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Responses of soil dissolved organic matter to long-term plantations of three coniferous tree species

Shunbao Lu [a,b,d], Chengrong Chen [b,*], Xiaoqi Zhou [c], Zhihong Xu [c], Gary Bacon [c], Yichao Rui [c], Xiaomin Guo [a,**]

[a] *College of Forestry, Jiangxi Agricultural University, Nanchang 330045, China*
[b] *Griffith School of Environment, Environmental Futures Centre, Griffith University, Nathan 4111, Australia*
[c] *School of Bio-molecular and Physical Sciences, Environmental Futures Centre, Griffith University, Nathan 4111, Australia*
[d] *College of Life Science, Jiangxi Normal University, Nanchang 330022, China*

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ABSTRACT

Tree species have significant effects on the availability and dynamics of soil organic matter. In the present study, the pool sizes of soil dissolved organic matter (DOM), potential mineralizable N (PMN) and bio-available carbon (C) (measured as cumulative CO_2 evolution over 63 days) were compared in soils under three coniferous species — 73 year old slash (*Pinus elliottii*), hoop (*Araucaria cunninghamii*) and kauri (*Agathis robusta*) pines. Results have shown that dissolved organic N (DON) in hot water extracts was 1.5–1.7 times lower in soils under slash pine than under hoop and kauri pines, while soil dissolved organic C (DOC) in hot water extracts tended to be higher under slash pine than hoop and kauri pines but this was not statistically significant. This has led to the higher DOC:DON ratio in soils under slash pine (32) than under hoop and kauri pines (17). Soil DOC and DON in 2 M KCl extracts were not significantly different among the three tree species. The DOC:DON ratio (hot water extracts) was positively and significantly correlated with soil C:N ($R^2 = 0.886$, $P < 0.01$) and surface litter C:N ratios ($R^2 = 0.768$, $P < 0.01$), indicating that DOM was mainly derived from litter materials and soil organic matter through dissolution and decomposition. Soil pH was lower under slash pine (4.5) than under hoop (6.0) and kauri (6.2) pines, and negatively correlated with soil total C, C:N ratio, DOC and DOC:DON ratio (hot water extracts), indicating the soil acidity under slash pine favored the accumulation of soil C. Moreover, the amounts of dissolved inorganic N, PMN and bio-available C were also significantly lower in soils under slash pine than under hoop and kauri pines. It is concluded that changes in the quantity and quality of surface litters and soil pH induced by different tree species largely determined the size and quality of soil DOM, and plantations of hoop and kauri pine trees may be better in maintaining long-term soil N fertility than slash pine plantations.

1. Introduction

Improved understanding of the size, nature and dynamics of soil organic matter is essentially required for developing effective forest management regimes in order to achieve forest productivity and sustainability (Burton et al., 2007; Chen and Xu, 2005; Jiang et al., 2010). Dissolved organic matter (DOM) is a key component of soil organic matter and an essential source of available carbon (C) and nutrients for soil microorganisms and plants (Chen and Xu, 2008; Filep and Rékási, 2011; Marschner and Kalbitz, 2003; Qualls and Haines, 1991). DOM plays a vital role in biogeochemical cycling in terrestrial ecosystems and thus affects ecosystem productivity and sustainability (e.g. Chen and Xu, 2008; Kalbitz et al., 2000; Müller et al., 2009; Neff et al., 2003). On the other hand, DOM is sensitive to the changes of land-use, management practice, disturbance and environmental conditions (e.g. Guo et al., 2011; Huang et al., 2008; Smolander et al., 2005; Wang and Wang, 2010) and has been widely used as an indicator of lability of soil organic matter, although it generally comprises only a small part of soil organic matter (<1%) (e.g. Chen and Xu, 2008).

Plant species can affect soil C and nutrient dynamics through the plant–soil interaction and feedback mechanisms (e.g. Bréchet et al., 2009; Vivanco and Austin, 2008). Shifts in tree species can lead to changes in root–microbe associations, litter quality inputs and micro-environmental conditions, which will greatly modify biogeochemical cycling processes (Chen et al., 2008; Vivanco and Austin, 2008). For example, different tree species significantly affected soil pH, N availability and N mineralization and nitrification rates (e.g.

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[*] Correspondence to: C.R. Chen, Griffith School of Environment and Environmental Futures Centre, Griffith University, Nathan, Queensland 4111, Australia. Tel.: +61 7 3735 7494; fax: +61 7 3735 7773.
[**] Correspondence to: X. Guo, College of Forestry, Jiangxi Agricultural University, Nanchang 330045, China. Tel.: +86 791 3813337; fax: +86 791 3813243.
E-mail addresses: c.chen@griffith.edu.au (C. Chen), gxmjxau@163.com (X. Guo).

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Burton et al., 2007; Ste-Marie and Paré, 1999). Bréchet et al. (2009) found that variations in soil respiration under 16 tree species were mainly related to leaf litterfall and basal area of stems. However, how soil DOM responds to changes in tree species is largely unknown, particularly for tropical and subtropical environments (Chen et al., 2005; Xing et al., 2010). Smolander and Kitunen (2002) and Smolander et al. (2005) found that levels of DOM in soils under birch and Norway spruce were higher than under Scots pine. Jiang et al. (2010) and Xing et al. (2010) reported that soils under broadleaf forest species had greater DOM than under coniferous species, while those under mixed species were intermediate. Burton et al. (2007) found concentrations of soil SON under hoop pine plantations to be lower than those under native forests. Mechanisms responsible for differences in the pool size of soil DOM under different forest species are poorly understood. It has been suggested that it may be attributed to differences in the quantity and quality of organic matter inputs and associated microbial transformation processes (Burton et al., 2007; Smolander and Kitunen, 2002). The presence of larger quantity and more labile organic inputs generally contributes to the greater amount of soil DOM (e.g. Burton et al., 2007; Smolander and Kitunen, 2002; Xing et al., 2010).

Slash pine (*Pinus elliottii* Engelm. var. *elliottii)* is one of the key exotic pine species which was introduced from the southeastern United States and is widely grown in Queensland (e.g. Chen and Xu, 2005), while hoop pine (*Araucaria cunninghamii* Ait) is a native rainforest species grown successfully in a plantation environment, with currently covering ca. 50,000 ha (plantation) in Queensland (Xu et al., 2008). Kauri (*Agathis robusta* C. Moore) also occurs naturally in eastern Queensland and belongs to the Araucaria genus, with a small area found in plantation. Slash pine is a fast-growing species with lower level of nutrients (N, P and K) in its litter layers (Maggs, 1985), while hoop and kauri pines are N-demanding species and are known to accumulate relatively recalcitrant N in the forest floor materials (Bubb et al., 1998; Silvester, 2000). Little is known about the impacts of these coniferous tree species on the availability and dynamics of soil organic matter and long-term site sustainability. The aim of this study was to investigate impacts of the 73-year-old adjacent stands of slash, hoop and kauri pines on the pool size of soil DOC and DON and transformation of soil C and N in subtropical Australia. It was hypothesized that the size and quality of soil DOC and DON pools vary with tree species due to their differences in litter quantity and quality (e.g. N contents and C/N ratio), with greater amounts of DOC and DON being present in soils under hoop and kauri pines than under slash pine.

