Int. J. Forest, Soil and Erosion, 2013 3(1): 45-53
ISSN 2251-6387

Research Paper

Short-term effects of site preparation practices for afforestation on soil properties

Witness Mojeremane[1, 3], Robert M. Rees[2] and Maurizio Mencuccini[1]
1.School of GeoSciences, University of Edinburgh, Crew Building, West Mains Road, Edinburgh, EH9 3JN, Scotland
2.Scottish Agricultural College, West Mains Road, Edinburgh EH9 3JG, Scotland, United Kingdom
3.Present address: Department of Crop Science and Production, Botswana College of Agriculture, Private Bag 0027, Gaborone, Botswana

Received: 2012-10-31 **Accepted: 2012-12-13**

Abstract: A field study was conducted at Harwood Forest, NE England to investigate the effects of forest management practices (drainage, mounding and fertilization) on soil properties from 2006 to 2008. The experiment was laid out in a factorial split plot design on grassland in peaty gley soil. Mounding increased soil bulk density, while drainage reduced carbon concentration in 0−10 cm layer. Soil organic carbon concentration in the 0−10 cm layer was increased by fertilisation. Mounding did not have any effect in soil organic carbon. The concentration of nitrogen in the in 0−10 cm was significantly reduced by drainage and was not affected by mounding or fertilisation. Soil microbial biomass carbon was not affected by drainage, mounding or fertilisation. Ammonium (NH_4^+) was significantly increased by mounding and fertilisation, while none of the treatment affected nitrate (NO_3^-) availability.

Keywords: Drainage, Fertilisation, mounding, peaty gley soil organic carbon, nitrogen

Introduction

Soils are home to a substantial, if not the largest, proportion of biodiversity in terrestrial ecosystems, and form the basis for all forest growth (Bauhus et al., 2002; Hopmas et al., 2005), play a crucial role in the carbon, nutrient (Neill et al., 1997; Bauhus et al., 2002; Hopmas *et al*., 2005) and hydrological cycles (Bauhus et al., 2002; Hopmas et al., 2005). World's soils constitute a significant reservoir of carbon (C) in both the organic and mineral forms; thereby play a crucial role in mitigating or contributing C to the atmosphere (Zerva and Mencuccini 2005a). Globally, soils are the largest C pool in the terrestrial environment (Wang and Amundson 1999) and contain more than two thirds of the total C stored in living plants (Schlesinger, 1990; Harmon et al., 1990; Schimel, 1995) and almost twice the amount in the atmosphere (Schlesinger, 1990; Schimel 1995).

Successful establishment of forest plantations in peatland sites characterised by poor drainage, low temperatures and poor soil fertility (e.g. Bubier et al., 1998; Strom and Christensen 2007) necessitated provisions for subsurface drainage. Land use changes related to forest management practices can affect the C cycle and C storage in soils (Parfitt et al., 2003) as well as the cycling of nitrogen (N) in soils. The interaction between C and N cycles may influence C storage (Conant et al., 2001) and regulate N availability (Parfitt et al., 2003). These possible soil organic carbon (SOC) losses have detrimental effects on soil structure and soil fertility, contributing to global warming by further increasing the atmospheric concentration of carbon dioxide (CO_2) (von Lützow and Kögel-Knabner 2009).

Afforestation or the conversion of historically treeless areas into forests is a rapidly spreading land-use change which has potential to sequester carbon (Berthrong, 2009). In the UK forest plantations are often established on former grasslands on peaty gley soils that require drainage and mounding to lower the water table and prepare planting spots (Mojeremane 2009). These practices may change the soil's physical, chemical and biological properties (Jurgensen et al., 1997; Merino et al., 1998) and influence the amount, quality and distribution of soil organic matter (SOM) (Paul et al., 2002). Machinery used in forest management operations such as site preparation affect C and N by compacting the soil, thereby altering properties such as bulk density (McNabb et al., 2001; Xu et al., 2002).

Effects of site preparation for afforestation or replanting on soil C and N are not only important because C and N are often the major factors determining soil quality but also because soil act as a C source or sink on a global scale (Johnson and Curtis, 2001). Site preparation and timber harvesting activities may turn soils into sources of C to the atmosphere (Detwiler and Hall 1988). The main site preparation for afforestation in the UK used to be mechanically lowering the soil water table depth by open drainage ditches. Currently, the construction of new drainage channels is discouraged, but the practice of excavating old drainage channels upon replanting is still widespread practice (Mojeremane et al., 2012). While ploughing is discouraged and current best practices favours the use of mounding or surface scarification, there is little qualitative information on the impact of these practices on the soil properties and C and N concentrations. Based on the UK's prevailing environmental conditions, we hypothesised that site preparation would increase soil bulk density and decrease C and N. The objective of this this research was to assess the above mentioned hypothesis.

Martial mad Methods

Site description

The field experiment was initiated in May 2006 at Harwood forest, NE England (55°10'N, 2°3'W, 200−400 m asl) on seasonally waterlogged peaty gley with a superficial organic layer varying between 15−40 cm. The forest covers 4000 ha dominated by even aged Sitka spruce (*Picea sitchensis* (Bong.) Carr.) stands. The average annual precipitation and temperature at Harwood are 950 mm and 7.6°C, respectively (Zerva and Mencuccini, 2005a). The establishment of the forest started in the 1930s with planting on moorland and upland rough pasture. Mounding at 2 × 2 m spacing in now used for new planting and restocking

(Mojeremane et al., 2012). The present experiment was established on unplanted unimproved grassland situated between two second rotation Sitka spruce stands. The grassland is dominated by *Festuca ovina* and *Deschampsia flexuosa* with *Calluna vulgaris* and occasionally *Eriophorum vaginatum* and had been used to graze domestic stock a year prior to the study started (Mojeremane, 2009). There was no evidence of drainage present at the site prior to the experiment (Mojeremane, 2009).

Experimental design and layout

The field layout comprised of a full factorial split-plot design with six plots measuring 30 × 8 m each established in May 2006 (Mojeremane, 2009). Three plots were selected at random and drained by an excavator following local standard practices. The open drainage ditches were placed 1.5 m from plot edges and excavated to a depth of 65−70 cm (Mojeremane et al., 2012). About 10-m-wide buffer strips isolated drained and undrained plots. Four subplots (8 × 6 m) isolated by 2-m-wide buffer strips were established in each main plot (Mojeremane *et al*., 2012). Two randomly selected subplots were mounded, while the remainder were left unmounded with the mounds being ~40-cm wide and 30-cm deep (Mojeremane *et al*., 2012). Fertilisation was carried out in one mounded and one unmounded subplot randomly chosen within each subplot in a crossed design with mounding (Mojeremane et al., 2012) by applying a compound fertilizer with 81 kg N ha^{-1}, 72 kg P ha^{-1} and 35 kg ha^{-1} (Taylor, 1991). Hence, the main plots allowed testing for drainage effects, whereas the subplots allowed testing for mounding, in isolation or combined (Mojeremane et al., 2010, 2012). Each treatment was replicated three times (Mojeremane et al., 2010).

