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Effects of sylvicultural practices on nutrient status in a *Pinus radiata* plantation: Nutrient export by tree removal and nutrient dynamics in decomposing logging residues

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Abstract – The effects of logging residue management practices on export and dynamics of nutrients were studied in a plantation of *Pinus radiata* D. Don growing on an infertile soil, in a humid, temperate area of NW Spain. The export of nutrients due to the removal of wood and logging residues during thinning and clear-cutting was evaluated by estimation of nutrient stores in the above-ground biomass and in the soil. Nutrient dynamics in decomposing slash needles and twigs were monitored over one year in a thinned stand and in an adjacent clear-cut area. Comparison of nutrient release in decaying residues with the nutrient store in tree biomass as well as inputs via litterfall and atmosphere allowed discussion of possible implications for sustainable sylviculture in these plantations. Nutrient release from decomposing material increased following clear-cutting and to an even greater extent, after mechanical incorporation of logging residues to the mineral soil, which substantially increased the short-term flush of some nutrients.

logging residues / decomposition / tree harvesting / thinning / forest nutrient cycling

Résumé – Effets des pratiques forestières sur la nutrition d'un peuplement de *Pinus radiata* : exportation des éléments minéraux et dynamique des résidus en décomposition. Les effets de l'utilisation des résidus d'exploitations forestières sur l'exportation et la dynamique des éléments minéraux ont été étudiés dans une plantation de *Pinus radiata* D. Don située sur une station non fertile et dans une région humide et tempérée du Nord-Ouest de l'Espagne. Le flux d'éléments minéraux dû à l'exportation du bois et des résidus de l'exploitation forestière à la suite d'une éclaircie et d'une coupe rase a été évalué à partir de l'estimation des réserves d'éléments minéraux dans la biomasse aérienne forestière et dans le sol. La dynamique des éléments minéraux provenant des résidus en décomposition d'aiguilles et de brindilles a été suivi pendant un an dans une parcelle éclaircie et aussi dans une zone de déboisement adjacente. La comparaison de la libération d'éléments minéraux en décomposition avec la réserve d'éléments minéraux dans la biomasse des arbres, de même que les apports par les pluviolessivats et les pluies incidentes nous ont permis de discuter des implications possibles pour assurer la pérennité de la production forestière. La libération des éléments minéraux à partir de matières en décomposition augmente après le défrichement total, et ceci tout particulièrement après l'incorporation mécanique des résidus d'exploitations forestières au sol minéral, laquelle augmente de façon appréciable la libération d'éléments minéraux.

résidus d'exploitation forestière / décomposition / récolte / éclaircissement / dynamique des éléments minéraux

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1. INTRODUCTION

In areas of forest plantations designated for timber production, logging residues are subjected to different management techniques during thinning, clear-felling and site preparation. Owing to their high nutrient contents, these components are of considerable importance to the nutrient economy of forest sites. In clear-cut stands the residues can be left on site at the surface, removed (in some cases along with the humus layer), mixed with the mineral soil or burnt. The repeated removal of the residues in short-rotation plantations can reduce the ability of the system to restore the nutrients extracted during forest exploitation [14, 17, 35]. As a consequence, this practice is observed to reduce the base saturation in final felling as well as in first thinnings [25]. When not removed, accumulation of the residues on the ground or their incorporation into the soil can have a substantial effect on soil environmental conditions, such as soil moisture and temperature. This can significantly alter microbial activity, which influences the rate of decomposition of organic matter and the nutrient turnover [8, 13, 16]. These, in turn, have an important influence on soil nutrient status as well as on the growth and survival of seedlings [21].

In Northern Spain, *Pinus radiata* is grown on rotations ranging between 25 and 35 years, depending on site characteristics and environmental factors [33]. As these plantations are not fertilized, forest growth largely depends on the cycling of nutrient elements. Thinning is a common practice (tree density is reduced from 1 500–2 000 trees ha^{-1} to 600–800 trees ha^{-1} during the first operation and to 300–500 trees ha^{-1} during subsequent felling) and which logging residues are deposited on the forest floor. After clear-felling, highly mechanized operations, including deep soil ploughing and/or removal of logging residues, are often employed to prepare the site for planting. Previous studies have shown that such intensive management practices have a significant effect on soil conservation [10] and lead to a reduction in soil fertility [20], which has consequences for the nutrient status and production of the following rotation [19]. It is thought that these changes may be partially caused by the removal of nutrient-rich residues and by increased decomposition following clear-felling. Other studies [9] point out that the relatively low release of Ca and Mg by weathering and the strong mineral uptake of fast growing stands can lead to negative nutrient budgets.

The aim of the present study was to investigate the influence of logging residue management during thinning, clear-felling and site preparation operations on soil nutrient status. The possible consequences of tree biomass removal on nutrient export were assessed by estimation of nutrient stores in the above-ground biomass and in the soil. The influence of logging residue management on decomposition rates and nutrient dynamics in decaying logging residues was monitored for one year in a thinned stand and in an adjacent clear-cut area. In the latter, the effect of intensive site preparation involving logging residue incorporation to the mineral soil was compared with the conventional practice of leaving it on the forest floor. In all plots, the release or accumulation of nutrients in decomposing material was compared with storage in the ecosystem and atmospheric inputs.