2. Materials and methods

2.1. Site description and soil sampling

The site is located at Cooloola, Tin Can Bay, southeast Queensland, Australia (25°56′49″S, 153°5′27″E). The altitude at the site is 43 m above sea level. The soil is classified as Gleyic Acrisol (FAO Soil Classification), developed from quartz-rich sandstones. Annual rainfall varies from 741 to 2106 mm, with an average of 1287 mm. About 40% of annual rainfall (501 mm) is distributed in summer (Dec–Feb), while ca. 15% (192 mm) falls in winter (Jun–Aug). Winter temperatures range from 7 to 23 °C and summer temperatures from 18 to 30 °C. The tree species trial was established in 1935 on the original banana farm. Three pine species, *P. elliottii v. elliottii*, *A. cunninghamii* and *A. robusta* were adjacently planted on the broad gently undulating plain. The sizes of plots for these three species are 1.087, 0.308 and 0.428 ha, respectively. No fertilizer has been applied since planting. Brush tending was carried out in 1940 and in 1948. In 1963, merchantable thinning was carried out in these plantations, and the final stocking densities of *P. elliottii v. elliottii*, *A. cunninghamii* and *A. robusta* were 140, 120 and 120 trees/ha respectively. No pruning has been conducted since then. These stands were 73 years old at the time of sampling. Four 10 × 20 m subplots of each pine plantation were randomly selected for soil sampling in this study. The thickness of litter (L) and fermentation (F) layers was ca. 5–6 cm and 1–2 cm for slash pine, respectively, while the corresponding values were ca. 4–5 cm and 1–2 cm for both hoop and kauri pines. The humus (H) layer was not well distinguished. The forest floor materials were removed before soil sampling. A total of ten soil cores at the 0–10 cm depths were randomly collected in each subplot using a 7.5 cm diameter auger and bulked as a composite sample in November 2008. Each sample was placed in a sterile plastic bag, sealed and transported to the laboratory on ice. All field-moist samples were passed through a 2-mm sieve with fine roots and large debris removed. A portion of fresh samples were stored at 4 °C for analysis of soil inorganic and organic N, potentially mineralizable N and CO_2 respiration. The other portion of fresh samples were air-dried and stored at room temperature prior to analysis of soil particle size, while a subsample of air-dried soil sample was finely ground (<150 μm) for analysis of soil total C, N and P and pH.

2.2. Measurement of biologically available soil C — incubation method

Biologically available soil organic C (bio-available organic C) was determined using the incubation method as described by Chen et al. (2000). In brief, 25 g of air-dried soil was adjusted to 60% of the field capacity and aerobically incubated at 22 °C in a 1-l sealed glass jar and CO_2 evolved from soil was trapped in 0.1 M NaOH and measured by 0.1 M HCl titration after 1, 3, 7, 14, 21, 28, 35, 42, 49, 56 and 63 days. The bio-available organic C was estimated by calculating the cumulative production of CO_2 from soils during the 63-day incubation.

2.3. Extraction and analysis of soil dissolved organic C and N

Soil DOC and DON pools were measured in both hot water (DOC_{HW}, DON_{HW}) and 2 M KCl (DOC_{KCl}, DON_{KCl}) extracts as described by Chen et al. (2005). For hot water extraction, 6.0 g (dry weight equivalent) of air-dried soil was incubated with 30 ml of deionized water in a capped test tube at 70 °C for 18 h, and test tubes were then shaken for 5 min on an end-to-end shaker and filtered through a Whatman 42 paper, followed by a 0.45-μm filter membrane. Soil DOC_{KCl}, DON_{KCl} were measured by extracting 5.0 g (dry weight equivalent) of air-dried soil with 50 ml of 2 M KCl, shaking on an end-to-end shaker for 1 h and filtering through a Whatman 42 paper followed by a 0.45 μm membrane. The DOC and total soluble N (TSN) concentrations in the filtrates of both extracts were determined using SHIMADZU $TOC_{-VCPH/CPN}$ analyzer (fitted with a TN unit) as above.

Concentrations of NH_4^+-N and NO_3^--N in the hot water and 2 M KCl extracts were determined using the LACHAT Quickchem Automated Ion Analyzer (QuikChem Method 10-107-06-04-D for NH_4^+-N and QuikChem Method 12-107-04-1-B for NO_3^--N). Soil dissolved inorganic N (DIN) was calculated as the sum of NH_4^+-N and NO_3^--N. The DON in the extracts was calculated as the difference between TSN and the DIN.

2.4. Determination of potential mineralizable N

Potentially mineralizable N (PMN) was determined using the water logging incubation method (Waring and Bremner, 1964). Briefly, one portion of 5 g of air-dried soil was incubated with 25 ml deionized water in a capped and sealed test tube at 40 °C for 7 days, and then 25 ml of 4 M KCl was added. The test tube was shaken on an end-to-end shaker for 60 min and then centrifuged for 20 min at 2000 rpm and the extract was filtered through a Whatman No. 42 filter paper. The other portion of 5 g of air-dried soil was immediately extracted with 50 ml of 2 M KCl as above before incubation.

Concentrations of NH_4^+-N in the extracts were determined using the LACHAT Quickchem Automated Ion Analyzer (QuikChem Method 10-107-06-04-D). The PMN was calculated as the difference in the concentration of NH_4^+-N in the extracts before and after incubation.

2.5. Analysis of other soil properties

Soil particle size and bulk density were measured using the methods described by Rayment and Higginson (1992). Soil pH was determined in 1:5 (v/v) soil/water extracts using a combination glass electrode and moisture by drying at 105 °C for 48 h. Soil total C and N were determined using an isotope ratio mass spectrometer with a Eurovector Elemental Analyzer (Isoprime-EuroEA 3000, Milan, Italy).

2.6. Statistical analysis

One-way analysis of variance (ANOVA) was employed to determine the effect of three tree species on NH_4^+-N, NO_3^--N, dissolved organic C and N, PMN, bio-available C and other soil properties. The normality of all data was checked and met before ANOVA. Means and least significant differences at 5% level were calculated to separate the difference among the tree species. Pearson correlation coefficients among soil parameters were also calculated. These chemical and biochemical parameters were also subject to the principal component analysis (PCA) to determine if tree species had distinct impacts on the soils. All statistical analyses were performed using SPSS 12.0 software (SPSS Inc., USA).