Soil sampling

Soil sampling was done during November 2006, February and August 2007, February and June 2008. Soil samples were collected from four randomly selected locations within subplots. A manually driven square soil corer (5×5cm) was used to obtain samples from 0−20 cm depth (November 2006, and February 2008). August 2007 and June 2008 samples were collected from 0−10, 10−20, and 20−30 cm depth. Soil samples were bulked by subplot to make composite samples and taken to the laboratory in black polythene bags for storage in a freezer (–4°C) awaiting analyses.

Soil pH and bulk density determination

Soil samples were analysed for pH in a 1:2.5 soil/water ratio by a combination glass electrode (Wall and Hytönen, 2005; Xue *et al*., 2006). The bulk density was determined by the core method (Grossman and Reinsch, 2002) using 5.4 cm diameter and 6 cm long cores. Bulk density was calculated according to Eliot et al. (1999).

$Pb = M/V$

Where, Pb is the bulk density (g cm^{-3}), M is the dry mass of a given soil sample (g) and V its fresh volume (cm^3).

Soil Chemical analyses

For soil organic carbon (SOC) and total N analyses were performed on August 2007 and June 2008 soil samples Soil samples were passed through a 4 mm sieve and oven dried to constant weight at 60°C. Dried samples were passed through a 2mm sieve using hand applied pressure before grinding in a Ball Mill to pass through a 0.5mm sieve. Both SOC and N concentrations were determined by the dry combustion method (Nelson and Summers, 1982) using a C/N analyser (Carlo-Erba, N 2500). The mass of C and N in soil samples was calculated using the following equation:

$M_c = M_d \times C/N\ (\%)/100$

Where, M_c is total mass of C or N in the sample; M_d is dry matter of sample; and C or N is the percentage obtained from C/N analyser. C and N concentrations were expressed in g kg^{-1}.

Determination of soil Microbial biomass C

Soil microbial biomass carbon (MBC) was determined from the November 2006, February and August 2007 samples using the previously published chloroform fumigation extraction method (Brookes et al., 1985; Vance et al., 1987). About 20 g of soil were fumigated with ethanol-free chloroform for 24 hrs in a vacuum oven containing a vial with soda lime. Both the fumigated samples and their non-fumigated counterparts (control) were extracted with 80 mL of 0.5M K_2SO_4 on a reciprocal shaker set at 100 rev. $min^{-1}$for an hour. Solutions were then transferred into 50 ml tubes and centrifuged at 4000 rev. min^{-1} for 10 minutes. The supernatant was transferred to 20 ml plastic vials and filtered through 0.45um Millipore filters. Inorganic C was removed from the supernatant by acidifying to a pH of 2 using a concentrated phosphoric acid and purging with N_2 to degas samples. Organic C in the extract was analysed in an automated total OC analyser (DC-80, Sartec Ltd., Kent, England) with UV-persulphate oxidation and IR detector (Wu et al., 1990). Microbial biomass was calculated using previously published method (Wu *et al*., 1990; Jorgensen and Mueller, 1996; Jorgensen, 1996). The MBC was calculated as follows:

Microbial biomass C = E_C/K_{EC}

Where E_C = (OC extracted from fumigated soil) − (OC extracted from non-fumigated soils) and K_{EC} = 0.45.

Determination of Inorganic N

For analyses of inorganic N (NH_4^+ and $NO3^-$) August 2007 and February 2008 soil samples were used. Soil was sieved through a 2 mm aperture sieve followed by weighing of 5 g samples into glass bottles. About 100 mL of 1M KCl was added to each sample, sealed and the solution was thoroughly mixed on an orbital shaker set at 150 rev. min^{-1} for an hour. The solution was then filtered through a filter paper, Ashless Paper 2, and the extracts analysed for NH_4^+ and NO_3^- in a continuous flow Series 3 Auto analyser system.

Determination of above-ground plant biomass evaluation

Above-ground plant biomass was measured in June 2007. Two 1×1 m quadrants were randomly established in each subplot and all plants within quadrants were clipped at ground level using pruning shears and bagged in black polythene bags for transportation to the laboratory where they were transferred into paper bags and oven dried to constant weight at 80°C. The plant dry biomass (DM) was expressed in tons per hectare of dry mass (t ha^{-1} DM).

Statistical analysis

All data were checked for normality and transformed when required. Data were analysed using the general linear model (GLM) for analysis of variance. The GLM included the effects of drainage, mounding and fertilisation entered as fixed factors and plot entered as a random factor. The initial GLM included all possible second and third order interactions. If interactions. If interactions were found not significant, they were excluded and model run again without them to confirm the significance of the main factors. In case of significant interactions, the data set was split and separate analysis run for each combination. All analyses were run in Minitab 15 using GLM procedure.

Results

Soil bulk density and pH

The soil bulk density significantly increased with soil depth across treatments (P=0.0001). The soil bulk density ranged from 0.12−0.15, 0.18−0.23 and 1.02−1.13 g cm^{-3} in the 0−10, 10−20 and 20−30 soil depths across treatments, respectively. Soil bulk density from both sampling occasions was not affected by drainage or fertilisation. Soil bulk density was significantly increased by mounding in the 0−10 cm depth in August 2007 (P=0.05) and June 2008 (P=0.001). Mounding also increased the soil bulk density in the 10−20 cm depth in both sampling dates (all P=0.01). Soil pH varied significantly with soil depth (P=0.0001) and was not affected by drainage, mounding or fertilisation. Soil pH varied from 3.9−4.0, 3.8−3.9 and 4.1−4.2 in the 0−10, 10−20 and 20−30cm depth, respectively.

Soil organic carbon

SOC concentrations are shown in Table 1. SOC concentration varied with depth on both sampling dates (P = 0.0001). SOC in 0−10 cm depth was significantly decreased by drainage in August 2007 (P = 0.03) and June 2008 (P = 0.04) but not the 10−20 and 20−30 cm depths. There was a significant decrease in SOC in the fertilised treatment in 0−10 cm layer (P = 0.02) in August 2007 only. In none of the sampling occasions was SOC affected by mounding.

