Chapter 3
Nutrient Cycling in Mixed-Forest Plantations

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3.1 Introduction

Nutrient cycling in forests was defined by Attiwill and Adams 1993 as the range of natural processes that govern the availability of nutrients for the forest trees, as well as the interactions between plants and soil in the uptake and return of nutrients, microbial interactions in which nutrients are transformed between organic and inorganic forms, and balance between input and output of nutrients. Thus, nutrient cycling is a term used to cover all the pathways and processes by which nutrients enter, leave, and move within forest ecosystems.

In planted or managed natural forest for wood production the nutrient cycle is open once a large amount of nutrients is removed with harvest and in some places large amounts of nutrients are applied through fertilizers. The magnitude of the nutrient output and, consequently, the dependence on fertilizer application increase with the management intensity. In Brazil, most of the wood consumed and exported comes from planted forest managed in short rotation (5–7 years) with high productivity (from 20 to 80 m^3 ha^{-1} $year^{-1}$). The main genus planted is *Eucalyptus*. This system of production is highly efficient and highly productive, but highly dependent on fertilizer application. This dependency is intensified because of highly weathered soils, poor in nutrients or plantation established at steep sites susceptive to soil erosion. As commented in other chapters an alternative to reduce the dependence of fertilizer is the introduction of nitrogen-fixing trees (NFT) into eucalypt plantations.

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In natural ecosystems, the wood productivity is lower and there is no dependence on fertilizer application; on the other hand, in eucalypt plantation, the high wood productivity increases the dependence in terms of fertilizer application. As suggested in this book, perhaps the sustainable alternative is somewhere in between the natural forest and the traditional monospecific eucalypt plantation. Thus, the main goal of this chapter is to compare the nutrient cycling in mixed forest (mainly *Acacia* with *Eucalyptus*) with monospecific plantation and natural forest (Atlantic Forest and Cerrado—Brazilian savannah). Nutrient cycling can be divided into six main stages, as suggested by Attiwill and Adams (1993). They are (1) inputs of nutrients by rain, dust, biological fixation, and parental rock weathering; (2) uptake and accumulation of nutrients by trees; (3) outputs of nutrients by leaching and gaseous forms and in harvested material; (4) internal redistribution of nutrients within and among plants; (5) return of nutrients from plant to soil; and (6) decomposition of the forest floor and nutrient mineralization. Some of these subjects are presented in more details in Chaps. 4 and 6.

3.2 Nutrient Inputs

In tropical planted forest, fertilizer application is frequently the main nutrient input into the system, but atmospheric deposition, biological N_2 fixation, and parental rock weathering can also play an important role. Biological N_2 fixation (BNF) is discussed in another chapter. In this chapter, we discuss the role of atmospheric deposition and parental rock weathering.

3.2.1 Atmospheric Deposition

In forest plantations the importance of atmospheric deposition increases with the annual deposition rate and with the length of the rotation (Ranger and Turpault 1999; du Toit et al. 2014). The main sources of nutrients contributing to atmospheric deposition are mineral and marine aerosols, wildfires, industrial activity, combustion of fossil fuel, and agricultural activity (Wieder et al. 2016; Lequy et al. 2014; Nyaga et al. 2013).

The amount of nutrients deposited is highly dependent on the source, and highly variable in the spatial and temporal scale. In the literature, we found references to annual depositions of N, P, K, Ca, Mg, and S ranging from 1 to 10, 0.1 to 5, 1 to 25, 1 to 30, 0.3 to 3, and 1 to 10 kg ha^{-1} $year^{-1}$, respectively (Table 3.1). The deposition reduced exponentially with the distance from the emission center. Unlike N and S deposition, the K, Ca, and Mg depositions occur more concentrated around the emission center (Wieder et al. 2016; Nyaga et al. 2013). Wieder et al. (2016) found small Ca and Mg deposition rates 69 km from the emission center, while for N and S a small deposition rate was present even in the most distantly assessed point (251 km).

