ANALYSIS OF GROWTH AND NUTRITION OF A YOUNG *Castanea x coudercii* PLANTATION AFTER APPLICATION OF WOOD-BARK ASH

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Abstract

The aim of the present study was to evaluate the effects of the application of wood-bark ash (WBA) on the growth and nutritional status of a five year old hybrid chestnut plantation in two consecutive periods of three and four years. A field experiment, which included 3 treatments and 4 blocks, was established on an acidic, organic-matter rich mineral soil. The treatments were two different doses of ash (10 and 20 t ha^{-1}) and an unfertilized control. The WBA was spread on the ground. As the four growth variables studied showed non-random spatial structures, the data was adjusted for spatial autocorrelation by semivariograms and kriging. Application of the ash produced an increase in diameter and height growth, particularly during the first three years; the response was also significant for the subsequent period, particularly with the higher dose of ash. The ash had a positive, although clearly short-lived effect on available soil Ca and Mg. The nutritional status of the plantation was improved, mainly in terms of Ca and Mg, and the vector analysis indicated that these elements were limiting forest production.

KEYWORDS: Forest fertilization, wood-bark ash, *Castanea x coudercii*, foliar analysis, tree growth.

1. Introduction

Most of the ash generated at present in Spain is produced in heat and power plants that adjoin pulp mills and particle and fiber board plants. Disposal of the ash in landfills is still the main method of managing the residue (Ministerio de Medio Ambiente, 2002). Although an heterogeneous material, wood and bark ash is in general highly alkaline and contains a wide variety of plant nutrients: calcium, potassium, magnesium and to a lesser extent phosphorus (Etiégni and Campbell, 1991), and generally low amounts of nitrogen and trace elements (Khanna et al., 1994; Vance, 1996).

In response to lower population densities in rural areas, as well as environmental and economical strategies, arable land is increasingly used for newly planted forests in the Iberian Peninsula. Chestnut is readily accepted for planting by private landowners, and the current plantation rate in Portugal, northern Spain and France has been estimated at 4500 ha per year. Chestnut is attractive to landowners because of the prospect of valuable timber production in relatively short rotations. The use of the ink-disease resistant hybrids, obtained by crossing *Castanea sativa*, *Castanea crenata* and *Castanea mollissima* became popular around 1960, and several clones have been selected for their desirable characteristics in terms of timber production, i.e., straightness, branchiness and rapid height growth. Nutritional problems in southern European forest plantations (Zás and Serrada, 2003) and the capacity of ash to improve growth on N-rich mineral soils and peat soils (Ferm et al., 1992, Jacobson, 2003) led to particular interest in the use of wood ash in broadleaf plantations.

Ingerslev et al (2001) considered that there was an urgent need for research concerning recycling of the nutrients by the application of wood ash, in light of the widespread use of forest residues for energy production. There is much information about the effect on tree growth of wood ash applied to peat soil (Moilanen et al, 2002, 2004) and mineral podzolic soils (Jacobson, 2003; Saarsalmi et al, 2006), but there is very little information about the growth of temperate broadleaf species following the application of wood-bark to mineral soils. Furthermore, there is still a need to analyse the long term effects of ash application, and to consider the spatial heterogeneity usually present in forest trials.

The aim of the present study was to assess the effect of two doses of ash on the growth of a hybrid chestnut plantation in two consecutive periods of 3 and 4 years, while considering the spatial autocorrelation of the data, and the relationship between growth and the foliar and soil nutrients.

2. Materials and methods

2.1. Site description

The study was carried out in a hybrid chestnut plantation aged 5 years in July, 2001. The plantation was established in a former grassland, in which the soil was prepared by rotovating and subsoiling, then planting of layers 1.2 to 1.5 m height, at a regular spacing of 5x5 m, to provide a density of 400 trees ha^{-1}. Fertilization was carried out at establishment, by placing 50 g of a controlled release fertilizer (9-13-18-2: N, P_2O_5, K_2O and MgO) in the hole at planting. Weed control (by chopping rollers) and low pruning to a height of 1.5 m were carried out as tending operations, always with the main goal of timber rather than nut production.

The plantation is located near the city of Santiago de Compostela, northern Spain (42º 54´N, 8º 16´W, 330 m asl.). The average annual precipitation in the area is 1,836 mm and mean annual temperature is 12.8 ºC. The soil is developed on biotitic schists and, according to the FAO-UNESCO system is classified as an Umbrisol, with an A_h horizon at a depth of 0–25 cm and an AB horizon of 25–60 cm depth. The surface horizon of the soil is characterized by being acidic (pH 5.2) with a high content of organic matter (13.1%), loam texture (7.2% of coarse sand, 37.8 % of fine sand, 42.1% of loam, 12.8% of clay), and slightly low concentrations of available cations. The C:N relation was 8.6, well below the usual values for granitic rock in the area. The understory consisted of a complete cover of herbaceous vegetation, mainly *Dactylis glomerata*, *Plantago lanceolata* and *Holcus mollis*.

