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Original article

Initial mineralization of organic matter in a forest plantation soil following different logging residue management techniques

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Abstract – The influence of tree harvesting and site preparation on inorganic N, net N mineralization and nitrification, microbial biomass and emission of CO_2 from soil were evaluated in a field experiment. The study was carried out in a plantation of *Pinus radiata* D. Three different site preparation techniques were used: a) whole tree harvesting with removal of logging residues and forest floor, b) mechanical incorporation of logging residues and forest floor into the upper 20 cm of the mineral soil, and c) logging residues left on-site. The incorporation of residues into the mineral horizon favoured N immobilization. This effect was accompanied by a higher metabolic activity, as indicated by the higher microbial biomass and CO_2 emissions, as well as the higher N contents in decomposing logging residues. In the plot with residues left on site, no changes in soil microbial biomass were observed, although there was a high degree of N immobilization.

forest soils / soil organic matter / *Pinus radiata* / microbial biomass / carbon / nitrogen / mineralization / nitrate / ammonium

Résumé – Minéralisation de la matière organique dans le sol d'un peuplement forestier après différentes méthodes de gestion des résidus d'exploitation forestière. L'influence des défrichements et de la préparation du terrain sur l'azote inorganique, la minéralisation et la nitrification nette de l'azote (N), la biomasse microbienne ainsi que sur l'émission du CO_2 degagé du sol, a été evaluée par une expérience sur le terrain. L'étude a été menée pendant 12 mois dans des peuplements de *Pinus radiata* D. Don sur un sol infertile, acide et sableux dans une zone humide et tempérée du Nord-Ouest de l'Espagne. Trois méthodes différentes de préparation du terrain ont été utilisées : a) exploitation totale des résidus forestiers, b) incorporation mécanique des résidus sur une épaisseur de sol de 15 cm, c) abandon des résidus d'exploitation à la surface du sol. L'incorporation des résidus dans l'horizon minéral a favorisé l'immobilisation de N. Cet effet a été accompagné d'une part, par une activité métabolique supérieure, indiquée par une biomasse microbienne élevée et des émissions de CO_2 croissantes, et d'autre part, par des contenus de N élevés dans la décomposition des déchets du bois. Par contre, dans la parcelle où l'on avait abandonné les résidus en surface il n'y a pas eu de changements dans la biomasse microbienne, même s'il y a eu une forte inmobilisation de l'azote (N). L'enlèvement des résidus d'exploitation a à peine eu une influence sur le minéralisation.

sols forestiers / matière organique du sol / *Pinus radiata* / biomasse microbienne / carbone / azote / minéralisation / nitrate / ammonium

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1. INTRODUCTION

Harvesting regimes and site preparation techniques used in forest ecosystems can have a significant effect on soil organic matter and nutrient budgets. Forest management practices, designed to reduce competing vegetation and to prepare a seed-bed for the next rotation, involve different types of logging residue management techniques. These residues can be removed, incorporated with the humus layer into the mineral soil or left on the surface of the soil. The accumulation on the ground or the incorporation of large quantities of logging residues into the soil over a short period of time can have notable effects on soil environmental conditions such as soil moisture and temperature, and, therefore, may alter microbial activity [34, 40] as well as organic matter decomposition and mineralization [7, 16, 21, 36]. These changes particularly affect the actively cycling fractions of soil organic matter, which comprise plant debris, microbial biomass and some humified organic matter and also affect related functions such as, soil structure, aeration, water retention capacity and nutrient availability [25, 27, 37].

The release of plant-available N after harvesting and site preparation is an important factor influencing the growth of tree seedlings. Mineralization and immobilization of organic N during decomposition are key processes in the N cycle [42]. Soil disturbances and management of plant residues during site preparation disrupt biological processes controlling N mineralization. Mechanical site preparation, in which organic residues are mixed with mineral soil, has been found to stimulate activity of soil microorganisms [35]. However, the composition of elements and the quantity of plant residues added to the soil determine the dynamics of N during decomposition, and this, in turn, influences the rates of mineralization-immobilization [39]. Therefore, after harvesting, N can either be mineralized [42] or it can be immobilized in the mineral soil [43] or in organic residues [21]. These factors determine the availability of N to plants and export of N in both the short and long term.

In Northern Spain, commercial forest plantations make up more than 30% of the land area. The plantations are highly productive, and therefore managed on short rotations (12–30 years). Intensive site preparation techniques are regularly used. Mechanical site preparation and the removal of logging residues or their incorporation into the mineral soil are techniques employed widely. Previous studies have shown that intensive site preparation techniques may lead to the depletion of soil organic matter, nitrogen and other nutrients in the months following forest harvesting [26]. This can have a negative effect on tree growth and nutrition in the following rotation [25]. High rates of soil loss due to organic matter depletion have been recorded [9]. Although most of these effects appear to be due to mixing of soil layers and losses by erosion, they may be partly caused by increased decomposition and mineralization of organic matter resulting from the higher temperature and moisture content of soils following harvesting.

