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Effect of landscape position on the acidification of loess-derived soils under *Pinus radiata*

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Abstract Interactions between landscape position and the acidifying effect of trees planted into loess-derived grassland soils were studied in the Ventana region of Argentina. Forests of *Pinus radiata* planted at the end of 1940, were selected in two different positions from the landscape, plains and slopes. Samples of the soil surface mineral horizon were taken from landscape positions at four distances from the trees and compared with grassland soils. The values of the main soil chemical properties changed significantly with distance from trees, with a decrease in pH, base saturation, exchangeable Ca^{2+}, Mg^{2+} and K^+, and increase in Na^+, Al^{3+} and particularly H^+ closer to the trees. This pattern confirms the prominent role of vegetation in bringing about changes in soil properties. Regression models showed high levels of explanation ($r^2 > 0.85$) indicating that a high percentage of the spatial variability of soil chemical properties is systematic and predictable with distance from the trees. The pH in KCl proved an excellent tool for predicting the cationic composition of soils. Organic carbon and total nitrogen were significantly higher in the plains positions than in the slopes under the trees, whereas there was no difference under grassland. The slopes of the regression lines indicated that acidification is more intense in soils on the plains. Vegetation was the main factor influencing acidification of the studied soils. The landscape position regulates the bio-hydrological factor and thus the speed of acidification process.

Key words: landscape–vegetation interaction, pH KCl-prediction models, soil acidification, tree.

INTRODUCTION

Terrestrial ecosystems consist of a complex mosaic characterized by interactions among landform, climate, lithology, vegetation and soils, as well as by natural and anthropogenic disturbances (Hole & Campbell 1985). Disturbances are a major cause of variability in components of ecosystems. The magnitude and speed of modifications that take place in the soils are closely related to the disturbance level that the system can absorb. The soil resistance to the change will depend on the characteristics and properties of the soils and also on the intensity of the stress to which they are subjected (Seybold *et al.* 1999). Significant landscape transformations are brought about by drastic modifications in the vegetative cover. Vegetation is an active factor in pedogenesis, so that changes in natural vegetation can affect soil formation, particularly when exotic species are introduced which by virtue of their composition, characteristics and architecture lead to particular pedogenetic processes. Numerous studies have demonstrated that the introduction of forest species into natural grassland areas triggers a secondary soil formation process associated with the mechanisms involved in forest soil genesis. As a consequence of this process, the soil suffers degradation by acidification, attributed to the leaching of bases, production of strong organic acids and H_2CO_3, acidic hydrolysis, alteration of the cationic/anionic absorption balance, an increment in ionic strength, nitrification and fungal activity (Driscoll & Likens 1982; Nilsson *et al.* 1982; Binkley 1986; Binkley & Richter 1987; Pallant & Riha 1990; Urrego 1997). Amiotti *et al.* (2000) demonstrated acidification in the surface horizons of loess-derived soils below forest stands of *Pinus radiata* D. Don. Owing to the particular structure and dynamics of the forest ecosystem, the natural habitat shows fragmentation into patches revealing anthropogenic degradation, with borders defined by an abrupt change in the type of vegetation. The uniformity of plant composition within the forest system does not lead to increased homogeneity of the soils. On the contrary, it results in increased lateral variability as a consequence of the influence of each individual tree. Despite the significantly greater spatial heterogeneity of the soils, closer observation indicates that they have a high degree of non-random variability. Vegetation plays an active role in soil formation. Many studies that have assessed the degree of anthropogenic disturbance, take biota as the only independent variable. However, the type and/or the speed of the processes resulting from the substitution of the natural vegetation are determined by the interaction of biotic and abiotic factors. We aimed to identify the combination of influencing factors that ultimately determines the speed at which the soil resource is depleted.