2.2. Experimental design

The ash was obtained from a paper pulp processing plant and was mainly derived from the combustion of bark (70% *Pinus* spp. and 30% *Eucalyptus* spp.). The composition of ash and the corresponding amounts of elements applied to the soil are shown in Table 1. The main properties of this product are as previously described (Solla-Gullón et al, 2006). The ash was applied in July 2001, when the plantation was 5 years old, before canopy closure, by use of a small rotary spreader with a 400 kg graduated hopper.

The study was carried out as a factorial design with four blocks and three treatments. The size of each plot was 35 x 35 m and the treatments included no fertilization (control) and two doses of MWBA, D10 (10 Mg dry weight ha^{-1}) and D20 (20 Mg ha^{-1}). In relation to the total nutrient requirements for forest production calculated for a chronosequence of chestnut coppice (Ranger and Colin-Belgrand, 1996), D10 would add only a quarter of the P and K requirements, two-thirds of Mg and all the Ca requirements, whereas D20 would add half of the P and K requirements and all the requirements in Ca and Mg (see Table 1). The concentration of P was low, as usually reported for wood and bark ash (Demeyer et al, 2001). The low amount of N in the MWBA was acceptable because of the high availability of N in the soils under study.

2.3. Sampling and analysis of plants and soil

Soil samples were collected just before and one month after ash application, then every three months for 27 months (June 2001 to September 2003). No further samples were taken because of rapid convergence of the treatments. Samples from the upper mineral horizon (20 cm) were collected at random from six points and were mixed to obtain one composite sample per plot. Soil samples for chemical analysis were air dried and sieved with a 2 mm screen. Total C, N and S were analysed with a LECO CNS Analyzer. Available P, Ca, Mg, K, Mn, Fe, Cu, Ni and Zn were extracted by the Mehlich 3 procedure (Mehlich, 1984) and were determined by ICP-OES.

Leaf samples were collected twelve times, starting in July 2001, i.e., five growing seasons after plantation. The samples were collected three times a year (April, July and September) in 2001, 2002 and 2003. Undamaged and full-sized leaves were sampled from dominant and codominant trees in the upper third of unshaded crowns in the plot. Each sample consisted of 100 leaves, which were pooled to provide a composite foliage sample for each plot, so that there were 12 samples per date. Foliar samples were oven-dried (65ºC) to a constant weight, milled (0.25 mm) and extracted with H_2SO_4/H_2O_2 (Jones et al., 1991). The concentrations of P, K, Ca, Mg, Mn, Fe, Cu, Ni and Zn in the leaf extracts were determined by ICP-OES. The contents of N and S in solid milled material were determined in a LECO Analyzer.

To determine the nutritional status of the trees, the reference foliar levels for *Castanea sativa* proposed by González-Rodríguez (1975), Leonardi et al (1996) and Portela et al (2003) were used. Comparisons were also made with the mean levels observed for young plantations of this species in Galicia by Álvarez et al. (2004). References values are shown in Table 2. The second approach used for foliar analysis was the vector analysis technique (Timmer and Stone, 1978), in which the relative concentrations and relative nutrient contents in biomass are presented graphically, considering the control as the comparison level. This method allows the identification of dilution (slight increase in content with decreasing concentration), sufficient levels (increase in content without change in concentration), deficiency (increase in content with slight increase in concentration), luxury consumption (increase in content and concentration at the same rate) and even excessive levels or toxicity (in the case of decreasing content). The dry weight of each leaf was estimated from the weight of 100 representative leaves.

2.4. Tree measurements and data analysis

The breast height diameter and total height were measured in April 2001, September 2003 and again in July 2008 in all trees within the plots. The diameter at breast height was measured in two directions on all the trees, to within 1 mm. Tree height was measured with telescopic measuring rods, to within 10 cm. Cross measurement of crown diameter was determined in July, 2008, and the geometric mean calculated (DC12). Increments were calculated as differences between measurements; the variables considered for analysis were the diameter and height increment between age 5 and 8 years (ID8 and IH8) and the increments between ages 8 and 12 years (ID12 and IH12). As the trees were planted following a regular 5x5 m grid, the approximate x–y coordinates of each tree were recorded considering their position in the block.

