Responses of a Non–N-Limited Forest Plantation to the Application of Alkaline-Stabilized Dewatered Dairy Factory Sludge

Beatriz Omil, Rosa Mosquera-Losada, and Agustín Merino* Universidad de Santiago de Compostela

Amendment of forest soils with dewatered dairy factory sludge (DDFS), characterized by low heavy metal contents and high amounts of degradable C, can prevent the depletion of soil nutrients that results from intensive harvesting in forest plantations. However, this practice involves environmental risks when N supplies exceed the demand of plants or when the strong acidity of the soil favors the mobility of trace metals. These aspects were assessed in a young radiata pine plantation growing in a sandy, acidic, and organic N-rich soil for the 7 yr after application of a DDFS. The supply of limiting nutrients (mainly P, Mg, and Ca) provided by application of the DDFS, along with control of the ground vegetation, improved the nutritional status of the stand and led to increases in timber volume of more than 60 to 100%. Increases in soil inorganic N were observed during the first months after amendment. Data from soil incubation experiments revealed that some of the additional N was immobilized and, to a lesser extent, denitrified due to the readily available organic C content of the DDFS. Leaching and increased plant uptake of N were prevented by a combination of the latter processes and the low rate of nitrification. The strong acidity of the soil enhanced the availability of Mn and Zn to plants, although the maximum concentrations did not reach levels harmful to organisms. We conclude that although application of DDFS has positive effects on tree nutrition and growth and the environmental risks are low, repeated application may favor mobility of N and availability of heavy metals.

The use of sewage sludge to improve intensively managed forest plantations in temperate areas is a possible alternative to application of the waste on agricultural land. If environmentally and technically feasible, this procedure may alleviate large exports of nutrients as a consequence of harvesting, which often lead to nutritional deficiencies (Folster and Khanna, 1997).

The preferred method of treatment and disposal of the waste water produced by dairy factories is to spread the liquid effluent on the soil. However, sludge may be dewatered to reduce the transportation costs. The use of dewatered sludge rather than liquid sludge leads to lower losses through leaching (Bramryd, 2001). This not only reduces the risk of ground water contamination but may also provide a supply of nutrients over a longer time, which is important in forest systems.

Although a number of studies have been conducted to assess the response of grasslands or forest plantations to application of sewage sludge (López-Mosquera et al., 2000; Bramryd, 2001; Wang et al., 2004), there is little information about the short- and long-term chemical and biological processes that occur in forest ecosystems after application of sludge generated by the dairy industry. In contrast to sewage sludge, the sludges generated in the waste water treatment plants of dairy industries are characterized by low contents of heavy metals and other trace elements (López-Mosquera et al., 2000). The sludge typically has a high content of easily degradable C-lactose, protein, and milk fat, which may have important effects on the dynamics of nutrients affected by soil microbial activities, such as N or P (Degens et al., 2000).

The particularly low heavy metal content of dairy sludge reduces the chance of contaminants entering the trophic chain. The high amount of organic matter in forest soils exerts an important control on the dynamics of transfer of metals to plants and limits their availability (McBride et al., 1997). However, some authors (White et al., 1997; Antoniadis and Alloway, 2001) have found that the availability of these elements may be increased in the long term as a consequence of organic matter decomposition and soil acidification.

Because sludge is usually very rich in N, loading of this element is often a limiting factor when designing a program for forest soil fertilization. In forest systems, high amounts of N may lead to increased stress in tree vegetation as a consequence of secondary deficiencies and imbalances in nutrients, reduction in resistance to
climate, drought, frost, and attacks by insects or fungi (Fangmeier et al., 1994). There are also environmental risks associated with the leaching of N, such as eutrophication of waters.

In spite of the environmental risks related to N, in practice, application of sludge is increasingly performed even where N does not limit forest production. Studies of the N dynamics in forests systems in which the N supplies exceed the demand of plants are scarce (Meiws et al., 1998; Johnson et al., 2000; Borken et al., 2004). These studies have revealed that, even with large inputs of N, forest soils show a high capacity to absorb more N through biotic and abiotic processes (Johnson et al., 2000). Because of the large supply of degradable C provided, soil amendment with dewatered dairy factory sludge (DDFS) may stimulate N immobilization and denitrification in the soil (Ghani et al., 2005), preventing uptake of N by plants and NO₃⁻ leaching.

