/10.1007/s10705-010-9364-6

IPNI (2012) In: Bruulsema TW, Fixen PE, Sulewski GD (eds) 4R Plant nutrition manual: a manual for improving the management of plant nutrition. International Plant Nutrition Institute, Norcross, GA. http://www.ipni.net/article/IPNI-3255 (22 November 2017)

Janzen HH (2004) Carbon cycling in earth systems—a soil science perspective. Agric Ecosyst Environ 104(3):399–417

Jesus GL d, Silva IR, Almeida LFJ et al (2015) Produtividade do eucalipto, atributos físicos do solo e frações da matéria orgânica influenciadas pela intensidade de tráfego e resíduos de colheita. Rev Bras Cienc Solo 39:1190–1203. https://doi.org/10.1590/01000683rbcs20140494

Kaye JP, Resh SC, Kaye MW, Chimner RA (2000) Nutrient and carbon dynamics in a replacement series of eucalyptus and albizia trees. Ecology 81:3267–3273. https://doi.org/10.1890/0012-9658(2000)081[3267:NACDIA]2.0.CO;2

Kindel A, Garay I, do CCAFS, Lima JA de S (2003) Quantificação dos horizontes húmicos e dinâmica da decomposição de material foliar em solos florestais. Comunicado Técnico EMBRAPA 1:1–8

Kirkby CA, Kirkegaard JA, Richardson AE et al (2011) Stable soil organic matter: A comparison of C:N:P:S ratios in Australian and other world soils. Geoderma 163:197–208. https://doi.org/10.1016/j.geoderma.2011.04.010

Kirkby CA, Richardson AE, Wade LJ et al (2014) Nutrient availability limits carbon sequestration in arable soils. Soil Biol Biochem 68:402–409. https://doi.org/10.1016/j.soilbio.2013.09.032

Koutika L-S, Epron D, Bouillet J-P, Mareschal L (2014) Changes in N and C concentrations, soil acidity and P availability in tropical mixed acacia and eucalypt plantations on a nutrient-poor sandy soil. Plant Soil 379:205–216. https://doi.org/10.1007/s11104-014-2047-3

Koutika L-S, Mareschal L (2017) Acacia and eucalypt change P, N and C concentrations in POM of Arenosols in the Congolese coastal plains. Geoderma Reg 11:37–43. https://doi.org/10.1016/j.geodrs.2017.07.009

Koutika L-S, Richardson DM (2019) Acacia mangium Willd.: benefits and threats associated with its increasing use around the world. Forest Ecosyst 6:2. https://doi.org/10.1186/s40663-019-0159-1

Kuzyakov Y, Friedel JK, Stahr K (2000) Review of mechanisms and quantification of priming effects. Soil Biol Biochem 32:1485–1498

Laclau J-P, de MoraesGonçalves JL, Stape JL (2013) Perspectives for the management of eucalypt plantations under biotic and abiotic stresses. For Ecol Manage 301:1–5

Laclau J-P, Ranger J, de MoraesGonçalves JL et al (2010) Biogeochemical cycles of nutrients in tropical Eucalyptus plantations: Main features shown by intensive monitoring in Congo and Brazil. Forest Ecol and Manag 259:1771–1785. https://doi.org/10.1016/j.foreco.2009.06.010

Lal R (2005) Forest soils and carbon sequestration. Forest Ecol and Manag 220:242–258. https://doi.org/10.1016/j.foreco.2005.08.015

Landsberg JJ, Gower ST (1997) Soil organic matter and decomposition (Chapter 6). In: Landsberg JJ, Gower ST (eds) Applications of physiological ecology to forest management. Academic, San Diego, pp 161–184

Lange M, Eisenhauer N, Sierra CA et al (2015) Plant diversity increases soil microbial activity and soil carbon storage. Nat Commun 6:6707. https://doi.org/10.1038/ncomms7707

Leal JR, Velloso ACX (1973) Adsorção de fosfato em latossolos sob vegetação de cerrado. Pesqui Agropecu Bras 8:81–88

Lehmann J, Kleber M (2015) The contentious nature of soil organic matter. Nature 528:60–68. https://doi.org/10.1038/nature16069