2. MATERIALS AND METHODS

2.1. Site description

The study was carried out on a mature (25 year-old) *Pinus radiata* D. Don. plantation located 10 km east of Lugo (NW Spain) at an altitude of about 500 m. The climate of the area can be classified as Temperate Subtropic with Humic Winter. The average annual precipitation is 1 022 mm and temperature, 11.7 °C. The topography of the study site is relatively flat. The soil, a Humic Cambisol [11] developed on granodiorite, has a sandy loam texture (15–17% clay content), high bulk density (1.4 g cm^{-3}), moderate organic matter content in the upper mineral horizon (3.0%) and is strongly acidic (pH in KCl 3.3).

2.2. Experimental design

In November 1996 part of the plantation was thinned to reduce the tree density from 500 to 350 trees ha^{-1}, while the remainder of the plantation was clear-cut. A plot was established in the thinned plantation, while in the clear-cut area, two different management techniques were used for site preparation. In one area, the residues and litter were mechanically mixed into the upper 20 cm of the mineral soil, whereas in the other area the residues were left on site without any soil disturbance. The study was carried out over the 12 months following harvesting and site preparation. Biomass and nutrient stores were determined in above-ground tree components, litter and soil, and nutrient input by litterfall and canopy drip was recorded at regular intervals during

1997. Soil temperature, moisture and slash decomposition were measured in the thinned and clear-cut areas throughout the period of the study.

2.3. Nutrient store and cycling in the stand

For estimation of biomass, the breast height diameter (dbh) of all trees was measured and, during thinning, five trees of different dbh were selected for weighing and sampling of the different components. Estimates of above-ground biomass of the stand before and after thinning were carried out on the basis of previous equations established for *Pinus radiata* in different plantations in the region [7]. The above ground biomass, comprising the following components: branches (more than 1 cm), twigs (less than 1 cm), needles, stem bark and stem wood, was measured separately.

Litterfall in the thinned stand was collected monthly in each of six litter traps (0.25 m^2) located at random in the plot, and analysed. Six rain gauges were set at random in the plot and in the nearby open area to collect throughfall and bulk deposition, respectively. Six trees were chosen to collect stemflow (using polyethylene collars). Organic horizons were sampled using 30 cm diameter rings at six sites in the plot. For mineral soil samples, 3 pits were dug and samples collected from each horizon for physical and chemical analysis.

2.4. Decomposition rates and nutrient dynamics in decomposing logging residues.

The temperature of the soil was measured (at a depth of 10 cm) every hour, from the beginning of February onwards, with a thermistor connected to a data logger. Soil moisture content was determined gravimetrically (at 0–12 cm).

Rates of decomposition of slash needles and twigs were estimated in the thinned and harvested plots using the litterbag technique. Needles and twigs (maximum diameter 1 cm) were collected from logging residues during harvesting and were thoroughly mixed. Decomposition was determined as the loss of weight of the incubated material. The equivalent of 6 g oven-dry weight (65 ºC) of fresh needles or twigs were placed in nylon bags (15 × 15 cm) with a mesh size of 0.5 mm. This size of opening was used to avoid physical loss and provide soil organisms with access to the litter, although it excluded larger arthropods and earthworms [8]. Forty litterbags were mixed with ground cover of logging residues (thinned stand and unprepared clear-cut area) or buried at a depth of 15 cm (prepared clear-cut area). Incubations were started in December, 1996 and were carried out until December, 1997. Every sampling, 8 litterbags (4 with needles and 4 with twigs) were chosen at random from each plot, and carefully transported to the laboratory avoiding loss of material. The samples were oven dried at 65 ºC to constant weight and weighed accurately.

The annual decay constant (k) was calculated following the negative exponential decay model [24]:

$$k = \ln (X/X_o)/t,$$

where X_o is the initial dry weight, X is the dry weight remaining at the end of the investigation and t is the time interval.

2.5. Vegetation and soil analyses

The oven-dried (60 ºC) samples of the vegetal material were milled (0.25 mm) and digested with H_2SO_4/H_2O_2 [26]. Soil samples collected in cores for bulk density were oven-dried to constant weight at 105 ºC. Soil samples for chemical analysis were air-dried and sieved with a 2-mm screen before analysis. Soil available P was extracted using the Mehlich III procedure. Soil exchangeable cations (K^+, Ca^{2+} and Mg^{2+}) were extracted with unbuffered 1 N NH_4Cl. Determinations of, K, Ca, Mg in the vegetal digested samples and in soil extracts were made by atomic absorption spectrophotometry, whereas P was determined photometrically by the molybdenum-blue-method. Carbon, N and S in needles were analyzed in milled material by combustion, using a Leco analyzer.

Total element storage in the soil was calculated from the depth of each horizon, bulk density and mean result for the analysis and the adjusted for gravel content.

