

1 **RESPONSE OF *Pinus radiata* SEEDLINGS TO APPLICATION OF MIXED WOOD-**
2 **BARK ASH AT PLANTING IN A TEMPERATE REGION: NUTRITION AND**
3 **GROWTH**

4 Fernando Solla-Gullón, Martín Santalla, César Pérez-Cruzado, Agustín Merino, Roque
5 Rodríguez-Soalleiro

6 Unidade de Xestión Forestal Sostible, University of Santiago de Compostela, E-27002 Lugo,
7 Spain

8 Tel.: (+34) 982 285900 Ext 23120, Fax: (+34) 982 285926

9 *e-mail: roquers@lugo.usc.es. Corresponding author

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12 **Abstract**

13 The aim of the present study was to evaluate the initial effects of the application of
14 mixed wood-bark ash (MWBA) on growth and nutritional status of a *Pinus radiata* plantation,
15 and on the dynamics of some of the nutrients. A field experiment, which included 4
16 treatments and 4 replicates in a completely random design, was established on an acidic,
17 mineral soil rich in organic matter. The treatments were two different doses of ash (5 and 10 t
18 ha⁻¹), a soluble NPK fertilizer 8:24:16 (200 g per plant) and an unfertilized control. The
19 MWBA was incorporated into the soil after cutting and chopping the existing shrub
20 vegetation and before planting. Application of the ash produced an increase in soil pH, and in
21 the availability of P, Ca, Mg and K. The effects on soil pH and available Ca and Mg persisted
22 for five growing seasons. The prolonged response in this study may be attributable to the
23 effect of ash incorporation, which may have enhanced the solubility of wood ash compounds,
24 despite the partly combusted material present in the ash. The ash improved the nutritional
25 status, mainly in terms of Ca and Mg, and the vector analysis indicated that these elements

1 were limiting forest production. The soluble NPK fertilizer did not produce any improvement
2 in growth relative to the control. The concentrations of heavy metals in both soil and plant
3 tissue were always low and did not increase significantly after application of the wood-bark
4 ash. The positive effect of ash application on height and diameter growth of ash application
5 was significant after five years, with similar results for both doses of ash. The improvement
6 was attributed to the increases in Ca and Mg

7 The differences between the treatments with ash and the control were much greater
8 when the values of biomass per unit area were considered, due to the accumulative effect of a
9 lower mortality and the enhanced growth in basal diameter and height.

10 **KEYWORDS:** Forest fertilization, mixed wood-bark ash, *Pinus radiata*, foliar analysis,
11 vector analysis, tree growth.

12

13 **1. Introduction**

14 The generation of ash derived from the combustion of bark and wood fuels is on the
15 increase in Europe, especially as biomass energy must be promoted to reach the target of 20%
16 of renewable energy by 2020 (Commission of the European Communities, 2007). In Spain,
17 wood ash is produced in heat and power plants adjoining pulp mills and particle and fiber
18 board plants, and the annual amount produced exceeds 70,000 Mg. At present, most of the ash
19 generated is considered to be a waste material and is disposed of in landfills (Ministerio de
20 Medio Ambiente, 2002).

21 The silviculture of radiata pine plantations in northern Spain is based in the
22 replantation of previously clearcut areas, where large amounts of nutrients may have been
23 extracted through harvesting (Rodríguez Soalleiro et al, 2007). The nutritional problems in the
24 southern European forest plantations (Zás and Serrada, 2003) and the capacity of ash to
25 improve growth in N-rich mineral soils (Ferm et al., 1992, Jacobson, 2003) have led to special

1 interest in applying wood ash. In other countries (mainly Nordic Countries) it is accepted that
2 ash can be used as a liming agent, to counteract soil acidification and nutrient deficiencies,
3 and that its application to soils is a convenient way of restoring nutrient elements exported
4 by clear cutting (Jacobson, 2003; Saarsalmi et al, 2001, 2004; Williams et al., 1996; Demeyer
5 et al., 2001).

6 Power plants produce two types of wood ash, which are distinguished by their
7 reactivity and soluble contents of nutrients and heavy metals (Narodoslawsky and
8 Obernberger, 1996). Bottom or boiler ash, produced in wood fired furnaces, is rich in charcoal
9 and other unburned organic materials and contains low levels of readily soluble nutrients and
10 trace elements. Fly powdered ash (typically light-grey) which is captured in cyclones from
11 boiler emissions, contains greater amounts of easily soluble elements and trace elements, and
12 is therefore relatively reactive (Pitman, 2006). Thus, because most of the soluble elements
13 (including trace elements) concentrate in the fine fly ash fraction, the use of bottom wood ash
14 or a mixture of both (mixed wood ash) as a soil amendment reduces the risk of nutrient
15 leaching and heavy metal contamination.

16 Different studies have shown that wood ash is a very heterogeneous material. Wood
17 ash varies widely in solubility, nutrient concentrations, trace metal contents and in other
18 compounds present due to differences in biomass fuels, combustion techniques and
19 preconditioning (Carlson and Adriano, 1993; Larsson and Westling 1998; Demeyer et al.,
20 2001). However, in general, fly ash is highly alkaline and contains a wide variety of plant
21 nutrients (Campbell, 1990; Etiégni and Campbell, 1991). Calcium, potassium, magnesium
22 and, to a lesser extent, phosphorus are usually the dominant cations in wood-bark ash, and the
23 amounts of nitrogen and trace elements are generally low (Khanna et al., 1994; Vance, 1996).

24 Ingerslev *et al* (2001) considered that there was an urgent need for research
25 concerning recycling of the nutrients by the application of wood ash, in light of the intense

1 use of forest residues for energy production. There exists much information about the effect
2 on tree growth of wood ash applied to peat (Moilanen et al, 2002, 2004) and mineral podzolic
3 soils (Jacobson, 2003; Saarsalmi et al, 2001, 2004, 2006), but there is very little information
4 about the nutrient status and growth of fast growing species following the application of
5 mixed wood-bark to mineral soils. Furthermore, it has been suggested that wood ash could be
6 applied once each rotation to conifers, at the point of most rapid growth in the thicket or early
7 mid-rotation stage (Saarsalmi and Malkönen, 2001), but there is little information about the
8 effect of applying wood ash at planting (Saarsalmi and Levula, 2007), as a starter fertilizer for
9 seedling establishment. The mixed wood ash considered in the present study, which is
10 relatively unreactive, was incorporated into the soil, a practice that has been poorly studied
11 until now.

12 The aim of the present study was to compare the short term (5 years) effects of two
13 doses of mixed wood-bark ash incorporated into the soil at planting and a commercial soluble
14 NPK fertiliser applied on top of the soil at planting on: 1) the availability of nutrients in the
15 soil, 2) on the nutrient status of the tree stand, as based on foliar analysis and 3) tree growth
16 and plantation development.

17 **2. Materials and methods**

18 **2.1. Site description**

19 The study began at establishment of a *Pinus radiata* plantation in a site located near
20 the city of Lugo, northern Spain (43° 03'N, 7° 41'W, 495 m asl.) in 2000. The average annual
21 precipitation in the area is 1,277 mm and the average minimum and maximum temperatures
22 are 2.1°C and 21.4°C, and occur in January and July, respectively. The soil is developed on
23 granites and, according to the FAO-UNESCO system is classified as an Umbric Regosol with
24 a single A horizon of 30-50 cm. Briefly, the surface horizon of the soil is characterized by
25 being strong acidic (pH 4.4) with a high content of organic matter (9.7%), sandy texture and

1 low concentrations of available cations, the initial values of which are shown in Fig. 1. The
2 previous vegetation consisted of a complete cover of shrubs more than 2 m high, composed of
3 *Ulex europaeus*, *Cytisus scoparius*, *Pterospartum tridentatum* and *Erica australis*. The total
4 amount of shrub dry biomass was estimated as 25-30 t ha⁻¹.