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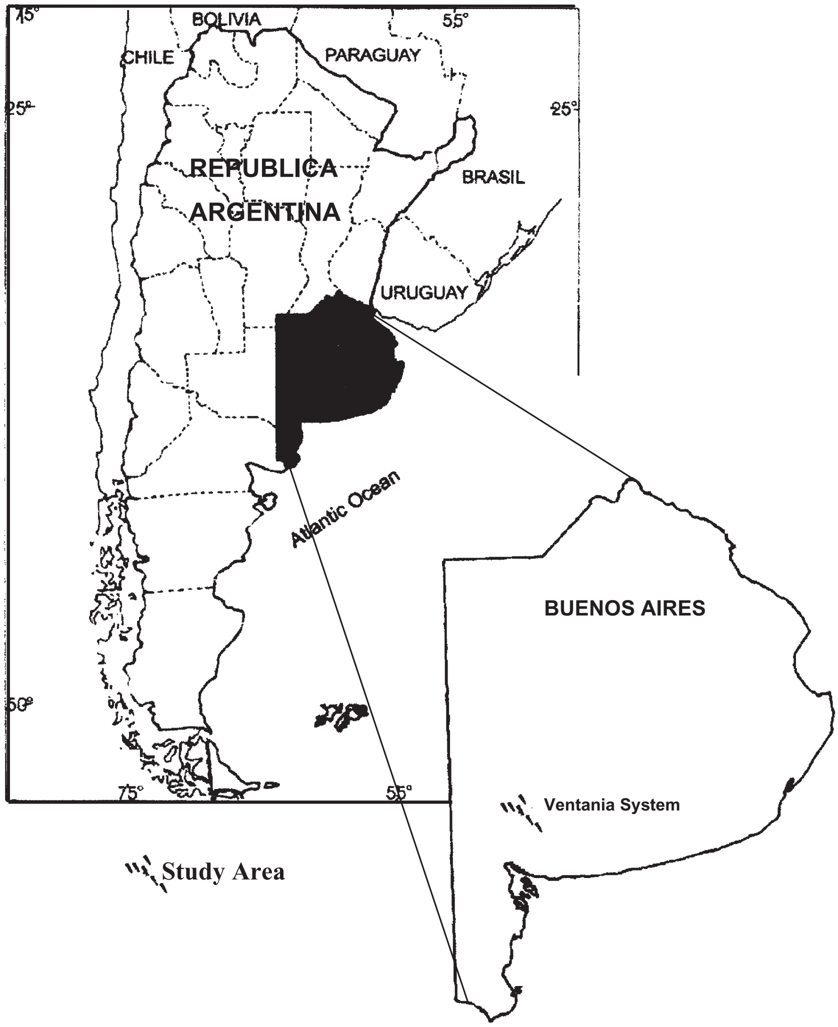

Fig. 1. Geographical location of the study area.

Under similar climatic conditions, the impact of the disturbance caused by a drastic change in vegetative cover is absorbed differently in different reliefs. The purpose of the present study was to evaluate the interactions between the acidifying effect of coniferous vegetation and local variations in the landscape, in loess-derived soils of the Ventania area of Argentina. Our ultimate objective was to establish the degree of interdependence among factors and to determine soil resistance in different landscape positions within the mountain system.

MATERIALS AND METHODS

Characteristics of the area

The study area was located in the Ventania system in the south-west of the Province of Buenos Aires, Argentina, at an elevation of 650 m above sea level (Fig. 1). The topography ranges from steep slopes at high elevations of the mountain system to gentler slopes at lower levels (piedmont). The climate is humid and temperate, with a mean annual temperature of 14.5°C, and an average annual rainfall of 850 mm. The regional soils are Typic and Lithic Argiudolls and Hapludolls developed from pure loess sediments or mixed with rock detritus (Vargas Gil & Scoppa 1973). The natural vegetation consists of *Stipa ambigua*, *S. caudata* and *S. neesiana*. *Paspalum quadrifarium* covers the humid slopes, and endemic gramineous species such as *Festuca ventanicola*, *F. pampeana* and *Stipa pampeana* are present above 500 m. Endemic trees consist of isolated specimens of *Prunus mahaleb* (Cabrera 1968). A number of different forest species have been introduced into the area since the early 1900s such as *P. radiata* D. Don, *Pinus halepensis* Mill (Roxb) Loudon and *Cupressus sempervirens* f. Horizontalis (Mill) Voos.