2.6. Data analysis

T-tests were used to test for significance of differences among the four plots and between the two materials, needles and twigs, at specified sampling times. Differences were considered significant at $p < 0.05$, for all parameters.

3. RESULTS AND DISCUSSION

3.1. Nutrient store and export rates by harvesting and thinning

Table I shows the element concentrations in above-ground tree components. The highest concentrations of elements in the living organs were found in needles and fruits, and the lowest in stem wood. There was a general trend of decreasing concentrations of nutrient elements in the order, needles, fruits, twigs, branches, stem bark and stem wood. The concentration of P in needles was below the critical levels at which growth is potentially reduced, whereas that of Mg was close to the limit [38]. This coincides with other studies in the region [19, 30, 33], which showed that the growth of these plantations is mainly limited by availability of these elements. In comparison with needles and twigs, the organic horizon had lower concentrations of almost all elements, especially N and K, but had a higher concentration of Ca. These lower concentrations were probably due to retranslocation before abscission of needles, (as shown by the composition of abcised needles, *table I*) and to losses during decomposition.

The above-ground biomass of the stand and the contents of nutrients in the tree biomass are shown in *table II*. Biomass accumulation in the stand was 252,4 tons ha^{-1}, and the proportions of needles, fruits, twigs, branches, stem bark and stem wood were 3.9, 2.6, 0.6, 18.3, 3.1 and

Table I. Concentrations of nutrient elements (mg g^{-1}) in above-ground tree components and soil humus layer.

Components	Nutrient elements					
	N	P	S	K	Ca	Mg
Needles	16.1	0.9	1.4	7.8	2.7	0.9
Abcised needles*	8.4	0.4	0.8	4.2	2.7	0.4
Fruits	8.4	0.7	0.7	4.8	2.1	0.4
Twigs	6.4	0.4	0.6	5.6	2.5	0.8
Branches	2.3	0.2	0.4	4.4	1.4	0.7
Stem bark	1.8	0.2	0.13	0.9	1.9	0.3
Stem wood	0.9	0.07	0.17	1.9	1.1	0.3
Humus layer	9.9	0.7	0.9	1.2	3.9	0.7

* Average values from samples collected monthly throughout the 12 months.

Table II. Mass and contents of nutrient elements in the above-ground tree biomass before thinning.

Components		Nutrient elements (kg ha^{-1})					
	Mass (tons ha^{-1})	N	S	P	K	Ca	Mg
Needles	9.9	159.8	14.4	9.0	77.4	26.3	9.1
Fruits	1.4	11.4	1.2	0.9	6.5	2.8	0.5
Twigs	6.4	41.3	3.8	2.3	36.3	15.8	5.0
Branches	46.1	105.1	17.5	10.1	203.4	65.0	31.4
Stem bark	7.8	14.0	1.0	1.2	7.2	14.6	2.4
Stem wood	180.7	160.9	30.9	12.1	345.2	207.9	59.6
Logging residues(1)	**63.9**	**317.6**	**36.9**	**22.4**	**323.6**	**110.0**	**46.0**
Total biomass	252.4	492.5	68.8	35.8	676.0	332.5	108.1
Organic Hor.	29.2	289.4	25.9	21.6	35.6	112.6	19.3
Mineral Hor. (0–20 cm) (2)	–	1701.5	215.3	17.5	3252.5	390.5	502.4

(1) Includes needles, fruits, twigs and branches. (2) N an S are total amounts. P, K Ca and Mg are available amounts.

71.6%, respectively. Stem wood contained the greatest proportion of elements (48%) within the stand. Total nutrient element accumulation in the organs decreased in the following order: stem wood, branches, needles, twigs, stem bark and fruits. Levels of nutrient elements decreased in the following order: K, N, Ca, Mg, S and P. Needles, twigs and branches, although representing only 25% of the biomass of the stand, accumulated the largest proportion of N, P and S contained in above-ground tree biomass. Stem wood plus bark contained the largest proportions of Ca, Mg and K contained in the biomass. This pattern is similar to that reported by Schlatter et al. [34] for some radiata pine plantations in Chile. The amounts of nutrients contained in the organic horizon were considerably lower than those reported by Barraqueta and Basagoiti [4] for another *Pinus radiata* plantation located on a more fertile soil.

The P content of the total biomass was slightly lower than the amount contained in the organic horizon plus the extractable P in the mineral soil (0–20 cm depth). The total contents of N and S in the mineral soil were much higher than the amounts in the total biomass. The amounts of extractable K, Ca and Mg in the mineral soil were also substantially higher than those in the total biomass.

Annual nutrient accumulation and uptake were calculated for the thinned stand (*table III*). The increase in annual biomass was 7.07 mg ha yr^{-1}, and the annual accumulation of nutrient elements was 50 kg ha^{-1} yr^{-1}, which is within the range reported for other coniferous forest systems [8, 28].