5 **2.2. Experimental design**

6 The ash used in this study was obtained from a thermal power plant attached to a
7 chipboard factory (Tablicia, S.A., Lugo, Spain). It was derived from the combustion of pine
8 bark and woody untreated residues from *Pinus radiata* (70%) and *Pinus pinaster* (30%). The
9 logs are debarked before processing, and bark is the principal component (65%) burned in the
10 plants. The composition of the wood-bark ash and the amounts of elements applied are shown
11 in Table 1. The ash, which was not subjected to any conditioning treatment, was a mixture of
12 bottom ash (rich in charcoal and other unburned organic materials) and cyclone fly ash
13 derived from a grate fired boiler (powdered ash). This mixed wood-bark ash (MWBA) had
14 been left outdoors for two weeks and had a moisture content of 11.5%.

15 The MWBA was not previously sieved and contained a large amount of coarse
16 unburned fragments. The particle size was classified as follows: < 2 mm (40.5 %), 2-4 mm
17 (26.5 %), 4-8 mm (5.8 %) and 8-20 mm (27.2 %). The material was alkaline, with a pH of
18 10.4, but with an equivalent neutralizing value, according to Khanna et al (1994), of only
19 7.7%, expressed as percentage of standard limestone. The concentrations of trace metals
20 (Table 1) were below the current limits established by the EU (European Communities, 1986)
21 for biosolids applied to agricultural soils. Analysis of the Mehlich 3 extract, which can be
22 considered as an indicator of element availability (Mehlich, 1984), revealed low to moderate
23 proportions of available trace elements.

24 The study was carried out as a random four-block design with four treatments. The
25 size of the plots was 24 x 24 m and the treatments included no fertilization (control), two

1 doses of MWBA, D5 (5 t dry weight ha⁻¹) and D10 (10 t ha⁻¹) incorporated into the soil before
2 planting, and a dose of 200 g of soluble fertilizer NPK 8:24:16 (N:P₂O₅:K₂O) applied on top
3 of the soil within a radius of 60 cm around each plant (total dose 247 kg ha⁻¹), (this is the most
4 common method of initially fertilizing radiata pine plantations in the area). In relation to the
5 nutrient exports calculated for radiata pine plantations, D10 would largely replenish the
6 amounts of Ca and Mg accumulated in the total biomass of old stands (50-100 and 35-75 kg
7 ha⁻¹, respectively). However, the amounts of total P and K thus applied would not be
8 sufficient if it is considered that 40-70 and 150-250 kg ha⁻¹ respectively would be required to
9 compensate for the extractions in a 30 years old stand (Rodríguez Soalleiro et al, 2007). The
10 ash contained a lower amount of total P than usually contained in fly wood ash (Demeyer et
11 al, 2001; Solla-Gullón et al., 2006), and the percentage solubility was 15.4%. The low amount
12 of N in the MWBA was acceptable because of the high availability of N in the soils under
13 study, explained by the high mineralization rates of this element (Pérez-Batallón et al., 2001)
14 and N fixation by leguminous shrubs in the forest understorey.

15 Mechanized clearing of brushwood with chopping rollers was carried out in April
16 2000 and loggings residues were incorporated by harrowing (to a depth of 30-40 cm). The
17 MWBA was spread by hand, to ensure an even distribution, in April 2000, just after
18 mechanized soil preparation, and NPK was applied in October 2000, just after planting. With
19 the aim of favoring the incorporation of the MWBA, the soil was lightly harrowed to a depth
20 of 20 cm, leading mineral soil to be present directly in the surface. The plantation was
21 established in October, 2000, by planting 1 year-old bare root *Pinus radiata* seedlings of New
22 Zealand provenance, corresponding to genetically improved stock of grade GF14. The
23 planting spacing was 3 x 2.7 m.

24 The study included the period comprised between June 2000, where initial soil
25 samples were taken before planting and November 2004. In each plot, soil and foliar sampling

1 were carried out and tree growth parameters were measured. The cover and height of the
2 understorey vegetation were monitored during the study.

3 **2.3. Sampling and analysis of plants and soil**

4 Soil samples were collect monthly during the first five months, then each three months
5 (October, January, April and July) for 36 months, and the final sampling was carried out in
6 November 2004, 5 years after application of the MWBA. Samples from the upper mineral
7 horizon (15 cm) were collected at random from six points, and mixed to provide one
8 composite sample per plot. Soil samples for chemical analysis were air dried and sieved with
9 a 2 mm screen. The pH was measured in H₂O and 0.1 M KCl (soil: solution ratio 1:2.5) with a
10 glass electrode. Total C, N and S were analyzed with a LECO CNS Analyzer. Available P,
11 Ca, Mg, K, Mn, Fe, Cu, Ni and Zn were extracted by the Mehlich 3 procedure, which includes
12 CH₃COOH, NH₄NO₃, HNO₃ and EDTA (Mehlich, 1984) and were determined by ICP-OES.

13 Soil biological properties were determined in May 2002, two years after application of
14 wood-bark ash. Microbial biomass C (MB-C) was measured following the method of
15 fumigation of soil samples with ethanol-free chloroform vapor (Vance et al., 1987). Three
16 subsamples of 25 g were taken from the upper 15 cm layer of each plot. The soil was digested
17 with 0.5 M K₂SO₄. Organic C was determined in the extracts by digestion with K₂Cr₂O₇ and
18 titration with (NH₄)₂FeSO₄. The differences in C in fumigated and non-fumigated samples
19 were calculated and converted to biomass C by multiplying them by 2.64. For each of the 16
20 plots, C was extracted in triplicate and determined in each extract in duplicate.

21 The production of CO₂ (basal soil respiration) in the samples collected from different
22 plots was measured following the alkali absorption technique (Witkamp, 1966). For this, 70 g
23 of fresh soil (three subsamples taken from the upper 15 cm layer in each plot) were placed in
24 a glass container (1 L capacity) and the moisture content was adjusted to 80%. The samples
25 were incubated at 25 °C for 10 days to allow the respiration to stabilize and the respiration

1 was then measured in terms of changes in CO₂ produced. The microbial metabolic quotient
2 (*q*CO₂), an index used to evaluate the efficiency of the soil microbial community in utilizing
3 the substrate, and which can be used to assess the process of soil development or degradation,
4 was calculated from the soil respiration rate and microbial biomass C (Anderson and Domsch,
5 1985).

6 Duplicate soil subsamples were extracted with 2 M KCl before and after incubation
7 and the N mineralization capacity was calculated as the difference between these values.
8 Anaerobic mineralizable N was determined by the method of Waring and Bremner (1964).
9 Three subsamples from each plot were placed under water and maintained at a constant
10 temperature of 40 °C for 7 days. The NH₄⁺ and NO₃⁻ present before and after incubation were
11 extracted with 2 M KCl and measured with a flux injection analyzer (FIAstar 5000). The
12 initial concentrations of NH₄⁺ and NO₃⁻ were subtracted to calculate mineralizable N.

13 Needle samples were collected nine times, starting in October, 2001, i.e., one growing
14 season after the plantation. The samples were collected once every 3 months during the first
15 year, then every four months in the second year and once a year thereafter. Undamaged, full-
16 sized needles of the current season's growth were sampled from the upper third of the
17 unshaded crowns of all trees (minimum 30) in the plot. Each sample consisted of 100 needles,
18 which were pooled to provide a composite foliage sample for each plot, so that there were 16
19 samples for each sampling time. Before analysis, the needles were thoroughly washed with
20 deionized water. Foliar samples were oven-dried (65°C) to a constant weight, milled (0.25
21 mm) and extracted with H₂SO₄/H₂O₂ (Jones et al., 1991). The concentrations of P, K, Ca, Mg,
22 Mn, Fe, Cu, Ni and Zn in the needle extracts were determined by ICP-OES. Nitrogen and S in
23 needles were analyzed in solid milled material, with a LECO Analyzer.

24 To determine the nutritional status of the trees, the critical and marginal foliar levels
25 for *Pinus radiata* proposed by Will (1985) was used. Comparisons were also made with the

1 mean levels observed for young plantations of this species in Galicia by Zás and Serrada
2 (2003). Reference values are shown in Table 2.