Table 1. Effects of drainage, mounding and fertilisation on SOC and N concentration

			Treatment					
Sampling date	Parameter	Soil depth	Drained	Undrained	Mounded	Unmounded	Fertilised	Unfertilised
August 2007	Total C (g kg^{-1})							
		0−10	419.2±13.4a	458.2±5.6b	436.8±13.7a	440.7±9.6a	451.2±7.5a	426.3±14.0b
		10−20	448.3±23.9a	452.0±15.5a	447.6±26.3a	452.7±11.0a	459.9±13.7	440.4±24.6
		20−30	37.5±4.4a	37.2±4.6a	39.7±4.9a	35.1±3.8a	36.8±3.6	38.0±5.2
	Total N (g kg^{-1})							
		0−10	18.3±0.8a	20.8±0.3b	19.5±0.7a	19.6±0.7a	19.4±0.5a	19.7±0.9a
		10−20	15.3±0.7a	15.4±0.7a	15.7±0.9a	15.0±0.5a	15.9±0.6a	14.8±0.8a
		20−30	1.26±0.2a	1.23±0.1a	1.4±0.2a	1.1±0.1a	1.2±0.1a	1.3±0.2a
	C/N ratio							
		0−10	23.1±0.6a	22.1±0.5a	22.5± 0.6a	22.7± 0.6a	23.5± 0.5a	21.8±0.5b
		10−20	29.2±0.8a	29.7±0.6a	28.5± 0.7a	30.3± 0.5a	29.2± 0.6a	29.7±0.7a
		20−30	30.1±1.2a	30.0±1.1a	29.0±1.2	31.0± 1.1a	30.7± 1.3a	29.4±0.9a
June 2008	Total C (g kg^{-1})							
		0−10	429.4±8.1a	460.9±5.02b	446.2± 8.1a	444.2 ±8.3a	449.0± 7.9a	441.3± 8.4a
		10−20	444.2±16.5a	452.0±12.2a	452.2± 17.7a	443.9±10.4a	447.2± 15.0a	449.0± 14.1a
		20−30	35.8±3.8a	41.9±7.1a	39.9 ±4.4a	37.7± 6.9a	35.9 ±3.3a	41.8 ±7.4a
	Total N (g kg^{-1})							
		0−10	17.1±0.3a	18.41±0.2b	17.8± 0.3b	17.7± 0.3a	17.9± 0.3a	17.6 0.3a
		10−20	17.8±0.7a	18.0±0.5a	18.1 ±0.7a	17.7± 0.4a	17.9± 0.6a	17.9 0.6a
		20−30	1.0±0.2a	1.2±0.3a	1.2 ±0.2a	1.1± 0.3a	1.0± 0.1a	1.2 0.3a
	C/N ratio							
		0−10	25.1±0.01a	25.0±0.01a	25.1± 0.0a	25.1± 0.0a	25.1± 0.0a	25.1± 0.0a
		10−20	25.1±0.03a	25.1±0.02a	25.1± 0.0a	25.1± 0.0a	25.0± 0.0a	25.1± 0.0a
		20−30	40.1±2.4a	38.6±2.2a	38.7± 2.6a	40.1± 1.9a	38.9 ±1.8a	39.9± 2.8a

Values are mean± standard error. Different letters in bold following values within lines denotes a statistically significant difference between drained and undrained, mounded and unmounded, fertilised and unfertilised treatment (P<0.05).

Soil nitrogen

Total soil N concentration is shown in Table 1. Total soil N concentration varied significantly with soil depth (P = 0.0001) and was higher in the 0−10 and 10−20 cm soil depth compared to the 20−30 cm depth. Drainage significantly increased soil N concentration only in the 0−10 cm soil depth in August 2007 (P = 0.04). In June 2008, the total soil N was significantly decreased by drainage in the 0−10 cm depth (P = 0.04) but not in the 0−20 and 20−30 cm soil depths. In none of the sampling dates was total N affected by fertilisation or mounding. Soil C:N ratio varied significantly with soil depth (P = 0.0001). The C:N ratio was significantly increased by fertilisation only in the 0−10 cm depth in August 2007 (P=0.01). In none of the sampling dates was the C:N ratio affected by drainage or mounding.

Soil microbial biomass C

The mean values for soil MBC are shown in Table 2. The undrained had slightly higher MBC than drained treatment in November 2006. In February 2007 soil MBC was marginally increased by drainage (P = 0.6). Similarly, soil MBC was slightly higher (but not significant) in the drained that undrained treatment in August 2007. The sampling dates differed significantly (P = 0.0001) in soil MBC. Soil MBC was slightly higher (but not significant) in the fertilised than unfertilised treatment during all sampling occasions. The mounded treatment had slightly higher (but not significant) MBC that the unmounded treatment during all the sampling occasions.

Table 2. Effects of drainage, mounding and fertilisation on soil microbial biomass C (mg g^{-1})

	Treatment					
Sampling date	Drained	Undrained	Mounded	Unmounded	Fertilised	Unfertilised
November 2006	1.54±0.28a	2.14±0.13a	1.92±0.25a	1.77±0.22a	1.74±0.22a	1.95±0.25a
February 2007	2.69±0.30a	1.98±0.21a	2.57±0.30a	2.11±0.24a	2.30±0.34a	2.38±0.2a
August 2007	3.50±0.07a	2.85±0.23a	3.27±0.20a	3.08±0.19a	3.06±0.17a	3.29±021a

Values are mean±standard error. Different letters following values within lines denotes a statistically significant difference between drained and undrained, mounded and unmounded, fertilised and unfertilised.

Inorganic N

The inorganic N (NH_4^+ and NO_3^-) concentrations are shown in Table 3. In none of the sampling dates was ammonium (NH_4^+) affected by drainage. Ammonium concentration was significantly increased by both fertilisation and mounding in August 2007 (all P=0.01). In none of the sampling occasions was nitrate (NO_3^-) affected by drainage mounding or fertilisation.

Table 3. Effects of drainage, mounding and fertilisation on inorganic N (mg g^{-1})

		Treatment					
Sampling date	Variable	Drained	Undrained	Mounded	Unmounded	Fertilised	Unfertilised
August 2007	NH_4^+	0.09±0.02a	0.06±0.02a	0.10±0.02a	0.06±0.02b	0.21±0.02a	0.05±0.01b
	NO_3^-	0.02±0.01a	0.04±0.01a	0.03±0.01a	0.03±0.01a	0.02±0.01a	0.04±0.01a
February 2008	NH_4^+	0.02±0.00a	0.03±0.00a	0.03±0.01a	0.02±0.00a	0.02±0.00a	0.03±0.01a
	NO_3^-	0.02±0.00a	0.02±0.00a	0.02±0.00a	0.02± 0.00a	0.02±0.00a	0.02±0.00a

Values are mean±standard error. Different letters following values within lines denotes a statistically significant difference between drained and undrained, mounded and unmounded and fertilised and fertilised.

Above plant biomass

Standing above plant biomass assessed as dry mass is shown in Table 4. Above-ground plant biomass was significantly increased by drainage (P = 0.04) and fertilisation (P = 0.002). Above-ground plant biomass was not affected by mounding.