3. Results

3.1. Soil basic properties

Soil pH was lower in the slash pine plantation (4.5) than in hoop and kauri pine plantations (6.0–6.2) ($P < 0.05$) (Table 1). Soil total C was greater in soils under slash pine compared with hoop and kauri pines, but there were no significant differences in soil total N and P contents among the three pine plantations (Table 1). However, the C:N ratio was much higher in soils under slash pine (36) than under hoop and kauri pines (21). The particle size in these soils was dominated by sand fraction (ca. 96%). Compared with this fraction, the differences in silt or clay fractions among the three pine plantations were small (<2%) (Table 1). There were no significant differences in soil moisture and bulk density among the three pine plantations.

3.2. Dissolved organic and inorganic N extracted by 2 M KCl

Concentrations of DON_{KCl} ranged from 8.1 to 11.3 mg N kg^{-1}, accounting for 27.8–30.7% of total extractable N and 0.15–0.22% of total N (Table 2), but differences among the three pine plantations were not significant. Concentrations of DOC_{KCl} ranged from 95 to 147 mg kg^{-1}, while differences in DOC_{KCl} and DOC:DON ratio among three pine plantations were not significant (Table 2). Soil NH_4^+-N was the predominant form of inorganic N in KCl extracts under all three pine plantations, ranging from 18.1 to 21.7 mg kg^{-1} and accounting for 70.9–99.9% of total inorganic N (Table 2). Differences in NH_4^+-N were not significant across the three pine plantations. Concentrations of NO_3^--N were higher in soils under the kauri pine plantation (7.64 mg kg^{-1}) than under the slash and hoop pine plantations (0.02–1.80 mg kg^{-1}).

3.3. Dissolved organic and inorganic N extracted by hot water

Concentrations of DON_{HW} were three to four times greater than those in 2 M KCl extracts (Tables 2 and 3), ranging from 26.7 to 46.27 mg kg^{-1} and accounting for 55.2–65.4% of total soluble N and 0.50–0.82% of total N (Table 3). Concentrations of DON_{HW} were significantly lower in soils under the slash pine plantation than under the hoop and kauri pine plantations, while DOC_{HW} in hot water extracts tended to be higher under slash pine than hoop and kauri pines but not statistically significant. This has resulted in the significantly higher DOC: DON ratio (hot water extracts) in slash pine (32) than in hoop and kauri pine plantations (17) (Table 3). Across the different forest ecosystems, NH_4^+-N was the dominant form of inorganic N (21.4–22.9 mg kg^{-1}), while concentrations of NO_3^--N were generally <8.02 mg kg^{-1}. There were no significant differences in the concentration of NH_4^+-N, while the concentration of NO_3^--N was significantly greater in soils under kauri pine than under slash pine (Table 3).

3.4. Potential mineralizable N

The values of PMN ranged from 43 mg kg^{-1} in the slash pine plantation to 77 mg kg^{-1} in the hoop pine plantation, comprising 6.4–18.5% of soil total N (Fig. 1). The PMN was significantly lower in soils under slash pine than under hoop and kauri pine plantations (Fig. 1). The PMN values were positively related to DON_{HW} ($r = 0.697$, $P < 0.05$), but negatively related to soil C:N ratio ($r = 0.614$, $P < 0.05$) and DOC_{HW}:DON_{HW} ratio ($r = 0.604$, $P < 0.05$).

3.5. Bio-available soil organic C

Bio-available organic C in soils was measured as the cumulative CO_2 evolved during the 63-day incubation and shown in Fig. 2. The amounts of bio-available organic C were significantly higher in soils under kauri (average 680 mg CO_2-C kg^{-1} soil) and hoop pine (average 565 mg CO_2-C kg^{-1} soil) plantations than under slash pine plantation (average 278 mg CO_2-C kg^{-1} soil). However, there were no significant differences in soil bio-available organic C between kauri and hoop pine plantations (Fig. 2). Bio-available organic C was highly correlated with PMN ($r = 0.744$, $P < 0.01$).

3.6. Principle component analysis of effects of tree species on soil properties

Results from principle component analysis (PCA) have shown the distinct effect of exotic pine (slash pine) and native pines (hoop and kauri pines) on soil properties (Fig. 3). The soil samples from slash pine plantation were clearly separated from soil samples from hoop and kauri pine plantations along the PC1 axis, while there was no clear separation between hoop and kauri pines (Fig. 3). The PC1 accounted for 48.4% of total variation in the soil properties, while PC2 explained 27.1% of total variation. Soil pH is the most important parameter which correlated with ($r = 0.873$) and positively contributed to the PC1 (Table 4). DON_{HW}, inorganic N (in KCl extracts), bio-available C, DOC_{KCl}, PMN and inorganic N (in hot water extracts) were also

Table 1
Selected chemical and physical properties in surface soils (0–10 cm) under three 73 year old pine plantations.

Tree species	Soil moisture (%)	pH	Total C (%)	Total N (%)	Total P (mg kg^{-1})	C:N ratio	Clay (%)	Silt (%)	Sand (%)	Bulk density (g cm^{-3})
Slash pine	4.9 ± 0.8a	4.5 ± 0.1b	1.94 ± 0.19a	0.054 ± 0.005a	28.2 ± 3.0a	35.9 ± 0.5a	3.7 ± 0.2b	0.6 ± 0.2b	95.7 ± 0.1a	1.04 ± 0.04a
Hoop pine	2.6 ± 0.4a	6.0 ± 0.1a	1.25 ± 0.18b	0.057 ± 0.007a	32.4 ± 3.9a	21.9 ± 0.3b	2.9 ± 0.4b	1.4 ± 0.5ab	95.7 ± 0.3a	1.16 ± 0.04a
Kauri pine	3.4 ± 1.0a	6.2 ± 0.3a	1.08 ± 0.11b	0.052 ± 0.002a	29.9 ± 2.0a	20.8 ± 1.9b	2.0 ± 0.2a	2.0 ± 0.4a	96.0 ± 0.3a	1.16 ± 0.03a

Data are mean ± S.E. (n = 4). Different letters within columns showed significantly different at $P < 0.05$.

Table 2
Dissolved organic C (DOC_{KCl}) and N (DON_{KCl}) and inorganic N (DIN_{KCl}) extracted by 2 M KCl in soils (0–10 cm) under three 73 year old pine plantations in subtropical Australia[a].

Tree species	DIN_{KCl} (mg kg^{-1})		DON_{KCl}			DOC_{KCl}	DOC:DON ratio
	NH_4^+-N	NO_3^--N	mg kg^{-1}	% (TSN)[b]	% (TN)[c]	(mg kg^{-1})	
Slash pine	18.1 ± 1.6a	0.02 ± 0.00b	8.1 ± 0.9a	30.7 ± 1.4a	0.15 ± 0.01a	95 ± 11a	12.0 ± 1.4a
Hoop pine	27.1 ± 6.3a	1.80 ± 1.32ab	10.5 ± 1.18a	27.8 ± 3.3a	0.19 ± 0.02a	147 ± 26a	14.2 ± 2.2a
Kauri pine	18.6 ± 3.4a	7.64 ± 3.01a	11.3 ± 1.6a	29.9 ± 3.6a	0.22 ± 0.03b	142 ± 11a	13.2 ± 1.5a

[a] Data are mean ± S.E. (n = 4). Different letters within columns showed significantly different at $P < 0.05$.
[b] %TSN, percentage of DON over total soluble N.
[c] %TN, percentage of DON over total soil N (TN).