3 The second approach used for foliar analysis was the graphic technique proposed by
4 Timmer and Stone (1978), often known as vector analysis, in which the relative concentration
5 and relative nutrient content in biomass are presented graphically, with the control considered
6 as the comparison level. This method allows the identification of different fertilization effects
7 (dilution, luxury consumption, deficiency, sufficient or excessive levels) in a much more
8 complete way than the use of nutrient concentration alone. The dry weight of each needle was
9 estimated from the weight of 100 representative needles.

10 **2.4. Tree measurements and biomass estimation**

11 The basal diameter and total height were measured annually (2001 to 2005) in all trees
12 within the plots, at the end of the growing season. The basal diameter was measured in two
13 directions on all the trees, to within 1 mm. Tree height was measured with telescoping
14 measuring rods, to within 1 cm. In order to assess the effect of fertilizer on the branchiness
15 and stem quality, the number of whorls, total number of branches along the stem and number
16 of forked trees were also recorded.

17 An inventory of competing vascular plants was made in autumn 2003 and 2005 by
18 visually estimating the coverage per species within five square 2 x 2 m plots for each plot.

19 To estimate the total aerial and root biomass a sample of 48 seedlings was
20 destructively sampled at age 5 years (12 per treatment or 3 per plot) after stratifying by basal
21 diameter to cover the pooled diameter distribution. One composite sample of the three
22 seedlings was considered per plot. The plants were selected at random, but excluding those
23 located near the edge of the plantation or with signs of damage or infestation by pests.
24 Biomass was separated and weighed in the field as needles, twigs (diameter, d, of less than
25 0.5 cm at the insertion), branches (d from 0.5 to 2 cm) main stem (over bark, considering a

1 thin-end diameter of 2 cm) and roots (extracting those of d greater than 2 cm). The samples
2 were transferred to the laboratory, where nutrient analyses were carried out independently for
3 each component in the 48 seedlings, and composite samples were dried to constant weight at
4 65 °C to determine the dry weight ratios for tree components

5 For each biomass component several models with one (M1, M2, M3 and M5) or two
6 (M4 and M6) explanatory variables were fitted, according to the list shown below.

7 (M1) $W = a d^b$

8 (M2) $W = a e^{b \cdot d}$

9 (M3) $W = a + b d + c d^2$

10 (M4) $W = a d^b h^c$

11 (M5) $W = a + b d^2$

12 (M6) $W = a + b d^2 h$

13 where e is the base of natural logarithms, d is basal diameter, in cm; h is total height, in
14 metres; W is biomass weight, in kg; and a , b and c are model parameters.

15 In order to achieve compatibility between the estimates of the sum of each fraction
16 and total biomass, and taking into account the correlation among the equation errors (Parresol,
17 2001), the equations for all tree components were fitted by Seemingly Unrelated Regression
18 (SUR), by the SAS/ETS Model Procedure (SAS Institute Inc., 2004) in an attempt to
19 simultaneously minimize the errors associated with these equations.

20 The comparison of the models was based on graphical analysis of the residuals and
21 three statistical indices: the root mean square error (RMSE) and the adjusted coefficient of
22 determination (R^2_{Adj}), as a measure of precision, and the mean error (\bar{E}), as a measure of the
23 bias (Gadow and Hui, 1999).

24 2.5. Statistical analysis

1 The PROC GLM procedure of SAS (SAS Institute, 2004) was used to carry out
2 analysis of variance (ANOVA) to test the effects of addition of ash and NPK fertilizer on soil
3 chemical properties, foliar concentration of macro and microelements, and tree growth. An
4 ANOVA with repeated measures was used to analyze data over time, when needed. Since the
5 sphericity assumption was violated in most cases, the degrees of freedom for the univariate
6 test were adjusted with the Greenhouse-Geisser and Huynh-Feldt Epsilon correction factors.
7 The within-subjects factor (time), between-subject (fertilization treatment) and the interaction
8 time x treatment were tested. For pair-wise comparisons, the Tukey's studentized range (HSD)
9 test was used, to increase the probability that two means that have been declared different are
10 really so. In the case of variables measured as percentages (mortality or vegetation coverage),
11 one-way non-parametric ANOVA was carried out, with the Kruskal-Wallis test implemented
12 in the NPAR1WAY procedure of SAS (SAS Institute, 2004), because normality of the data
13 was not achieved through transformations. All references to statistical differences in these
14 cases are thus based on ranked values.

15 **3. Results**

16 **3.1. Soil acidity and chemical and biological properties**

17 The soil studied was acid, with an initial pH value of approximately 4.4 (Figure 1).
18 After establishment of the experiment, there was a significantly increase in soil pH, both in
19 the fertilized plots and the control plots. The response to the MWBA treatments was an initial
20 increase of 0.4-0.6 pH units relative to the control. Maximum differences in pH were
21 observed 10 months after application. The effect was still evident five years after the
22 treatment, with differences of 0.2 to 0.3 pH units. The repeated measures ANOVA showed
23 that fertilization ($p < 0.01$) and time ($p < 0.001$) had significant effects, but that there was no
24 significant interaction between treatment and time, which would indicate possible

1 convergence. The plots to which NPK was added remained on a similar level as the control
2 plots during the whole period of study, as expected.

3 During the study period, the concentration of soil available P in the control plots
4 decreased from values close to 20 mg kg⁻¹ to very low levels of 2-4 mg kg⁻¹, probably due to
5 the effects of site preparation. Available phosphorus increased significantly in the soil soon
6 after the application of D10, but 15 months after the treatment it decreased again and
7 remained on a level similar to the control (Figure 1). Even if the overall effect of fertilization
8 was significant (p<0.05), the time × treatment interaction for this element was statistically
9 significant (p<0.01), and there was a clear initial divergence among treatments and a final
10 convergence to levels slightly lower than 5 mg kg⁻¹.

11 The most important short-term effect of MWBA fertilization in the soil was the
12 increase in available Ca, Mg and K. Values in untreated plots were low, no higher than 75, 10
13 and 30 mg kg⁻¹ for Ca, Mg, and K after the incorporation of the chopped brush, respectively
14 (Figure 1). Application of MWBA led to significant increases in these levels, up to 300, 45
15 and 65 mg kg⁻¹ in the first months after application. Although the initial effect decreased
16 gradually, mainly from spring 2002 onwards, for Ca and Mg the differences were significant
17 throughout the five years of the study (Figure 1). On the contrary, for available K, the effect
18 was limited to the first 15 months. The increase in the mean concentrations of Ca, Mg and K
19 was strongly dose-dependent, and was highest in the soil treated with the highest dose of
20 MWBA, as revealed by the Tukey test for comparison of means. As expected, NPK
21 application did not result in significant variations in soil available concentrations of Ca, Mg
22 and K (Figure 1), in spite of the addition of 29.5 kg ha⁻¹ of soluble K.

23 Addition of ash did not have significant effect on soil extractable Fe, Mn, Cu, Zn and
24 Ni concentrations (Figure 1), which remained stable during the whole period of study (data
25 not shown for Ni, range 0.04 to 0.15 mg kg⁻¹).

1 Microbial biomass, which ranged between 290 and 456 $\mu\text{g C g}^{-1}$ dry soil, was not
2 significantly affected by the treatments (Table 3), although there was a trend of increasing
3 concentrations in the plots that received the highest dose. Analysis of variance did not reveal
4 any significant effect on activity of the soil microbial biomass.

5 MWBA application did not result in significant variations in organic N or C/N ratio
6 (Table 3). In all plots, concentrations of inorganic N, most as NH_4^+ , were low. The application
7 of highest dose of mixed wood ash led to slight increases in ammonification, although the
8 effect was not significant.