Table 4. Effects of drainage, mounding and fertilisation on standing above plant biomass (t ha^{-1} DM)

		Treatment			
Drained	Undrained	Mounded	Unmounded	Fertilised	Unfertilised
7.760.35a	6.03±0.30b	6.84±0.36a	6.95±0.47a	7.53±0.37a	6.26±0.37b

Values are mean±standard error. Different letters following values within lines denotes a statistically significant difference between drained and undrained, mounded and unmounded and fertilised and fertilised

Discussion

Soil bulk density and pH

Bulk density increased with soil depth, which is consistent with findings of others (Tamminen and Starr, 1994; Zerva, 2004). Tamminen and Starr (2004) investigated the relationship between bulk density and organic matter content, soil structural properties and depth and found that density increased with soil depth and remained uniform at soil depth greater than 20 cm. Bulk density was not affected by drainage or fertilisation but was significantly increased by mounding in the 0−10 cm depth. The increase is consistent with results of other studies which reported that the bulk density in compacted soils increased after site preparation and timber harvesting (Cullen et al., 1991; Johnson et al., 1991; Merino et al., 1998; McNabb et al., 2001). The increase in bulk density in the mounded treatment was probably enhanced by the combined influence of compaction caused by machinery (Banco-Canqui et al., 2004; Mojeremane, 2009) and decrease in SOC concentration (Li et al., 2007)

Soil organic carbon

Soils are the major reservoir of C in terrestrial ecosystems (Henderson, 1995) and research has shown that soil C is negatively affected by land use changes and soil management practices (Batjees, 1996; Ross et al., 1999; Post and Kwon, 2000; Prentice et al., 2000). Drainage reduced soil organic C in the 0−10 cm depth in this study. This result is in agreement with previous studies conducted in peaty gley soil which demonstrated that drainage and ploughing used in afforestation and replanting decrease soil C in peaty gley soils (Zerva and Mencuccini 2005a; Zerva et al., 2005). It has been demonstrated that drainage increase organic matter decomposition and enhances C losses to the atmosphere as CO_2 fluxes (e.g. Martikainen et al., 1995; Nykänen et al., 1995). The water table depth in this study was lowered by drainage, which increased soil temperature and improved aeration

(Mojeremane, 2009). Changes in these environmental variables have been shown to create aerobic conditions that stimulate the soil microbial activity and enhance organic matter decomposition (Smith *et al*., 1994; Trettin et al., 1995; Olson et al., 1996; Merino et al., 1998; Zerva et al., 2005; Tate et al., 2006) which caused C losses as CO_2 in the present study (Mojeremane et al., 2012). SOC losses from drained organic soils have been attributed to oxidation and enhanced soil respiration linked to improved aeration and increased temperature (Raich and Schlesinger, 1992; Rey et al., 1992; Euskirchen et al., 2003; Saiz et al., 2006). It is also possible that drainage increased the production of highly decomposable fine roots (Thomas et al., 1996) in the present study, thereby simulating soil microbial activity and enhancing organic matter decomposition rates (Lohila *et al*., 2003 Kuzykov and Cheng, 2004). The decrease in SOC observed in the drained treatment was lower when compared to studies conducted elsewhere, probably because of differences in climate, soil type, the intensity of drainage and the time since the site was drained (Mojeremane, 2009).

Fertilisation increased SOC in August 2007, similar to effects observed in fertilised forest soils (Berg and Matzner, 1997; Franklin *et al*., 2003; Foereid et al., 2004; Olsson et al., 2005; Jandl et al., 2007). Increased SOC in fertilised soils have been attributed to the suppression of ligninolytic enzymes of soil microbes and by chemical stabilisation (Arnebrant et al., 1996; Jandl et al., 2007). The effect of fertilisation was not significant in June 2008, probably because N uptake by plants (Vitousek and Matson, 1985; Emmett et al., 1991), loss of N as N_2 and N_2O (Robertson *et al*., 1987; Sitaula et al., 1995) and NO_3^- leaching (Vitousek and Matson, 1985; Smith et al., 1994) exhausted the N pool in the soil.

Soil nitrogen

Soil N in 0−10 cm depth was significant affected by drainage but not fertilisation or mounding. Drainage decreased N concentration, which is consistent with others who reported that timber harvesting and mechanical site preparation decrease N in forest soils (Smith et al., 1994; Merino et al., 1998). Decreased N in the drained treatment could probably be attributed to increased soil temperature and aeration which created aerobic conditions that favoured the mineralisation of N in the SOM and increased N uptake by plants or losses as N_2 and N_2O emissions or dissolve nitrates (Mojeremane, 2009). Prior studies demonstrated that site preparation practices increased leaching in upland and boreal forest soils (Nieminen, 1998; Mannerkoski et al., 2005; Piirainen et al., 2007) which probably occurred in the present study.

Soil microbial biomass carbon

Soil microbes play a critical role in mediating feedbacks between terrestrial ecosystems and global climate change (Dooley and Treseder, 2012). They regulate the transfer of C from terrestrial ecosystems to the atmosphere through organic matter decomposition in soil (Swift *et al*. 1979). They also regulate soil nutrients via organic matter mineralisation and solubilisation of soil minerals (Mazzarino et al., 1993; Franzluebbers *et al*., 1994; Fritze et al., 1994; Blazier et al., 2005), especially in infertile natural and agricultural systems (Yao et al., 2000). The soil microorganism populations and activity may be reduced in infertile waterlogged soils such as peaty gley soil in the present study site. Lowering the water table of saturated soils for forestry and agriculture uses through drainage increases soil temperature, oxygen and nutrient availability (Lieffers and Rothwell, 1987; Lieffers, 1988) and may favour populations and activity of soil microorganisms. However, the activity of soil microorganisms measured as MBC was not affected by drainage, mounding or fertilization in the present study.

The MBC was slightly increased by drainage in February and August 2007. Low soil pH and fertility observed in the present study site may have affected the soil microbial population and activity. The lowest MBC was observed in November and February (winter months), suggesting that the ecosystem activity was low during the winter months and nutrients requirement by soil microorganisms and plants was probably met by background nutrient levels of soils (Insam et al., 1989). In the late summer (August 2007) the soil microbial biomass in all treatment increased with soil temperature (Mojeremane, 2009). It seems, therefore that effects of treatments may have been masked by seasonal effects, which is consistent with others who observed that fluctuations in soil temperatures affected MBC (Lynch and Panting, 1982; Sarathchandra et al., 1988, 1989).