Table 3
Dissolved organic C (DOC_{HW}) and N (DON_{HW}) and inorganic N (DIN_{HW}) extracted by hot water in soils (0–10 cm) under three 73 year old pine plantations in subtropical Australia[a].

Tree species	DIN_{HW} (mg kg^{-1})		DON_{HW}			DOC_{HW}	DOC:DON ratio
	NH_4^+-N	NO_3^--N	(mg kg^{-1})	% (TSN)[b]	% (TN)[c]	(mg kg^{-1})	
Slash pine	22.4 ± 1.8a	0.03 ± 0.03b	26.7 ± 3.2b	55.2 ± 1.5b	0.50 ± 0.03b	851 ± 80a	32 ± 2a
Hoop pine	22.9 ± 4.7a	2.38 ± 1.84ab	46.2 ± 4.4a	65.4 ± 3.1a	0.82 ± 0.06a	815 ± 125a	17 ± 1b
Kauri pine	21.4 ± 2.7a	8.02 ± 3.35a	39.2 ± 2.8a	57.0 ± 3.0ab	0.76 ± 0.06a	692 ± 117a	17 ± 1b

[a] Data are mean ± S.E. (n = 4). Different letters within columns showed significantly different at $P < 0.05$.
[b] %TSN, percentage of DON over total soluble N.
[c] %TN, percentage of DON over soil total N (TN).

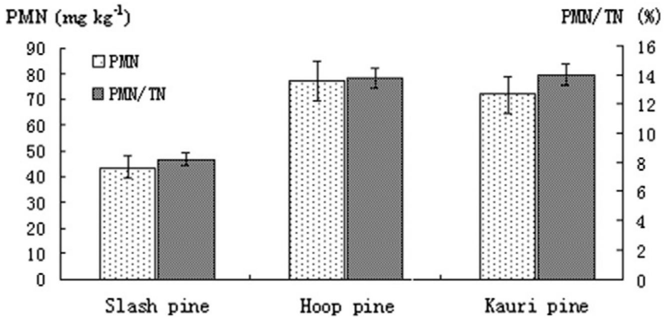

Fig. 1. Potential mineralizable nitrogen (PMN) in soils (0–10 cm) under three 73 year old pine plantations in subtropical Australia. Error bars are shown above the column. PMN/TN (%), the percentage of PMN over total soil N.

positively correlated with the PC1. Soil C:N ratio and DOC_{HW}:DON_{HW} ratio negatively contribute to the PC1. DOC_{HW}, soil total N and total C and moisture contribute significantly to the PC2 (Table 4). Soil pH, soil C:N ratio, DON_{HW} and DOC_{HW}:DON_{HW} ratio contribute 38% to the PC1, while DOC_{HW}, soil total N and total C contribute 52% to the PC2 (Table 4).

4. Discussion

In this study, three pine species (slash, hoop and kauri pines) were adjacently (distance < ca. 30 m) planted on the broad gently undulating plain ca. 73 years ago. Before the establishment of these plantations, banana plants were grown in these soils and the same management practices (including rock Nuaru fertilization regime) were applied. The soils under the three plantations were developed from the same parent

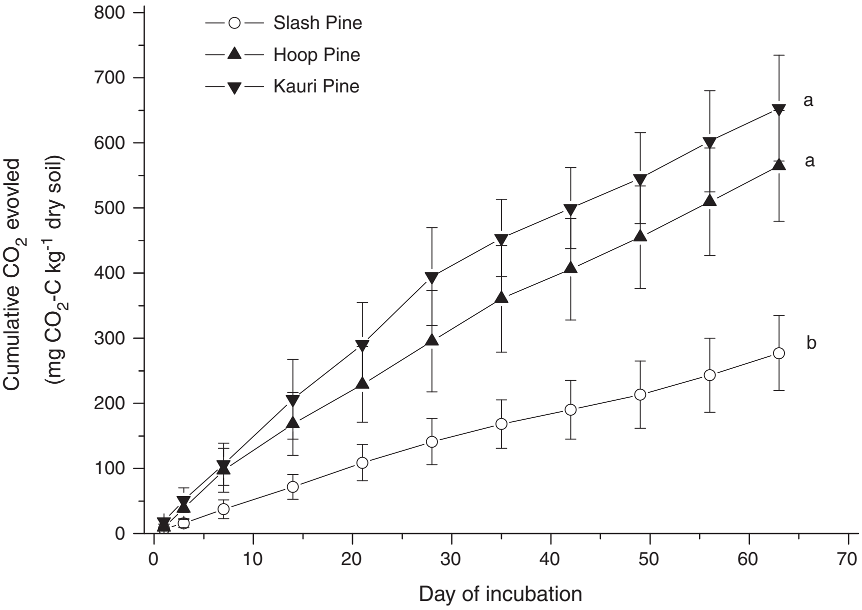

Fig. 2. Bio-available organic C measured as cumulative CO_2-C evolved in soils (0–10 cm) over the 63 day period under three 73 year old pine plantations in subtropical Australia.

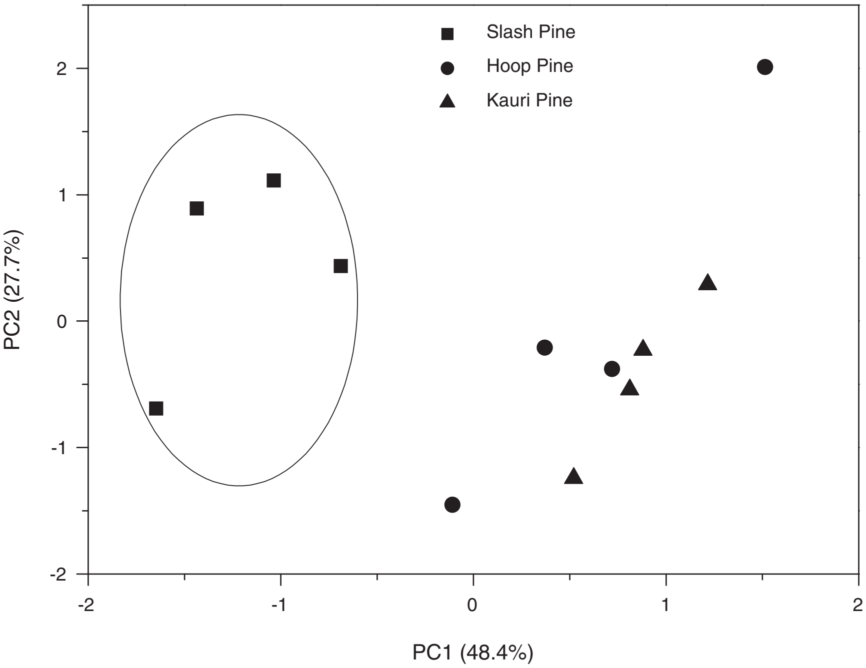

Fig. 3. Ordination plot of principal components analysis (PCA) of soil properties under different forest types. Numbers in parentheses are percentage variance by each principal component (PC).