Leite FP, Barros NF, Novais RF, Fabres AS (1998) Acúmulo e distribuição de nutrientes em Eucalyptus grandis sob diferentes densidades populacionais. Rev Bras Cienc Solo 22:419–426. https://doi.org/10.1590/S0100-06831998000300007

Lima AMN, Silva IR, Neves JCL et al (2006) Soil organic carbon dynamics following afforestation of degraded pastures with eucalyptus in southeastern Brazil. Forest Ecol and Manag 235:219–231. https://doi.org/10.1016/j.foreco.2006.08.331

Lloyd J, Bird MI, Veenendaal EM, Kruijt B (2001) Should phosphorus availability be constraining moist tropical forest responses to increasing CO_2 concentrations? In: Schulze ED, Heimann M, Harrison S, Holland E, Lloyd J, Prentice IC, Schimel D (eds) Global biogeochemical cycles in the climate system. Academic, San Diego, pp 95–114

Malhi Y, Wood D, Baker TR et al (2006) The regional variation of aboveground live biomass in old-growth Amazonian forests. Glob Change Biol 12:1107–1138. https://doi.org/10.1111/j.1365-2486.2006.01120.x

Maquere V, Laclau JP, Bernoux M et al (2008) Influence of land use (savanna, pasture, Eucalyptus plantations) on soil carbon and nitrogen stocks in Brazil. Eur J Soil Sci 59:863–877. https://doi.org/10.1111/j.1365-2389.2008.01059.x

Marklein AR, Winbourne JB, Enders SK et al (2016) Mineralization ratios of nitrogen and phosphorus from decomposing litter in temperate versus tropical forests. Glob Ecol Biogeogr 25:335–346. https://doi.org/10.1111/geb.12414

Mochiutti S, de Queiroz JAL, Junior NJM (2006) Produção de serapilheira e retorno de nutrientes de um povoamento de taxi-branco e de uma floresta secundária no Amapá. Boletim de Pesquisa Florestal, Colombo, pp 3–20

Motta PEF, Curi N, Siqueira JO, Van Raij B, Neto AEF, Lima JM (2002) Adsorção e formas de fósforo em latossolos: influência da mineralogia e histórico de uso. Revista Brasileira de Ciência do Solo 26(2):349–359

Negi JD, Sharma SC (1996) Mineral nutrition and resource conservation in Eucalyptus plantation and other forest covers in India. In: Attwill PM, Adams MA (eds) Nutrition of eucalyptus. CSIRO, Collingwood, pp 399–416

Nottingham AT, Whitaker J, Turner BL et al (2015) Climate warming and soil carbon in tropical forests: insights from an elevation gradient in the Peruvian Andes. Bio Science 65:906–921. https://doi.org/10.1093/biosci/biv109

Nouvellon Y, Laclau J-P, Epron D et al (2012) Production and carbon allocation in monocultures and mixed-species plantations of *Eucalyptus grandis* and *Acacia mangium* in Brazil. Tree Physiol 32:680–695. https://doi.org/10.1093/treephys/tps041

Novais RF, Barros N (1997) Sustainable agriculture and forestry production systems on acid soils: Phosphorus as a case-study. In: Moniz AC, Furlani AMC, Schaffert RE, Fageria NK, Rosolem CA, Cantarella H (eds) Plant-soil interactions as low pH: Sustainable agriculture and forestry production, Viçosa, pp 39–51

Novotny EH, Rodrigues AF, Balieiro F de C et al (2013) Avaliação das alterações estruturais da serapilheira de florestas plantadas em decomposição por meio da espectroscopia vibracional

(FTIR) aliada à análise de componentes principais (PCA). In: Embrapa Solos-Resumo em anais de congresso (ALICE)

Ometto JC (1981) Bioclimatologia vegetal. Agronomica Ceres, Sao Paulo

Oorts K, Vanlauwe B, Cofie OO et al (2000) Charge characteristics of soil organic matter fractions in a Ferric Lixisol under some multipurpose trees. Agrofor Syst 48:169

Pandey R, Zinta G, AbdElgawad H et al (2015) Physiological and molecular alterations in plants exposed to high [CO_2] under phosphorus stress. Biotechnol Adv 33:303–316. https://doi.org/10.1016/j.biotechadv.2015.03.011