There is at present a need for information on how logging residues can be managed so that soil organic matter is retained in these systems and long-term soil nutrient supply rates are maintained. The main objective of this research was to examine the effect of harvesting and slash management on mineralization of soil organic matter in a forest soil intensively managed. In a previous paper [28], nutrient export by tree removal and nutrient dynamics in decaying logging residues was discussed.

2. MATERIALS AND METHODS

2.1. Study site and soil characteristics

The study was carried out in a mature (25 year-old) *Pinus radiata* D. Don. plantation located 10 km east of Lugo (NW Spain) at an altitude of 500 m above sea-level. The understorey vegetation consisted of *Rubus spp.*, *Adenocarpus complicatus* and young trees of different deciduous species, such as *Betula pubescens*, *Quercus robur* and *Castanea sativa.* The stocking was 350 trees ha^{-1} and the mean DBH (diameter at breast height), 31.8 cm. Analysis of needles revealed a deficiency of P and low concentrations of N and Mg.

According to the FAO system of climate classification, the area can be described as Temperate Subtropic with Humic Winter. The average annual precipitation is 1022 mm. Although precipitation is evenly distributed throughout the year, winter is the most humid season and intense rainstorms occur in spring and autumn. Precipitation is usually in the form of rain, with infrequent, non-persistent snow during cold winters. The average annual temperature is 11.7 ºC. The general soil moisture regime in the region is Udic and the soil temperature regime, Mesic. The topography of the study site is relatively flat. The soil, a Humic Cambisol [12] developed on granodiorite, has a sandy loam texture, high bulk density, moderate organic matter content in the upper mineral horizon and is strongly acidic (*table I*). Available P was found at very

Table I. Soil properties of the organic and inorganic horizons under mature plantations. Values given are means of 4 profiles.

Organic horizon

	Depth.	C	N	P	S	Ca*	Mg*	K*
	cm	mg g^{-1}						
O	3–5	470.2	9.92	0.74	0.88	3.86	0.66	1.22

Mineral horizons

Hor.	Depth (cm)	B.D. (g cm^{-3})	Clay (%)	Sand (%)	O.M. (%)	Total N (%)	Avail. P (mg g^{-1})	pH (KCl)	Ca^{2+**}	Mg^{2+**}	K^{+**}
									(cmolc kg^{-1})		
Ah1	0–10	1.56	18.5	64.5	2.51	0.08	7.9	3.37	0.05	0.11	0.1
Ah2	10–17	1.48	22.6	60.6	1.76	0.05	6.1	3.54	0.10	0.12	0.08
Bw1	17–40	1.47	16.0	70.6	1.09	0.03	1.2	3.65	0.25	0.15	0.05
Bw2	40–80	1.34	22.4	71.0	0.97	0.02	1.1	3.75	0.30	0.14	0.05
BC	> 80	1.42	11.7	73.1	0.29	0.001	0.001	3.89	0.36	0.15	0.07

* total elements; ** exchangeable cations (extracted with 1M NH_4Cl).

low concentrations, normally below 10 mg kg^{-1}. The clay fraction is dominated by kaolinite and Fe and Al oxides. The humus layer averages 3 cm in thickness.

2.2. Experimental design

Part of the plantation was harvested in September 1996. Disturbances were minimal as trees were carried, rather than dragged off-site. A reference plot was established in the remaining part of the plantation, while different management practices were used for site preparation in three separate sections of the harvested area: a) whole tree harvesting with removal of logging residues and forest floor, b) mechanical incorporation of logging residues and forest floor into the upper 20 cm of the mineral soil, and c) logging residues left on-site and not windrowed (large pieces of logging debris were fragmented). The estimated mass of slash derived from above-ground biomass in the uncut stand was 64 Mg ha^{-1} dry weight. This amount of residues was added to the organic layer, with an average dry mass of 29 Mg ha^{-1}. Nutrient removals by stem-only and whole-tree harvesting are shown in Ouro et al. [28].

The study was carried out over the 12 months following harvesting and site preparation. During this time measurements were made of soil temperature and humidity, microbial biomass C, in situ N mineralization and CO_2 emissions.