9 3.2. Foliar nutrient concentrations

10 Foliar N and P concentrations in the control plots ranged from 14-22 and 0.8-1.9 mg g^{-1} ,
11 respectively (Figure 2). According to Will (1985), these values are considered as sufficient
12 in this species. Neither of the fertilizers, NPK or mixed wood ash, led to increased foliar P
13 and N concentrations in the short-term (Figure 2). The time effect was significant ($p < 0.001$)
14 in both cases, and there was a decreasing trend and a slight recovery of initial values in the
15 last sample. The contents of both elements increased without any clear increase in relative
16 concentrations and vector analysis indicated that both elements were sufficient for satisfactory
17 growth of the plantation (data not shown).

18 Apart from the soil, the most important short-term effect of ash fertilization was in the
19 foliar concentrations of Ca and Mg. The initial mean concentration of Ca in the control plot
20 was 1.4 mg g^{-1} , which can be considered as adequate (Figure 2), although lower than the
21 average for young plantations in Spain (Zás and Serrada, 2003). Ash application led to
22 significant increases throughout the study period ($p < 0.001$ in the repeated measures
23 ANOVA), with higher levels for the higher dose (10 Mg ha^{-1}). Vector analysis clearly showed
24 that Ca was a limiting nutrient for growth (Figure 3): the concentration of Ca also increased

1 with increasing Ca content. There was also a significant correlation between soil and foliar
2 concentrations of Ca ($r= 0.41$, $p< 0.001$).

3 The seedling in the control plots showed initial foliar concentrations of Mg lower than
4 1 mg g^{-1} , which were within the optimal range for *Pinus radiata* ($0.7 - 1.0 \text{ mg g}^{-1}$; Will, 1985)
5 but lower than the average regional values (2.1 mg g^{-1} ; Zás and Serrada, 2003). Fertilization
6 with wood-bark ash increased the foliar concentration of this element to above the deficiency
7 level (Figure 2) although the response was not statistically significant for the whole period.
8 The comparison of means for the last sample, measured after 5 growing seasons, indicated an
9 increase in both treatments with MWBA (Figure 2). The results of vector analysis confirmed
10 the possibility that this element limited tree growth, because both the concentration and the
11 content were higher than in the control (Figure 3). The relationship between foliar and soil
12 concentrations was also clear for Mg ($r= 0.39$, $p< 0.001$).

13 All plots showed optimal foliar concentrations of K (Figure 2), higher than 5 mg g^{-1}
14 and also higher than the average values for the region (6.2 ; Zás and Serrada, 2003). After
15 April, 2002, there was a decrease in K foliar concentrations in all treated plots, which did not
16 correspond to the concentrations in the soil. This decrease was less pronounced in the plots to
17 which mixed wood ash was applied (Figure 2). These trends and the effects shown by the
18 vector analysis, with a slight decrease in foliar K concentrations and increase in total content,
19 are representative of a dilution process, i.e., increased content with decreased concentration,
20 derived from the enhanced growth (Figure 3).

21 Addition of ash or NPK fertilizer did not result in significant variations in foliar Mn,
22 Fe, Zn, Cu or Ni concentrations (Figure 2). Data for Cu ($2 \text{ to } 7 \text{ mg kg}^{-1}$) and Ni ($0.2 \text{ to } 1 \text{ mg}$
23 kg^{-1}) are not shown.

24 3.3. Understorey cover, seedling growth and mortality

1 After three growing seasons, the grass cover had increased (*Agrostis* spp and
2 *Pseudarrenatherum longifolium*) by 18% (D5 MWBA) and 29% (D10 MWBA). This effect
3 was no longer significant after five years, when the understorey vegetation was dominated by
4 shrubs, with an average cover of 70% and an average height of 0.7 m, irrespective of the
5 treatment applied.

6 Average seedling mortality was high throughout the study (18.1%). Although the
7 effect was not significant, ash application reduced the number of dead seedlings, with average
8 mortalities of 4% (D10), 8% (D5), 30% (NPK) and 30% in the control plots.

9 Fertilization at planting did not affect seedling growth during the first three years.
10 After four growing seasons, seedlings tended to be larger in the plots fertilized with MWBA,
11 but the differences were only statistically significant after five years ($p < 0.005$) (Table 4).
12 NPK application did not lead to differences in basal diameter and height relative to the
13 control. The repeated measures analysis of variance for the overall treatment showed
14 significant increases in basal diameter ($p = 0.006$) and height ($p = 0.003$) after addition of
15 MWBA. The treatment \times time interaction was not statistically significant, which indicates
16 parallel trends in growth. There were no significant differences in growth in the plots to which
17 the different doses of ash were applied

18 The fertilization had no effect on the branchiness or frequency of forked trees. The
19 average values at age 5 years for all the representative variables were: number of whorls per
20 meter along the stem: 4.58, number of branches per meter of stem: 28.6, number of branches
21 per whorl: 6.25, average number of forked trees per 30x30 m plot 1.46.

22 The biomass equation finally selected for each component of seedling biomass at age
23 5 years is shown in Table 5. Basal diameter (d) was the best predictor variable for biomass.
24 However, total height (h), in combination with d, was often also a significant predictor
25 variable.

1 The use of these equations with the data corresponding to trees measured in the plots
2 after 5 growing seasons allowed calculation of the total amount of biomass per component
3 and treatment, as shown in Table 6. The differences among treatments were much clearer in
4 this case than for basal diameter or height, as is show in the table in respect to the Tukey's
5 means test. This was partly due to the lower mortality of seedlings in the plots fertilized with
6 ash. The higher dose was not optimal for biomass accumulation because of slight differences
7 in mortality, and the NPK fertilizer provided no better results than the control plots. The
8 component for which maximum differences between ash application and the control plots was
9 found was branches (96 and 56% more for the D5 and D10 dose, respectively). The D5
10 MWBA treatment produced 76% more total biomass than the control, and the D10 MWBA
11 49% more than the control.

12 The stem was the most abundant biomass component in all the treatments, and
13 represented on average 40.4% of the total biomass; the order of the remaining components
14 was needles (23.1%), branches (20.6%), roots (13.0%) and twigs (2.8%). There was a slight
15 variation in this order for treatment D5 MWBA, with branches being more abundant than
16 needles.

17 **3.4. Nutrient concentrations in biomass components**

18 The concentrations of the main macronutrients in biomass components are shown in
19 Table 7. The concentrations of N, P and K followed the order needles >>twigs >branches
20 >roots >stem, whereas for Ca and Mg twigs and branches had similar or higher concentrations
21 than those of needles. In ash-treated plots the concentrations appeared to be considerably
22 higher than in control plots, although the concentrations did not differ significantly between
23 treatments, except for the foliar Ca, the values of which were higher when mixed wood ash
24 was added.

1 The data from the chemical analysis and biomass allowed calculation of the total
2 amounts of nutrients accumulated in each component (Table 8). Again, significant differences
3 were only found in the case of the amount of Ca in needles.

4 The comparison between the amounts of nutrients supplied by the fertilization in an
5 available form, the changes in soil content and the increase in the biomass content of nutrients
6 allowed calculation of a balance, shown in Table 8. It should be pointed out that the amount
7 of P in the biomass was higher than the amount applied with the ash, which could be only
8 understood considering that mobilization of this element due to the increased soil pH derived
9 from the application of MWBA. The D5 MWBA appears to be the most efficient treatment,
10 since 3% of the available Ca applied was accumulated in the plantation biomass (relative to
11 the control), 15.3% of Mg and 24.1% of K. The quantity not incorporated into the soil or the
12 plantation biomass may have been leached or taken up by the understory vegetation, for
13 which no data are available. This percentage was particularly high (91%) in the case of K and
14 with the higher dose of ash (10 t ha⁻¹). Almost all of the K appeared to be leached in the plots
15 fertilized with NPK.