material — sandstone and dominated by sand fraction (ca. 96%). Therefore, it is reasonable to assume that soil was the same or similar before the plantations were established and the differences in soil properties observed under the different plantations reflected the effects of growth of three pine species. This has been the base for many paired-site or adjacent site studies (Chen et al., 2004; Davis and Condron, 2002; Smolander and Kitunen, 2002). This long-term experiment makes it possible to appreciate the different effects of tree species on soil properties since such effects may not be observed in the short term (Priha and Smolander, 1997).

4.1. Soil DOM pools and their relationships

The amounts of DOC and DON measured by 2 M KCl and hot water extraction were within the normal ranges reported in the literature (Burton et al., 2007; Chen and Xu, 2008; Smolander et al., 2005; Xing et al., 2010). Hot water extracted 3–4 times more soil DON and 4–8 times more DOC than 2 M KCl (Tables 2 and 3), which was consistent with other results in forest soils (e.g. Burton et al., 2007; Jiang et al., 2010). Both KCl and hot water extractions have been used to measure the pool size and dynamics of dissolved organic matter in soils (e.g. Burton et al., 2007; Curtin et al., 2006; Murphy et al., 2000; Xing et al., 2010). The KCl extraction measures physically absorbed DOM from clay minerals and organic colloids, while hot water extracts the readily decomposable fraction of DOM that originates from soil microbial biomass, root exudates, and lysates (Curtin et al., 2006; Ros et al., 2009). In this study, the amounts of DOC and DON in 2 M KCl extracts were not significantly correlated with those in hot water extracts (data not shown). The DON in hot water extracts was significantly related to PMN ($r = 0.660$, $P < 0.05$), while there was no such relationship present between the PMN and the DON in KCl extracts (data not shown). This indicated that the DON in hot water extracts may better represent available organic N pool in soil than that in KCl extracts.

Table 4
Soil properties with significant correlation coefficients ($P < 0.05$) and contributions (%) for principal components 1 (PC1) and 2 (PC2) in principal components analysis of soil variables under three 73 year old pine plantations in subtropical Australia.

Variables	r	Contribution (%)
PC1		
pH	0.873	9.85
Soil C:N	−0.869	9.76
Dissolved organic N (hot water)	0.841	9.14
DOC:DON ratio (hot water)	−0.837	9.05
Dissolved inorganic N (KCl)	0.837	9.05
Cumulative CO_2 evolved (63 days)	0.833	8.97
Dissolved organic C (KCl)	0.815	8.58
Potential mineralizable N	0.778	7.82
Dissolved inorganic N (hot water)	0.688	6.12
Total P	0.649	5.44
PC2		
Dissolved organic C (hot water)	0.937	20.16
Soil total N	0.856	16.82
Soil total C	0.803	14.81
Soil moisture	0.626	9.00

4.2. The effect of coniferous species on DOM pools

The effects of tree species on soil properties have been reflected in the result of PCA of soil properties (Fig. 3; Table 4). Soil pH and labile organic matter (DOC, DON and DOC:DON ratio in hot water extracts) are the key factors contributing to the clear separation of soil samples collected from slash pine plantation from those collected from the other two plantations.

Tree species can affect the availability and transformation of soil C and N through modification of chemical and physical environments in soil and microbial community abundance and composition via root–soil interactions and inputs of litters of different quantity and quality (e.g. Chen et al., 2008; Menyailo et al., 2002; Vivanco and Austin, 2008; Witt and Setälä, 2010). Differences in DOM under different tree species have been observed in a number of studies (e.g. Burton et al., 2007; Jiang et al., 2010; Menyailo et al., 2002; Smolander et al., 2005; Wang and Wang, 2010; Xing et al., 2010). It has been reported that soils under broadleaf forest species had higher DOC and DON than under coniferous species (e.g. Smolander et al., 2005; Wang and Wang, 2010; Xing et al., 2010). This has been attributed

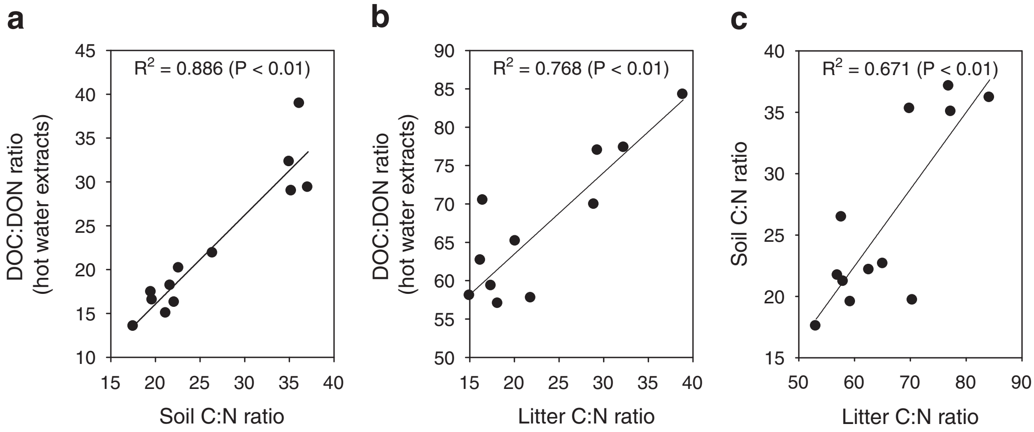

Fig. 4. Relationships between DOC:DON ratio (hot water) and soil C:N ratio (a), between DOC:DON ratio (hot water) and litter C:N ratio (b) and between soil C:N ratio and litter C:N ratio (c) under three 73 year old pine plantations in subtropical Australia.

to: a) the higher leaf litter biomass and root production in broadleaf forest species than the coniferous species tested (Wang and Wang, 2010; Xing et al., 2010); b) nutrient-rich (e.g. N) litter (low C:N ratio) found in the broadleaf forests compared with nutrient-poor litters (high C:N ratio) in coniferous forests (Jiang et al., 2010; Smolander et al., 2005); and c) greater soil microbial biomass and activities and N-associated enzyme (e.g. Protease) activities under broadleaf forests than under coniferous forests (Jiang et al., 2010; Xing et al., 2010).