2.3. Sample collection and laboratory analyses

The temperature of the soil in the four established plots was measured (at a depth of 10 cm) every hour during the study period with a thermistor connected to a data logger. Soil moisture content was determined gravimetrically (at 0–12 cm) each time the samples were taken to determine gas contents, N mineralization or microbial biomass.

Microbial biomass C was measured monthly, using the method of fumigation of soil samples with ethanol-free chloroform vapour [41]. Organic C was extracted with 0.5 M K_2SO_4 and determined by digestion with $K_2Cr_2O_7$ and titration with $(NH_4)_2FeSO_4$. The difference in organic C in 3 fumigated and 3 unfumigated (control) samples was calculated.

Nitrogen mineralization was measured by monthly in situ incubations, a technique that yields indices of annual rates of N mineralization [33]. At each sampling time and in each of the plots, paired soil cores were collected from the upper 15 cm of the A horizon at nine random points, using a PVC core (50 mm diameter). After removing larger organic debris, one of the cores from each pair was sealed, to prevent leaching, and replaced in its original site for incubation in the absence of plant uptake. Above ground portions of vegetation were excluded from the cores and plant roots were severed by core installation. The remaining soil cores were taken to the laboratory, where three composite samples made for each plot were sieved (2 mm). Determinations were made of initial moisture content and NH_4^+ and NO_3^- concentrations. After 30 days, the incubated soil cores were retrieved and analysed to determine final ammonium and nitrate concentrations. Ammonium and NO_3^- were extracted with 2 M KCl and measured photometrically. Monthly net N mineralization rates were calculated from the difference in mineral N content of the field-exposed and non-exposed soil core samples. Net N mineralization was calculated as final NH_4-N plus NO_3-N minus initial NH_4-N plus NO_3-N. Nitrification was calculated as final NO_3-N minus initial NO_3-N. Annual net N mineralization and nitrification were estimated as the sum of the net inorganic N produced over the period of the study.

A static chamber system, as described by Hutchinson and Mosier [17], was used to measure surface CO_2 emissions from the soil. Fluxes of CO_2 were recorded every 2–3 weeks at 3 randomly selected sites in each plot. Three frames per plot were permanently inserted into the soil to a depth of 2 cm. Gas-tight chambers (19.5 cm high, 29.5 cm diameter) were fixed on the frames. Measurements were taken between 10 and 12 h, because soil respiration at this time of the day can be used to estimate the mean daily rate of respiration [20]. Surface plant cover was cut before measurements were made. In order to avoid disturbance and variations in results, gas sampling restricted to 30 min. Samples were collected every 10 min. in glass vacuum flasks (60 mL) in each chamber. Concentrations of CO_2 were determined by using a gas chromatograph fitted with an electron capture (EC) detector. Gas fluxes were calculated from the linear increase or decrease in gas concentrations in the chambers (using a porapack column and N_2 as the carrier gas). All samples were analysed within 2 weeks of collection (previous tests showed that this period of time did not affect the concentration of any of the gases analysed).

2.5. Statistical analysis

Analysis of variance and Tukey test were used to test the significance of differences among the four plots at specified sampling times. Differences were considered significant at $p < 0.05$ for all parameters. Single and multiple-variable regression models were employed to analyse correlations between different parameters for each management method.

3. RESULTS

3.1. Environmental soil conditions

The temperature of the soil increased considerably following tree harvesting. The greatest effect was seen after the removal of logging residues, which led to an increase of 2.7 ºC in the mean daily temperature compared to the soil in the uncut plot (*figure 1*). Temperature differences between harvested and uncut plots were greatest in July and August, when maximum differences were 5.0 ºC in the plot without residues, 4.5 ºC in the plot where residues were incorporated and 3.6 ºC in the plot with residues left on site. Forest harvesting also increased the minimum and maximum daily temperatures (data not shown).

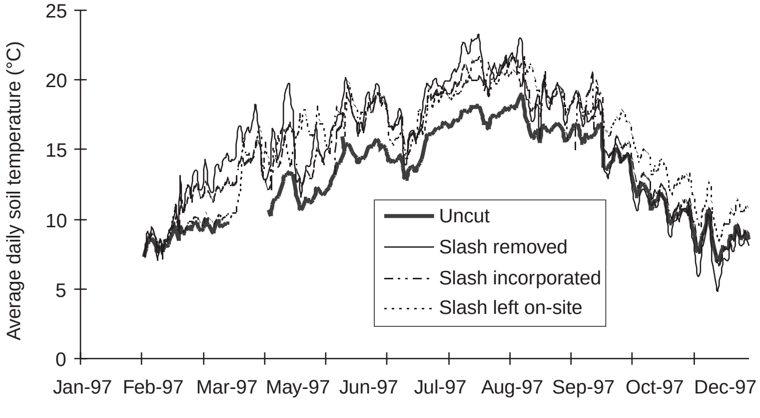

Figure 1. Daily average soil temperature (15 cm depth) throughout the study period in the uncut forest soil and in the harvested plots with different logging residue management techniques.