The input of nutrient elements via litterfall was 40.9 kg ha^{-1} yr^{-1}. Litterfall composition was dominated by N (50%), K (26%) and Ca (14%) (*table III*). The amount of needle litterfall corresponds with the pattern reported by [37] for radiata pine plantations of different ages, although lower than the data reported by Barraqueta and Basagoiti [4] for another *Pinus radiata* plantation in a less limited site in Northern Spain.

The most abundant elements in bulk deposition and throughfall were N and K. With the exception of N and Mg, the concentrations of all elements were higher in the throughfall than in bulk deposition, the largest differences being for K and Ca. This data reflects the importance of dry deposition and the leaching of ions from the canopy. The amount of nutrients leached from the canopy and boles was estimated as the total amount of nutrients in throughfall and stemflow minus the amount of nutrients in bulk deposition (*table III*).

The annual uptake (*table III*) of nutrients by the stand was estimated as the sum of the annual retention of nutrients, the amount returned to the soil in litterfall and the amount leached from the canopy and boles [37]. The nutrients returned by litterfall and leaching made up around 60% of the N, P, K and Ca assimilated annually in the stand. Similar figures have been reported by Pastor and Bockeim [27].

3.2. Decomposition rates of logging residues and nutrient release

3.2.1. Soil environment

Soil temperature increased substantially following clear-cutting. Thus, the mean daily temperatures in the

Table III. Annual accumulation, return, leaching and uptake of the radiata pine stand. For leaching, values in brackets are given in L m^{-2}.

		Nutrient elements (kg ha^{-1} $year^{-1}$)				
	Mass (tons ha^{-1} $year^{-1}$)	N	P	K	Ca	Mg
Annual accumulation	7.1	13.8	1.00	18.9	9.3	3.00
Return by litterfall*	2.4	20.6	1.03	10.7	5.6	1.03
Leaching						
Throughfall	(882.9)	6.9	0.49	21.4	9.6	3.15
Stemflow	(5.2)	0.7	0.02	0.3	0.02	0.01
Bulk deposition	(1 054.1)	8.1	0.19	4.2	1.9	5.56
Total leaching		–0.4	0.32	17.5	7.7	–2.4
Uptake by trees		34.4	2.35	47.2	22.6	4.03

* Needles, branches and fruits.

Table IV. Comparison of mean daily temperature (T), mean daily minimum temperature (T_m) and mean daily maximum temperature (T_M) and soil moisture content (at a depth of 10 cm) in thinned plantation and harvested plots where different logging residue management techniques were used.

Plot	$T^{(1)}$ (ºC)	$T_m^{(1)}$ (ºC)	$T_M^{(1)}$ (ºC)	$T_M–T_m^{(1)}$ (ºC)	Moisture (%)
Thinned stand	13.1	12.7	13.6	0.9	15.4
Residues incorporated	14.8	13.7	15.7	2.0	23.8
Residues left on site	15.4	14.4	15.8	1.4	28.1

(1) Measurements made between February and December 1997.

unprepared and prepared sites, were 1.7 and 2.3 ºC higher, respectively, than in the thinned stand (*table IV*). The diurnal amplitude of soil temperatures also increased after clear-cutting, especially in the unprepared plot. The increases in soil temperature recorded after harvesting were probably due to the greater incidence of solar radiation following removal of tree cover. In the untreated plot, the slash remaining on the surface may have acted as a mulch keeping the soil warmer during the night.

Clear-cut plots also had higher soil moisture contents than the thinned stand, and much more than the unprepared plot (*table IV*). The higher soil moisture contents in harvested plots were probably due to the greater input of water as a consequence of the tree cover removal; the vegetation cover in the uncut stand intercepted rainfall, decreasing by up to 27% the amount of water reaching the soil (during the study period bulk deposition was 1 054 mm and canopy drip plus stemflow, 888 mm). Moreover, the incorporation of logging residues into the soil probably enhanced water retention, whereas in the plot where they were deposited on site, evaporation may have been reduced by the layer of residues on the surface.

3.2.2. Weight loss of decomposing residues

Changes in weight loss of needles and twigs are shown in *figure 1*. The decomposition rate in the unprepared plot did not differ significantly from that of the thinned stand, which may have been due to desiccation of the superficial layer of logging residues. Clear-cutting and site preparation techniques led to higher decomposition rates of slash needles and twigs, than in the thinned stand. The greatest weight losses were observed in the plots where logging residues were incorporated into the