MBC in the fertilised treatment was slightly lower (but not significant) than in the control which is in agreement with others who reported lower MBC in fertilised grasslands than control treatment (Yates et al., 1997; Bardgett and Cook, 1998). This result is comparable to several other studies which failed to detect significant effects of fertilisation on MBC (Castro et al., 1994; Vose et al., 1995; Sarathchandra et al., 2001). In contrast, others reported increased MBC in fertilised forest (Hobbie, 2000; Vestgarden, 2001) and agricultural soils (Lynch and panting 1982; Hesebe et al., 1985). Soil pH in the present study was low (3.8−4.2) (Mojeremane, 2009) and could have negatively affected MBC (Shah et al., 1990; Nodar et al., 1992). Acidic soils have been shown to favour fungal populations relative to their bacterial counterparts (Nodar et al., 1992).

Inorganic N

Lowering the water table depth increases the mineralisation of N and subsequent nutrient availability to plants in peaty soils (Grootjans et al., 1985; Updegraff et al., 1995; Bridgham et al., 1998). Our results show that inorganic NH_4^+ and NO_3^- were no affected by drainage probably because N mineralisation was compensated by increased losses. Ammonium was availability was increased by mounding in August 2007 probably due to increase in net mineralisation of the organic matter on top of mounds. This was not surprising because changes in the microtopography related to mounds and hollows after mounding modifies a number of important environmental variables (Liechty et al., 1997), such as soil temperature and moisture (Nohrstedt, 2000) as well as the thickness and distribution of organic and mineral soil layers (Beatty and Stone, 1986; Schaetzl et al., 1990). Mounding buried the soil organic layers beneath the mineral soil of mounds and increased soil temperature in 0−5 cm depth (Mojeremane, 2009) and aeration. These changes may have favoured microbial activity on the top of mounds and accelerated N mineralisation. Nitrate was not affected by mounding in this study.

Fertilisation increased NH_4^+ in August 2007 and the increased was not evident at the end of study (June 2008), probably due to increased uptake by plants or losses as oxides of nitrogen in year one of study (Mojeremane, 2009). Nitrate availability was not affected by fertilisation and there is a possibility that NO_3^- was leached to deeper layers or lost through drainage water (Baker and Johnson, 1981; Bergstrom and Brink, 1986; Mojeremane, 2009).

Standing above-ground plant biomass

Standing above-ground biomass production measured a year after establishment of the experiment was increased by drainage. The increase probably resulted from increased soil temperature and improvement in aeration of the root zone which favours root growth and nutrient availability. Water-saturated soils like those in the present study site have been shown to negatively affect plant growth by limiting root and shoot growth (Huang et al., 1994; McDonald et al., 2001; Malik et al., 2001, 2002). The increase in plant biomass in the present study could be attributed to increased substrate temperature and oxygen availability after drainage, which increased nutrient availability since organic matter decomposition is enhanced under aerobic conditions (Clymo, 1984). Plant biomass was also increased by fertilisation. The uptake of nitrogen, potassium and phosphorus by plants from the applied fertiliser may have enhanced their growth. Our results are in agreement with other studies conducted in Calluna dominated vegetation on heathland which reported increased plant growth application of N (Aerts et al., 1991; Caporn et al., 1995; Uren et al., 1997; Carroll et al., 1999). Increased above-plant biomass in the fertilised treatment in the present study may suggest that the site is poor in nutrient.

Conclusion

Soil organic carbon and nitrogen in the present study site were decreased by drainage in 0−10 cm soil layer. Lowering the water table by drainage increases oxygenation and soil temperature and thus increases the mineralisation of SOM and N in the organic matter which resulted in the loss of C and N to the atmosphere. Fertilisation increased SOC accumulation in the 0−10 cm layer. Soil microbial biomass carbon and inorganic N were not affected by the imposed treatments due to acidic soil conditions and poor soil fertility.

Acknowledgment

Witness Mojeremane was supported by Botswana College of Agriculture Scholarship. We thank Forestry Commission for providing study site. We also thank Andy Gray, John Parker, John Morman, Graeme Allan and Ann Mennim for their assistance in soil and other analysis.

Reference

Aerts R, Boot RGA, van der Aart PJM (1991). The relation between above and below ground biomass allocation patterns and competitive ability. Oecologia 128:94−98.

Armentano TV, Menges ES (1986). Patterns of change in the carbon balance of organic wetland of the temperate zone. J. Ecol. 74:755−774.

Arnebrant K, Bääth E, Söderström B, Nohrstedt and HÖ (1996). Soil microbial activity in eleven Swedish coniferous forests in relation to site fertility and nitrogen fertilization. Scand. J. For Res. 1:1−6.

Ball T, Smith KE, Moncrief JB (2007). Effect of stand age on greenhouse gas fluxes from Sitka spruce [Picea sitchensis (Bong.) Carr.] Chronosequence on a peaty gley soil. Glob. Change Biol. 13:2128−2142.

Bardgett RD, Cook R (1998) Functional aspects of soil animal diversity in agricultural grasslands. Appl. Soil Ecol.10:263−276.

Baker JC, Johnson HP (1981). Nitrate-nitrogen in tile drainage as affected by fertilisation. J. Environ. Qual. 10:519−522.

Batjes NH (1996). Total carbon and nitrogen in the soils of the world. European J. Soil Sci. 47:151–163.

Bauhus J, Khanna PK, Hopmans P, Weston C (2002). Is soil carbon a useful indicator of sustainable forest management?-a case study from native eucalyptus forests of south-eastern Australia. For. Ecol. Manage. 171:59−74.

Beatty SW, Stone EL (1986). The variety of soil microsites created by tree fall. Can. J. For. Res. 16:539−548.

Berg B, Matzner E (1997). Effect of N deposition on decomposition of plant litter and soil organic matter in forest systems. Environ. Rev. 5:1−25.

Bergstrom L, Brink N (1986). Effects of differentiated applications of fertilizer N on leaching losses and distribution of inorganic N in the soil. Plant Soil 93:333−345.

Berthrong ST (2009). The effect of afforestation on soil microbes and biogeochemistry across multiple scales. PhD. Dissertation. Duke University.

Blanco-Canqui JA, Gantzer CJ, Anderson H, Alberts EE (2004). Tillage and crop influences on physical properties for an Epiaqualf. Soil Sci. Soc. Am. J. 68:567−576.

Blazier MA, Hennessey TC, Deng S (2005). Effects of fertilization and vegetation control on microbial biomass carbon and dehydrogenase activity in a juvenile loblolly pine plantation. For. Sci. 51:449−459.

Bridgham SD, Updegraff K, Pastor J (1998). Carbon, nitrogen fertiliser on the soil microbial biomass under permanent pasture. Ecol. 79:1545−1561.

Brookes P.C, Landman A, Pruden G, Jenkinson DS (1985). Chloroform fumigation and release of soil nitrogen: A rapid direct extraction method for measuring microbial nitrogen in soil. Soil Biol. Biochem. 17:837−842.

Bubier JL, Crill PM, More TR, Savage K, Varner RK (1998). Seasonal patterns and controls on net ecosystem CO2 exchange in a boreal peatland complex. Glob. Biogeochem. Cycl. 12:703−714.