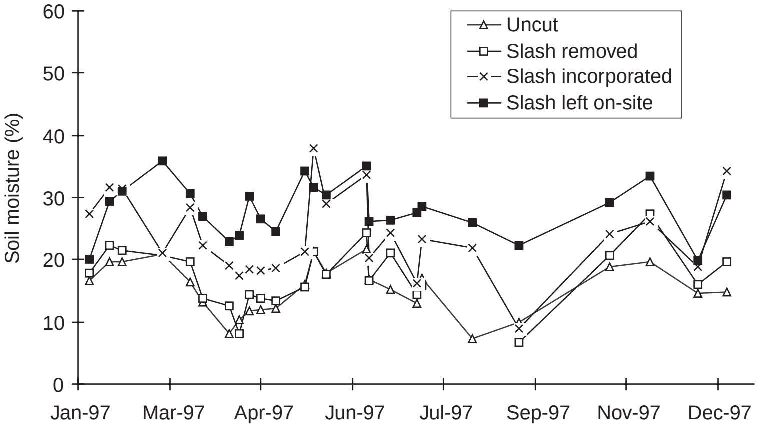

Figure 2. Changes in soil moisture contents (g H_2O 100 gr^{-1} dry soil) in the uncut forest soil and in the harvested plots with different logging residue management techniques.

Soils were driest in April and August and wettest in February and May. Harvested plots with logging residues showed significant increases ($p < 0.05$) in soil moisture contents compared to the uncut soil. These increases were greater when residues were left on site (*figure 2*).

3.2. Microbial Biomass

There was a clear seasonal development in microbial biomass C in all plots. The maximum contents were found in April and the minimum in May-June (*figure 3*), coinciding with lower soil moisture contents.

Microbial biomass C contents were significantly affected by harvesting and logging residue management. During the first 2 months of the study, the plot where logging residues were removed had low amounts of microbial C compared to the uncut soil, but thereafter the two plots had similar levels. The highest values were observed in the harvested plot where logging residues were incorporated, microbial C being 1.5 times greater than in the other plots throughout the entire period of the study (*table II*). The change in the amount of biomass C in the plot with residues left on site was similar to that in the uncut plot.

3.3. CO_2 fluxes

Soil CO_2 emissions were subject to notable seasonal fluctuations (*figure 4*). The lowest CO_2 emissions were measured in January and April, and the highest in March and July.

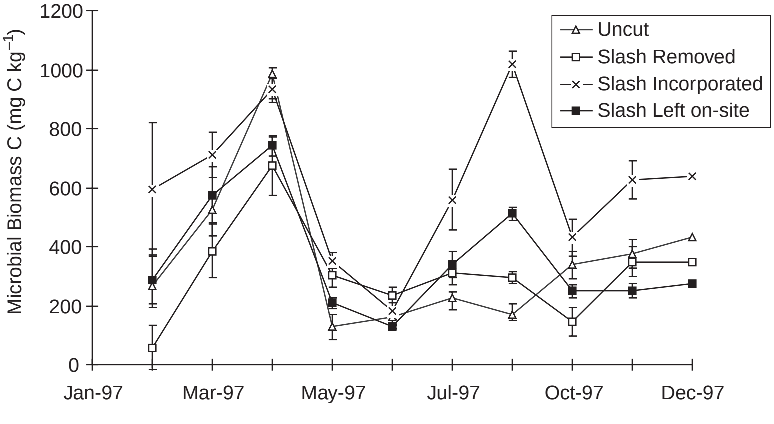

Figure 3. Microbial biomass C (0–15 cm depth) in the uncut forest soil and in the harvested plots with different logging residue managements. Values given are means and standard errors of three measurements.

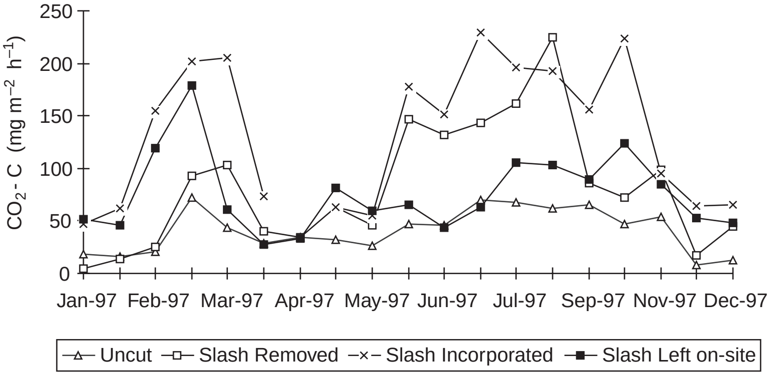

Figure 4. Emissions of CO_2 in the uncut forest soils and harvested plots with different logging residue management techniques. Values given are means of three measurements.