Slash pine, an exotic coniferous species, is widely known to have lower amounts of N, P and K in the litter fall than other conifers (Gholz et al., 1985; Maggs, 1985). Slash pine will respond to the addition of N only in the presence of adequate P (Richards and Bevege, 1967). On the other hand, hoop and kauri pines, native coniferous species, are N-demanding species; the addition of N is beneficial for successful development (Bubb et al., 1998; Richards and Bevege, 1967; Silvester, 2000). It has been reported that hoop pine litter C was predominately in a recalcitrant form and associated N might not be rapidly released during decomposition (Bubb et al., 1998), while kauri pine tends to accumulate relatively recalcitrant N in the forest floor materials (Silvester, 2000). In the present study, slash pine had higher soil C contents than hoop and kauri pines, with no significant differences in soil total N content among these three species but greater soil C:N ratio under slash pine (36) than under hoop (22) and kauri (21) pines (Table 1). Surface litter biomass at this study site was greater under slash pine (13.2 t ha^{-1}) than hoop (12.3 t ha^{-1}) and kauri (11.2 t ha^{-1}) pines, while litter C:N ratios were also greater under slash pine (71) than under hoop (61) and kauri (60) pines (data not shown). Richards and Bevege (1967) also reported that 5-year old slash pine had higher amount of surface litter but less soil N than hoop and kauri pines of the same age. Concentrations of DON in hot water extracts were significantly higher in soil under hoop and kauri pines than under slash pine, while concentrations of DOC tended to be greater in soil under slash pine compared with hoop and kauri pine, although this difference was not statistically significant (Table 3). This led to greater DOC$_{HW}$:DON$_{HW}$ ratio in soils under slash pine (32) than under hoop and kauri pines (17) (Table 3). DOC$_{HW}$:DON$_{HW}$ ratio was significantly correlated with soil C:N ratio (Fig. 4a) and litter C:N ratio (Fig. 4b), while soil C:N ratio was positively correlated with litter C:N ratio (Fig. 4c). These results confirmed that DOC and DON were mainly derived from the litter materials and soil organic matter through dissolution and decomposition (Chen and Xu, 2008) and tree species largely determined the quantity and quality of soil DOM.

Another significant modification of soil chemistry by the different tree species was the lower values of soil pH under slash pine (pH 4.5) compared with those under hoop (pH 6.0) and kauri (pH 6.2) pines (Table 1). Soil acidification under coniferous species is mainly attributed to the production of acidic leaf litters, although root exudation of H$^+$ may also contribute to the lower soil pH (e.g. Jongkind et al., 2007; Menyailo et al., 2002). The greater amounts of acidic litters observed in slash pine than in hoop and kauri pines might be responsible for the lower pH values in the soil under slash pine compared with hoop and kauri pines (Table 1). Across the three pine plantations, soil pH was negatively correlated with soil total C content (Fig. 5a), but not related to soil total N (Fig. 5b), which leads to negative and significant relationship between soil pH and soil C:N ratio (Fig. 5c). Similarly, soil pH also tended to correlate negatively with DOC$_{HW}$, but not significantly (Fig. 6a). However, soil pH was positively and significantly

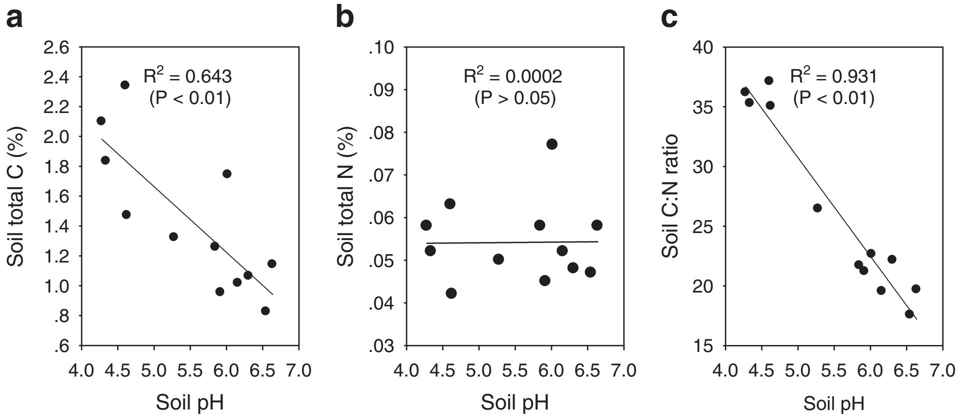

Fig. 5. Relationships between soil pH and soil total C (a), soil total N (b) and soil C:N ratio (c) under three pine plantations in subtropical Australia.

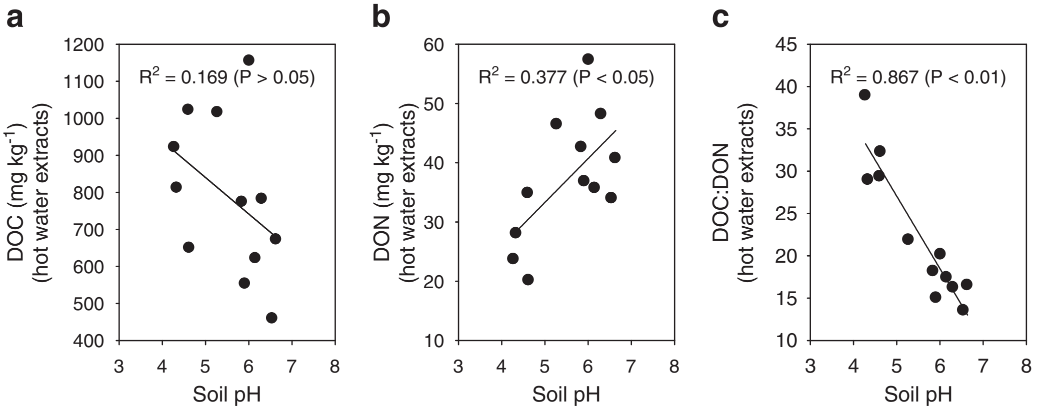

Fig. 6. Relationships between soil pH and DOC (a), DON (b) and DOC:DON ratio (c) in hot water extracts under three 73 year old pine plantations in subtropical Australia.

related to $\mathrm{DON_{HW}}$ (Fig. 6b) and thus negatively and significantly related to $\mathrm{DOC_{HW}}$:$\mathrm{DON_{HW}}$ ratio (Fig. 6c). These results indicated that: a) soil pH significantly affected the quality (i.e. C:N ratio) of total and labile pools of soil organic matter; and b) lower soil pH under slash pine favored the accumulation of soil C and thus led to greater amount of DOC and lower $\mathrm{DOC_{HW}}$:$\mathrm{DON_{HW}}$ ratio compared with hoop and kauri pines. This is consistent with the results in arable soils reported by Filep and Rékási (2011), in which soil acidity had a positive effect on DOC and a negative effect on DON. Soil pH is considered as a dominant factor controlling microbial transformation of organic matter (Adams and Adams, 1983; Kemmitt et al., 2006). It has been shown that soil microbial biomass C and N and basal respiration increased with soil pH (e.g. Kemmitt et al., 2006). There was no significant difference in soil microbial biomass C and N among the three tree species in the present study (data not shown), but microbial respiration in soil under slash pine was much lower than that under hoop and kauri pines (Fig. 2). Therefore, lower soil pH under slash pine compared with hoop and kauri pines may also affect microbial composition and activity and reduce the substrate availability, and thus limit microbial decomposition and lead to greater C accumulation in the former than in the latter.