Table 3.1 Nutrient deposition by rainfall (kg ha^{-1} year^{-1})

Location	N	P	K	Ca	Mg	S	Source
Alberta, Canada	1.2	0.1		9.0	2.0	5.0	Wieder et al. (2016)
Northeastern France		0.5	1.1	0.8	0.3		Lequy et al. (2014)
West coast of South Africa	3.9	0.1	3.0	15	5		Nyaga et al. (2013)
São Paulo, Brazil	4.1		3.6	9.3	1.5		Laclau et al. (2010)
Kondi, Congo	5.4		6.2	7.3	3.1		Laclau et al. (2010)
São Paulo, Brazil	4.2		4.4	7.4	2		Vital et al. (1999)
Rio de Janeiro, Brazil	15.5						de Souza et al. (2017)
Average	**3.8**	**0.2**	**3.7**	**8.1**	**2.3**	**5.0**	

3.2.2 Rock Weathering

Rock weathering rates are difficult to be quantified and frequently low in relation to the rotation scale. Many methods have been proposed, and despite the good relationship among the results, the accuracy of absolute data is uncertain (Hodson and Langan 1999; Klaminder et al. 2011; Koseva et al. 2010; Ouimet and Duchesne 2005; Whitfield et al. 2006, 2011). Generally, in highly weathered soils, with low levels of primary minerals, nutrient inputs by weathering are effectively negligible (Melo et al. 2005).

In young and shallow soils, rich in primary minerals and where trees are grown in long rotations, this nutrient input can be important for nutrient supply to the stand. Starr and Lindroos (2006) assessed the rate of Ca and Mg released by weathering in a soil chronosequence ranging from 340 to 5279 years of age in Finland with the same parent material under *Pinus sylvestris* forests. They found releases of around 2.0 and 0.6 kg ha^{-1} year^{-1} of Ca and Mg, respectively, in the youngest soil, and releases of 0.4 and 0.2 kg ha^{-1} year^{-1} of Ca and Mg in older soil. There was a drastic reduction in the Ca and Mg release up to soil ages of 1000 years followed by stabilization thereafter. Under an 80-year-old *P. sylvestris* forest in Finland, Starr et al. (2014) found weathering rates (1.8, 0.5, and 0.7 kg ha^{-1} year^{-1} of Ca, Mg, and K, respectively) which almost equaled the leaching rate. They reported that the quantities of exchangeable cations at the 0–40 cm soil layer are equivalent to approximately 30 years of weathering and the quantities accumulated in the aboveground biomass are equivalent to almost 50 years of weathering. These data sets indicate that in some sites weathering on its own is sufficient to supply the K, Ca, and Mg requirements of the trees. However, in Oxisols in tropical climate, the release of K, Ca, and Mg is very close to zero (Melo et al. 2005).

3.3 Nutrient Uptake and Accumulation

The nutrient uptake and consequent accumulation in the biomass are linearly related with the growth rate in planted forest, but are also related with the site nutrient availability (Gonçalves et al. 2014; Rocha et al. 2019). In natural unmanaged forest on steady state, the uptake rate is equal to the nutrient return to soil and the amount of nutrients accumulated in the biomass is proportional to the biomass stock.

The amount of nutrients accumulated in the biomass is equally affected by the species composition. Santos et al. (2017), comparing mixed-species and monospecific plantations of *Acacia mangium* and *Eucalyptus* (hybrid between *E. urophylla* and *E. grandis*), found 354 t ha^{-1} of aboveground biomass and 268 kg ha^{-1} of N accumulated in this biomass in monospecific eucalypt at 5-year-old stands. At the same site and age, these authors found, in the monospecific acacia plantation, 107 t ha^{-1} of aboveground biomass and 186 kg ha^{-1} of N accumulated. The overall N concentration of the aboveground biomass of eucalypt was 2.19 g kg^{-1} and of acacia was 2.44 g kg^{-1}. If the productivity of both stands were the same, the N accumulation in the acacia aboveground biomass would be 11% bigger than in the eucalypt plantation. When we look at the overall P concentration in the aboveground biomass for the same productivity, the eucalypt monospecific plantation accumulates around 33% less P than acacia monospecific plantation. Due to genetic differences among the species, when we mix acacia and eucalypt in a plantation, there is an increase in the N, P, K, Ca, and Mg content per ton of biomass produced (Santos et al. 2017).