Table II. Mean values (and standard deviations) of microbial biomass (C_{mic}), Mineral N, N mineralization-immobilization and fluxes of CO_2 in the control uncut plantation and harvested plots with different logging residue managements.

Plot	$C_{mic}$$^{(1)}$ (mg C kg^{-1})	NO_3^--N (mg kg^{-1})	NH_4^+-N (mg kg^{-1})	Ammonification	Nitrification	CO_2 (mg C m^{-2}h^{-1})
Uncut	361.9	1.1	12.5	–0.3	1.1	40.5
	(254.1)	(0.4)	(7.1)	(4.3)	(0.9)	(20.7)
Residues removed	311.0	3.4	17.2	–2.5	2.5	81.6
	(162.4)	(2.0)	(10.4)	(6.2)	(3.6)	(59.4)
Residues incorporated	605.0	2.3	18.8	–1.7	0.9	134.1
	(251.1)	(1.8)	(10.8)	(8.7)	(5.0)	(66.9)
Residues left on site	357.0	15.4	53.6	–7.2	1.7	75.7
	(191.1)	(18.5)	(15.4)	(6.0)	(2.1)	(37.6)

The lowest and most stable emissions were observed in the uncut stand. Analysis of the data indicated significant effects of harvesting and site preparation on surface CO_2 fluxes ($p < 0.05$, *table II*, *figure 4*). Harvesting led to considerable increases in CO_2 emissions throughout the entire study period. During the overall study period, the surface CO_2 fluxes in the harvested soils were more than 2 times greater than in the uncut soil, whereas in the summer months they were up to 4 times greater. Highest CO_2 emissions were always found from the plot where residues were incorporated, in keeping with the high microbial biomass and the higher decomposition rates found in this plot (*table II*).

3.4. Inorganic N

Large differences in KCl extractable NO_3^- were found among treatments (*figure 5a*, *table II*). Average NO_3^--N concentrations in the uncut forest soil were always less than 2 mg kg^{-1} of dry soil. In the harvested plots NO_3^- concentrations increased from the first month ($p < 0.05$). The highest concentrations appeared in the plot with logging residues left on site, where a maximum of 40 mg kg^{-1} was recorded (in September). In the other harvested plots, maximum concentrations of up to 8 mg kg^{-1} were observed between April and May, coinciding with low moisture contents in the soils.

Ammonium was the dominant N form in all plots (*figure 5b*, *table II*). The NH_4^+ concentrations decreased throughout the summer and autumn months but increased again in winter. The highest NH_4^+-N concentrations were found in the harvested plots where residues were left on site. However, no significant differences were detected between uncut and other harvested plots, where levels lower than 20 mg kg^{-1} were observed throughout the entire study period.