In intensively managed forest plantations, ground vegetation is abundant after clear felling and before canopy closure. Because ground vegetation plays an important role in the functioning of forest ecosystems, adequate weed control may be critical for avoiding possible detrimental effects of forest fertilization and achieving a positive response (Rose and Ketchum, 2002). Thus, some studies have shown that liming has an important effect on the structure of ground vegetation, favoring a higher proportion of grass (Misson et al., 2001). Despite its importance, few studies have examined the effects of sewage sludge on the biomass and chemical composition of ground vegetation (Dutch and Wolstenholme, 1994; Mosquera-Losada et al., 2001).

The present study was undertaken to assess the responses of an intensively managed forest ecosystem, deficient in Ca and P but not limited by N, to the application of a dairy sludge with a low content of heavy metals and a high content of degradable C. The changes in chemical and biological properties and the responses of ground and tree vegetation were monitored over 7 yr. The data obtained in the present study will help to define rational criteria for application of this type of sludge and to diminish the associated environmental risks.

### Materials and Methods

#### Site Description

The study site is located in Ames (42°55′ N and 8°38′ W, A Coruña, NW Spain) at an altitude of about 250 m. The climate of the area can be classified as temperate subtropic with a humid winter. The average annual precipitation is 1860 mm, and the average annual temperature is 14.5°C. The topography of the study site is relatively flat. Selected soil properties are shown in Table 1. The soil is a humic Umbrisol (FAO-Unesco system) with a single Ah horizon to a depth of 50 cm. It was developed on granite and is highly weathered, well drained, of sandy loam texture, high in organic matter content, and strongly acidic. The soil does not contain litter or an organic horizon.

The study was performed in a 9-yr-old second rotation *Pinus radiata* plantation with a site index (the total height to which dominant trees of a given species grow on a given site at 20 yr) of 16.4 m (Dieguez-Aranda et al., 2005). The initial foliar analyses revealed deficient levels of P, Ca, Mg, and Cu, which is common in *Pinus radiata* plantations in the region (Sánchez-Rodríguez et al., 2002).

After the clear felling of the previous stand, the site preparation involved chopping the logging residues and ripping the soil. Before treatment, the stand density was 2600 trees ha⁻¹, and the stand basal area was 4 m². Competing vegetation largely consisted of grasses (mainly *Poa annua*, *Pteridium aquilinum*, *Agrastis stolonifera*, and *A. curtisii*) and shrubs (mainly *Ulex europaeus*, *Halimium latzittatum subsp. alyssoides*, and *Erica cinerea*).

#### Experimental Design

Treatment was performed just before canopy closure and after pruning when the leaf growth responds more readily to fertilization. The DDFS was obtained from the waste water treatment plant of a dairy factory located in Caldas de Rei, Pontevedra, Spain. The characteristics of the DDFS are shown in Table 1. The sludge, which was stabilized by adding CaO, was highly alkaline, rich in N and Ca, and contained moderate amounts of Mg and P. Trace metals in the sewage sludge were present at low concentrations compared with the current limits established by the EU for sewage sludge applied to agricultural soils, and the heavy metal loadings were less than 20% of the permitted pollutant loadings (European Communities, 1986).

Three treatments were applied in a randomized block design with four replicates: (i) control, (ii) 3.1 Mg of DDFS ha⁻¹, and (iii) 6.2 Mg of DDFS ha⁻¹ on a dry matter basis. The plot size was 20 by 20 m and included 36 to 42 trees. A minimum buffer zone of 6 m was left between plots. The ground vegetation in the stand was brushed with chopping rollers before treatment. Brushing was also performed in 2001.