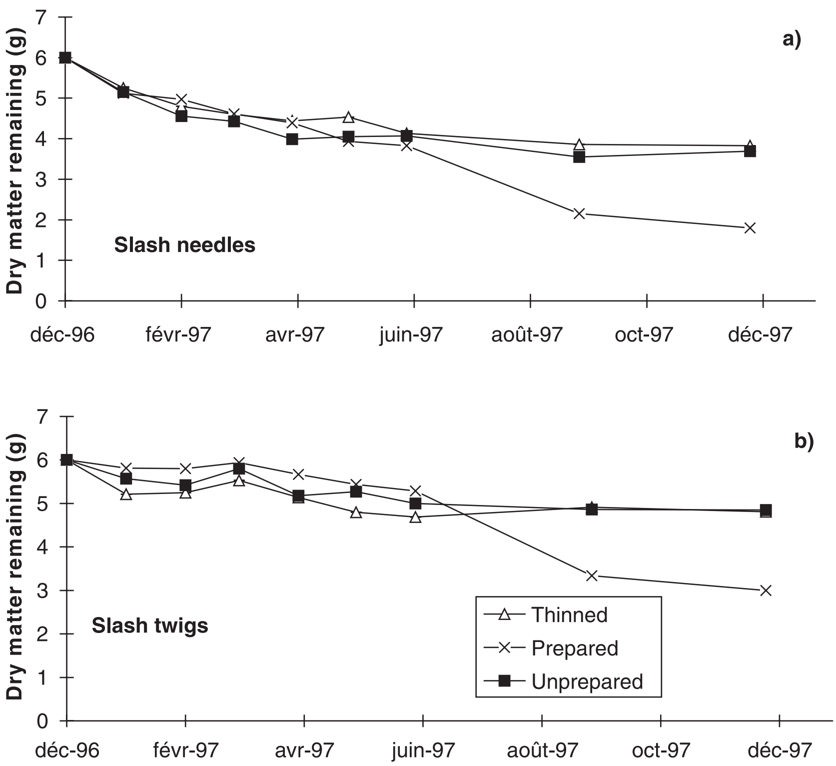

Figure 1. Remaining slash needles (a) and twigs (b) after decomposition in the thinned stand and in the prepared and unprepared plots after clear-felling. Each value is the mean of four samples.

mineral horizon. By the end of the 12-month period, the needles in these plots had lost 70% of their initial dry weight. In the thinned plot and in the plot with logging residues on the ground the mass losses were 36 and 38% respectively. The needle decomposition rate constants (k) in the thinned stand and in the prepared and unprepared harvested plots were estimated to be –0.45, –1.2 and –0.51, respectively. Twigs decomposed more slowly than needles in all plots studied. The greatest losses occurred in the plot where logging residues were incorporated (50%), whereas weight losses were similar (20%) in the other plots.

The decomposition constants recorded in the stand is typical of temperate forests [6]. The decomposition rates of slash needles (greater than 30% for the 12 month-period) were high in comparison with those observed by others authors for the same species in other temperate areas [3, 8]. The annual decay constant (k) of 1.2 yr^{-1} in the plot where logging residues were incorporated is comparable to those reported for buried fine roots in a subtropical humid forest [1]. The increased decomposition following mechanical incorporation of logging residues was also observed by Lundmark-Thelin and Johansson [16]. This effect is possibly due to the higher microbial activity resulting from the incorporation of fresh and easily decomposable organic matter [32], and the higher soil temperature and humidity in the soil. Measurements of microbial biomass made in the plots confirm this [29].

3.2.3. Nutrient dynamics in decomposing residues

The changes in absolute levels of different elements are shown in *figure 2*. The nutrient contents of decomposing needles and twigs incubated throughout 12 months (expressed as a percentage of the initial nutrient content) were calculated for each element from the nutrient concentration and the amount of dry weight loss (*table V*).

In all plots the concentrations of some elements (K, P and S) in incubated needles decreased consistently throughout the study period. Some of the nutrients (Ca and Mg), however, accumulated in the needles before the release began. In contrast, in twigs no elements were lost from the beginning of the incubation period.

There was an initial accumulation of N in slash needles during the three first months in all plots (*figure 2a*). In the thinned stand, there was subsequent accumulation of N, resulting in net accumulation of this element by the end of the study period. In the harvested plots, on the other hand, there was a clear net release of N. By the end of the incubation period, the greatest release had taken place in the prepared plot, where 42% of the initial amount of N in needles was lost (*table V*). The N dynamics of twigs followed a very different trend to that of needles. The level of N did not change during the first 10 months of incubation and thereafter it was retained in all plots, especially in the uncut stand.

Accumulation of N in the initial stage of decomposition, followed by net release has also been described for leaves by other authors [5, 22]. The accumulation of N is due to microbial immobilization and simultaneous degradation of easily decomposable substances, such as carbohydrates, along with additions by atmospheric N deposition during decomposition. The initial C/N ratios of slash needles and twigs were 33 and 75, respectively – values that are high enough to favour N immobilization. The higher immobilization of N in twigs may reflect the higher C/N ratio of this material. This behaviour

Table V. Nutrient contents at the end of the study period expressed as the percentage of the initial content. Positive values indicate net accumulation and negative values, net loss.