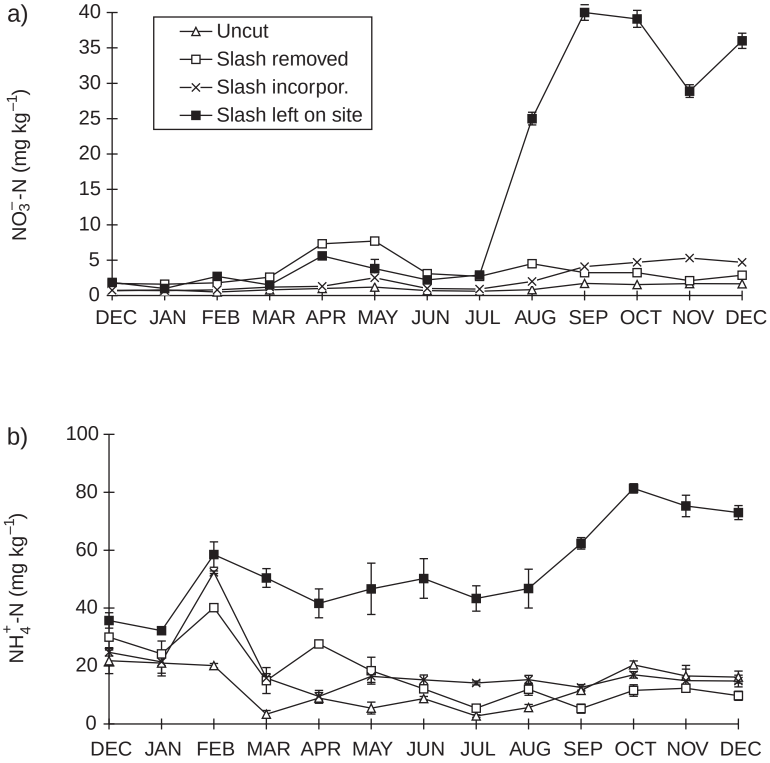

Figure 5. Monthly changes in the concentrations of: a) NO$_3^-$-N and b) NH$_4^+$-N in soil (0–15 cm depth) after harvesting and site preparation. Values given are means and standard errors of three measurements.

3.5. N mineralization

In the uncut soil, net N mineralization showed a seasonal pattern. Most of annual net mineralization took place during spring and early autumn (*figure 6a*), possibly due to the moderate temperature and high water availability. Annual net mineralization in this plot was 9.3 mg N kg^{-1}, which equates to an annual N mineralization of 19 kg ha^{-1}.

In contrast to the uncut stand, soil inorganic N was immobilized in the harvested plots where residues were incorporated or left on site following harvesting. In the plot where residues were incorporated, an initial period of immobilization (February–March) could be distinguished. In the soil with residues left on site N immobilization was notable from September onwards. The annual N immobilization was 1.1 and 76.5 mg N kg^{-1} (1.6 and 112.4 kg N ha^{-1}), in the plots where residues were incorporated or left on site, respectively.

A different pattern was seen in the plot where residues were removed. In this plot N mineralization was positive during the first 4 months after treatment and later became negative. The annual mineralization in this soil was slightly negative (–0.2 mg N kg^{-1}, –0.3 kg N ha^{-1}).

In the uncut soil, the yearly net nitrification was 13 mg kg^{-1} (19.1 kg N ha^{-1}), which represented 100% of the net mineralization. In all plots, nitrification peaked in summer, the most pronounced effects being seen in the plot with residues left on site and in the plot with residues removed (*figure 6b*). Nitrification appeared to be enhanced by both clearcutting and site preparation but differences compared to the uncut stand were only significant from summer onwards. In the harvested plots, the rate of nitrification varied greatly, depending on the residue management practice used. The highest values were found in the harvested plots where residues were removed (29 mg kg^{-1}, 42.6 kg N ha^{-1}) or incorporated (20 mg kg^{-1}, 29.4 kg N ha^{-1}), whereas the plot with residues left on site had similar values to the uncut plot (10.3 mg kg^{-1}, 15.1kgN ha^{-1}).

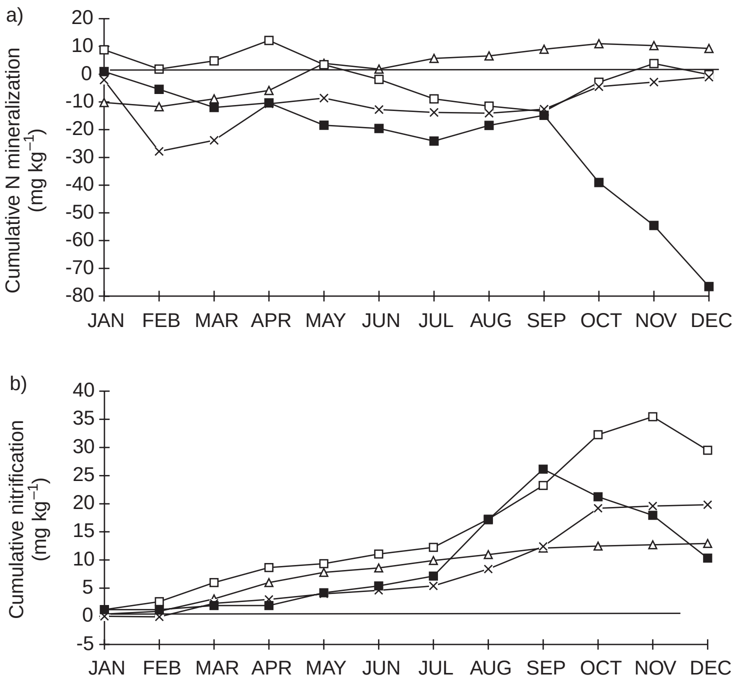

Figure 6. Net monthly: a) mineralization and b) nitrification in soil after harvesting and site preparation (0–15 cm depth). Values given are means of three measurements.