Carroll JA, Capron SJM, Cawley L, Read DJ, Lee JA (1999). The effect of increased deposition of atmospheric nitrogen on Calluna vulgaris in upland Britain. New Phyt. 141:423−431.

Castro MS, Peterjohn WT, Melillo JM, Steudler, PA Gholz HL, Lewis D (1994). Effect of nitrogen fertilization on fluxes of N2O, CH4 and CO2 from soils in a Florida slash pine plantation. Can. J. For. Res. 24:9−13.

Clymo, R.S. 1984. The limits to peat bog growth. Philos. Trans. Roy. Soc. Lond. B303:605−654.

Conant RT, Paustian K, Elliott ET (2001). Grassland management and conversion into grassland: Effects on soil carbon. Ecol. Appl. 11:343–355.

Conrad, RZ (1996). Soil microorganisms as controllers of atmospheric trace gases (H-2, CO, CH4, OCS, N2O, and NO). Microbiol. Rev. 60: 609–640.

Cullen SJ, Montagne C, Ferguson H (1991). Timber harvest trafficking and soil compaction in western Montana. Soil Sci. Soc. Am. J. 55:1416−1421.

Detwiler RP, Hall CAS (1988). Tropical forests and global carbon cycle Sci. 239:42−47.

Dooley SR, Treseder KK (2012). The effect of fire on microbial biomass: a meta-analysis of field studies. Biogeochem. 109:49–61.

Elliot ED, Heil JW, Kelly EF, Monger, HC (1999). Soil Structure and Other Properties. Standard Soil Methods for Long-Term Ecological Research. p. 71–85. In: Robertson GP, Coleman DC, Bledsoe CS, Sollins P (eds.). Oxford University Press, New York, USA.

Emmett BA, Anderson, JM, Hornung M (1991). Nitrogen sinks following two intensities of harvesting in a Sitka spruce forest (N. Wales) and effect on the establishment of the next crop. For. Ecol. Manage. 41:81−93.

Euskirchen ES, Chen JQ, Gustafson EJ, Ma SY (2003). Soil respiration at dominant patch types within managed northern Wisconsin landscape. Ecosyst. 6:595−607.

Foereid B, de Neergaard A, Hogh-Jensen H (2004). Turnover of organic matter in Miscanthus field. Effect of time Miscanthus cultivation and nitrogen supply. Soil Biol. Biochem. 36:1075−1085.

Franklin O, Högberg P, Ekblad A, Ågren G.I (2003). Pine forest floor carbon accumulation in response to N and PK additions: bomb 14C modelling and respiration studies. Ecosyst. 66:644−659.

Franzluebbers AJ, Hons FM, Zuber DA (1994). Organic carbon in soil biomass and mineralizable C and N in wheat management systems. Soil Biol. Biochem. 26:1469−1475.

Fritze HA, Smolander A, Levula T, Kitunen V, Mälkönen E (1994). Wood-ash fertilisation and fire treatments in a Scots Pine forest stand: effects on the organic layer, microbial biomass, and microbial activity. Biol. Fert. Soils 17:57−63.

Grootjans AP, Schipper PC, van der Windt MJ (1985). Influence of drainage on N-mineralisation and vegetation response in wet meadows. Acta Oecol. Planta 6:403−417.

Grossman RB, Reinsch TG (2002). Bulk density and linear extensibility. Methods of soil analysis. Part 4. P.201−240. In: Warren AD (eds.). American Society of Agronomy, Monograph 9. Madison, WI, USA.

Harmon ME, Ferrell WK, Franklin JF (1990). Effects on carbon storage of conversion of old-growth forests to young forests. Science 247:699–702.

Hesebe A, Kanazawa S, Takai Y (1985). Microbial biomass in paddy soil, 2: "microbial biomass carbon" as measured by Jenkinson fumigation. Soil Sci. Plant Nutr.31:349−359.

Henderson GS (1995). Soil organic matter: a link between forest management and productivity. Carbon forms and functions in forest soils. p. 419−435. In: McFee WW, Kelly JM (eds.). Soil Science Society of America, Madison, USA.

Hobbie SE (2000). Interactions between litter lignin and soil nitrogen availability during litter decomposition in a Hawaiian montane forest. Ecosyst. 3:484−494.

Hopmans P, Bauhus J, Khanna P, Weston C (2005). Carbon and nitrogen in forest soils: potential indicators for sustainable management of Eucalyptus forests in south-eastern Australia. For. Ecol. Manage. 220:75−87.

Huang BR, Johnson JW, Nesmith S, Bridges DC (1994). Root and shoot growth of wheat genotypes in response to hypoxia and subsequent resumption of aeration. Crop Sci.34:1538−1544.

Jandl, R., M. Linder, L. Vesterdal, B. Bauwens, R. Baritz, F. Hagedorn, D.W. Johnson, K. Minkkinen and K.A. Byrne. 2007. How strong can forest management influence soil carbon sequestration? Geoderma 137:253−268.

Insam H, Parkinson D, Domsch KH (1989. Influence of microclimate on soil microbial biomass. Soil Biology and Biochemistry 21:211−221.

Joergensen, R.G. 1996. The fumigation-extraction method to estimate soil microbial biomass: calibration of the KEC factor. Soil Biol. Biochem. 28:25−31.

Joergensen, RG, Mueller T (1996). The fumigation extraction method to estimate soil microbial biomass: calibration of the KEN value. Soil Biol. Biochem. 28:33−37.

Johnson CE, Johnson HA, Huntington TG, Siccama TG (1991). Whole tree clear-cutting effects on soil horizons and organic matter pools. Soil Sci. Soc. Am. J. 55:497−502

Johnson DW, Curtis PS (2001). Effects of forest management on soil C and N storage: a meta-analysis. For. Ecol. Manage. 140:227−238.

Jurgensen MF, Harvey AE, Graham RT, Page-Drumroese DS, Tonn JR, Larsen MJ, Jain TB (1997). Impact of timber harvesting on soil organic matter, nitrogen, productivity, and health of inland Northwest forests. For. Sci. 42:234−251.

Kuzyakov Y, Cheng W (2004). Photosynthesis controls of CO2 efflux from maize rhizosphere. Plant Soil 263:85−99.

Li XG, Li FM, Zed R, Zhan ZY, Singh B (2007). Soil physical properties and their relations to organic carbon pools as affected by land use in an alpine pastureland. Geoderma 15:98−105.

Liechty HO, Jurgensen MF, Mroz GD, Gale, GR (1997). Pit and mound topography and its influence on storage of carbon, nitrogen and organic matter within an old growth forest. Can. J. For. Res. 16:1201−1206.

