

Soil Carbon and Nutrient Pools in Three Adjacent Forest Ecosystems

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Abstract

Soil carbon (C) and nutrient pools were assessed for adjacent natural forest (NF), first rotation (1R) (50-year-old), and second rotation (2R) (1-year-old) hoop pine plantations in southeast Queensland. Five transects spaced 3 m apart with 9 sampling points along each transect were selected (9.6 m x 12.0 m each site), with 45 soil cores (7.5 cm in diameter) collected and separated into 0-10 and 10-20 cm depths. These soils were analysed for total C, total nitrogen (N), C ($\delta^{13}\text{C}$) and N ($\delta^{15}\text{N}$) isotope composition. The 0-10 cm soils were analysed for pH, CEC, exchangeable cations, total P and total K, and assayed for microbial biomass C and N, respiration, metabolic quotient, potentially mineralizable N (PMN), gross N mineralization (*M*) and immobilization (*I*). Total C and N in 0-10 cm soils were higher under NF and 1R plantation than under 2R plantation, while they were highest in 10-20 cm soils under NF, followed by the 1R and then 2R plantation. $\delta^{13}\text{C}$ was lower under NF than under the plantations, while $\delta^{15}\text{N}$ was higher under NF than under the plantations. Total P was the highest under NF, followed by the 1R and then 2R plantation, while total K was higher under the 2R plantation. No significant differences were detected for pH, CEC, exchangeable cations, microbial C and N, respiration and metabolic quotient among the 3 sites. PMN and *M* were higher under NF, while *I* was the highest under the 2R plantation, followed by the NF and then 1R plantation.

Key Words

Soil microbial activity, soil nutrient availability, spatial variability, hoop pine plantations, forest management, plantation productivity.

Introduction

An improved understanding of important soil carbon (C) and nutrient pools as well as microbial activities in forest ecosystems is required for developing effective forest management regimes underpinning forest productivity and sustainability (Bubb et al. 1998; Carlyle et al. 1998; Chen et al. 2002, 2004; Mao et al. 2002; Mather and Xu 2003). Forest types (Riha et al. 1986; Saetre and Bååth 2000; Verchot et al. 2001; Mao et al. 2002; Chen et al. 2004) and management practices (Carlyle 1994; Pu et al. 2001; Chen et al. 2002, 2003; Blumfield and Xu 2003; Mathers et al. 2003) can have significant impacts on soil C and nutrient pools as well as biological properties in forest ecosystems. Hoop pine (*Araucaria cunninghamii*) is a native rainforest species of south-east Queensland. Most of the current hoop pine plantations (ca. 50,000 ha) in south-east Queensland were established on the previous natural forest land. Little information is available about the impacts of conversion from natural forest to hoop pine plantations and about the effects of plantation management on soil chemical, physical and biological properties. Better information on spatial variability in soil chemical, physical and biological properties in forest ecosystems can assist in the development and application of effective soil sampling strategies for quantifying the impacts of forest types and management practices on soil C and nutrient pools and dynamics in relation to soil quality and forest productivity (Hirobe et al. 1998; Morris and Boerner 1999; Laverman et al. 2000; Prasolova et al. 2000b; Rayment and Jarvis 2000). Recent advances in development and application of ^{15}N labelling methods have highlighted the potential for studying gross nitrogen (N) transformations such as gross N mineralization, immobilization and nitrification rates in forest soils (Murphy et al. 1999; Neill et al. 1999; Wang et al. 2001; Chen et al. 2002; Bengtsson et al. 2003). The objectives of this study were to: (1) quantify the impacts of forest types (natural forest dominated by eucalypt species vs hoop pine plantations) and management practices (harvesting and conversion from the first rotation to second rotation hoop plantation) on soil C and nutrient pools in adjacent natural forest (NF), 50-year-old first rotation (1R) and 1-year-old second rotation (2R) hoop pine plantations; (2) examine the spatial variation in soil C and N parameters and number of soil samples to be taken for assessing the forest type and management impacts on these soil properties in the 3 adjacent forest ecosystems; and (3) assess microbial properties and gross N transformations in the top 10 cm soil under the adjacent NF, 1R and 2R hoop pine plantations in south-east Queensland.