4. DISCUSSION

4.1. Environmental soil conditions

The results of this study show that harvesting produced changes in environmental soil conditions that affected the decomposition and mineralization of organic matter as well as the dynamics of CO_2. These effects were greatly influenced by the type of post-harvesting management carried out. The increases in soil temperature recorded in the harvested plots can be related to the greater incidence of solar radiation resulting from removal of tree cover. The subsequent removal of logging residues increased this effect even further. On the other hand, in the uncut stand, plant cover intercepted the rainfall, decreasing by up to 17% the amount of water reaching the soil (data not shown). The higher soil moisture in the plots where logging residues were incorporated or left on site was probably due to the greater input of water and to the effects of logging residues on water retention (increases) and evaporation (decreases).

4.2. Microbial Biomass

Microbial biomass C accounted for only a small proportion of the soil organic matter, which is typical of acid forest soils. The levels of microbial C found in the present study fell within the range given for other forest soils in Northern Spain [8]. Seasonal variations have also been reported by other authors [18]. The annual fluctuation of this parameter was related to the temperature and moisture content of the soil, as confirmed by multiple regression analysis carried out on the average monthly measurements (uncut plot, $r^2 = 0.92$; harvested + logging residues removal plot, $r^2 = 0.81$; harvesting + logging residues incorporated plot, $r^2 = 0.94$; harvesting + logging residues left on site, not significant). The low levels found in May-June were probably due to the low soil moisture contents in the previous month (April), in which soil moisture would have reached wilting point in all plots. Other studies have identified soil moisture content and temperature as factors that influence microbial biomass [1, 3].

After harvesting, microbial C increased in the plot where logging residues were incorporated into the mineral soil. This effect has also been observed in other forest plantations [6, 15, 34] and may be a result of the increased supply of available carbon, and the higher temperature and moisture content, factors that favour a rapid increase in the microbial population. Increased microbial biomass may also be favoured by mechanical disturbance of the soil by increasing the availability of carbon. According to Salonius [35], disturbance of the soil creates aerobic microenvironments and gives microorganisms access to organic C, thus increasing microbial development.

In contrast, the lower levels of microbial C found after removal of logging residues may be explained by the lower availability of C and the lower soil moisture content. In accordance with these results, Hendrickson et al. [15] and Ross et al. [34] also found lower levels of microbial C in whole-tree harvested stands, whereas Bauhus and Barthel [3] observed decreases in microbial C following treefall gap and removal of logging residues.

4.3. CO_2 fluxes

The CO_2 emission rates observed in the uncut soil were comparable to other forest systems where similar analytical methodologies were used [5, 20]. Harvesting led to considerable increases in CO_2 emissions, although the effect varied greatly with the post-harvesting management. Previous studies have also reported increases in CO_2 as a consequence of tree felling [11, 13, 22], whereas other studies have shown the enhancing effect of addition of logging residues to forest soils on microbial C biomass and CO_2 release [2]. Some authors, however, observed decreases in CO_2 flux after forest harvesting, which was attributed to drier soil conditions [14, 23] or to a decrease in respiration of living roots [5].

In all four plots CO_2 flux was significantly correlated to soil temperature ($r^2 = 0.75$ in the uncut stand; $r^2 = 0.58$, 0.51 and 0.33 in the plots with residues removed, incorporated and left on site, respectively), but not to soil moisture. Several studies have also shown a greater effect of temperature on CO_2 fluxes than that of soil moisture [10, 11].

The CO_2 released from soils originated from two different sources, decomposition of litter and organic matter and respiration of living roots (vegetation cover was cut at the soil surface). These were inevitably measured together with the technique employed in this study. Different studies [4, 10] have estimated that root decomposition and root respiration represent between 65 and 80% of total soil CO_2 emission.

The lowest CO_2 emissions were found during winter, probably because the low soil temperature limited soil microbial activity and plant growth. Soil moisture may have been important in reducing CO_2 emissions in April, when soil moisture contents fell below 10%, coinciding with lower microbial biomass at this time. In fact, decreases in CO_2 emission coincided with a large decrease in microbial biomass. The increases in CO_2 emissions seen from May onwards in the plots where logging residues were removed or incorporated can be explained by high rates of root respiration due to the fast growth of grass in these plots and by the higher microbial activity, as shown by the increases in microbial biomass.

The increased microbial biomass observed in the plot where residues were incorporated indicates that in this soil increased soil respiration may make a significant contribution to CO_2 fluxes. However, in the soil where residues were removed or left on site, the increase in surface CO_2 fluxes was not related to a greater microbial biomass. This fact suggests that the increases in CO_2 fluxes observed in these plots may be mainly attributable to the higher rate of root development or to slash decomposition.