Lieffers, VJ (1988). Sphagnum and cellulose decomposition in drained and natural areas of an Alberta peatland. Can. J. Soil Sci. 68:755−761.

Lieffers VJ, Rothwell RL (1987). Effects of drainage on substrate temperature and phenology of some trees and shrubs in Alberta peatland. Can. J. For. Res. 17:97−104.

Lohila A, Aurela M, Regina K, Laurila T (2003). Soil and total respiration in agricultural fields: effect of soil and crop type. Plant Soil 251:325−338.

Lynch JM, Panting LM (1982). Effects of season, cultivation and nitrogen fertiliser on size of the microbial biomass. J. Sci. Food Agric. 33:249−252.

Malik AI, Colmer TD, Lambers H, Schortemeyer M (2001). Changes in the physiological and morphological traits of roots and shoots of wheat in response to different depth of waterlogging. Aus. J. Plant Physiol. 28:1121−1131.

Malik AI, Colmer TD, Lambers H, T.L. Setter and Schortemeyer, M (2002). Short-term waterlogging has long-term effects on the growth and physiology of wheat. New Phytol. 153:225−236.

Mannerkoski H, Finér L, Piirainen S, Starr, M (2005). Effects of clear-cutting and site preparation on the level and quality of ground water in some headwater catchments in eastern Finland. For. Ecol. Manage. 220:107−117.

Martikainen PJ, Nykänen H, Alm J, Silvola J (1995). Changes in fluxes of carbon dioxide, methane and nitrous oxide due to forest drainage of mire sites of different trophy. Plant Soil 168/169:571−577.

Mazzarino MJ, Szott L, Jimenez M (1993). Dynamics of soil C and N, microbial biomass and soluble C in tropical Agroecosystems. Soil Biol. Biochem. 25:205−214.

McDonald MP, Galwey NW, Ellneskog-Staam P Colmer TD (2001). Evaluation of Lophopyrum elongatum as a source of genetic diversity to increase the waterlogging tolerance of hexaploid wheat (Tricium aestivum). New Phytol. 151:369−380.

McNabb DH, Stratsev AD, Nguyen H (2001). Soil wetness and traffic level effects on bulk density and air-filled porosity of compacted boreal forest soils. Soil Sci. Soc. Am. J. 65:1238−1247.

Merino A, Edeso JM, Gonzalez MJ Marauri P. (1998). Soil properties in a hilly area following different harvesting management practices. For. Ecol. Manage. 103:235−246.

Mojeremane W (2009). Effects of site preparation for afforestation on soil properties and greenhouse gas emission. PhD. thesis, University of Edinburgh.

Mojeremane W, Rees RM, Mencuccini M (2010). Effects of site preparation for afforestation on methane fluxes at Harwood Forest, NE England. Biogeochem. 97:89−107.

Mojeremane W, Rees RM, Mencuccini M (2012). The effects of site preparation practices on carbon dioxide, methane and nitrous oxide fluxes from a peaty gley soil. Forestry. 85:1−15.

Nelson DW, Sommers LE (1982). Total carbon, organic carbon, and organic matter, laboratory methods. Methods of soil analysis. Part 2. 2nd ed. p. 539−579. In: Page AL (eds.). Agronomy Monograph 9. Soil Science Society of America. Madison, WI, USA.

Niell C, Melillo JM, Steudler PA, Cerri CC de Moraes JFK, Piccolo MC, Brito M (1997). Soil carbon and nitrogen stocks following clearing for pasture in the south-western Brazilian Amazon. Ecol. Appl. 7:1216−1225.

Nodar R, Acea M, Carballas T (1992). Microbial response to Ca (OH2)2 treatments in forest soil. FEMS Microbiol. Letters 86:213−219.

Nohrstedt H- (2000). Effects of soil scarification and previous N fertilisation on pools of inorganic N in soil after clear-felling a Pinus sylvestris (L.) stand. Silva Fen. 34:195−204.

Nykänen H, Alm J, Lang K, Silvola J, Martikainen PJ (1995). Emissions of CH4, N2O and CO2 from a virgin fen and a fen drained for grassland in Finland. J. Biogeogra. 22:351−357.

Olsson B, Bengtsson J, Lundkvist H (1996). Effects of different forest harvest intensities on the pools of exchangeable cations in coniferous forest soils. For. Ecol. Manage. 84:135−147.

Olsson P, Linder S, Giesler R. Högberg P (2005). Fertilisation of boreal forest reduces both autotrophic and heterotrophic soil respiration. Global Change Biol. 11:1745−1753

Parfitt RL, Scott NA, Ross DJ, Salt GJ, Tate K.R (2003). Land-use change effects on soil C and N transformations in soils of high N status: Comparisons under indigenous forest, pasture and pine plantation. Biogeochem. 66:203−221.

Paul KI, Polglase PJ, Nyakuengama JG, Khanna PK. (2002). Change in soil carbon following afforestation. For. Ecol. Manage. 168:241−257.

Piirainen C, Finér L, Mannerkoski H, Starr M (2007). Carbon, nitrogen and phosphorus leaching after site preparation at a boreal forest clear-cut area. For. Ecol. Manage. 243:10−18.

Prentice IC, Heimann M, Sitch S (2000). The carbon balance of the terrestrial biosphere: ecosystem models at atmospheric observations. Ecol. Appl. 10:1553−1573.

Post WM, Kwon KC (2000). Soil Carbon Sequestration and Land-Use Change: Processes and Potential. Global Change 6:317–328.

Rab RM (1994). Changes in physical properties of a soil associated with logging of Eucalyptus regnas forest of south-eastern Australia. For. Ecol. Manage. 138:29−50.

Raich JW, Schlesinger WH (1992). The global carbon-dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus 44B:81–99.

Retallack GJ (2003). Soils and global change in the carbon cycle over geological time. Treat. Geochem. 5:1−28.

Rey A, Pegoraro E, Tedeschi V, De Parri I, Jarvis PG, Valentini R (2002). Annual variation in soil respiration and its components in a coppice oak forest in Central Italy. Global Change Biol. 8:851−866.

Robertson GP, Vitousek PM, Matson PA, Tiedje JM (1987). Denitrification in a clear-cut loblolly pine (Pinus taeda L.) in the south-eastern US. Plant Soil 97:119−129.

Ross DJ, Tate KR, Scott NA, Feltham CW (1999). Land-use change: effects on soil carbon, nitrogen and phosphorus pools and fluxes in three adjacent ecosystems. Soil Biol. Biochem. 31:803–813.

Ryan DF, Huntington TG, Martin CW (1992). Redistribution of soil nitrogen, carbon and organic matter by mechanical disturbance during whole-tree harvesting in northern hardwoods. For. Ecol. and Manage. 49:87−99.