16 4. Discussion

17 4.1. Nutritional status of the stand

18 Results showed that the application and subsequent incorporation into the soil of
19 mixed wood ash (fly and bottom wood ash) produced moderate increases in soil pH, between
20 0.4 and 1 units. The sharp increase in pH of the control plots was apparently due to the
21 incorporation of the chipped brush into the soil. In spite of low Ca carbonate equivalence (i.e.
22 neutralizing capacity with respect to lime) of the mixed ash used, the effect on soil pH was
23 comparable to that observed in a loamy soil from the same region where more amount of fly
24 wood ash was spread without incorporation into the soil (Solla-Gullón et al., 2006). In
25 accordance with the long-term changes in humus layer acidity reported for mineral soils

1 (Saarsalmi et al., 2001, 2004, 2005), in this study the increase in pH was still evident after five
2 growing seasons. The rapid and prolonged response in this study may be attributable to the
3 effect of ash incorporation, which could have enhanced the solubility of wood ash
4 compounds, despite the character of partly combusted material of this ash. But also the low
5 buffering capacity of this soil as a consequence of the lower clay content and cation exchange
6 capacity made more mobile the ash constituents (Kahl et al., 1996).

7 The addition of soluble NPK fertilizer did not lead to changes in foliar N
8 concentrations, possible because initial levels were sufficient for the tree seedlings. High
9 foliar N levels are usual in *Pinus radiata* plantations from Northern Spain (Sanchez-
10 Rodriguez et al., 2002; Merino et al., 2003) due to the high N mineralization rates (Omil et
11 al., 2007). Since the content of N in the wood ash was low, no effect on foliar and soil
12 concentrations were neither expected. However, the application of wood ash led to light
13 increases in ammonification, possibly as a consequence of the increased pH. Greater increases
14 in N mineralization have been found after the application of wood ash in histosols (Weber et
15 al., 1983).

16 Although wood ash contains low amounts of P, the availability of the element
17 increased in the soil soon after the treatment. It is possible that the incorporation of the wood
18 ash into the soil enhanced the solubility of compounds containing this element. A year after
19 the treatment, however, the levels decreased to similar levels to that control. This pattern has
20 also been reported in other studies (Mandre et al., 2006; Solla-Gullón et al., 2006) and it could
21 be attributed to the low amount of P in the ash, but also to the decreased availability due to the
22 low soil pH (at pH lower than 5 the readily available ion species, HPO_4^{-2} and H_2PO_4^- , are
23 reduced) and to the uptake of elements by the ground vegetation. Foliar P did not increase in
24 any of the treatment, even in the NPK treatment. The foliar P concentrations and the vector
25 analysis indicated that the initial concentration of this element was sufficient for satisfactory

1 growth of this species. In spite of the lack of increased concentration the nutrient balance
2 calculations indicated that the ash application enhanced the supply of this element.

3 The increases in soil extractable K in wood ash was short-lived, which is consistent
4 with the findings of other researchers (Meiwes, 1995). The depletion of this nutrient was due
5 to both the nutrient removal of the ground vegetation and **probable** losses by leaching due to
6 the high mobility of this element. Foliar K levels were not increased due possible to the short
7 period of effect in the soil, but also because the optimal levels of this element in the tree
8 seedlings.

9 The study showed that the application of wood ash improved the nutritional status of
10 the plantation with respect Ca and Mg, whose effect, unlike P and K, persisted for at least five
11 years. The gradual release from less soluble compounds in wood ash, such as carbonates and
12 ettringite (Steenary and Lindqvist, 1997; Ludwig et al., 2002), may have contributed to
13 maintaining the higher levels of Ca and Mg in soil and needles. Similar improvements in tree
14 nutritional status after wood ash application have been reported in other forest systems (i.e.
15 Arvidsson and Lundkvist, 2002; Solla-Gullón et al., 2006).

16 Since the contents of the trace element in the mixed ash used were low, no increases
17 were expected. Subsequently, no increases in soil and plant tissues were found, even for Mn
18 and Zn whose contents were moderate. However, others factor might have also reduced the
19 mobility of these elements. Thus, the increase in soil pH probably reduced the mobility of the
20 elements by affecting biological and chemical processes. The high organic matter content in
21 the soil and in the ash itself may have reduced the availability of trace elements. This effect is
22 due to the high CECE of the organic compounds and their ability to form chelates complexes
23 with certain elements, such as Cu and Mn (Kabata-Pendias and Pendias, 2001). Thus,
24 different researchers have reported decreased availabilities in Zn, Cd and Cu (Moilanen et al.,
25 2002; Omil et al., 2007) and Mn (Saarsalmi et al., 2004, **2005**, 2006) after the application of

1 wood ash. Previous studies carried out in the region have shown increases in Mn in soils and
2 Douglas fir needles after the application of 20 Mg ha⁻¹ of fly wood ash (Solla-Gullón et al.,
3 2006); the repeated application of mixed wood ash also led to increased Mn in mushrooms
4 (Omil et al., 2007).

5 **4.2. Effects on ground vegetation and trees**

6 The rate of growth of *Pinus radiata* plantations in northern Spain has been shown to
7 be highly influenced by nutrient availability (Sánchez-Rodríguez et al., 2002; Zás et al, 2004;
8 Zás and Serrada, 2003). Radiata pines are grown in 30-35 year rotations in N-rich mineral
9 soils and an important extraction of nutrients is produced by pruning, thinning and clearcut,
10 especially if the logging residues are removed (Merino et al., 2003, Rodríguez Soalleiro et al,
11 2007). This fact causes impoverishment of forest land and leads to significant nutrient
12 deficiencies, mainly P, Mg and Ca, both in mature stands (Romanyà and Vallejo, 1996;
13 Sánchez-Rodríguez et al., 2002) and young trees (Merino and Edeso, 1999; Zás and Serrada,
14 2003).

15 The aim of forest fertilization is to improve the growth and vitality of a tree stand by
16 adding nutrients, which are limitant. Increases in tree growth have been observed on N-rich
17 peatland where P and K were limiting growth (Moilanen et al, 2002, 2004); whereas in N-
18 poor mineral soils the growth increase was negligible (Saarsalmi et al, 2004, 2005). Wood
19 ash has been found to add basic cations whose retention in soils depends upon the exchange
20 sites existing in the soil, reduce exchangeable Al in acid soils and counteract the acidification
21 of nutrients resulting from tree harvesting and leaching (Khanna et al, 1994; Saarsalmi and
22 Mälkönen, 2001). Fertilization with ash can be applied at different stage of stand
23 development, but it has been employed mainly near the age of maximum volume growth.
24 Most of the growth increases reported in the literature refer to fertilizations made at the pole
25 stage in Scots pine (Saarsalmi et al, 2004, 2006; Moilanen et al, 2005; Jacobson, 2003). It has

1 been shown that volume increment could be 4 to 5 fold improved in peatlands (Ferm et al,
2 1992) and that the effect of wood ash is usually longer lived than that of PK commercial
3 fertilizers **in peatlands**, due to a longer effective duration of P (Silfverberg and Hotanen 1989;
4 Moilanen et al, 2004). **Mandre et al (2006) observed slight increases in height and diameter**
5 **growth 2 years after applying 2.5 t ha⁻¹ to an established Scots pine stand in a sandy soil.**
6 **Saarsalmi and Levula (2007) found increases in height growth of 24-27% 15 years after**
7 **applying ash to Scots pine at planting in a podzolic soil, although ploughing after wood ash**
8 **application almost totally obscured the effect, as may have happened in the present study.**
9 **Increases in height and diameter growth of Scots pine have also been reported when ash was**
10 **applied soon after planting in peat-rich agricultural land (Hytönen, 2003).**

11 The effect of fertilization at stand establishment may be negligible, since the nutrients
12 added as fertilizers are mainly used by understorey vegetation (Saarsalmi and Malkönen,
13 2001). Hytönen (2003) has shown that the combination of ash application and post planted
14 weed control significantly increased the height growth of *Pinus sylvestris*. Huotari et al (2007)
15 have found a positive effect of ash in the formation of ground vegetation, both mosses and
16 vascular plants, on cut-away peatlands. In our study an initial effect of promoting grasses was
17 found, but after five years the recolonization of shrubs was almost complete. An increase in
18 the cover of grasses and depletion of brush in some sites was also **obtained** after application of
19 low doses in Sweden (Arvidsson *et al*, 2002). Since the presence of shrubs could be important
20 as reservoirs of nutrients that could have been leached, we consider that no mechanical
21 cleaning should be applied before 5 years, if the ash is to be incorporated before planting.