Sampling, laboratory determinations and statistical analysis

Three forests of *P. radiata* established at the end of the 1940s were selected. In each, paired samples of soils were collected in plains (plains: P_1) and in slopes with 10% gradient (slopes: P_2). Soils in P_1 were classified as Typic Argiudolls developed from thick loess sediments containing an average of 34% clay, quite good drainage and slow run-off. In P_2 the loess sediments were mixed with rock detritus and contained less clay (28%). The dominant soils were Lithic Hapludolls, well-drained and with medium to rapid run-off.

In order to evaluate the influence of topography on the rate of acidification by individual trees, soil surface mineral horizon samples (epipedon: 0–18 cm) were taken in P_1 and P_2, at four sampling sites: 0, 1 and 2 m distance in transects from the trunk towards the periphery of the crown, and 4 m which is outside the sphere of influence of the tree. In both landscape positions the last soil samples (4 m) were compared with grassland soils (controls). We selected three pairs of positions (P_1 and P_2), two trees per position and four distances to the trunk, totalling 48 samples within the forest. The transects were traced randomly in different directions in order to obtain representative samples.

Soil samples were air-dried and sieved to remove any coarse fragments (particles >2 mm diameter) and the following determinations were made: pH in 1:2.5 soil-water suspension, and a 1:2.5 soil-KCl 1 mol L^{-1} suspension using a glass electrode pH meter; organic carbon (OC) by dry combustion (LECO carbon analyser) and total nitrogen (N) by the macro Kjeldahl technique. The exchangeable cations were extracted with 1 mol L^{-1} NH_4OAc, pH 7; Ca^{2+} and Mg^{2+} were determined by EDTA titration; Na^+ and K^+ by flame photometry; Al^{3+} by plasma spectrometry after extraction by 1 mol L^{-1} KCl; and cation exchange capacity was determined by saturation with 1 mol L^{-1} NaOAc, pH 8.2, and extraction through 1 mol L^{-1} NH_4OAc, pH 7 (Rhoades 1982). Total acidity was calculated by subtraction of exchangeable bases from the cation exchange capacity determined by ammonium exchange at pH 7.0.

The grassland controls and the distance 4 m to the trunk were compared using two-way ANOVA. The effects of the distance from the trunk, the landscape position and their interaction were evaluated by repeated measures ANOVA. Mean values of soil variables were compared by the Least Significant Difference test (LSD) when the *F*-test indicated significant differences. In order to compare P_1 and P_2, correlations among all the soil variables were carried out by defining simple linear regressions between these variables and the distance from the tree trunk ($n = 24$). Regressions were checked by the study of deviations and residuals data. Linear regressions were compared by covariance analysis (Steel & Torrie 1981).

RESULTS

Chemical properties of soil mineral horizons under gramineous vegetation (controls) at two landscape position are shown in Figure 2 (position 5 on the *x*-axis). In these controls the pH in water was slightly acid (6.4–6.8) in P_1 and in P_2. In both cases soils exhibited a high saturation with bases (>90%) prevailing Ca^{2+} and Mg^{2+} contents with a low proportion of monovalent cations. Approximately 11% of charges were saturated with H ions and there was no Al^{3+} at the exchange sites. OC levels higher than 5.5 g kg^{-1} and total N levels higher than 0.4 g kg^{-1} were observed in both controls P_1 and P_2. The C/N ratio was lower in P_2 than in P_1 indicating more favourable conditions for organic matter mineralization.

At 4 m from the trunk, outside the sphere of influence of the trees, the analysed variables were similar to those obtained in soil controls ($P > 0.12$–0.98), indicating that the acidifying effect of trees exclusively occurred under the projection area of their crown.

In both landforms (plains and slopes) patches of *P. radiata* caused modifications of soil properties, differentiating them from those of the surrounding native grassland (Fig. 2). The effect on soil chemical properties exerted by each individual tree was clearly manifested both on the plains (P_1) and on the slopes (P_2). Exchangeable Ca^{2+}, Mg^{2+} and K^+, saturation with bases and pH decreased with distance from the tree while the concentration of exchangeable Al^{3+} and H^+ increased closer to the trunks.