Residuals of each variable after subtraction of the treatment effects were used to explore the spatial structure of the data. A one-way analysis of covariance with the treatment effect considered as fixed was carried out with the initial diameter (or height) as the covariate, by use of the GLM procedure of SAS (SAS Institute 2004). The spatial structure of the resulting residuals was modelled with a semivariogram, which plots the semi-variance among trees as a function of the distance between them (Cressie 1993). The semi-variance γ(h) was calculated as:

$$\gamma(h) = \frac{1}{2n}\sum_{i=1}^{n}\left[z(s_i) - z(s_{i+h})\right]^2 \tag{1}$$

where n is the number of pairs of neighbouring trees separated by distance h (called the lag distance), $z(s_i)$ is the measured variable for a tree located at s_i, and $z(s_{i+h})$ is the value for a tree located at a distance h from s_i. Experimental semivariograms were constructed by use of the VARIOGRAM procedure in SAS (Sas Institute, 2004). An exponential theoretical semivariogram $\gamma(h)=c_n+c_0(1-e^{-h/a0})$ was fitted to the experimental semivariogram by the NLIN procedure in SAS (SAS Institute 2004).

The variation of residuals was parted into spatially autocorrelated variation and random error by kriging. The kriging values at each tree location were used to correct the original values of each variable in relation to their spatial variation. The kriging analysis was performed by the KRIG2D SAS procedure (SAS Institute 2004).

Values adjusted for the spatial structure were then analysed with the following random model:

$$y_{ijk} - k_{ijk} = x_{ijk} + \mu + T_i + B_j + TB_{ij} + \delta_{ijk} \qquad (2)$$

where y_{ijk} is the value of the original variable of the *k*th tree in the *j*th block and the *i*th treatment, k_{ijk} is the kriging estimate at the position of that tree, x_{ijk} is the covariate, μ is the overall mean, F_i, *Bj*, and FB_{ij} are the random effects of treatment *i*, block *j*, and the interaction, and δ_{ijk} is a spatially independent error. The same statistical model was also used to analyse uncorrected original values. The GLM procedure of SAS (SAS Institute, 2004) was used for analysis of covariance. The use of Eq 2 results in diameter increments adjusted for differences in initial diameters and therefore, treatments were tested for their impacts on adjusted means. Tukey's studentized range (HSD) was employed.

3. Results

3.1. Effect of ash in tree growth and mortality

The residuals obtained after subtracting treatment effects revealed non-random spatial structures. The semivariograms revealed spatial autocorrelation, but of pattern and intensity that varied greatly among the different growth variables and periods, as is shown in Fig. 1. Spatial heterogeneity was much more evident for the first growth period, as revealed by higher path-nugget variance ratios (c_o/c_n), but was also present for the second period. Height growth had a greater intensity of spatial structure than diameter growth.

The effective range ($3a_o$) or patch size of the exponential theoretical semivariograms was also variable, although generally lower than the block side (35 m) for the first growth period, indicating spatial heterogeneity within blocks that implies a violation of the block design assumptions. As an example, the spatial variation in ID8, modelled by kriging, is shown in Fig. 2.

The results of the ANCOVA are shown in Table 3, for both the non-spatial and the two spatial analyses. The initial height or diameter value was always considered as a covariate in the analysis to explain growth. The interaction was completely removed when the position of each tree was considered in the analysis using the iterative kriging. The effect of the treatment was much clearer after spatial analysis, and the least-squares means (LSmeans) classification provided a better understanding of the differences between treatments. Application of the ash enhanced the diameter and height growth in the first 3-year period, with better growth as the dose increase. For the second 4-year period, the effect was still significant, but only the D20 dose provided a response that was significantly different from the control. The block effect, which was always significant for the non-spatial analysis, was removed by kriging in the case of ID8 and IH8.

Seedling mortality after ash application was analysed throughout the study. Average mortality was 4.1% (D20), 7.1% (D10) and 17.7% in the control plots. The combined effect of mortality and crown width led to a clear increase in the percent of canopy cover (58.1% in D20, 64.7% in D10 but only 35.7% in the control plots).