Plots	Weight	C	N	S	P	K	Ca	Mg	Mn
NEEDLES									
Thinned	–36.2	–35	+24	–47	–63	–84	–23	–70	+27
Prepared	–70.0	–64	–42	–71	–77	–87	–66	–83	–48
Unprepared	–38.5	–23	–20	–63	–51	–47	–35	–64	+35
TWIGS									
Thinned	–19.8	–29	+161	+30	–12	–11	–53	–31	+4
Prepared	–50.0	–44	+96	+53	–28	–74	–58	–55	–55
Unprepared	–19.2	–17	+66	+20	–10	–78	–39	–34	+10

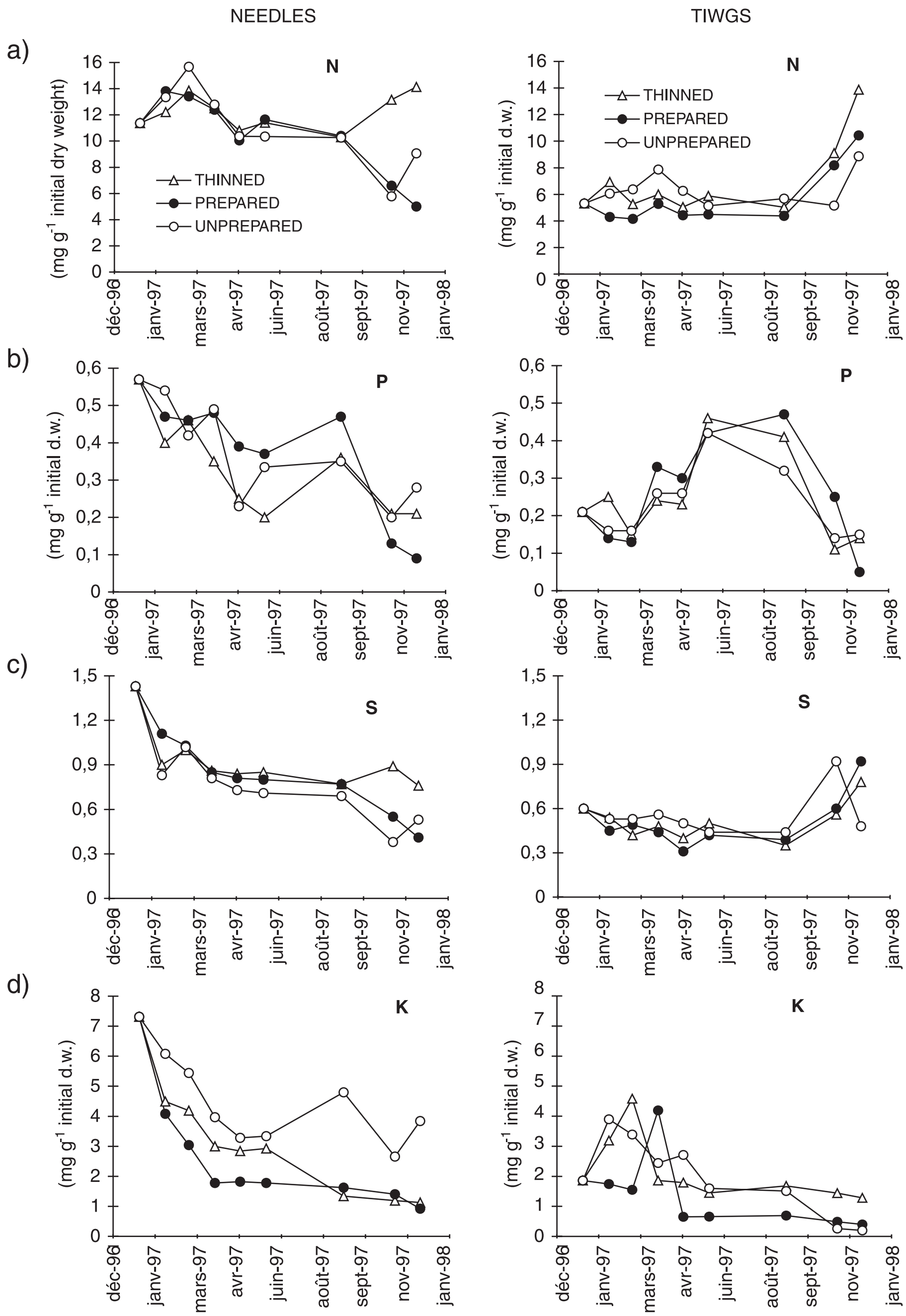

Figure 2 (continued on next page). Changes in absolute amount of elements with time for radiata pine slash needles and twigs incubated in the thinned stand and in the prepared and unprepared plots after clear-felling.

indicates that initial levels of N in decomposing material were below the requirements of decomposing organisms. Release of N from decomposing material takes place when this element reaches a certain critical level, high enough so that microbial activity is not limited [5].