Vegetation played a predominant role in determining the changes in soil properties, however, the results for most of the analysed variables revealed an interaction between landscape position and the rate of acidification in forest stands (Table 1). Base saturation decreased significantly from the natural grassland towards the tree. Distance from the tree played a greater role in this effect than position in the landscape.

A high degree of acidification was observed close to the trees in both landscape positions. Statistical analysis showed that soil pH increased linearly with distance from the trunk ($P < 0.001$). This behaviour was similar in both landscape positions but the regression slope was greater in P_1 than in P_2 ($P < 0.01$) where the acidification process was more intense. A decrease of 2.0 and 1.5 pH units was found next to the trunks in P_1 and P_2, respectively (Fig. 2a). The similar decreasing trend was observed with the base saturation and divalent exchangeable cations but with differential loss rates. In both landscape positions, significant losses of exchangeable Ca^{2+} ($P < 0.05$) were observed under the

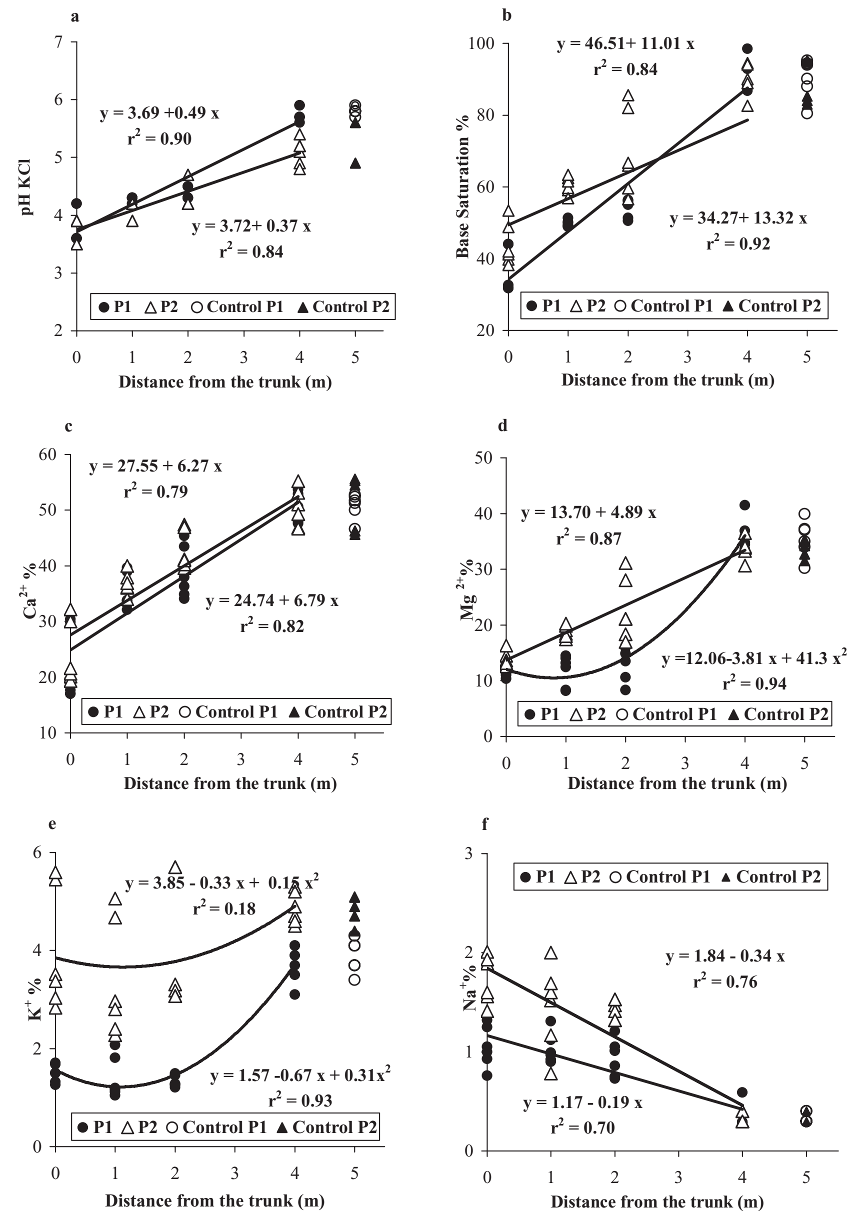

Fig. 2. Relations between soil properties and distance from the trunk of *Pinus radiata*. ($n = 24$). Base saturation, Ca^{2+}, Mg^{2+}, K^+ Na^+, H^+ and total acidity expressed as CEC% (cmol kg^{-1}).

pine cover. The Ca^{+2} content was reduced to less than half close to the trunk in comparison with the grassland soils. No differences between landscape positions were detected (interaction not significant, $P > 0.50$).