22 **Although** a rapid response of growth was expected **on the basis of** the deficiencies
23 found in plantations on acid soils on granites (Sanchez-Rodriguez et al., 2002), **on previous**
24 **results of growth response in mineral N-rich soils (Jacobson, 2003)** and on the incorporation
25 of the ash, the positive effect of ash fertilization on growth did not become significant until

1 the fifth year. The incorporation of chipped brushes to the soil may have promoted the
2 availability of nutrients for some years, making the ash effect on growth only perceptible
3 when the positive effect of tilling in nutrient availability had declined, and the nutrient
4 requirement of seedlings became bigger (Saarsalmi and Malkönen, 2001). Increased growth
5 of fertilized seedlings compared to control was associated with improved nutrient status,
6 mainly in Ca and Mg. The improved growth was in our case accompanied by a reduction in
7 the early mortality, which was not negligible, being this result also found by other authors in
8 other species (Hytönen, 2003).

9 The lack of a growth response to the NPK fertilizer may be due to the optimum levels
10 of these nutrients in the tree seedlings, especially after tilling and incorporation of the chipped
11 brush into to soil. Different authors have shown that the low dose applied with these fertilizers
12 are clearly insufficient and their effect is short-lived, up to 3 years (Zás and Serrada, 2003;
13 Merino et al., 2003).

14 In the case of incorporation of mixed MWBA to the soil at the time of mechanical site
15 preparation before planting, a dose of 5 t ha⁻¹ would be sufficient, and a reapplication of the
16 same dose before canopy closure or after a resplacement operation would be more efficient
17 than treatment with large amounts of ash.

18 **5. Conclusions**

19 Mixed wood ash, comprised of fine fly ash and bottom wood ash, can be used as a
20 fertilizer at establishment of forest plantations. This product is much less reactive and
21 contains lower amounts of trace elements than fly wood ash. These characteristics prevent the
22 release of elements to soil water and reduce the risk of heavy metal contamination, which
23 makes mixed wood ash suitable for use at plantation establishment. Fertilization with ash in
24 N-rich mineral soils in temperate areas allows improved nutrient conditions for trees. The
25 large quantity of wood ash produced, the plant nutrients that it contains and its capacity to

1 increase tree growth have led to particular interest in use of this waste product. Judicious use
2 of this material both solves a waste disposal problem and provides forest owners with an
3 economically attractive alternative to chemical fertilizers.

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1 **Tables**

2 Table 1. Chemical composition of the ash used in the study and amounts of nutrients added
 3 with the doses employed.

4 .

	Total ^(a)	Available ^(b)	MWBA application 5 - 10 t ha ⁻¹ (kg)
Organic matter ^(c) (%)	56.1		
C (g kg ⁻¹)	505.1		2525.5 – 5051.0
N (g kg ⁻¹)	5.56		27.8 – 55.6
S (g kg ⁻¹)	0.32		1.6 – 3.2
P (g kg ⁻¹)	2.6	0.4	13.0 – 26.0
Ca (g kg ⁻¹)	25.0	13.8	125.0 – 250.0
Mg (g kg ⁻¹)	6.0	1.5	30.0 – 60.0
Na (g kg ⁻¹)	2.4	1.2	12.0 – 24.0
K (g kg ⁻¹)	11.1	5.0	55.5 – 111.0
Al (g kg ⁻¹)	16.2	n.d	81.0 – 162.0
Cd (mg kg ⁻¹)	1.8	1.1	0.01 – 0.02
Cr (mg kg ⁻¹)	23.7	3.7	0.12 – 0.24
Cu (mg kg ⁻¹)	32.9	4.5	0.16 - 0.33
Fe (mg kg ⁻¹)	1391	380	6.9 – 13.9
Mn (mg kg ⁻¹)	1472	353	7.4 – 14.7
Ni (mg kg ⁻¹)	14.0	8.1	0.07 – 0.14
Pb (mg kg ⁻¹)	47.0	14.0	0.23 – 0.47
Zn (mg kg ⁻¹)	1704.0	44.0	8.52 -17.04
Hg (mg kg ⁻¹)	< 1	< 1	< 0.01

5 ^(a)Digestion in HNO₃ in a microwave oven; ^(b) Extraction with Mehlich 3; ^(c) Analyzed

6 with a Leco analyzer

1 Table 2. Marginal range and foliar concentrations in Galicia (NW Spain) for *Pinus radiata*
2 plantations.

3

	Marginal range ¹	Young plantations (NW Spain) ²
N (mg g ⁻¹)	12.0 – 15.0	16.9
P (mg g ⁻¹)	1.2 – 1.4	1.1
K (mg g ⁻¹)	3.0 – 5.0	6.2
Ca (mg g ⁻¹)	1.0	2.1
Mg (mg g ⁻¹)	0.7 – 1.0	0.8
Fe (mg kg ⁻¹)		71.3
Mn (mg kg ⁻¹)		189.2
Cu (mg kg ⁻¹)		8.4
Zn (mg kg ⁻¹)		30.1

4 ¹ Will (1985); ² Zás and Serrada (2003)

5

6

1 Table 3. Some biological properties in the 20 cm uppermost soil layer of radiata pine
 2 plantation to which different amounts of mixed wood-bark ash were applied, measured two
 3 years after treatment. The number of observations (*n*) was 16.

4

	Control	D5 MWBA	D10 MWBA
Organic C (mg g ⁻¹)	59.3	64.5	60.0
Microbial biomass-C (μg g ⁻¹ soil)	303.9	290.3	456.4
Soil respiration (μg CO ₂ -C g ⁻¹ dw h ⁻¹)	1.88	2.04	2.00
<i>q</i> CO ₂ (μg CO ₂ -C h ⁻¹ mg MB-C)	0.19	0.19	0.27
Organic N (mg g ⁻¹)	4.1	4.3	4.0
C/N	14.4	15.0	15.2
Microbial biomass-C / organic C	0.53	0.45	0.70
NH ₄ ⁺ -N (mg N kg ⁻¹)	0.75	1.29	3.17
NO ₃ ⁻ -N (mg N kg ⁻¹)	3.53	1.17	0.95
Ammonification (mg N kg ⁻¹)	0.67	0.54	0.91
Nitrification (mg N kg ⁻¹)	-1.52	0.24	0.87
Mineralization (mg N kg ⁻¹)	-0.84	0.78	1.78

5

1 Table 4. Mean basal diameter (d), in cm, and mean height (h), in m, of pine seedlings for the
 2 different treatments throughout five growing periods. The standard deviations are shown
 3 in brackets

4

Treatment	October 2002		October 2003		October 2004		October 2005	
	d	h	d	h	d	h	d	h
Control	1.3 (0.5)	0.58 (0.22)	3.0 (0.6)	1.20 (0.35)	4.7 (0.7)	1.64 (0.20)	6.3a (0.4)	1.97a (0.10)
D5 MWBA	1.4 (0.6)	0.61 (0.21)	3.0 (0.8)	1.25 (0.28)	5.7 (0.8)	1.85 (0.15)	7.1b (0.2)	2.17b (0.06)
D10 MWBA	1.5 (0.6)	0.63 (0.22)	3.0 (0.8)	1.25 (0.31)	5.2 (0.7)	1.71 (0.16)	6.5ab (0.2)	2.03ab (0.06)
NPK	1.5 (0.5)	0.62 (0.20)	3.2 (0.9)	1.25 (0.27)	4.9 (0.6)	1.65 (0.18)	6.3a (0.3)	1.97a (0.08)

5

6

1 Table 5. Equations fitted to estimate biomass components of five year old radiata pine. W_i
 2 denotes the biomass component (g), d is mean basal diameter (cm) and h is seedling height
 3 (m). The values for adjusted coefficient of determination R^2_{ADJ} , root mean square error
 4 (RMSE) and bias (\bar{E}) are included as a measure of the goodness of fitting. In all the cases the
 5 number of observations (n) was 48.