4.3. Effect of tree species on soil N fertility

Dissolved inorganic N ($\mathrm{NH_4^+}$, $\mathrm{NO_3^-}$) consisted of ca. 70% of dissolved N in KCl extracts and 35–45% in hot water extracts (Tables 2 and 3). Among the inorganic N pools, $\mathrm{NH_4^+}$-N was predominant and played an important role in tree N nutrition. On the other hand, lower levels of $\mathrm{NO_3^-}$-N found in soils under all three tree species may be related to the leaching loss in the well-drained sand soils (Table 1). Lower level of $\mathrm{NO_3^-}$-N (near zero) in the soil under slash pine compared with that under hoop and kauri pines may be partially associated with the lower soil pH found in the former than in the latter (Table 1) since low soil pH might inhibit the nitrification process (e.g. Ste-Marie and Paré, 1999). PMN has been used as an indicator of lability of organic N for plant and microbial utilization (e.g. Chen et al., 2002) and is greater in soils under hoop and kauri pines than under slash pine (Fig. 1). Likewise, the amount of bio-available C was also greater in soils under hoop and kauri pines than under slash pine (Fig. 2) and positively correlated with the PMN ($r = 0.744$, $P < 0.01$). These, together with higher amounts of dissolved inorganic and organic N found in soils under hoop and kauri pines than under slash pine (Tables 2 and 3), have clearly shown that soil organic matter under hoop and kauri pines is more labile than under slash pine. Plantations of hoop and kauri trees may be better in maintaining long-term soil N fertility compared with slash pine.

It is evident that the chemical and biological nature of DOM is important for the understanding of its ecological function. The information about the nature of DOC and DON in soils under these three species is scarce. Condense tannin has been found in the litters and the soils of all three forest species (slash, hoop and kauri pines) in other studies (e.g. Bubb et al., 1998; Mathers and Xu, 2003; Verkaik et al., 2007). Complexation of organic N (e.g. protein) by tannin may be responsible for the slow release of N during litter decomposition (Bubb et al., 1998; Verkaik et al., 2007). Further study should focus on: a) the nature of DOM, in particular, the phenolics and secondary metabolites, and its relationship with biological availability of DOM; b) microbial community composition under these three species and its role in shaping the composition of DOM.

5. Conclusions

Results have clearly demonstrated that DON in hot water extracts was significantly lower in soils under slash pine than under hoop and kauri pines, but DOC was not significantly affected by the tree species. This had led to higher DOC:DON ratio in soils under slash pine than under hoop and kauri pines. Soil DOC and DON in 2 M KCl extracts were not significantly different among the three forest species. Significant and positive relationships between DOC:DON ratio (hot water extracts) and soil C:N and surface litter C:N ratios indicated that DOM was mainly derived from litter materials and soil organic matter. Soil total C and C:N ratio and DOC and DOC:DON ratio (hot water extracts) decreased with soil pH, and thus stronger soil acidity under slash pine compared with under hoop and kauri pines favored the accumulation of soil C. The amounts of dissolved inorganic N, PMN and bio-available C were also significantly lower in soils under slash pine than under hoop and kauri pines. It is concluded that changes in the quantity and quality of surface litters and soil pH induced by different tree species largely determined the size and quality of soil DOM. Plantations of hoop and kauri trees may be better in maintaining long-term soil N fertility than the slash pine plantation.

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References

Adams, T.M., Adams, S.N., 1983. The effects of liming and soil pH on carbon and nitrogen contained in the soil biomass. Journal of Agricultural Science 101, 553–558.

Bréchet, L., Ponton, S., Roy, J., Freycon, V., Coûteaux, M., Bonal, D., Epron, D., 2009. Do tree species characteristics influence soil respiration in tropical forest? A test based on 16 tree species panted in monospecific plots. Plant and Soil 319, 235–246.

Bubb, K.A., Xu, Z.H., Simpson, J.A., Saffigna, P.G., 1998. Some nutrient dynamics associated with litterfall and litter decomposition in hoop pine plantations of southeast Queensland, Australia. Forest Ecology and Management 110, 343–352.

Burton, J., Chen, C.R., Xu, Z.H., Ghadiri, H., 2007. Soluble organic nitrogen pools in adjacent native and plantation forests of subtropical Australia. Soil Biology and Biochemistry 39, 2723–2734.

Chen, C.R., Xu, Z.H., 2005. Soil carbon and nitrogen pools and microbial properties in a 6-year-old slash pine plantation of subtropical Australia: impacts of harvest residue management. Forest Ecology and Management 206, 237–247.

Chen, C.R., Xu, Z.H., 2008. Analysis and behavior of soluble organic nitrogen in forest soils. Journal of Soils and Sediments 8, 363–378.

Chen, C.R., Condron, L.M., Davis, M.R., Sherlock, R.R., 2000. Effects of afforestation on phosphorus and biological properties in a New Zealand grassland soil. Plant and Soil 220, 151–163.

Chen, C.R., Xu, Z.H., Hughes, J.M., 2002. Effects of nitrogen fertilization on soil nitrogen pools and microbial properties in a hoop pine (*Araucaria cunninghamii*) plantation in southeast Queensland, Australia. Biology and Fertility of Soils 36, 276–283.

Chen, C.R., Xu, Z.H., Mathers, N.J., 2004. Soil carbon pools in adjacent natural and plantation forests of subtropical Australia. Soil Science Society of America Journal 68, 282–291.

Chen, C.R., Xu, Z.H., Zhang, S.L., Keay, P., 2005. Soluble organic nitrogen pools in forest soils of subtropical Australia. Plant and Soil 277, 285–297.

Chen, C.R., Condron, L.M., Xu, Z.H., 2008. Impacts of grassland afforestation with coniferous trees on soil phosphorus dynamics and associated microbial processes: a review. Forest Ecology and Management 255, 396–409.

Curtin, D., Wright, C.E., Beare, M.H., McCallum, F.M., 2006. Hot water extractable nitrogen as an indicator of soil nitrogen availability. Soil Science Society of America Journal 70, 1512–1521.

Davis, M.R., Condron, L.M., 2002. Impact of grassland afforestation on soil carbon in New Zealand: a review of paired site studies. Australian Journal of Soil Research 40, 675–690.