Exchangeable Mg^{2+} reacted differently to Ca^{2+} in the presence of acid input and there was a clear position/distance interaction. Although in both P_1 and P_2 there was pronounced loss of Mg^{2+} towards the periphery of the projection of the crown (2 m), the rate of decrease was much sharper in P_1. Statistically significant differences were found between plains and slopes at 1 m and 2 m ($P < 0.05$), but not at 0 m ($P > 0.21$).

In the case of exchangeable K^+, landscape position was highly significant ($P < 0.01$) at all distances from the tree, with lowest values in the plains. For Na^+ there was a significant distance–position interaction effect. In both landscape position Na^+ levels decreased with distance from the trunk, but there was a greater decrease on the slopes (P_2) because of the overall higher Na^+ levels close to the trunk in that landscape position.

The pronounced loss of basic cations under trees produced a sharp acidification of the topsoil. The influence of landscape position on total soil acidity was

Table 1. Summary analysis of variance for landscape position, distance from the tree trunk and interaction between position and distance

Soil Variable	Landscape position	Distance from the trunk	Position × distance	Trend components† (distance factor)
pH H_2O	*	***	NS ($P > 0.10$)	cubic
pH KCl	*	***	***	cubic
C.E.C.	***	***	***	cuadratic
B.S.	***	***	*	linear
Ca^{2+}%	NS ($P > 0.34$)	***	NS ($P > 0.50$)	cubic
Mg^{2+}%	***	***	***	linear
Na^{+}%	***	***	***	cubic
K^{+}%	***	***	***	cuadratic
H^{+}%	***	***	*	cuadratic
Al^{3+}%	NS($P > 0.18$)	***	NS ($P > 0.15$)	cuadratic
TA percentage	***	***	***	linear
OC g kg^{-1}	***	NS ($P > 0.55$)	***	NS ($P > 0.15$)
N g kg^{-1}	***	NS ($P > 0.78$)	***	NS ($P > 0.57$)
C/N	***	*	NS ($P > 0.64$)	linear

*, ***Significant at 0.05 and 0.001 level, respectively. †First, second or third order components obtained by orthogonal contrasts showed significant trends ($P < 0.01$). BS, soil base saturation; C/N, soil carbon nitrogen ratio; NS, not significant; OC, soil organic carbon; TA, soil total acidity.

significant at all distances from the tree, with higher levels of acidification being found in P_1. The presence of Al^{3+} in the exchangeable complex of soils close to the trunk and even up to a distance of 1 m indicated degradation processes linked to the acid hydrolysis of silicates at both positions in the landscape. The position/distance interaction was not significant ($P > 0.15$) mainly owing to the variability of the results from 1% to 8% in P_1 and from 3% to 15% in P_2.

The interrelationship between vegetation and landscape position was shown clearly in the chemical organic properties of the surface mineral horizon. While significant increases in OC and total N contents were observed in P_1 towards the tree ($P < 0.05$), no statistically significant differences were observed in P_2 ($P > 0.10$). No great differences in OC content of mineral soils from grassland and forest ecosystems in the same study area were reported by Zech *et al.* (1997) or Amiotti *et al.* (2000). However, the present study demonstrated that OC content was strongly influenced by the landscape position in the forest ecosystems.

In both landscapes, P_1 and P_2, the increment in C/N ratio under trees reflected reduced N mineralization attributable to less microbiological activity under low pH conditions (Amiotti *et al.* 2000) and also high resistance to decomposition of coniferous litter (Zalba & Peinemann 1987). Furthermore, the highest values of C/N ratios in P_1 were related to the higher accumulation of litter in this positions of the landscape.