Saiz G, Byrne KA, Butterbach-Bahl K, Keise R, Blujdea V, Farrell EP (2006). Stand age-related effects on soil respiration in a first rotation Sitka spruce chronosequence in central Ireland. Global Change Biol. 12:1007−1020.

Sarathchandra SU, Perrott KW, Boase MR, Waller JE (1988. Seasonal changes and the effects of fertiliser on some chemical, biochemical and microbiological characteristics of high-producing pastoral soil. Biol. Fert. Soils 6:328−335.

Sarathchandra SU, Perrott KW, Littler RA (1989). Soil microbial biomass: Influence of simulated temperature changes on size, activity and nutrient-content. Soil Biol. Biochem. 21:987−993.

Sarathchandra SU, Ghani A, Yeates GW, Burch G, Cox N (2001). Effect of nitrogen and phosphate fertilizers on microbial and nematode diversity in pasture soils. Soil Biol. Biochem. 33: 953−964.

Schaetzl RJ, Burns SF, Small TW, Johnson DL (1990). Tree uprooting: review of types and patterns of disturbance. Physical Geography 11:277−291.

Schimel, D. 1995. Terrestrial ecosystems and the carbon cycle. Global Change Biol. 1:77–99.

Schlesinger W (1990). Evidence from chronosequence studies for a low carbon storage potential of soils. Nature 348:232−234.

Shah Z, Adams WA, Haven CDV (1990). Composition and activity of the microbial population in an acidic upland soil and effects on liming. Soil Biol. Biochem. 22:257−263.

Sitaula BK, Bakken LR, Abrahamsen G (1995). CH4 uptake by temperate forest soils: effect of N input and soil acidification. Soil Biol. Biochem. 27:871−880.

Smith CT, Dyck WJ, Beets PN, Hodgkiss PD, Lowe AT (1994). Nutrition and productivity of Pinus radiate following harvest disturbance and fertilisation of coastal sand dunes. For. Ecol. Manage. 66:5−8.

Swift M, Heal O, Anderson J (1979). Decomposition in terrestrial ecosystems. Blackwell Scientific Publications, Oxford

Tamminen, P, Starr M (1994). Bulk density of forested mineral soils. Silva Fen. 28:53−60.

Ström, L, Christensen TR (2007). Below-ground carbon turnover and greenhouse gas exchanges in a sub-arctic wetland. Soil Biol. Biochem. 39:1689−1698

Tate KR, Ross DJ, Scott NA, Rodda NJ, Townsend JA, Arnold GC (2006). Post-harvest of carbon dioxide production, methane uptake and nitrous oxide production in Pinus radiata D. Don plantation. For. Ecol. Manage. 228:40−50.

Taylor CMA (1991). Forest fertilization in Britain. Forestry Commission Bulletin 95. HMSO, London.

Thomas KL, Benstead J, Davies KL, Lloyd D (1996. Role of wetland plants in the diurnal control of CH4 and CO2 fluxes in peat. Soil Biol. Biochem. 28:17−23.

Trettin CC, Jurgensen MF, Gale MR, McLaughlin JW (1995). Soil carbon in northern forested wetlands: impacts of silvicultural practices. Carbon forms and functions in forest soils. p. 437−461. In: McFee WW, Kelly JM (eds.) Soil Science Society of America, Madison, USA.

Updegraff K, Pastor J, Bridgham SD, Johnston CA (1995). Environmental and substrate controls over carbon and nitrogen mineralisation in northern wetlands. Ecol. Appl. 5:151−163.

Uren SC, Ainsworth N, Powers SA, Cousins DA, Huxedurp LM, Ashmore MR (1997). Long-term effects of ammonium sulphate on Calluna vulgaris. J. Appl. Ecol. 34:208−216.

Vestgarden LS (2001). Carbon and nitrogen turnover in the early stage of Scots pine (Pinus sylvestris L.) needle decomposition: effects of internal and external nitrogen. Soil Biol. Biochem. 33:465−474.

Vitousek PM, Matson PA (1985). Disturbances, nitrogen availability, and nitrogen losses in an intensively managed loblolly pine plantation. Ecology 66:1360−1376.

von Lützow M, Kögel-Knabner (2009). Temperature sensitivity of soil organic matter decomposition—what do we know. Biol.Fert. Soils 46:1–15.

Vose JM, Elliot KJ, Johnson DW, Walker RF, Johnson MG Tingey DT (1995). Effects of elevated CO2 and N fertilisation on soil respiration from ponderosa pine (Pinus ponderosa) in open-top chambers. Can. J. For. Res. 25:1243−1251.

Wall A, Hytönen J (2005). Soil fertility of afforested arable land compared to continuously forested sites. Plant Soil 275:247−260.

Wu J, Joergensen RG, Pommerening B, Chaussod R, Brookes PC (1990). Measuring of soil microbial biomass-C by fumigation-extraction-and automated procedure. Soil Biol. Biochem. 22:1167−1169.

Wang Y, Amundson R (1999). The impact of land use change on C turnover in soils. Glob. Biogeochem. Cycle 13:47−57.

Xu, Y-J, Burger, JA, Aust WM, Patterson SC, Miwa M, Preston DP (2002). Changes in surface water table depth and soil physical properties after harvest and establishment of loblolly pine (Pinus taeda L.) in Atlantic coastal plain wetlands of South Carolina. Soil Till. Res. 63:109−121.

Xue D, Yao H, Haung C (2006). Microbial biomass, N mineralisation and nitrification, enzyme activities, and microbial community diversity in tea orchard soil Plant Soil 288:319−331.

Yao H, He Z, Wilson MJ, Campbell CD (2000). Microbial biomass and community structure in a sequence of soils with increasing fertility and changing land use. Microbial Ecol. 40:223−237.

Yates GW, Bardgett RD, Cook R, Hobbs PJ, Bowling PJ, Potter JF (1997). Faunal and microbial diversity in three Welsh grassland soils under conventional and organic management regimes. J. Appl. Ecol. 34:453−470.

Zerva A (2004). Effects of afforestation and forest management of soil carbon dynamics and trace gas emissions in a Sitka spruce [Picea sitchensis (Bong.) Carr.] Forest. PhD dissertation. University of Edinburgh, Edinburgh.

Zerva A, Mencuccini, M (2005a). Carbon stock changes in a peaty gley soil profile after afforestation with Sitka spruce (Picea sitchensis). Ann. For. Sci. 62:873–880.

Zerva A, Mencuccini M (2005b). Short-term effects of clear-felling on soil CO2, CH4 and N2O fluxes in Sitka spruce plantation. Soil Biol. Biochem. 37:2025−2036.

Zerva A, Ball T, Smith KA, Mencuccini M (2005). Soil carbon dynamics in a Sitka spruce (Picea sitchensis (Bong.) Carr.) chronosequence on a peaty gley. For. Ecol. Manage. 205:227−240.