3.2. Growth in relation to nutrition

Foliar N and P concentrations in the control plots were between 18-21 and 1.7-3.5 mg g^{-1}, respectively, which can be considered as sufficient for this species (Table 2). The application of ash had no significant effect and the vector analysis indicated that both elements were sufficient for satisfactory growth of the plantation (data not shown). Foliar Ca concentrations were low in the control plots, between 5.5 and 8 mg g-1, and ash application did not have any effect on the concentrations. The concentrations of K ranged from 4.3 to 7 mg g^{-1}, clearly below the marginal values proposed for the species, also with no increase in concentrations resulting from ash application. In the case of Mg, the range was between 2.2 and 3.6 mg g^{-1}, well above the marginal concentration of 2 mg g^{-1} proposed for chestnut. Again ash application did not have any significant effect. For the last three elements, the vector analysis provided a positive response in terms of relative content and also relative concentration, indicating a slight positive effect in terms of nutrition (Figure 3).

Ash application had a significant effect on soil pH, which increased by up to 0.6 units (for the highest dose) in relation to the control plots (Figure 4). The effect was very short-lived, and the pH returned to values close to the initial values after only 18 months. The ash fertilization had a short term effect on the available concentrations of Ca, Mg and K, and was only significant in the case of K (Figure 4). The initial level of Ca was 535 mg kg^{-1}, a high level for the region, attributed to former use of the land as grassland. This was almost doubled by both doses of the ash, and the effect of the highest dose lasted longer. By July 2003, i.e., 24 months after fertilization, the levels returned again to the initial values. The initial concentration of available Mg was 54 mg kg^{-1}, also quite high for the region and it was also almost doubled by the fertilization, again with return to initial values after 24 months. The initial concentration of K was 75 mg kg^{-1}, close to the average levels for soils in the region, and there were no signs of previous fertilization with this element. The ash application led to very important increases in this element, exceeding 200 mg kg^{-1} for the dose of 10 t ha^{-1} in many samples. The effect was also short-lived and had almost disappeared after 24 months.

4. Discussion

Growth variables are very often affected by spatial heterogeneity. In this study, the intensity of the spatial structure was higher for the first period than for the second period; this appears reasonable if we consider that growth in the last phase is in fact much more affected by individual competition, as the plantation reaches canopy closure. Height growth displayed greater spatial correlation than diameter, as also found in genetic trials (Zas, 2006). The block structure of the randomized complete block design was not sufficient to account for this spatial heterogeneity, because the pattern of spatial structure was in small patches in relation to longer blocks, which were clearly too heterogeneous. The kriging procedure was able to remove the spatial variation.

The results of the present study showed that the ash treatment significantly affected growth of this young chestnut plantation. Although the duration of the effect is questionable, the increase in early growth can bring forward canopy closure in the plantation, thereby helping to check the growth of competing vegetation and reduce the risk of fire. Improved growth of tree species in response to wood-bark ash application has also been reported in studies of other forests growing in colder climates (Ferm et al., 1992; Moilanen et al., 2002) and, particularly, in fast growing species plantations when the ash is applied before canopy closure (Solla-Gullón et al, 2006). Taking into account the results obtained in the present study and from ash application in other fast growing plantations (Solla-Gullón et al., 2008), and considering the efficiency of the addition of ash, application of 10 Mg ha^{-1} of ash appears sufficient for each operation. In this study, the higher dose still had a clear effect after 7 years, although the repeated application of wood-bark ash in moderate amounts throughout the rotation appears more appropriate. The dose of 10 Mg ha^{-1} is higher that those reported in other colder climates and with less intensive silvicultural systems, in which doses of 3–7 Mg ha^{-1} are usually recommended (Hytönen, 2003).

The chemical soil properties of the chestnut habitat in Spain have been defined by Gandullo et al. (2004), but plantations in the northwestern area usually have values higher than the upper thresholds for the organic matter and soil total nitrogen (Blanco et al, 2000). It should be also considered that the plots had not yet reached canopy closure, and thus nutrient requirements of the stand were high in comparison with biomass production. After canopy closure, highly efficient nutrient recycling under low availability conditions can be expected (Ranger and Colin-Belgrand, 1996). Although European chestnut is known to grow on naturally acid soils, nutrient deficiencies can occur as a consequence of poor nutrient reserves or nutrient imbalances, leading to detrimental effects on tree growth and nut production (Portela et al. 2003). The results observed in the present study revealed a positive effect of ash fertilization in terms of Ca, Mg and K nutrition, even though the plantation was established on former agricultural land, in which there are generally no strong soil limitations for the species. The results are consistent with those obtained by Laroche et al (1997), who showed that addition of Ca and Mg had a positive effect on seedling growth.

5. Conclusions

The results of this 7-year-long study showed that the application of wood-bark ash improved the growth and nutritional status of a young hybrid chestnut stand. A dose of 10 Mg ha^{-1} repeated twice along the rotation appears appropriate for acid mineral soils in abandoned agricultural lands.