Highly significant linear relationships between the analysed variables and distance from the stems of the trees were found for both landscape positions (Fig. 2). Regression lines of pH, base saturation, exchangeable Ca^{2+}, Mg^{2+}, H^+ and total acidity all showed very high correlation coefficients ($r^2 > 0.80$). These regression models corroborated the systematic and predictable variation in soil properties with distance from trees. This behaviour was not observed when analysing variations in soil OC and total N content (r^2 between 0.28 and 0.47).

There were many statistically significant correlations between the studied variables for both position, though more so for the plains where the variability of soil properties was lower, a result of the stability in the landscape positions with low gradients. Soil from this less heterogeneous landscape position responded more uniformly to the acid input from each individual tree. In most cases, variables closely related to the acidification process showed higher percentages of correlation. Potential acidity, determined as the pH in KCl, showed very high regression coefficients ($r^2 > 0.80$) and proved to be an efficient way of predicting cationic soil balance in both landscape positions. Table 2 presents simple linear regressions taking pH in KCl as the independent variable.

DISCUSSION

Our results for the variables associated with the acidification processes (pH, exchangeable Al^{3+} and H^+) were in agreement with those reported by Zinke (1962), Ryan and McGarity (1983), Riha *et al.* (1986a,b), Wolfe *et al.* (1987), Boettcher and Kalisz (1990) and Amiotti *et al.* (2000), for different forest

Table 2. Equations from simple linear regressions for predicting soil cationic composition, base saturation and total acidity as function of pH in KCl ($n = 24$)

Landscape position	Equation	R^2
P_1	BS(%)† = −62.40 + 26.29. (pHKCl)	0.98*
P_2	BS(%) = −57.22 + 28.14. (pHKCl)	0.91*
P_1	Ca^{2+} (%) = −23.54 + 13.18. (pHKCl)	0.84*
P_2	Ca^{2+} (%) = −30.77 + 15.85. (pHKCl)	0.83*
P_1	Mg^{2+} (%) = −38.24 + 12.34. (pHKCl)	0.83*
P_2	Mg^{2+} (%) = −31.18 + 12.22. (pHKCl)	0.90*
P_1	H^+ (%) = 154.30 − 24.74. (pHKCl)	0.97*
P_2	H^+ (%) = 137.06 − 24.08. (pHKCl)	0.90*
P_1	TA(%) = 162.47 − 26.31. (pHKCl)	0.98*
P_2	TA(%) = 156.76 − 28.10. (pHKCl)	0.90*

*Significant at $P < 0.01$ probability level. †Expressed as CEC %. BS, soil base saturation; P_1, plain; P_2, slope; TA, soil total acidity.

species in USA, Europe, Asia, Australia and Argentina. Soil acidification in forest stands can be explained by the composition of the litter (highly acid and poor in bases) and by the quantity and quality of the rainwater penetrating into the soil.

The intensity of the acidification process set in motion around the trees varied with the landscape position. On the plains, the effect of acid input was greater than on the slopes owing to a higher degree of percolation of rain water throughout the whole projection area of the tree crown and to the higher accumulation of acid litter through which the water percolates. Moreover, on the plains the acidifying role of pines was intensified because of a larger accumulation of organic matter.

Our study confirmed the importance of tree vegetation in determining changes in grassland soil properties. In both studied landforms (plains and slopes), changes in the vegetation cover led to patches that were degraded by acidification of the topsoil. Soil properties that are a direct consequence of biotic factors had been altered rapidly and were approaching a new steady state associated with forest soil genesis.

Soils affected by acidification showed a distinctive spatial pattern based on radial symmetry around each individual tree. Regression models with high correlation coefficients indicated that a high percentage of the variability observed was systematic and predictable in both landscape positions. This behaviour is attributable to the differential impact of the bio-hydrological soil forming factor within the forest patch (Amiotti *et al*. 2000).

The study showed an interaction of vegetation and landscape position effects on soil properties. Landscape position affected the intensity of the acidification process in the surface mineral horizons. The slopes of the regression lines indicated that acidification was more pronounced in the plains. Vegetation determined the change in soil properties but landscape position controlled the speed of the acidification process.