The mixture of *A. mangium* with *Eucalyptus* plantation increases the fine root biomass and consequently the soil exploration, especially in deep soil layers (see also Chap. 2). Germon et al. (2018) studying soil exploration by fine roots down to a depth of 17 m found an increase of 58% in the root biomass when eucalypt was mixed with *acacia* (50%E 50%A), when compared with monospecific *Eucalypt* plantation. Beyond the root biomass, they also found an increase of 50% in the root specific area (cm^2 g^{-1}) of acacia in mixed plantations when compared with acacia in monospecific plantation. In this study, the root of eucalypt dominated the upper soil layer and “forced” acacia to increase the root density in deeper soil layers. The root front of the monospecific acacia plantation was down to 12 m while under mixed plantation acacia roots reached 17 m.

3.4 Nutrient Outputs

The harvest output increased linearly with stand productivity and with harvest intensity. Rocha et al. (2019), based on 45 stands, estimated the nutrient harvest output for three levels of productivity and two levels of harvest intensity for monospecific eucalypt plantations (Table 3.2). Santos et al. (2017) assessed the harvest outputs of 5-year-old monospecific and mixed plantations of eucalypt with acacia in Rio de Janeiro state, Brazil. The productivity of plantations was 110, 50, and 80 t ha^{-1} of stem wood, when comparing monospecific eucalypt, acacia, and mixed plantation, respectively. The nutrient harvest outputs of the monospecific *eucalypt* plantation were higher than those in the mixed plantation due to the higher productivity (Table 3.3).

Table 3.2 Nutrient outputs by harvesting[a] in eucalypt plantations (with and without bark) in rotations of 7 years and mean annual increment (MAI) ranging from 30 to 50 $m^3\ ha^{-1}\ year^{-1}$

Nutrient	MAI ($m^3\ ha^{-1}\ year^{-1}$)		
	30	40	50
	kg ha^{-1}		
Wood with bark			
N	198	264	330
P	41	54	67
K	116	155	194
Ca	202	270	338
Mg	23	31	39
S	37	49	61
Wood			
N	168	224	280
P	32	42	53
K	66	88	110
Ca	83	110	138
Mg	12	16	20
S	34	45	56

[a]Adapted from Rocha et al. (2019)

Table 3.3 Biomass and nutrient outputs[a] by harvest of a monospecific eucalypt plantation (hybrid between *E. urophylla* and *E. grandis*—100E), a monospecific *Acacia mangium* plantation (100A), and a mixed eucalypt with acacia plantation (50E50A), all 5 years old, harvested in the system of only stem and full tree

Biomass/nutrient	Stem			Full tree		
	100E	100A	50E50A	100E	100A	50E50A
Biomass (t ha^{-1})	110	50	80	123	63	95
N (kg ha^{-1})	120	62	92	269	187	232
P (kg ha^{-1})	13	10	12	23	23	24
K (kg ha^{-1})	98	43	74	189	135	165
Ca (kg ha^{-1})	84	56	76	130	125	137
Mg (kg ha^{-1})	19	13	17	40	39	41

[a]Adapted from Santos et al. (2017)

Beyond harvest outputs, other nutrient losses can be significant in forest plantation. The soil loss by erosion under eucalypt plantation managed by minimum tillage is low, ranging from 0 to 2 t ha^{-1} $year^{-1}$ and being influenced by the age and management of the plantation (Martins et al. 2003; Silva et al. 2011). The soil loss under acacia plantation is also low, around 1 t ha^{-1} $year^{-1}$ (Barros et al. 2009). Due to the depth of the root system and the low deep-water drainage, nutrient leaching under forest plantation is negligible (Laclau et al. 2013; Christina et al. 2017). Ammonia volatilization in forest plantations in Brazil is also negligible, because these plantations are established normally on acidic soils.

3.5 Nutrient Redistribution Within and Among Plants

Nutrient redistribution or biochemical nutrient cycling is a well-known process in deciduous trees as well as in evergreen trees. The nutrients differ greatly in their mobility. Calcium, for example, is considered immobile, because it is a structural element, while K is highly mobile due to being a nonstructural element. Some authors found that under conditions of high nutrient availability, the retranslocation tends to be reduced (Boerner 1984; Pugnaire and Chapin 1993; Andrews et al. 1999), but others found no nutrient retranslocation (Millard and Proe 1993).

Among species, the N retranslocation rate is higher in eucalypt trees, K and P retranslocation rate is higher in acacia trees, and the Mg retranslocation rate is equal in both species (Santos et al. 2017). These authors found no difference in the retranslocation rate of both species, when comparing mixed with monospecific plantations. Since the K and P retranslocation rates are higher in acacia trees, the introduction of this species in monospecific eucalypt plantations can increase the nutrient retranslocation (Table 3.4).