Materials and methods

Site description

The NF, 1R and 2R plantation sites are located in the Yarraman State Forest of south-east Queensland, Australia (26°52' S, 151°51' E), lying in the upper catchment of the Brisbane River. The soil is a Snuffy Mesotrophic Red Ferrosol (Soil Survey Staff, 1999). Altitude at the sites is about 428 m above sea level. Annual rainfall varies from 433 to 1110 mm, with an average of 791 mm. Winter temperatures range from 4 to 20°C, and summer temperatures from 17 to 29°C. The NF, 1R and 2R plantation sites are adjacent to each other with similar slope of approximately 2-3°. The NF site is classified as a rainforest/bastard scrub and dominated by bunya pine (*Araucaria bidwilli*), yellowwood (*Terminalia oblongata*), crows ash (*Pentaceras australis*) and lignum-vitae (*Premna lignum-vitae*), with emergent hoop pine (*Araucaria cunninghamii*). Before establishment of 1R hoop pine plantation, larger trees of natural forests were logged using bullock teams and small dozer, and the under story scrub and the residues were brushed off to a height no greater than 15 cm in order to be scattered evenly across the site, and were burnt when dry. The 1R hoop pine plantation was established in 1949 at approximately 1540 stems / ha by hand planting and then thinned to a final stocking of 430 stems / ha. The 2R hoop pine site was planted in November 2000 after clearcut harvest of part of the 1R hoop pine plantation using Timbco harvester in September 1999. For site preparation, a D5M dozer was used to form windrows of 1R harvest residues spaced at about 6 m apart. The stocking density at the 2R hoop pine site was approximately 620 stems / ha when the soil was sampled in October 2001.

Soil sampling

All three sites were sampled on the same grid pattern in August 2000, when the 1R plantation harvest residues were windrowed for about 4 months and the 2R hoop pine seedlings were planted about 3 months later. Five transects spaced 3 m apart with 9 sampling points along each transect (1.2 m between 2 adjacent sampling points) were selected for each of the 3 sites (9.6 m x 12.0 m), with 45 20-cm soil cores (ca. using an auger with 7.5 cm in diameter) taken from the relevant sampling points and separated into 0-10 and 10-20 cm depths. There were 90 soil samples from each forest site for determining soil total C, total N, stable C isotope composition ($\delta^{13}\text{C}$) and N isotope composition ($\delta^{15}\text{N}$), which were also used to estimate appropriate sample size or number required for detecting differences in these soil variables between the forest sites.

Following the preliminary study on the spatial variation in soil total C and N, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ in the top 20 cm soil, significant differences were detected in these soil parameters between the 3 sites. A second soil sampling (0-10 cm depth) was undertaken in October 2001 for assessing soil biological properties and gross N transformations in laboratory assays. The 1R hoop pine plantation was approximately 51 years old and the 2R hoop pine 2 years old when the second soil sampling was conducted. Each (ca. 30 m x 100 m) of the sampling areas under the adjacent NF, 1R and 2R hoop pine plantations, near the areas of the first soil sampling in August 2000, was divided into five subplots for soil sampling. A total of 25 soil cores (0-10 cm) were randomly collected with an auger of ca. 7.5 cm in diameter from each subplot and bulked (well mixed) in October 2001. In the 2R hoop pine plantation, the soil was sampled from areas between the windrows of harvest residues. Field-moist soil samples were sieved (< 2 mm) and stored at 4 °C (ca. 2 weeks) for soil biological assays. A sub-sample of each soil was air-dried for studying gross N transformations in the laboratory and for soil chemical and physical characterisation.

Soil analyses and biological assays

Total C and N, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ were determined using an Isoprime isotope ratio mass spectrometer (Isoprime-EuroEA 3000), as reported by Xu et al. (2003). Soil gross N mineralization and immobilization as well as soil biological assays (soil microbial biomass C and N, respiration and metabolic quotient) were determined as reported by Chen et al. (2002). Five 0-10 cm soil samples from each site were used to determine (a) soil chemical properties: pH, cation exchange capacity (CEC), exchangeable cations (K, Ca, Mg and Mn), total P and total K; and (b) physical properties: bulk density, particle sizes (clay, silt and sand) and electric conductivity as reported by Xu et al. (1995).