6

Component	Equation	R^2_{ADJ}	RMSE	\bar{E}
Needles	$W_5 = 19,29 \cdot d^{2,20} \cdot h^{-0,68}$	0.8456	4014	-0.121
Twigs	$W_4 = 3,83 \cdot d^{2,14} \cdot h^{-1,12}$	0.6999	159	-0.039
Branches	$W_3 = 16,66 \cdot e^{0,48 \cdot d}$	0.7722	957	-0.109
Stem	$W_2 = 11,84 \cdot d^2 \cdot h$	0.7363	9331	0.326
Roots	$W_1 = 7,34 \cdot d^{2,11}$	0.8439	912	0.039
Total biomass	$W_T = W_1 + W_2 + W_3 + W_4 + W_5$	0.9113	21779.2	0.955

7

1 Table 6. Total biomass and biomass per component in a *Pinus radiata* plantation five years
 2 after fertilization (at establishment). Different letters indicate significant differences between
 3 means (Tukey test, n=16).

Treatment	Biomass (kg ha ⁻¹)					Total
	Roots	Stem	Branches	Twigs	Needles	
Control	246 a	755 a	371 a	55 a	442 a	1869 a
D5 MWBA	415 bc	1333 bc	729 bc	87 bc	721 bc	3285 bc
D10 MWBA	360 b	1129 b	579 b	78 b	636 b	2783 b
NPK	193 a	562 a	245 a	45 a	357 a	1402 a

4

1 Table 7. Nutrient concentration in biomass components (mg g⁻¹) per treatment in samples
 2 collected in October, 2005. Different letters indicate significant differences between means
 3 (Tukey test). The number of observations (*n*) was 16 for each component.

Biomass component	Treatment	N	P	K	Ca	Mg
Roots	Control	4.9	0.47	3.14	1.06	0.73
	D5 MWBA	4.9	0.49	3.21	0.97	0.80
	D10 MWBA	4.8	0.53	3.80	0.96	0.79
	NPK	4.4	0.59	3.03	0.92	0.68
Stem	Control	3.5	0.41	2.94	1.11	0.78
	D5 MWBA	3.7	0.35	2.97	1.11	0.59
	D10 MWBA	3.3	0.33	3.10	0.96	0.54
	NPK	4.3	0.37	3.13	0.96	0.62
Branches	Control	7.1	0.68	4.32	1.41	1.00
	D5 MWBA	7.1	0.65	4.11	1.57	1.03
	D10 MWBA	7.3	0.77	5.14	1.68	1.03
	NPK	6.1	0.66	4.33	1.47	0.92
Twigs	Control	9.4	0.93	5.16	1.79	1.29
	D5 MWBA	9.3	0.91	5.31	1.74	1.23
	D10 MWBA	9.3	0.99	6.38	1.74	1.12
	NPK	8.6	0.94	5.17	1.50	1.10
Needles	Control	20.4	1.88	9.18	1.04ab	0.90
	D5 MWBA	20.7	1.79	8.61	1.49ab	1.09
	D10 MWBA	19.9	1.87	7.97	1.83b	1.21
	NPK	21.4	1.63	7.99	1.19a	1.05

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1 Table 8. Comparison of applied nutrients in available form, nutrients accumulated in plants
 2 and in soil five years after fertilization at establishment

3

Element	Treatment	Applied (kg ha ⁻¹) in available form	Biomass (kg ha ⁻¹)		Increment in soil (kg ha ⁻¹)
			Aboveground	Root	
P	Control	0	1.44	0.12	
	D5 MWBA	2	2.31	0.20	1.2
	D10 MWBA	4	2.09	0.19	1.6
	NPK	26.2	0.99	0.11	0.6
Ca	Control	0	1.92	0.26	
	D5 MWBA	69	3.85	0.40	31.6
	D10 MWBA	138	3.36	0.35	103.3
	NPK	0	1.39	0.18	5.4
Mg	Control	0	1.43	0.18	
	D5 MWBA	7.5	2.43	0.33	5.8
	D10 MWBA	15	2.06	0.28	15.3
	NPK	0	1.00	0.13	1.7
K	Control	0	8.16	0.77	
	D5 MWBA	25	13.62	1.33	13.8
	D10 MWBA	50	12.04	1.37	9.3
	NPK	33.2	5.91	0.59	0.8

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6

1 FIGURE CAPTIONS

2

3 Figure 1. pH and available concentrations of P, Ca, Mg, K and Fe in soils, for the different
4 treatments throughout five growing periods. On the x-axis, J is July, S is September, D is
5 December and M is March. The treatments are indicated by ● for control, ▲ for D10 MWBA,
6 Δ for D5 MWBA and X for NPK. Different letters show significant differences between
7 treatments at each sample date ($p < 0.05$, Tukey's test).

8

9 Figure 2. Macro and microelement concentrations in radiata pine needles sampled between
10 October 2001 and October 2004. On x-axis, J is July, S is September, D is December and M is
11 March. The treatments are indicated by ● for control, ▲ for D10 MWBA, Δ for D5 MWBA
12 and X for NPK. Different letters show significant differences between treatments at each
13 sample date ($p < 0.05$, Tukey's test).

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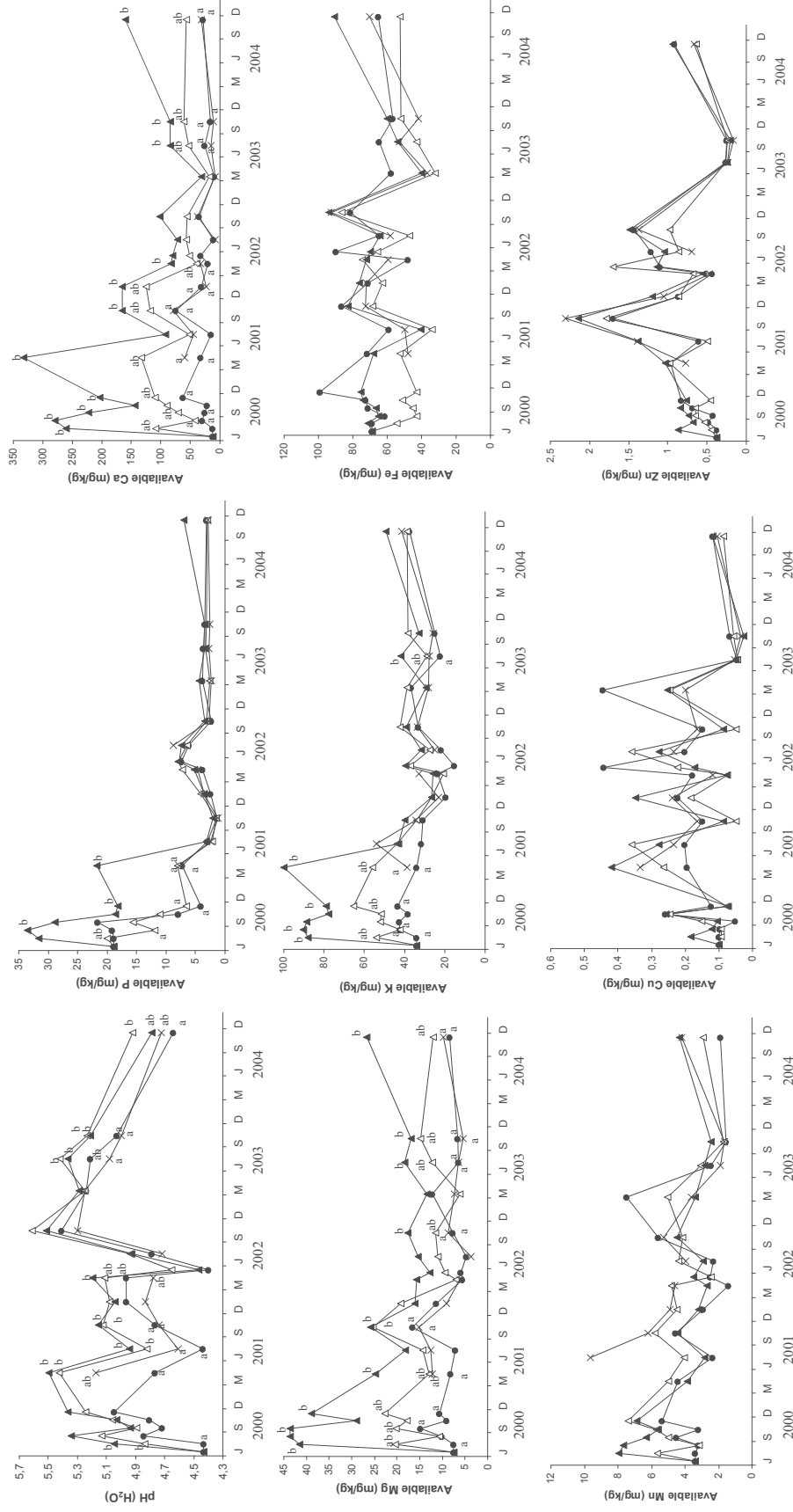
15 Figure 3. Vector analysis diagrams for the effects of wood ash treatments on foliage Ca, K
16 and Mg in the young radiata pine plantation. Relative concentrations and contents are
17 expressed as percentages of the control. The treatments are indicated by ● for control, ▲ for
18 D10 MWBA, Δ for D5 MWBA and X for NPK. The arrow shows the main trend in changes
19 derived from ash application.