Beyond the nutrient retranslocation within the trees, the nutrient retranslocation among trees can play an important role in the nutrition of mixed plantations, especially when there are NFTs. Paula et al. (2015), using ^{15}N, found transference from acacia to eucalypt trees 5 days after application among trees 6 m away from each other in a mixed plantation located in Itatinga, Brazil. These authors concluded that the transference belowground may provide a significant amount of N requirement of the tree close to NFT. This transference may be direct, when roots of eucalypt and acacia are connected by mycorrhizal network, or indirect, by root exudation of N compounds (See also Chap. 6).

3.6 Return of Nutrients from Plants to Soil

Monospecific eucalypt plantation returns to soil on average 5.6 t ha^{-1} $year^{-1}$ of litter (Table 3.5). The litterfall rate normally increases until 3 to 4 years of age and stabilizes or shows a little reduction afterwards (Rocha 2017). This litterfall rate results in a return to the soil of around 45, 2, 16, 40, 12, and 5 kg ha^{-1} $year^{-1}$ of N, P, K, Ca, Mg, and S, respectively. When compared with the native Atlantic Forest these amounts are markedly lower, especially for the nutrients, which indicates a lower nutrient concentration in the eucalypt litterfall (Table 3.5).

In mixed plantations, there is an increase in the total amount of nutrients deposited on the soil, especially N and P. This higher nutrient deposition is a result of higher nutrient concentration in the litter and of a higher litterfall rate (Table 3.5). These findings indicate that the introduction of acacia into monospecific eucalypt plantation accelerates and increases the nutrient cycling as also evidenced by Binkley (1992) and Forrester et al. (2005).

Table 3.4 Nutrient retranslocation rate[a] of *Eucalyptus* (hybrid between *E. urophylla* and *E. grandis*) and *Acacia mangium* trees at 30 and 60 months after planting

	N	P	K	Mg
Age (month)	%			
Eucalyptus				
30	77	68	61	34
60	51	70	70	43
A. mangium				
30	62	84	74	46
60	45	83	81	37

[a]Adapted from Santos et al. (2017)

Table 3.5 Litterfall rate and amount of nutrients deposited on the soil by litterfall in monospecific eucalypt plantation, Natural Forests, and in a trial which compares monospecific eucalypt plantation (100% eucalypt) with mixed-species plantation (50% eucalypt, 50% acacia)

			N	P	K	Ca	Mg	S	
Species	Age (year)	Mass (t ha^{-1} year^{-1})	kg ha^{-1} year^{-1}						Source [a]
Monospecific eucalypt plantation									
E. grandis and hybrid[b]	1–9	5.6[c] (3.8–7.8) [14]	44.0 (24.0–83.5) [14]	1.9 (0.9–5.1) [14]	15.8 (4.4–44.2) [14]	39.4 (11.2–84.0) [14]	11.7 (7.0–16.2) [13]	4.9 (2.5–8.1) [6]	1, 2, 3, 4, 5, 6, 7, and 8
Eucalypt with acacia trials									
100% Eucalypt	2–6	8.5 (5.0–11.5) [8]	49.5 (30.0–62.0) [8]	5.3 (1.8–8.8) [4]	15.6 [1]	30.0 [1]	8.8 [1]	–	9, 10, 11, and 12
50% Eucalypt 50% Acacia	2–6	8.7 (6.1–11.0) [8]	70.7 (63.0–80.0) [8]	6.2 (1.7–10.7) [4]	18.8 [1]	33.2 [1]	9.0 [1]	–	9, 10, 11, and 12
Natural Forest									
Atlantic Forest		9.1 (6.3–13.0) [10]	169.6 (122–218.9) [10]	5.9 (1.6–11.6) [10]	44.3 (11.7–67.7) [10]	148.2 (88.9–231.1) [9]	25.8 (11.0–38.7) [9]	13.6 (13.5–13.6) [2]	6, 13, 14, 15, 16, 17, 18, and 19
Cerrado		3,8 (2,1–7,8) [4]	34.4 (12.7–64.7) [4]	2.1 (0.4–4.7) [4]	6.3 (2.3–12.5) [4]	14.6 (4.7–26.5) [4]	5.2 (1.9–10.9) [4]	0.7 [1]	19 and 20