Statistical analyses and sample size estimation

Analysis of variance was carried out for all data on soil properties and gross N transformations with Statistix for Windows version 2.2 and least significant difference (LSD) ($P < 0.05$) was used to separate the means when differences were significant. Pearson linear correlations between the soil properties were

also conducted with Statistix for Windows version 2.2. The sample sizes were estimated for soil total C and N, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, as reported by Prasolova et al. (2000b).

Results

Soil total C and N, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$

Total C and N were significantly higher in the soil at 0-10 cm depth under NF and 1R hoop pine plantation (63-64 g C / kg and 5.5-5.8 g N / kg) than those under 2R hoop pine plantation (58 g C / kg and 4.9 g N / kg) (Table 1). While these corresponding values in 10-20 cm depth were highest under NF (47 g C / kg and 4.2 g N / kg), followed by the 1R and then 2R hoop pine plantation. Soil $\delta^{13}\text{C}$ was significantly lower in 0-10 and 10-20 cm depths under NF than those under 1R and 2R hoop pine plantations. Soil $\delta^{15}\text{N}$ was higher under NF than those under the plantations.

Table 1 Soil total carbon (C) and nitrogen (N), and stable C and N isotope composition ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) in 3 adjacent forest ecosystems^a

Forest type	Total C (g/kg)	Total N (g/kg)	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)
0-10 cm soil				
Natural forest	63.0ab ^b	5.5a	-25.89b	10.02a
First rotation hoop pine plantation	64.0a	5.8a	-25.36a	8.32b
Second rotation hoop pine plantation	58.0b	4.9b	-25.53a	8.03b
10-20 cm soil				
Natural forest	47.0a	4.2a	-25.32b	10.20a
First rotation hoop pine plantation	37.0b	3.7b	-24.54a	9.04b
Second rotation hoop pine plantation	30.0c	2.9c	-24.67a	8.72b

^aThere are no significant differences in soil bulk density (BD) among the 3 forest plots (mean BD = 0.717 g / cm³) for 0-10 cm soil depth;

^bMeans within a column for a given soil depth followed by the same letter are not different from each other at 5% level of significance by LSD.

It is interesting to note that the sample size required for estimating soil total C under NF (with the sample mean relative error at 10%) appears to be smaller (n=13) than for samples under 1R and 2R hoop pine plantations (n= 24-48), as shown in Table 2. The sample size pattern for soil total N is similar to that for soil total C. This suggests that soil total C and N appear to be less variable under NF than under the plantations. Only 2-3 soil samples would need to be collected for detecting differences in soil $\delta^{13}\text{C}$ between the sites, which are fewer than those (4-23) for soil $\delta^{15}\text{N}$.

Other soil chemical and physical properties

There were no significant differences in pH, CEC and exchangeable cation concentrations in the soil for 0-10 cm depth between the 3 adjacent sites under NF and hoop pine plantations (Table 3). Soil total P in 0-10 cm depth was highest under NF (1477 mg P / kg), followed by those under 1R (1116 mg P / kg) and then 2R plantation (748 mg P / kg). This indicates that close attention would need to be paid to the depletion of soil total P from NF to 1R and from 1R to 2R plantations, when P deficiency might become a major factor limiting hoop pine plantation productivity and soil microbial activity. However, soil total K was significantly higher under 2R plantation than those under NF and 1R plantation.

There were no significant differences in soil physical properties in 0-10 cm depth between the 3 sites: bulk density (0.69 – 0.74 g / cm³), electrical conductivity (0.10 – 0.13 dS / m), clay (39-45%), silt (22-29%) and sand (32-35%) (detailed data not presented here).

Soil microbial properties and gross N transformations

There were no significant differences in soil microbial biomass C, CO₂ respiration and metabolic quotient among the 3 sites (Table 4). Microbial biomass N was significantly lower in the soil for the 0-10 cm depth under 1R hoop pine plantation than those under NF and 2R hoop pine plantation. Potentially mineralizable N and gross N mineralization were significantly higher under NF than those under the plantations. Soil gross N immobilization was highest under 2R, followed by those under NF and then 1R hoop pine plantation.