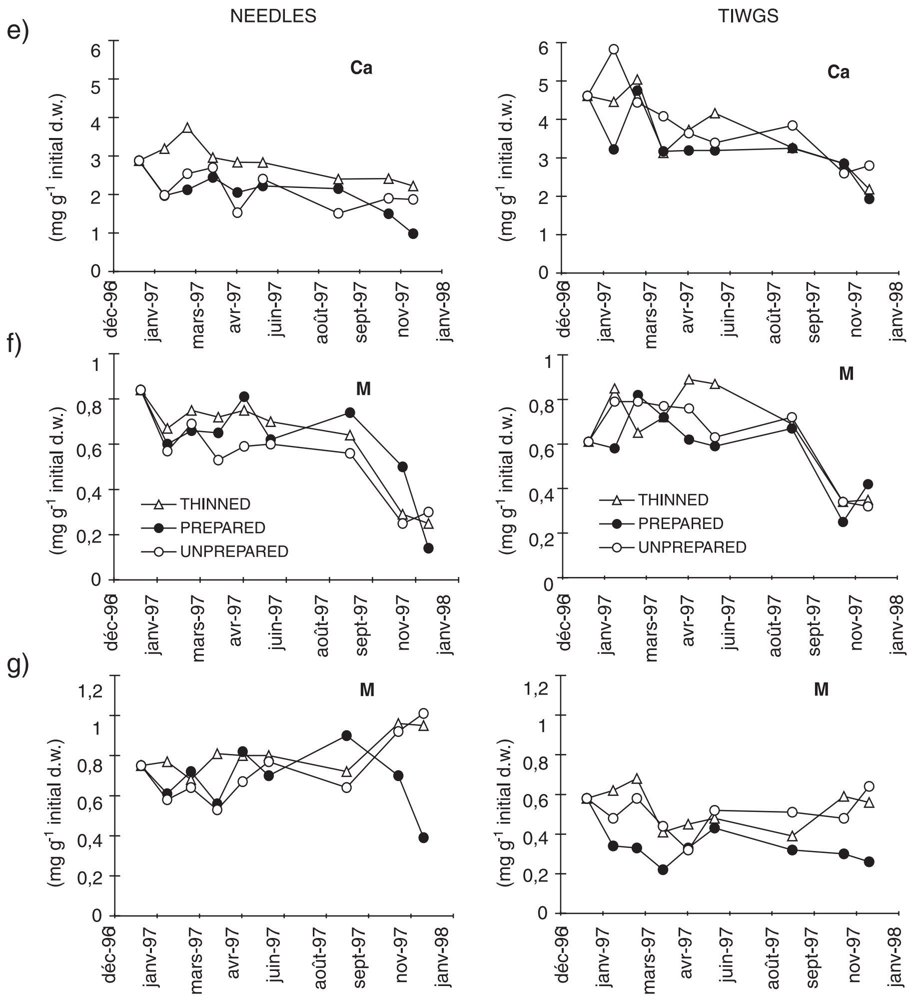

Figure 2 (continued). Changes in absolute amount of elements with time for radiata pine slash needles and twigs incubated in the thinned stand and in the prepared and unprepared plots after clear-felling.

Analysis revealed large differences in the P dynamics of decomposing needles and twigs. In the slash needles, although there was an initial rapid release of this element in all plots, the most rapid loss of P was observed in the prepared plot. Thus, the total losses of P from needles throughout the study period ranged from 51% in the unprepared harvested plot to 77% in the prepared plot (*table V*, *figure 2b*). Other studies have described similar patterns of P loss in incubated leaves of *Pinus radiata* [3, 8] and other species [16, 31]. In incubated twigs, P was accumulated during the first 9 months and levels then decreased rapidly. The losses of P in twigs made up between 10–12% in the uncut and unprepared plots and 28% in the prepared plot.

Sulphur was also released from the incubated needles in all plots (*figure 2c*). The levels of this element decreased sharply in the first months and thereafter decreased more gradually. At the end of the study period the lowest S losses were observed in the uncut plot, whereas no differences were found between the harvested plots. Other authors have also observed initial losses of S in incubated needles [6, 8]. In twigs, S contents were fairly constant in all plots during the first 9 months and then increased substantially.

The amounts of K in needles decreased rapidly from the beginning of the incubation until the end of the study period in all plots (*figure 2d*). The net losses of K in the incubated needles in the uncut and prepared plots were around 85%, whereas in the unprepared plot 47% of K was lost. The K content of twigs also decreased throughout the study period, although the losses were not continuous. High losses of K have been reported for other species [15, 31]. The high mobility of K is attributed to the fact that this element it is not a constituent of cell structures, and that its movement is mainly due to physical leaching [2].

After a short period in which Ca contents remained fairly constant, there was slow release of this element from needles and twigs throughout the rest of the incubation period (*figure 2e*). The greatest losses of Ca were observed in the prepared plot, where levels in needles and twigs decreased by 66 and 58%, respectively. The mg contents of needles and twigs did not change substantially during the first 9 months of incubation, but after this period, the levels decreased considerably (*figure 2f*). In both needles and in twigs, Ca and mg were relatively immobile during the initial stages of decomposition, as has been reported in other studies [15]. According to McClaugherty and Berg [18] these elements are confined to the structural compounds of plant tissues and are released during the decomposition of structural compounds. No large differences were detected in the total amounts of Mn released in the different plots (*figure 2g*).