[a]1—Gonçalves et al. (2000), 2—Zaia and Gama-Rodrigues (2004), 3—Cunha et al. (2005), 4—Ferraz (2009), 5—Silva (2006), 6—Gama-Rodrigues and Barros (2002), 7—Silva et al. (2013), 8—Rocha (2017), 9—Voigtlaender et al. (2019), 10—Koutika et al. (2014), 11—Santos et al. (2016), 12—Santos et al. (2017), 13—Vital et al. (2004), 14—Pinto et al. (2009), 15—Pimenta et al. (2011), 16—Godinho et al. (2013), 17—Domingos et al. (1997), 18—Pereira et al. (2008), 19—Toledo et al. (2002), 20—Nardoto et al. (2006)
[b]Hybrid between *E. grandis* and *E. urophylla*
[c]Average, followed by the amplitude between parentheses and followed by the number of sites plus the number of years assessed between brackets

Table 3.6 Litterfall, litter layer, decomposition rate (k), half lifetime, and decomposition time of 95% of the litter in monospecific eucalypt plantation and in Natural Forests

Species	Age (year)	Litterfall t ha^{-1} year^{-1}	Layer (t ha^{-1})	*k*	Decomposition time 50% year	Decomposition time 95% year	Source[a]
Monospecific eucalypt plantation							
E. grandis and hybrid[b]	1-9	5.6[b] (3.8–7.8) [10]	11.6 (3.9–23.7) [10]	0.63 (0.23–1.2) [10]	1.46 (0.58–2.97) [10]	6,31 (2,50–12,84) [10]	1, 2, 3, 4, and 5
Natural Forest							
Atlantic Forest		8.5 (6.3–10,6) [8]	6.0 (3.4–10.1) [8]	1.53 (0.93–2.45) [8]	0.49 (0.28–0.74) [8]	2.10 (1.22–3.22) [8]	5, 6, 7, 8, 9, and 10

[a]1—Zaia and Gama-Rodrigues (2004), 2—Cunha et al. (2005), 3—Ferraz (2009), 4—Gonçalves et al. (2000), 5—Gama-Rodrigues and Barros (2002), 6—Vital et al. (2004), 7—Morellato (1992); 8—Pinto et al. (2009), 9—Pimenta et al. (2011), 10—Godinho et al. (2013)

[b]Average, followed by the amplitude between parentheses and followed by the number of sites plus the number of years assessed between brackets

3.7 Decomposition of Forest Litter

We will discuss litter layer decomposition in detail in the next chapter. In this topic, we will be comparing only the litter decomposition in eucalypt stands with the natural vegetation. Under monospecific eucalypt plantation the litterfall and litter layer rates are around 5.5 t ha^{-1} year^{-1} and 11.6 t ha^{-1}, and, under Atlantic Forest, 8.6 t ha^{-1} year^{-1} and 6.0 t ha^{-1}, respectively. The decomposition rate (k) of the Atlantic Forest litter is 2.4 times greater than the k of eucalypt plantation (Table 3.6).

When NFTs are mixed with eucalypt despite an increase in the litter N and P concentration and a reduction in the concentration of phenol, the *k* does not necessarily increase (Bachega et al. 2016). A large increase in the N mineralization under NFT in monospecific or mixed plantations was detected (Voigtlaender et al. 2012, 2019). On the other hand, as discussed in Chap. 4, changes in decomposition rates could be site specific.

3.8 Conclusion

The introduction of NFT, such as *Acacia mangium*, at monospecific eucalypt stands can improve the capacity of the trees in obtaining nutrients, mainly due to the atmospheric N_2 fixation and by the wider soil exploration. The NFT also accelerates and increases nutrient cycling and contributes to a large return of nutrients to soil by litterfall, increasing the topsoil nutrient availability. The N mineralization increases greatly. Thus, the dependence of mixed plantations on nitrogen fertilizer application is lower. More studies need to be incentivized, encompassing other NFT species.

The concentration of some nutrients in the acacia biomass is higher than that in eucalypt biomass. If mixed plantations reach the same productivity of monospecific eucalypt plantation, an increase in the nutrient harvest output can occur.

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