Filep, T., Rékási, M., 2011. Factors controlling dissolved organic carbon (DOC), dissolved organic nitrogen (DON) and DOC/DON ratio in arable soils based on a dataset from Hungary. Geoderma 162, 312–318.

Gholz, H.L., Fisher, R.F., Prichett, W.L., 1985. Nutrient dynamics in slash pine plantation ecosystems. Ecology 66, 647–659.

Guo, J., Zhang, M., Zhang, L., Deng, A., Bian, X., Zhu, J., Zhang, W., 2011. Responses of dissolved organic carbon and dissolved nitrogen in surface water and soil to CO_2 enrichment in paddy field. Agriculture Ecosystems and Environment. doi:10.1016/j.agee.2010.12.014.

Huang, Z.Q., Xu, Z.H., Chen, C.R., 2008. Effect of mulching on labile soil organic matter pools, microbial community functional diversity and nitrogen transformations in two hardwood plantations of subtropical Australia. Applied Soil Ecology 40, 229–239.

Jiang, Y.M., Chen, C.R., Liu, Y.Q., Xu, Z.H., 2010. Soil soluble organic carbon and nitrogen pools under mono- and mixed species forest ecosystems in subtropical China. Journal of Soils and Sediments 10, 1071–1081.

Jongkind, A.G., Velthorst, E., Buurman, P., 2007. Sopil chemical properties under kauri (*Agathis australis*) in the Waitakere ranges, New Zealand. Geoderma 141, 320–331.

Kalbitz, K., Solinger, S., Park, J.H., Michalzik, B., Matzner, E., 2000. Controls on the dynamics of dissolved organic matter in soils: a review. Soil Science 165, 277–304.

Kemmitt, S.J., Wright, D., Goulding, K.W.T., Jones, D.L., 2006. pH regulation of carbon and nitrogen dynamics in two agricultural soils. Soil Biology and Biochemistry 38, 898–911.

Maggs, J., 1985. Litter fall and retranslocation of nutrients in refertilized and prescribed burned *Pinus elliottii* plantation. Forest Ecology and Management 12, 253–268.

Marschner, B., Kalbitz, K., 2003. Controls of bioavailability and biodegradability of dissolved organic matter in soils. Geoderma 113, 211–235.

Mathers, N.J., Xu, Z.H., 2003. Solid-state ^{13}C NMR spectroscopy: characterization of soil organic matter under two contrasting residue management regimes in a 2-year-old pine plantation of subtropical Australia. Geoderma 114, 19–31.

Menyailo, O.V., Hungate, B.A., Zech, W., 2002. Tree species mediated soil chemistry changes in a Siberian artificial afforestation experiment. Plant and Soil 242, 171–182.

Müller, M., Alewell, C., Hagedorn, F., 2009. Effective retention of litter-derived dissolved organic carbon in organic layers. Soil Biology and Biochemistry 41, 1066–1074.

Murphy, D.V., Macdonald, A.J., Stockdale, E.A., Goulding, K.W.T., Fortune, S., Gaunt, J.L., Poulton, P.R., Wakefield, J.A., Webster, C.P., Wilmer, W.S., 2000. Soluble organic nitrogen in agricultural soil. Biology and Fertility of Soils 30, 374–387.

Neff, J.C., Chapin, F.S., Vitousek, P.M., 2003. Breaks in the cycle: dissolved organic nitrogen in terrestrial ecosystems. Frontiers in Ecology and the Environment 1, 205–211.

Priha, O., Smolander, A., 1997. Microbial biomass and activity in soil and litter under *Pinus sylvestris*, *Picea abies* and *Betula pendula* at originally similar field afforestation sites. Biology and Fertility of Soils 24, 45–51.

Qualls, R.G., Haines, B.L., 1991. Geochemistry of dissolved organic nutrients in water percolating through a forest ecosystem. Soil Science Society of America Journal 55, 1112–1123.

Rayment, G.E., Higginson, F.R., 1992. Australian Laboratory Handbook of Soil and Water Chemical Methods. Inkata Press, Melbourne, Australia.

Richards, B.N., Bevege, D.I., 1967. The productivity and nitrogen economy of artificial ecosystems comprising various combinations of perennial legumes and coniferous tree species. Australian Journal of Botany 15, 467–480.

Ros, G.H., Hoffland, E., van Kessel, C., Temminghoff, E.J.M., 2009. Extractable and dissolved soil organic nitrogen — a quantitative assessment. Soil Biology and Biochemistry 41, 1029–1039.

Silvester, W.B., 2000. The biology of kauri (*Agathis australis*) in New Zealand. II. Nitrogen cycling in four kauri forest remnants. New Zealand Journal of Botany 38, 205–220.

Smolander, A., Kitunen, V., 2002. Soil microbial activities and characteristics of dissolved organic C and N in relation to tree species. Soil Biology and Biochemistry 34, 651–660.

Smolander, A., Loponen, J., Suominen, K., Kitunen, V., 2005. Organic matter characteristics and C and N transformations in the humus layer under two tree species, *Betula pendula* and *Picea abies*. Soil Biology and Biochemistry 37, 1309–1318.

Ste-Marie, C., Paré, D., 1999. Soil, pH and N availability effects on net nitrification in the forest floors of a range of boreal forest stands. Soil Biology and Biochemistry 31, 1579–1589.

Verkaik, E., Berendse, F., Gardner, R.O., 2007. Low soil water and nutrient availability below New Zealand kauri (*Agathis australis* D. Don) Lindl.) trees increase the relative fitness of kauri seedlings. Plant Ecology 191, 163–170.

Vivanco, L., Austin, A.T., 2008. Tree species identity alters forest litter decomposition through long-term plant and soil interactions in Patagonia Argentina. Journal of Ecology 96, 727–736.

.Wang, Q., Wang, S., 2010. Response of labile soil organic matter to changes in forest vegetation in subtropical regions. Applied Soil Ecology. doi:10.1016/j.apsoil.2010.12.004.

Waring, S.A., Bremner, J.M., 1964. Ammonium production in soil under waterlogged conditions as an index of nitrogen availability. Nature 201, 951–952.

Witt, C., Setälä, H., 2010. Do plant species of different resource qualities form dissimilar energy channels below-ground? Applied Soil Ecology. doi:10.1016/j.apsoil.2010.01.004.

Xing, S.H., Chen, C.R., Zhou, B.Q., Zhang, H., Nang, Z.M., Xu, Z.H., 2010. Soil soluble organic nitrogen and microbial processes under adjacent coniferous and broadleaf plantation forests. Journal of Soils and Sediments 10, 1071–1081.

Xu, Z.H., Ward, S., Chen, C.R., Blumfield, T., Prasolova, N.V., Liu, J.X., 2008. Soil carbon and nutrient pools, microbial properties and gross nitrogen transformations in adjacent natural forest and hoop pine plantations of subtropical Australia. Journal of Soils and Sediments 8, 99–105.