Parrotta JA (1999) Productivity, nutrient cycling, and succession in single- and mixed-species plantations of Casuarina equisetifolia, Eucalyptus robusta, and Leucaena leucocephala in Puerto Rico. For Ecol Manage 124(1):45–77

Payn T, Carnus JM, Freer-Smith P, Kimberley M, Kollert W et al (2015) Changes in planted forests and future global implications. Forest Ecol and Manag 352:57–67

Pereira AP d A, de Andrade PAM, Bini D et al (2017) Shifts in the bacterial community composition along deep soil profiles in monospecific and mixed stands of *Eucalyptus grandis* and *Acacia mangium*. PLoS One 12:e0180371. https://doi.org/10.1371/journal.pone.0180371

Ponge J-F (2013) Plant–soil feedbacks mediated by humus forms: A review. Soil Biol Biochem 57:1048–1060. https://doi.org/10.1016/j.soilbio.2012.07.019

Poorter L, Bongers F (2006) Leaf traits are good predictors of plant performance across 53 rain forest species. Ecology 87:1733–1743

Qiao Y, Miao S, Silva LCR, Horwath WR (2014) Understory species regulate litter decomposition and accumulation of C and N in forest soils: A long-term dual-isotope experiment. Forest Ecol and Manag 329:318–327. https://doi.org/10.1016/j.foreco.2014.04.025

Quesada CA, Lloyd J, Schwarz M et al (2010) Variations in chemical and physical properties of Amazon forest soils in relation to their genesis. Biogeosciences 7:1515–1541. https://doi.org/10.5194/bg-7-1515-2010

Rachid CTCC, Balieiro FC, Fonseca ES et al (2015) Intercropped silviculture systems, a key to achieving soil fungal community management in eucalyptus plantations. PLoS One 10:e0118515. https://doi.org/10.1371/journal.pone.0118515

Rachid CTCC, Balieiro FC, Peixoto RS et al (2013) Mixed plantations can promote microbial integration and soil nitrate increases with changes in the N cycling genes. Soil Biol Biochem 66:146–153. https://doi.org/10.1016/j.soilbio.2013.07.005

Rachid CTCC (2013) Biodisponibilidade de nutrientes e estrutura microbiana do sistema solo-serapilheira em floresta plantada mista de *Eucalyptus urograndis* e *Acacia mangium*. Universidade Federal do Rio de Janeiro, Rio de Janeiro, p 115. (PhD in Science Thesis)

Raven JA, Franco AA, de Jesus EL, Jacob-Neto J (1990) H+ extrusion and organic-acid synthesis in N2-fixing symbioses involving vascular plants. New Phytol 114:369–389. https://doi.org/10.1111/j.1469-8137.1990.tb00405.x

Reis MDGF, Barros NF (1990) Ciclagem de nutrientes em plantio de eucalipto. In: de Barros NF, de Novaes RF (eds) Relação Solo-Eucalipto. Centro de ciências agrárias, Viçosa

Reis MDGF, Kimmins JP, de Rezende GC, de BNF (1985) Acumulo de biomassa em uma sequência de idade de *Eucalyptus grandis* plantado no cerrado em duas áreas com diferentes produtividades. Rev Arvore:149–162

Resh SC, Binkley D, Parrotta JA (2002) Greater soil carbon sequestration under nitrogen-fixing trees compared with eucalyptus species. Ecosystems 5:217–231. https://doi.org/10.1007/s10021-001-0067-3

Rigatto PA, Dedecek RA, Mattos JLM (2005) Influência dos atributos do solo sobre a produtividade de Pinus taeda. Revi Árv 29:701–709. https://doi.org/10.1590/S0100-67622005000500005

Rocha PV, Ataíde DHS, Lima JSS, Santos FM, Chaer GM, Balieiro FC (2019) Preparo do solo e leguminosa arbórea fixadora de N_2 consorciada com eucalipto afetam os estoques de carbono e nitrogênio de solo arenoso. Simpósio Brasileiro de Solos Arenosos, III, Campo Grande