Table 2 Sample size required for estimation of mean soil total carbon (C) and nitrogen (N), and stable C and N isotope composition ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) in 3 adjacent forest ecosystems (9.6 m x 12.0 m for each of the 3 forest areas) with the sample mean relative error at 10% ($P_{\alpha}^{10\%}$) and 20% ($P_{\alpha}^{20\%}$) with 95% confidence^a

Forest Type	Total C (g/kg)		Total N (g/kg)		$\delta^{13}\text{C}$ (‰)		$\delta^{15}\text{N}$ (‰)	
	$P_{\alpha}^{10\%}$	$P_{\alpha}^{20\%}$	$P_{\alpha}^{10\%}$	$P_{\alpha}^{20\%}$	$P_{\alpha}^{10\%}$	$P_{\alpha}^{20\%}$	$P_{\alpha}^{10\%}$	$P_{\alpha}^{20\%}$
0-10 cm soil								
NF	13	6	12	5	3	3	23	8
1R	24	9	16	7	3	3	17	7
2R	39	13	20	7	3	3	8	4
10-20 cm soil								
NF	13	6	11	5	3	2	9	5
1R	48	15	31	10	3	3	10	5
2R	30	10	20	7	3	2	6	4

^aForest type: NF – natural forest; 1R – first rotation hoop pine plantation; and 2R – second rotation hoop pine plantation.

Table 3 Other chemical properties in 0-10 cm soil in 3 adjacent forest ecosystems^a

Forest Type	pH (1:5 H ₂ O)	CEC (cmol/kg)	Exchangeable cation (cmol/kg)				Total P (mg/kg)	Total K (mg/kg)
			K	Ca	Mg	Mn		
NF	5.0a ^b	35.7a	0.49a	3.85a	0.76a	0.046a	1477a	701b
1R	6.0a	38.7a	0.67a	6.85a	1.55a	0.018a	1116b	1191b
2R	5.4a	28.5a	0.52a	3.96a	1.13a	0.082a	748c	5588a

^aForest type: NF – natural forest; 1R – first rotation hoop pine plantation; and 2R – second rotation hoop pine plantation; and CEC – cation exchange capacity;

^bMeans within a column followed by the same letter are not different from each other at 5% level of significance by LSD.

Table 4 Microbial properties and gross nitrogen (N) transformations in 0-10 cm soil in 3 adjacent forest ecosystems^a

Forest Type	MBC (mg/kg)	MBN (mg/kg)	CO ₂ -C respired (mg/kg.h)	$q\text{CO}_2\text{-C}$ (μg/mg.MBC.h)	5 g soil incubated with 5 μg ¹⁵ NH ₄ -N in 50 ml solution (99% ¹⁵ N excess)		
					PMN (mg/kg)	<i>M</i> (mg/kg)	<i>I</i> (mg/kg)
NF	951a ^b	113.1a	0.503a	0.552a	114.6a	140.2a	25.6b
1R	686a	102.3b	0.414a	0.672a	62.6b	78.3b	15.8c
2R	930a	142.6a	0.571a	0.626a	58.7b	95.9b	37.2a

^aForest type: NF – natural forest; 1R – first rotation hoop pine plantation; and 2R – second rotation hoop pine plantation; MBC – microbial biomass carbon (C); MBN – microbial biomass nitrogen (N); $q\text{CO}_2\text{-C}$ – metabolic quotient; and potentially mineralizable N (PMN), gross N mineralization (*M*) and gross N immobilization (*I*);

^bMeans within a column followed by the same letter are not different from each other at 5% level of significance by LSD.

Relationships between soil properties

Soil microbial biomass C was significantly related to soil microbial biomass N ($r = 0.655$, $P < 0.01$) as shown in Figure 1. Soil respiration was significantly related to soil microbial biomass N ($r = 0.646$, $P < 0.01$), but not related to soil microbial biomass C ($P > 0.05$).

Soil $\delta^{13}\text{C}$ was negatively related to soil total C ($r = 0.666$, $P < 0.01$) as shown in Figure 2. In addition, soil total N was significantly related to soil total C ($r = 0.945$, $P < 0.01$), potentially mineralizable N ($r = 0.833$, $P < 0.01$), and gross N mineralization ($r = 0.863$, $P < 0.01$) (detailed data not presented here). It is not surprising that there were close correlations between potentially mineralizable N and gross N mineralization ($r = 0.991$, $P < 0.01$) (data not presented here).