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Tables

Table 1. Chemical composition of the ash used in the study.

	Total[a]	Available[b]	Applied in wood ash 10/20 Mg ha^{-1} (kg)
Organic matter[c] (%)	42.4		
C (g kg^{-1})	116.3		1163 - 2326
N (g kg^{-1})	1.9		19 - 38
S (g kg^{-1})	0.3		30 - 60
P (g kg^{-1})	5.2	0.07	52 - 104
Ca (g kg^{-1})	99.7	32,9	997- 1994
Mg (g kg^{-1})	20.2	5.0	202 - 404
Na (g kg^{-1})	7.7	6.5	77 - 154
K (g kg^{-1})	30.2	27.9	302 - 604
Al (g kg^{-1})	15.1	n.d	151 - 302
Cd (mg kg^{-1})	3.6	0.9	0.04 – 0.08
Cr (mg kg^{-1})	20.7	3.1	0.21 – 0.42
Cu (mg kg^{-1})	54.7	15.1	0.55 – 1.1
Fe (mg kg^{-1})	1385	26.7	13.8 – 27.7
Mn (mg kg^{-1})	6173	106.3	61.7 – 123.4
Ni (mg kg^{-1})	118.6	43.0	1.2 – 2.4
Pb (mg kg^{-1})	79.0	22.0	0.79 – 1.6
Zn (mg kg^{-1})	334.7	35.2	3.3 -6.6
Hg (mg kg^{-1})	< 1		< 0.01

Moisture content (%): 11.2; pH (H_2O): 13.

[a]Digestion in HNO_3; [b] Extraction with Mehlich 3; [c] Calcination

Table 2. Reference range and foliar concentrations in chestnut (*Castanea* spp.) plantations in Galicia (NW Spain) for Castanea ssp plantations.

	Reference [a,b,c]	Young plantations (NW Spain)[d]
N (mg g^{-1})	15 - 25	23.6
P (mg g^{-1})	1.3 - 1.8	1.6
K (mg g^{-1})	8 - 13	7.3
Ca (mg g^{-1})	5 - 8	5.1
Mg (mg g^{-1})	1 - 2	2.4
Fe (mg kg^{-1})		113
S (mg kg^{-1})		1.7
Mn (mg kg^{-1})		60
Cu (mg kg^{-1})		4
Zn (mg kg^{-1})		27

[a] González Rodríguez (1975), [b] Leonardo et al (1996), [c] Portela et al (1999), [d] Álvarez et al (2004).

Table 3. Results of the ANCOVA analysis before and after removal of the spatial effect.

Variable	p level of ANCOVA factors. No spatial structure considered				LS means classification		
	Covariate	Treatment	Block	Interaction	C	D10	D20
ID8	<0.0001	<0.0001	<0.0001	<0.0001	3.45a	3.79a	4.22ab
ID12	<0.0001	0.0473	<0.0001	0.0054	7.57	7.54	8.70
IH8	<0.0001	0.0009	0.0027	<0.0001	1.54a	1.71b	1.80b
IH12	<0.0001	0.0029	<0.0001	<0.0001	3.21a	3.63ab	3.98b

Variable	p level of ANCOVA factors. Iterative kriging method				LS means classification		
	Covariate	Treatment	Block	Interaction	C	D10	D20
ID8	<0.0001	<0.0001	0.674	0.673	3.44a	3.75b	4.25c
ID12	<0.0001	0.0219	0.0095	0.504	7.92a	7.61a	8.82b
IH8	<0.0001	<0.0001	0.0187	0.605	1.57a	1.69b	1.81c
IH12	<0.0001	0.0264	<0.0001	0.091	3.45a	3.68ab	3.97b

FIGURE CAPTIONS

Figure 1. Examples of the semivariograms of residuals after subtracting treatment effects in a first iteration for the four variables analised in the study. The reduction in semivariance at short distances indicated a patchy structure. The effective range ($3a_0$) and the nugget value (c_n) are represented as vertical and horizontal lines, respectively. The intensity of the spatial structure (c_0/c_n) is shown for each graph.

Figure 2. Plot of height residuals after subtracting treatment effects in a fertilization trial of chestnut trees, showing nonrandom spatial variation and modeling of this variation through iterative kriging. White values represent dead trees. Five tones of grey are used to represent the total range of residuals and the residuals estimated by kriging, with black points representing the highest values of the original variable. Black lines are the block boundaries.