Roscoe R, Machado PLOA (2002) Fracionamento físico do solo em estudos da matéria orgânica. Embrapa Agropecuária Oeste, Dourados, p 86

Sanchez P (1979) Soil fertility and conservations for agroforestry systems in the humid tropics of Latin America. In: O M PAH (ed) Soils research in agroforestry. ICRAF, Nairobi

Sanches PA (1997) Changing tropical soil fertility paradigms: from Brazil to Africa and back. In: Moniz AC, Furlani AMC, Schaffert RE, Fageria NK, Rosolem CA, Cantarella H (eds) Plant-soil interactions at low pH: sustainable agriculture and forestry production. Viçosa, Sociedade Brasileira de Ciência do Solo, pp 19–28

Sands R, Mulligan DR (1990) Water and nutrient dynamics and tree growth. Forest Ecol Manag 30:91–111. https://doi.org/10.1016/0378-1127(90)90129-Y

Santana GS, Knicker H, González-Vila FJ et al (2015) The impact of exotic forest plantations on the chemical composition of soil organic matter in Southern Brazil as assessed by Py–GC/MS and lipid extracts study. Geoderma Reg 4:11–19. https://doi.org/10.1016/j.geodrs.2014.11.004

Santana RC, de Barros NF, Novais RF et al (2008) Alocação de nutrientes em plantios de eucalipto no Brasil. Rev Bras Cien Solo 32:2723–2733. https://doi.org/10.1590/S0100-06832008000700016

Santos FM, Balieiro F de C, Ataíde DH dos S et al (2016) Dynamics of above ground biomass accumulation in monospecific and mixed-species plantations of Eucalyptus and Acacia on a Brazilian Sandy soil. Forest Ecol Manag 363:86–97. https://doi.org/10.1016/j.foreco.2015.12.028

Santos FM, Balieiro F de C, Fontes MA, Chaer GM (2018) Understanding the enhanced litter decomposition of mixed-species plantations of Eucalyptus and *Acacia mangium*. Plant Soil 423:141

Santos FM, Chaer GM, Diniz AR, Balieiro F de C (2017) Nutrient cycling over five years of mixed-species plantations of Eucalyptus and Acacia on a sandy tropical soil. Forest Ecol Manag 384:110–121. https://doi.org/10.1016/j.foreco.2016.10.041

Scheidegger A, Borkovec M, Sticher H (1993) Coating of silica sand with goethite: preparation and analytical identification. Geoderma 58:43–65. https://doi.org/10.1016/0016-7061(93)90084-X

Schlesinger WH, Lichter J (2001) Limited carbon storage in soil and litter of experimental forest plots under increased atmospheric CO_2. Nature 411:466. https://doi.org/10.1038/35078060

Schmidt MWI, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Kleber M, Kögel-Knabner I, Lehmann J, Manning DAC, Nannipieri P, Rasse DP, Weiner S, Trumbore SE (2011) Persistence of soil organic matter as an ecosystem property. Nature 478(7367):49–56

Senesi N, Loffredo E (1999) The chemistry of soil organic matter. In: Sparks DL (ed) Soil physical chemistry, pp 239–370

Silva LCR, Corrêa RS, Doane TA et al (2013) Unprecedented carbon accumulation in mined soils: the synergistic effect of resource input and plant species invasion. Ecol Appl 23:1345–1356. https://doi.org/10.1890/12-1957.1

Silva CF, Carmo ER, Martins MA, Freitas MSM, Pereira MG, Silva EMR (2015) Deposition and nutritional quality of the litter of pure stands of *Eucalyptus camaldulensis* and *Acacia mangium*. Biosci J 31:1081–1091

Silva EV, Goncalves JLM, Coelho SRF, Moreira RM, Mello SLM, Bouillet J-P, Jourdan C, Laclau J-P (2009) Dynamics of fine root distribution after establishment of monospecific and mixed species plantations of *Eucalyptus grandis* and *Acacia mangium*. Plant Soil 325:305–318

Sokol NW, Bradford MA (2019) Microbial formation of stable soil carbon is more efficient from belowground than aboveground input. Nat Geosci 12(1):46–53