Discussion

Total C and N in the soil for 0-10 cm depth were significantly lower under 2R hoop pine plantation than those under NF and 1R hoop pine plantation. There were significant reductions in total C and N from NF to 1R and from 1R to 2R hoop pine plantations in 10-20 cm depth soil. This highlights potential N deficiency in the 2R hoop pine plantations, and application of N fertilizers may be required to improve productivity of 2R hoop pine plantations, as reported by Bubbs et al. (1999) and Xu et al. (2002). Hoop pine families, particularly selected for better tree growth and higher water use efficiency (WUE) in the dry environment (Prasolova et al. 2000a, 2001; Prasolova and Xu 2003), were used in the hoop pine plantations of south east Queensland.

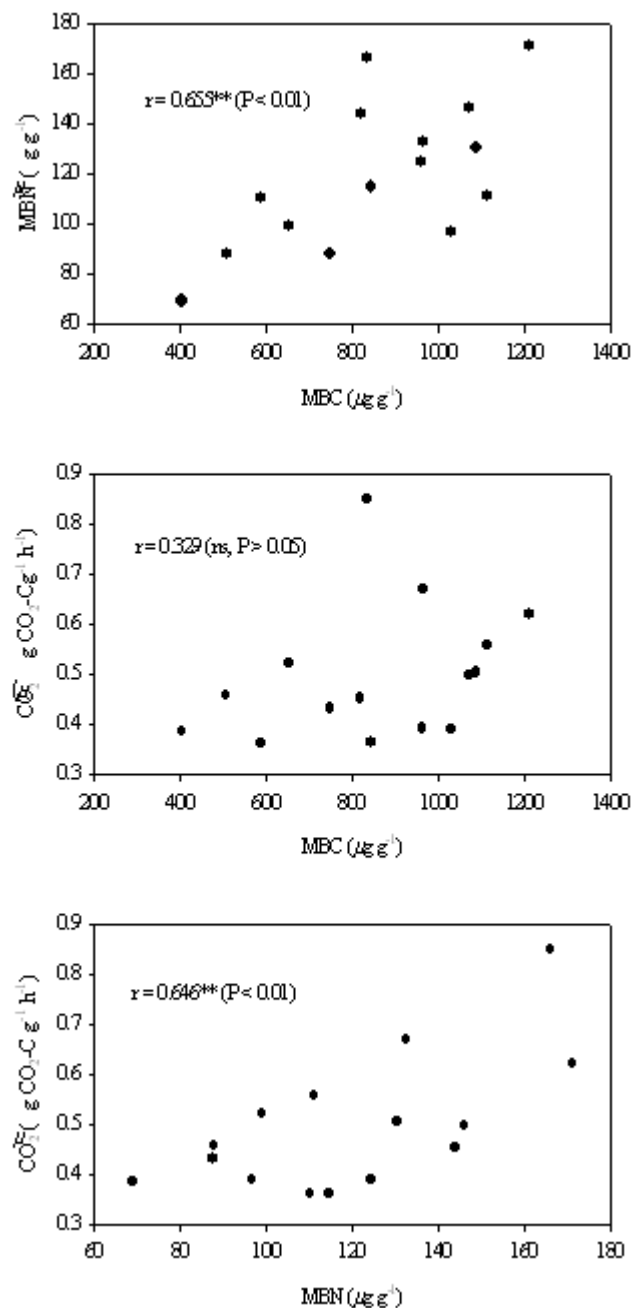


Figure 1. Relationships determined between microbial biomass C (MBC), microbial biomass N (MBN and CO_2 respiration in soils under adjacent natural forest, 1st rotation and 2nd rotation hoop pine plantations at the Yarraman site, southeastern Queensland, Australia (n=15)