4.4. Inorganic N and mineralization

Increased NH_4^+ and NO_3^- concentrations after harvesting have been observed in other harvested sites [15, 42, 43].

The large increases in NH_4^+ and NO_3^- concentrations observed in the harvested plot with residues left on site, from August onwards, may be partly associated with the higher temperatures and the decreased demand by plants due to their growth rates being slowed down by the layer of residues on the soil. In the other plots the development of grasses and shrubs from May onwards may have avoided the development of high concentrations of mineral soil N.

The annual rate of N mineralization recorded in the uncut stand, 19 kg N ha^{-1} yr^{-1}, is within the range reported for other undisturbed temperate forests [30]. This rate is slightly lower than the N input by litterfall measured in this plot at the same time (21 kg N ha^{-1} yr^{-1}, [28]). Harvesting affected the N dynamics and favoured the immobilization of this element, although the pattern of N immobilization appears to vary depending on whether the residues were removed, left on-site or incorporated into the soil.

The immobilization observed during most of study period in the plots with residues is in agreement with that observed in other harvested sites [2, 43] and treefall gaps [3]. Nevertheless, these results contrast with the increased mineralization of N found in other disturbed cleared forests [42].

Soil N dynamics are strongly influenced by the composition and amount of plant residues. Net mineralization is favoured when the N concentration is higher than 20 mg kg^{-1} and when the critical C to N ratio is lower than 20–30 [29]. In this study, the addition of large amounts of organic material with a high C to N ratio and the low N availability in the soil would have provided conditions favourable to microbial growth and immobilization of N in microbial tissues [32]. Thus, the N immobilization recorded by in situ incubations coincided with the N accumulations found in decomposing slash twigs contained in litterbags [28].

In the plot where residues were incorporated, negative mineralization was coupled with high CO_2 emissions and microbial biomass C, suggesting that the soil microbial community was actively immobilizing inorganic N into microbial biomass. The high degree of immobilization observed in this plot during the first months of the study period may have been due to fragmentation of the residues, making organic compounds more accessible to microoganisms, an effect that has also been observed by Agganga et al. [2].

In the plot with residues left on site, however, the high degree of N immobilization observed during the three last months of the year did not coincide with an increase in soil microbial biomass. It is possible that the observed immobilization took place directly in lignified residues and not in the mineral soil, where microbial activity was measured. It is also possible that anaerobic conditions, due to the high soil moisture content during this period, may have enhanced the denitrifier activity. In fact, measurements of N_2O showed increases in this plot [31], although the N losses by this route were small in comparison to the N immobilized.

Low nitrification rates, such as those found in the uncut stand, are normally found in undisturbed acid forest soils, and are attributed to low soil pH, low initial populations of nitrifying bacteria or low soil NH_4^+ availability [42]. In our study, nitrification took place in all plots, especially after the removal of logging residues.

It has previously been shown [24] that increases in NH_4^+ favour the formation of nitrifier populations and enhance nitrification, even in acid forest soils. The high soil NH_4^+ concentrations recorded in the plot with residues left on site may have favoured the nitrification process. However, in the remainder of the harvested plots the increased nitrification did not correspond to any increase in NH_4^+. It is possible that nitrification in this forest soil could be enhanced by soluble organic N [19], which was not measured. According to Stark and Hart [38] soil nitrification is not properly evaluated by increases in soil NO_3^- pool sizes in incubated soil cores because, in most soils, the NO_3^- produced is rapidly assimilated by microorganisms. These authors have proposed that increased NO_3^- levels found in disturbed soils are produced by a reduction in NO_3^- assimilation by soil microorganisms, rather than by an increased nitrification rate. Thus, it is possible that the increases in soil NO_3^- pool sizes observed in the disturbed soils could be due to changes in the demand for NO_3^- by soil microrganisms.

CONCLUSIONS

Decomposition and mineralization of organic matter were influenced by the post-harvesting management of logging residues, indicating that these processes are related to alterations in microclimate and C supply, both of which influence the microbial population and its activity. The incorporation of logging residues into the mineral soil implied higher rates of soil biological processes, which resulted in increased organic matter decomposition and in changes of N dynamics. The surface CO_2 fluxes and logging residues decomposition suggest that increased CO_2 emissions from the soil following harvesting were mainly caused by increased decomposition and root respiration. Thus, accelerated soil organic matter mineralization only partly explains the depletion in soil organic matter observed in intensively managed forest plantations in the region. The development of grass vegetation and biological immobilization seem to be the most influential factors in regulating the concentrations of mineral N. As a consequence of these processes, harvesting does not necessary lead to losses of N via leaching, even when decomposition of logging residues is enhanced by their incorporation, at least during this initial phase.

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