Sollins P, Homann P, Caldwell BA (1996) Stabilization and destabilization of soil organic matter: mechanisms and controls. Geoderma 74:65–105. https://doi.org/10.1016/S0016-7061(96)00036-5

de Souza MJH, Ribeiro A, Leite HG et al (2006) Disponibilidade hídrica do solo e produtividade do eucalipto em três regiões da Bacia do Rio Doce. Revista Árvore 30(3):399–410

Stape JL, Binkley D, Ryan MG et al (2010) The Brazil Eucalyptus Potential Productivity Project: Influence of water, nutrients and stand uniformity on wood production. For Ecol Manag 259:1684–1694. https://doi.org/10.1016/j.foreco.2010.01.012

Stape JL, Binkley D, Ryan MG, do Nascimento Gomes A (2004) Water use, water limitation, and water use efficiency in a Eucalyptus plantation. Bosque 25(2)

Tilman D (1999) The ecological consequences of changes in biodiversity: a search for general principles101. Ecology 80:1455–1474. https://doi.org/10.1890/0012-9658(1999)080[1455:TECOCI]2.0.CO;2

Tilman D, Reich PB, Knops J et al (2001) Diversity and productivity in a long-term grassland experiment. Science 294:843–845. https://doi.org/10.1126/science.1060391

Tisdall JM, Oades JM (1982) Organic matter and water-stable aggregates in soils. J Soil Sci 33:141–163. https://doi.org/10.1111/j.1365-2389.1982.tb01755.x

Vadez V, Lim G, Durand P, Diem HG (1995) Comparative growth and symbiotic performance of four Acacia mangium provenances from Papua New Guinea in response to the supply of phosphorus at various concentrations. Biol Fertil Soils 19(1):60–64

Vance CP (2001) Symbiotic nitrogen fixation and phosphorus acquisition. Plant nutrition in a world of declining renewable resources. Plant Physiol 127(2):390–397

Venterink HO (2011) Legumes have a higher root phosphatase activity than other forbs, particularly under low inorganic P and N supply. Plant Soil 347(1–2):137–146

Violle C, Navas M-L, Vile D et al (2007) Let the concept of trait be functional! Oikos 116:882–892. https://doi.org/10.1111/j.0030-1299.2007.15559.x

Voigtlaender M (2012) Produção de biomassa aérea e ciclagem de nitrogênio em consórcio de genótipos de Eucalyptus com Acacia mangium. Universidade de São Paulo, São Paulo

Voigtlaender M, Brandani CB, Caldeira DRM et al (2019) Nitrogen cycling in monospecific and mixed-species plantations of Acacia mangium and Eucalyptus at 4 sites in Brazil. Forest Ecol Manag 436:56–67. https://doi.org/10.1016/j.foreco.2018.12.055

Whitehead D (1998) Regulation of stomatal conductance and transpiration in forest canopies. Tree Physiol 18:633–644. https://doi.org/10.1093/treephys/18.8-9.633

Wieder WR, Cleveland CC, Townsend AR (2009) Controls over leaf litter decomposition in wet tropical forests. Ecology 90:3333–3341. https://doi.org/10.1890/08-2294.1

Withers PJA, Rodrigues M, Soltangheisi A et al (2018) Transitions to sustainable management of phosphorus in Brazilian agriculture. Sci Rep-UK 8:2537. https://doi.org/10.1038/s41598-018-20887-z

Zhou W-J, Sha L-Q, Schaefer DA et al (2015) Direct effects of litter decomposition on soil dissolved organic carbon and nitrogen in a tropical rainforest. Soil Biol Biochem 81:255–258. https://doi.org/10.1016/j.soilbio.2014.11.019

Zhou Z, Zhang Z, Zha T et al (2013) Predicting soil respiration using carbon stock in roots, litter and soil organic matter in forests of Loess Plateau in China. Soil Biol Biochem 57:135–143. https://doi.org/10.1016/j.soilbio.2012.08.010

Zinn YL, Resck DVS, da Silva JE (2002) Soil organic carbon as affected by afforestation with Eucalyptus and Pinus in the Cerrado region of Brazil. Forest Ecol Manag 166:285–294. https://doi.org/10.1016/S0378-1127(01)00682-X