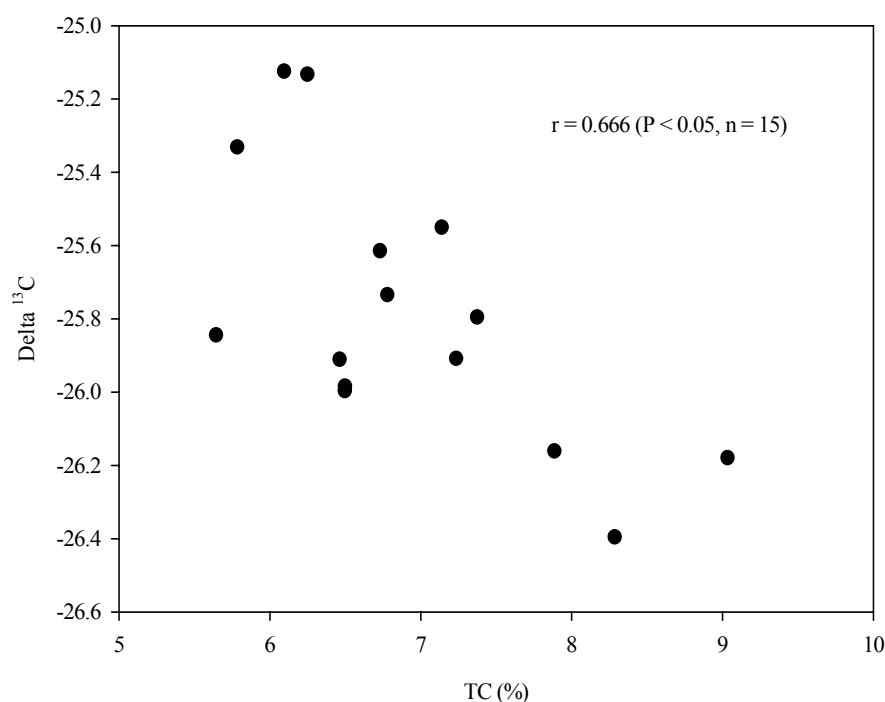


Figure 2 Relationship between soil total C (TC) and stable C isotope composition (delta ¹³C, ‰).

There were no significant differences in other chemical and physical properties in 0-10 cm depth soil among the 3 sites under NF, 1R and 2R hoop pine plantations, except for soil total P and K. The significant reduction in soil total P, with about a 24% decrease from NF to 1R and a further 33% reduction from 1R to 2R hoop pine plantation, is of particular concern, and warrants attention and further investigation, since the scale of reduction in soil total P appears to be much greater than those for soil total C and total N from NF to 1R and from 1R to 2R plantation. However, some of the ecosystem P might be retained in the windrows of 1R harvest residues, which might be released for plant uptake following residue decomposition. This suggests that P deficiency may become a secondary growth-limiting factor in the 2R hoop pine plantations once N deficiency is corrected by fertilizer N application. Indeed, this is supported by another fertilizer experiment on a relatively wet site of south-east Queensland, where application of 60 kg P / ha, in addition to 300 kg N / ha applied, has significantly improved tree growth, compared with the application of only 300 kg N / ha to a 7-year-old 2R hoop pine plantation (Xu et al. 2000). The higher total K in 0-10 cm depth soil under 2R hoop pine plantation, compared with those under NF and 1R hoop pine plantation, might be due to the major harvest residue distribution at plantation establishment and the leaching and mineralization of residue K into the surface soil. Soil total K on the 2R site would be expected to decline as the plantation is more established, since some of the soil available K would be taken up by the growing trees during the rotation period.

Soil microbial biomass C, respiration and metabolic quotient did not differ among the 3 sites, since these parameters were more variable, reflecting the more rapid biological processes than for soil total C and N as reported previously (Chen et al. 2002). However, soil potentially mineralizable N, gross N mineralization and immobilization were rather sensitive to the conversion of NF to hoop pine plantation and forest management practices. This is consistent with research findings reported elsewhere (Chen et al. 2002; Mathers and Xu 2003). There were close relationships between soil total N and total C, and between soil total N and potentially mineralizable N (or gross N mineralization), which are similar to those reported by Xu et al. (1996) and Chen et al. (2002).

Conclusion

Total C and N in the top 20 cm soil were highest under NF, followed by 1R and then 2R hoop pine plantations, indicating that N deficiency may become a growth-limiting factor in the 2R hoop pine plantations and subsequent rotations of hoop pine plantation. The sample size needed to estimate soil $\delta^{13}\text{C}$ with a sample mean error of 10% seems to be much smaller than those for soil total C and N as well as $\delta^{15}\text{N}$. The significant reductions in soil total P from NF to 1R and then from 1R to 2R hoop pine plantations highlight that P deficiency might become another growth-limiting factor in the second and

subsequent rotations of hoop pine plantations. Soil microbial properties such as microbial biomass C and respiration were very variable in these forest ecosystems, reflecting the more rapid biological processes involved than for soil total C and N. Soil potentially mineralizable N, gross N mineralization and immobilization were useful indices of soil N availability in response to forest types and management practices.

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