Figure 3. Vector analysis diagrams for the effects of wood ash treatments on foliage Ca, Mg and K in the young chestnut plantation. Relative concentrations and contents are referred to 100 for the control. The treatments are represented by ● for control, ▲ for D10 WBA, ♦ for D20 WBA. The arrow shows the main trend of change derived from ash application.

Figure 4. pH and available concentrations of Ca, Mg and K in soils, for the different treatments throughout three growing periods. On the x-axis, J is July, S is September, D is December and M is March. The treatments are represented with ● for control, ∆ for D10 WBA and ▲ for D20 WBA. Different letters show significant differences between treatments at each sample date ($p < 0.05$ in Tukey's test).

Figure

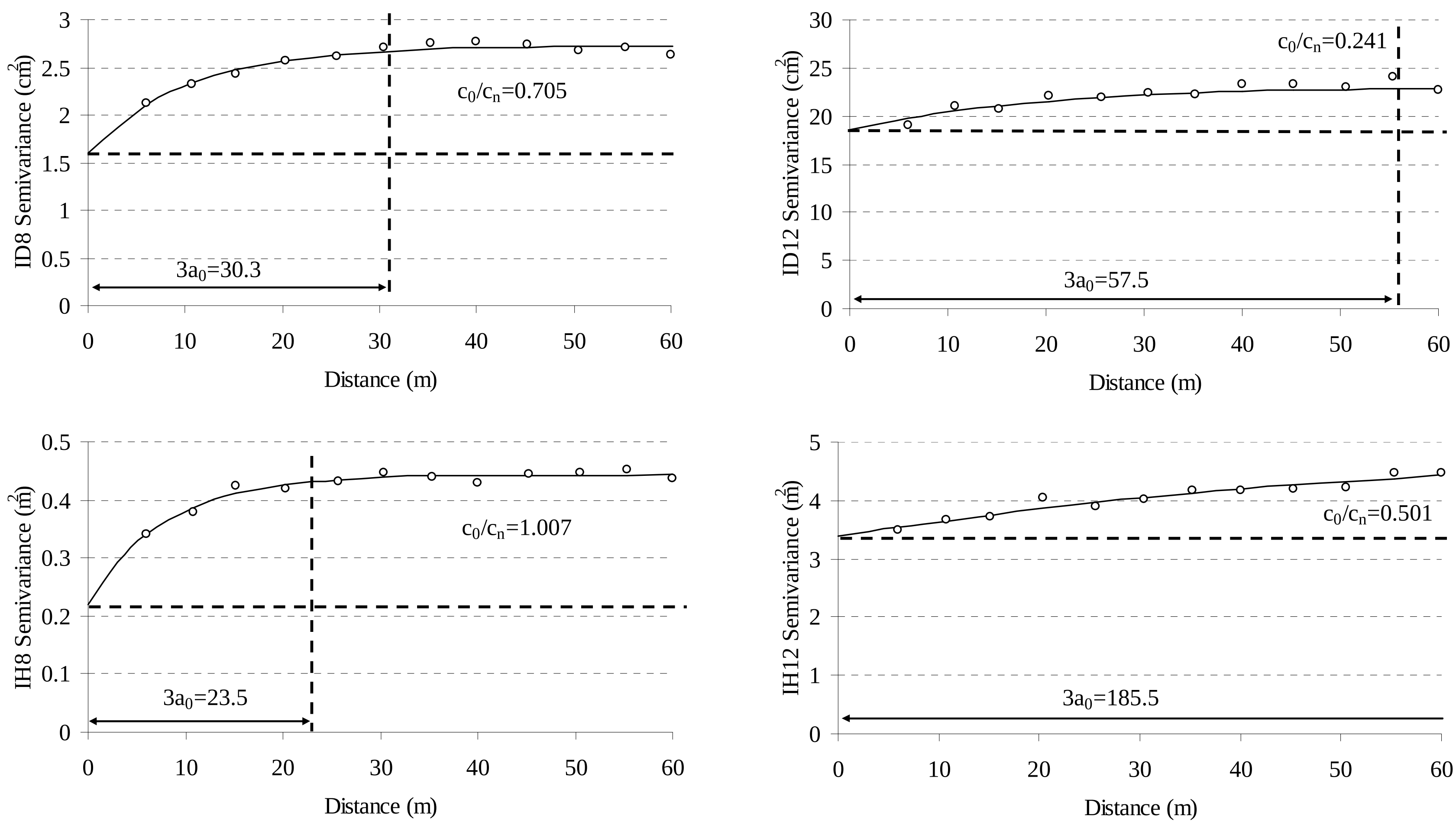

Figure 1

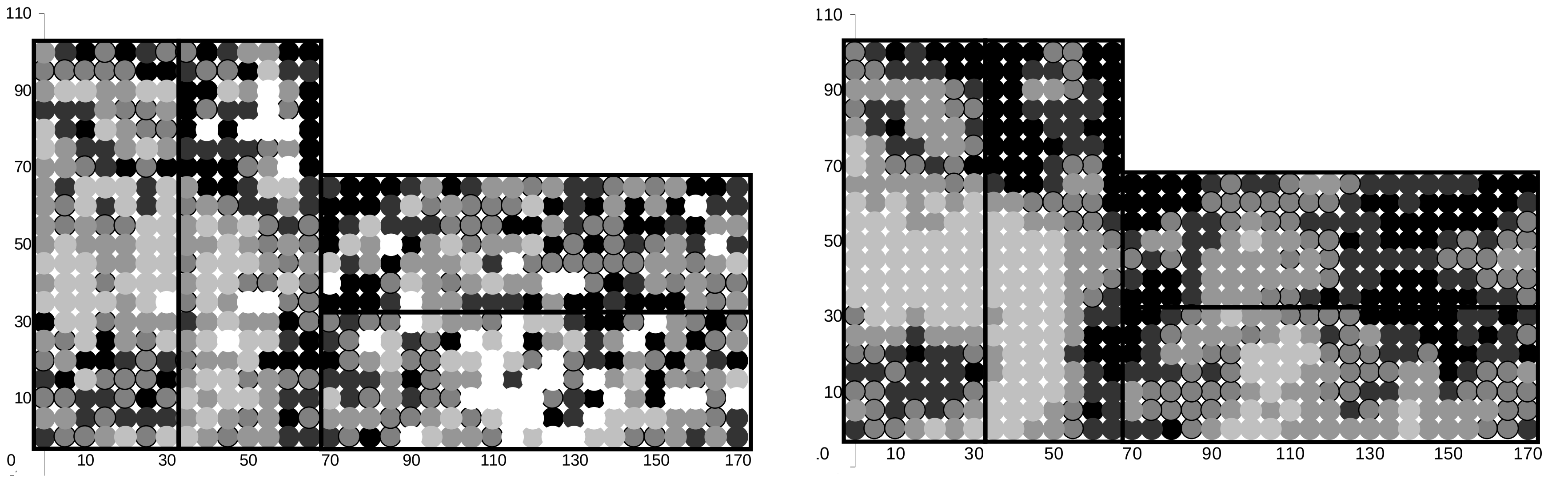

Figure 2

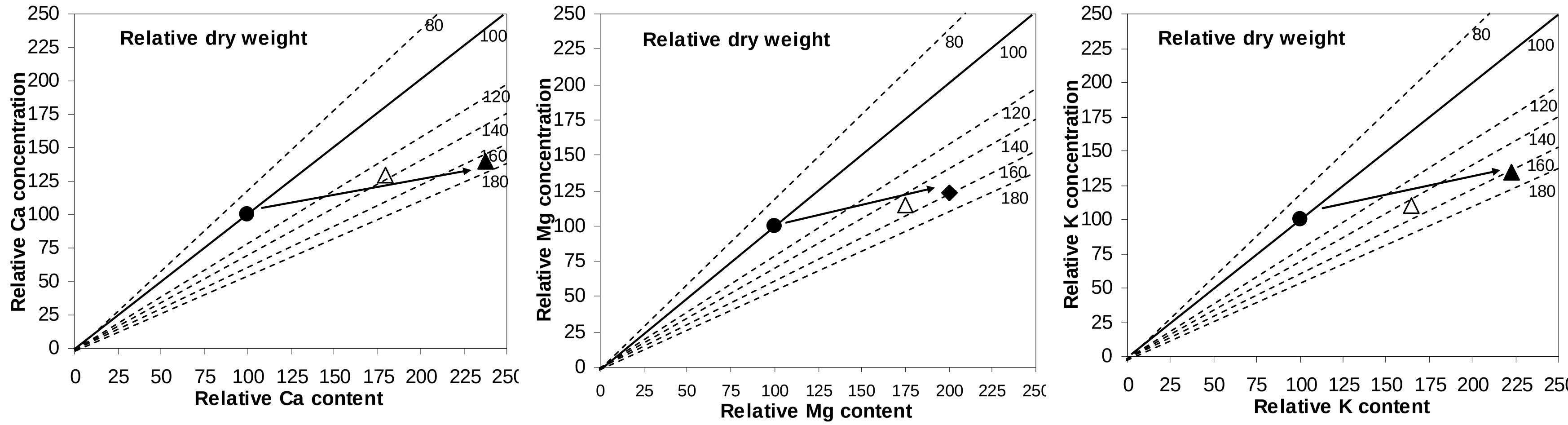
Relative dry weight
Relative Ca concentration
Relative Ca content
80
100
120
140
160
180
Relative dry weight
Relative Mg concentration
Relative Mg content
80
100
120
140
160
180
Relative dry weight
Relative K concentration
Relative K content
80
100
120
140
160
180