The unique application of DDFS was performed in No-
N and biological properties were analyzed in fresh soil samples. and total elements were dried at 40°C before analysis. Inorganic samples obtained for determining total C and N and available were sieved (2 mm) and mixed to ensure homogeneity. Sub-

Soil Sampling and Chemical Analysis of Soil and DDFS

The study was performed between November 1998 and November 2005. Soil pH and extractable elements as well as foliar elemental composition were analyzed in October or November of each year. Mineral N, soil microbial biomass, and basal fluxes of CO$_2$ and mineral N were analyzed quarterly during the first year (January, April, June, and November of 1999) and then in the fall of each year. Ground vegetation biomass measurements and collection of samples for analysis were performed in July of each year. Tree growth measurements and collection of needles for analysis were performed in November of each year.

Soil cores were collected from depths of 0 to 12 and 12 to 40 cm from four randomly selected points in each of the plots and at each sampling time with a PVC core (50 mm diameter). The samples were analyzed to determine chemical properties. Soil moisture and biological soil properties were determined in the 0- to 12-cm soil layer. The soil cores were transported to the laboratory, where composite samples from each plot were pro-

Soil Biological Analysis

Microbial biomass C was measured using the method of fumigation of soil samples with ethanol-free chloroform vapor (Vance et al., 1987). Following this procedure, organic C was extracted with 0.5 $M$ $K_2SO_4$ and determined by digestion with $K_2Cr_2O_7$ and titration with $(NH_4)_2FeSO_4$. The difference in organic C in three fumigated and three unfumigated (control) samples was calculated.

Basal respiration (the amount of CO$_2$ evolved without ad-

Tree Growth and Ground Vegetation Biomass

To test the effects of DDFS treatment over time, the diam-

Omil et al.: Application of Dewatered Dairy Factory Sludge in a Forest Plantation
fall of each year from 1998 to 2005. Diameter at breast height (dbh) was determined, and the ratio of the volume of timber to 7.5 cm thin-end stem diameter was calculated by use of the nationally developed stem volume equation (DGCN, 2000).

The aboveground vegetation biomass was estimated in July of each year by cutting the vegetation in four randomly selected squares of 0.36 m² in each plot. The samples were dried at 65°C, weighed, and sorted into grass and shrubs.

Data Analysis

To assess the nutritional status, the critical and marginal foliar levels for Pinus radiata proposed by Will (1985) were determined and compared with the mean levels observed for plantations of this species in the region (Sánchez-Rodríguez et al., 2002). The second approach used for foliar analysis was the graphic technique proposed by Timmer and Stone (1978), often known as vector analysis. This procedure allows interpretation of the response of the stand by use of data for plant growth, nutrient concentration, and nutrient content. The dry weight of each needle was estimated from the weight of 100 representative needles.

The effects of DDFS on soil properties and vegetation were analyzed by ANOVA. Data were assessed for homogeneity and normality. Changes over time were tested by analysis of repeated measurements. When this test revealed significant differences for the whole period, the monthly mean values were compared by Tukey means test at $P < 0.05$. Asterisks denote significant differences between the treatments compared within that month.

Results

Soil Chemical Properties

Slight initial increases in soil pH were observed after the application of DDFS (Fig. 1). However, the effect was limited to the first 2 yr after treatment. The application of the higher dose of sludge led to significant increases in extractable Ca, which were detected up to 6 yr after treatment. Increases in concentrations of P and Mg also occurred but were much more moderate. The deeper soil layers (12–40 cm) were subjected to more moderate changes (data not shown). The amendment did not lead to any significant change in the available concentrations of any of the trace elements investigated throughout the study period in either of the two soil layers investigated (data not shown).

Effects on Biological Soil Properties and N Dynamics

No significant changes in soil total C, N, and C/N ratio were found throughout the study period. Seasonal changes in some soil biological properties in the 0- to 12-cm upper soil layer throughout the first year after treatment (1999) are shown in Fig. 2. The highest levels of microbial C and microbial activity, measured as basal respiration, were recorded in spring and summer, coinciding with the highest temperatures and moderate soil moisture. Analysis of the data indicated significant effects of treatments on microbial biomass C and basal respiration for the spring-summer period. The metabolic quotient ($q_{\text{CO}_2}$) was also higher in the treated soils. No significant changes attributable to treatments were observed in subsequent years (data not shown).