The effect of the introduction of pines in grassland exceeded the level of disturbance the soil is able to tolerate, thus, irreversible degradation processes were generated. The presence of Al^{3+} in soils adjacent to trees is evidence that the soil system is probably unable to return to its initial state even after the forest replacement.

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REFERENCES

Amiotti N. M., Zalba P., Sánchez L. F. & Peinemann N. (2000) The impact of single trees on properties of loess-derived grassland soils in Argentina. *Ecology* **81,** 3283–90.

Binkley D. (1986) Soil acidity in loblolly pine stands with interval burning. *Soil. Sci. Soc. Am. J.* **50,** 1590–4.

Binkley D. & Richter D. (1987) Nutrient cycles and H^+ budgets of forest ecosystems. *Adv. Ecol. Head.* **16,** 1–51.

Boettcher S. E. & Kalisz P. J. (1990) Sail-tree influence on soil properties in the mountains of eastern Kentucky. *Ecology* **71,** 1365–72.

Cabrera A. L. (1968) *Flora de la Provincia de Buenos Aires.* Colección Científica. INTA IV (1). Colección Científica, Buenos Aires.

Driscoll C. T. & Likens G. E. (1982) Hydrogen ion budget of an aggrading forested ecosystem. *Tellus* **34,** 283–92.

Hole F. D. & Campbell J. B. (1985) *Soil Landscape Analysis.* Routledge & Kegan Paul, London, Melbourne and Henley.

Nilsson S. I., Miller H. G. & Miller J. D. (1982) Forest growth as a possible cause of soil and water acidification and examination of the concepts. *Oikos* **39,** 40–99.

Pallant E. & Riha S. J. (1990) Topsoil acidification under net pine and Norway spruce. *Soil Sci. Soc. Am. J.* **54,** 1124–30.

Rhoades J. D. (1982) Cation exchange capacity. In: *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*, 2nd edn. (eds A. L. Page, R. H. Miller & D. R. Keeney) pp. 149–57. Agron. Monogr. 9. ASA and SSSA, Madison.

Riha S. J., James B. R., Senesac G. P. & Pallant E. (1986a) Spatial variability of soil pH and organic matter in forest plantations. *Soil Sci. Soc. Am. J.* **50,** 1347–52.

Riha S. J., James B. R., Senesac G. P. & Pallant E. (1986b) Effects of forest vegetation on spatial variability of surface mineral soil pH, soluble aluminium and coal. *Water Air Soil Pollut.* **31,** 929–40.

Ryan P. J. & McGarity J. W. (1983) The nature and spatial variability of soil properties adjacent to large forest eucalyptus. *Soil Sci. Soc. Am. J.* **47,** 286–93.

Seybold C. A., Herrick J. E. & Bredja J. J. (1999) Soil resilience: a fundamental component of soil quality. *Soil Sci.* **164,** 224–34.

Steell R. G. & Torrie J. H. (1981) *Principles and Procedures of Statistics*, 2nd edn. McGraw-Hill, New York.
Urrego B. (1997) La reforestación con coníferas y sus efectos sobre la acidificación, podsolización y pérdida de fertilidad de los suelos. *INPOFOS Inf. Agr.* **28,** 6–12.
Vargas Gil J. & Scoppa C. (1973) Suelos de las Sierras Australes de la Provincia de Buenos Aires. *Rev. Invest. Agrop. Ser. 3* **X,** 57–79.
Wolfe M. H., Kelly J. M. & Wolt J. D. (1987) Soil pH and extractable sulfate-sulfur distribution are influenced by tree species and distance from stem. *Soil Sci. Soc. Am. J.* **51,** 1042–9.
Zalba P. & Peinemann N. (1987) Efectos de algunas especies forestales sobre ciertas propiedades fisicoquímicas del suelo. *Ciencia del Suelo* **5,** 71–6.
Zech W., Guggenberger G., Zalba P. & Peinemann N. (1997) Soil organic matter transformation in argentinian Hapludolls. *Z. Pfanzenernahr. Bodenk.* **160,** 563–71.
Zinke P. J. (1962) The pattern of influence of individual forest trees on soil properties. *Ecology* **43,** 130–3.