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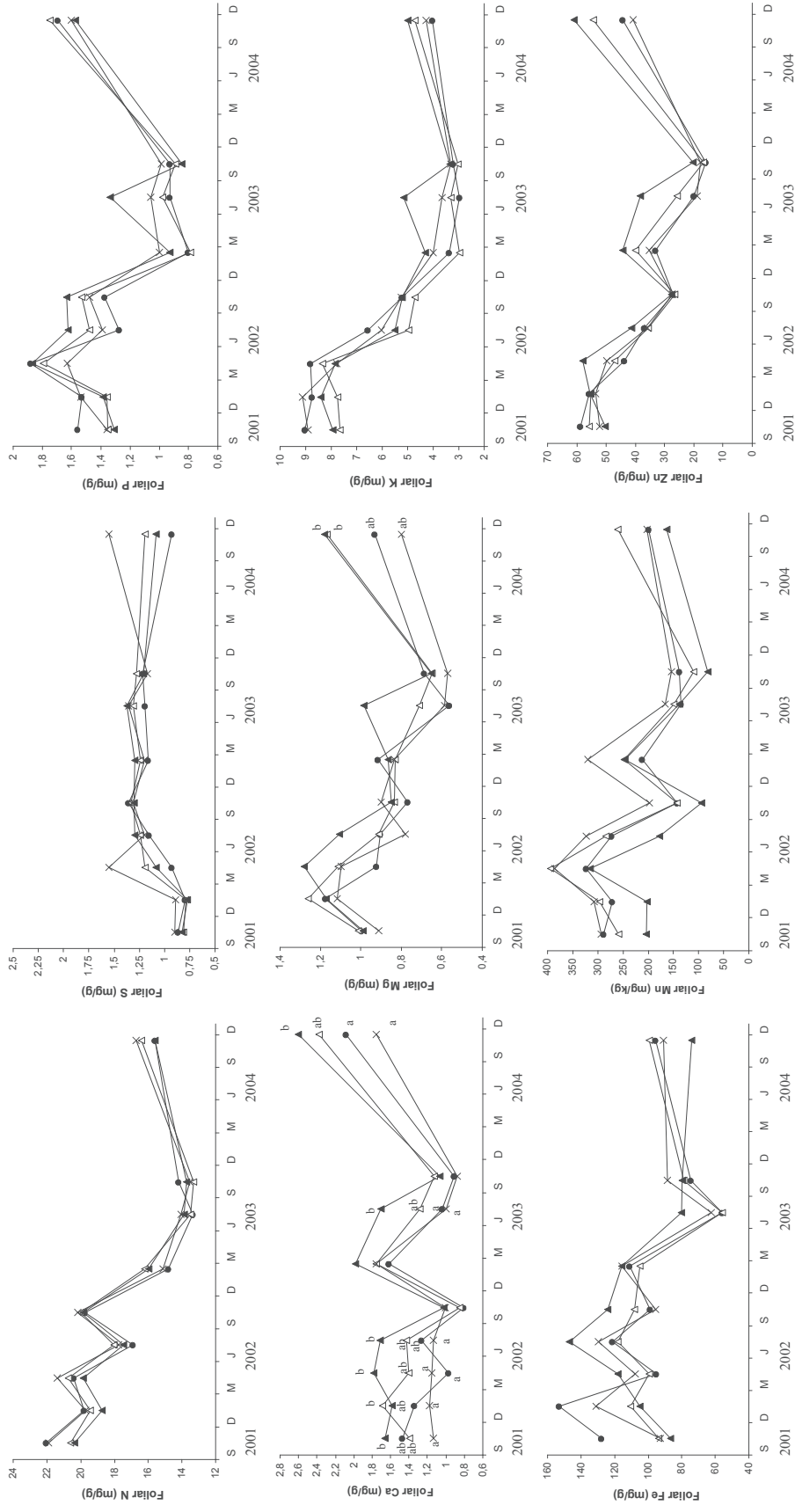
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1 Figure 1

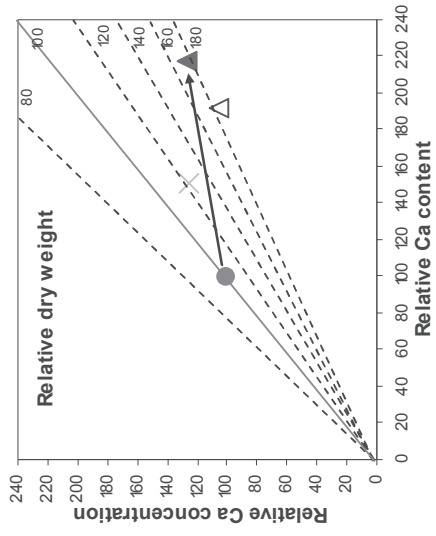


1 Figure 2

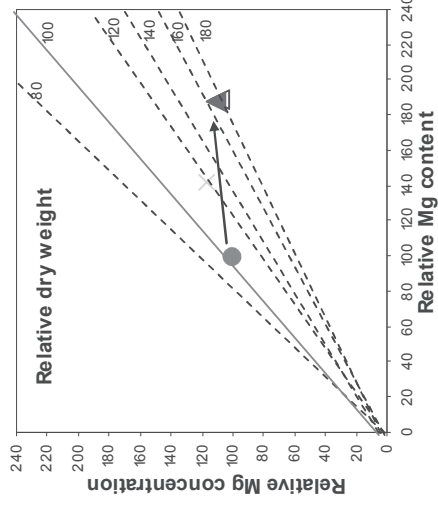
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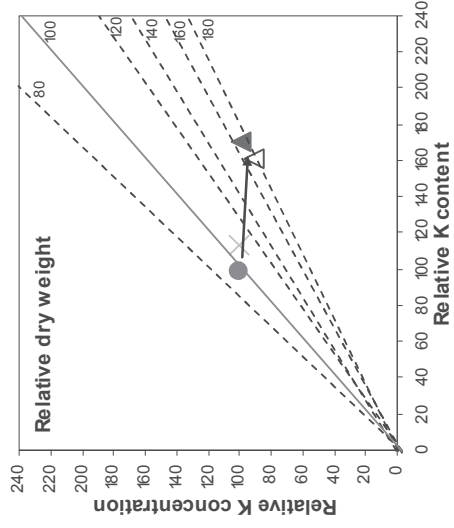
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15 Figure 3