The data of this study suggests the order of mobility of elements to be K > Mg > P > S > Ca, Mn, N, which generally corresponds to that previously reported for other forest systems and tree species [15, 31]. This pattern is partially due to the physical and biological degradation of cell walls and membranes required before the release of certain elements.

The higher rates of decomposition and nutrient release of needles compared with twigs are most likely to be due to the different initial nutrient concentrations [36]. Since needles were initially richer in all elements, microoganisms were not limited to the same extent as in twigs, implying that there is a more rapid release of elements from these components. Thus, the increases in N, P, K and mg observed in incubated twigs during the first months of incubation suggest that these elements were limiting to microbial growth and were consequently immobilized by microorganisms. The increased decomposition rate in needles may also be due to the greater concentration of labile components, such as proteins, soluble carbohydrates and phenolic compounds [23].

3.3. Possible implications of tree harvesting and logging residue management on nutrient status of forest plantations

Nutrient loss due to export of tree biomass in shown in *table VI*. The results of this study show that aboveground biomass includes a significant proportion of the nutrients accumulated in the system. Logging residues contain most of the N, S and P accumulated in the tree biomass, whereas stemwood and bark accumulate the highest amounts of K, Ca and Mg. Whole-tree harvesting leads to large losses of some elements, especially P and Ca and to a lesser extent, N and S. In the case of P, the export is much higher than the available amount of this element in the upper mineral soil layer (*table II*). This may partially explain the lower levels of P, N and S found in the soils and foliage in some plantations in the region where logging residues are removed after clear-cutting [19, 20]. Substantially lower losses were produced during thinning or stem-only harvesting.

The total amounts of nutrients mobilised during decomposition of the logging residues (*table VII*) can also be compared with the annual nutrient accumulation in tree biomass and the annual uptake by tree vegetation, which were calculated for the thinned stand (*table III*).

Table VI. Export of nutrients due to different harvesting methods (in kg ha^{-1}). In parenthesis the percentages with respect the storage in the upper 20 cm of soil mineral layer (*table II*) are shown.

	N	S	P	K	Ca	Mg
Thinning	52.6 (3.1)	9.6 (4.4)	3.9 (22.6)	105.7 (3.2)	66.5 (17.0)	18.6 (3.7)
Stem-only harvesting	174.9 (10.3)	31.9 (14.8)	13.4 (76.6)	352.4 (10.8)	222.5 (57.0)	62.0 (12.3)
Whole-tree harvesting	492.5 (28.9)	68.8 (31.9)	35.8 (204.6)	676.0 (20.7)	332.5 (85.1)	108.1 (21.5)

Table VII. Total amounts of nutrients released (kg ha^{-1}) from decomposition of slash needles and twigs over the 12 month study period. For the calculation, biomass of needles and twigs generated in thinning(1) (3 tons of needles ha^{-1}, 1.9 tons of twigs ha^{-1}) or clear-cutting(2) (9.9 tons of needles ha^{-1}, 6.4 tons of twigs ha^{-1}) were used.

	N	P	S	K	Ca	Mg
Thinned stand(1)	–18.0	1.4	2.6	25.5	4.7	2.6
Prepared(2)	14.2	5.4	8.0	72.0	36.0	9.8
Unprepared(2)	0.0	3.3	9.7	43.6	21.7	7.3

In the thinned stand the amounts of Ca, K and P released throughout the year by decomposing slash were higher than the inputs of this elements by throughfall and stemflow (*table III*). In this stand the release of Ca by decomposing material was higher than the amounts accumulated annually in the newly formed biomass, whereas the amounts of P, K and Mg released were similar to these accumulated in biomass. These results demonstrate the important contribution of the decomposing slash to the nutrient status of the plantation. Retention of N in green needles under thinned stands has also been found by Baker et al. [3], who suggested that this effect may cause lower N availability in N-poor sites. The possible effect of the removal of logging residues generated by thinning was considered in a recent study by Olsson [25], who found no measurable changes in soil nutrient pools in thinned stands where logging residues were removed.

The greater input of residues and the faster decomposition rates meant that harvested plots showed a greater net release of all elements than the thinned stand, especially for N, P and K. In both harvested plots the amounts of nutrients released from decomposing slash over the study period were higher than the annual nutrient accumulation in the tree biomass. Previous studies have also evaluated the nutrient dynamics of decomposing material following forest harvesting. Our data agrees with the study of Lundmark-Thelin and Johansson [16], who also found higher decomposition rates and nutrient release after incorporation of logging residues.

4. CONCLUSIONS

The results show that site preparation involving incorporation of residues to the mineral soil may lead to a loss of nutrients from the system. This however, will depend on the uptake by understorey vegetation and on nutrient immobilization processes by soil microorganisms. Thus, the rapid development of grasses and shrubs observed in these plantations may reduce the nutrient losses. Moreover, in the case of N, determinations of in situ mineralization in the same plots showed that immobilization by microorganisms played an important role in maintaining levels of this element in the soil [29]. Phosphorus can also be immobilised in this way, although the acidic conditions of the soils of this region will also reduce its mobility by fixation in insoluble compounds [12].

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