Figure 3

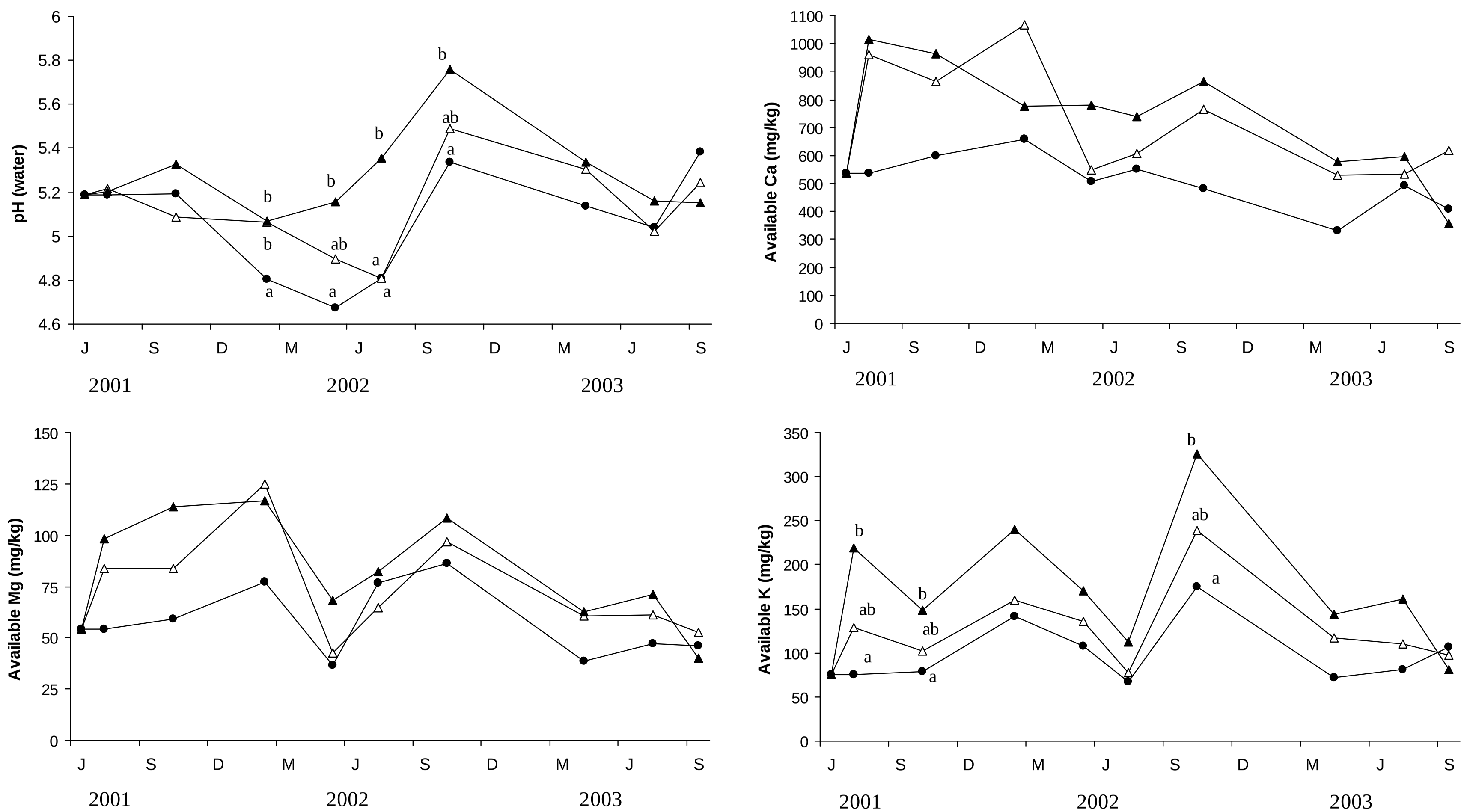
pH (water)
Available Ca (mg/kg)
Available Mg (mg/kg)
Available K (mg/kg)
J S D M J S D M J S
2001
2002
2003

Figure 4