The concentrations of inorganic N decreased throughout the warmest months and increased in the fall (Fig. 3). Extractable NH$_4$+ was the dominant form of inorganic N in all plots. Concentrations of NH$_4$+–N and NO$_3$–N increased during a few months after DDFS treatment. The greatest effect was observed for NH$_4$+–N, and maximum concentrations of up to 80 mg kg$^{-1}$ were recorded for the highest sludge application, whereas the concentrations of NO$_3$–N were always lower than 2 mg kg$^{-1}$. During the first 5 mo, N$_2$O production in the incubated samples increased—coinciding with the higher soil NO$_3$–N—and remained low thereafter (Fig. 3).

In the untreated soil, annual net mineralization throughout the first year was high (Table 2). In the treated plots, an initial period (February–March) of decreased N mineraliza-
tion and immobilization was distinguished (data not shown). Annual N mineralization rates in the first year were substantially lower in these plots. In all cases, the yearly net nitrification represented 3 to 15% of the net mineralization.

Concentrations of Elements in Needles and Ground Vegetation

Regardless of the treatment, the tree foliar concentrations of most macronutrients increased after brushing the ground vegetation in 2001 (Fig. 4). In all plots, the foliar N levels, which were above the limit for possible deficiency (12 mg g\(^{-1}\)) (Will, 1985), showed a similar trend over time, remaining rather constant during the first 5 yr and increasing between 2001 and 2003. Despite the amount of N added, the foliar concentrations of this element were low in the treated plots.

The concentration of Ca in the control plot remained low (<1 mg g\(^{-1}\)), whereas the concentration increased in the treated plots after ground vegetation was cleared. Tree foliar P, Mg, and K levels did not increase after treatment. On the contrary, slight decreases in the concentration of Mg were recorded during the first years. The concentrations of foliar Al and Mn were significantly lower than in the untreated plots (Fig. 4). Analysis of tree needles did not reveal any clear trend in the concentrations of trace elements. Slight and nonconsistent decreases in Cu, Cr, and Pb were observed in the treated plots some years after treatments (Table 3).

Unlike the tree needles, the ground vegetation samples underwent noteworthy changes as a consequence of the treatment (Ta-
ble 4). Important increases in plant tissue P, Ca, Mg, and K were recorded. However, the concentration of N decreased significantly after application of the sludge. Despite the lack of differences in soil-extractable concentrations, increases in Mn and Zn, the trace metals present at the highest concentrations in the sludge, were observed. On the contrary, the levels of Cd decreased significantly after the application of the highest dose of sludge.

**Effects on Tree Growth and Ground Vegetation Biomass**

During the first 5 yr after treatment, the rates of tree growth in all plots were low, and the response of trees in terms of growth was limited (Fig. 5). After the ground vegetation was cut in 2001, tree growth rate increased dramatically, and the differences between types of plots became more evident. From this moment, height, dbh growth, and stem volume production increased in parallel to the increase in the amount of sludge applied. Seven years after treatment, the differences in tree height in untreated and treated plots were approximately 2 m, whereas the combination of differences in total height and dbh resulted in increases in timber volume of more than 60 to 100%.

Vector analysis (Fig. 6) was useful for distinguishing the contributions of the different nutrients to tree growth. The corresponding data confirmed that the control plot was deficient in Ca and that application of the DDFS led to higher tree growth. Similar results were found for P and Mg, although the foliar concentra-

---

**Table 2. Net N mineralization in the 0- to 12-cm soil layer throughout the first year after application of the sludge. The values were calculated from the monthly data.**

|                  | Ammonification | Nitrification | Total mineralization |
|------------------|----------------|---------------|---------------------|
| Untreated        | 154.6b†        | 5.4a          | 160.0b              |
| 3.1 Mg DDFS ha⁻¹ | 74.8a          | 3.0a          | 77.8a               |
| 6.2 Mg DDFS ha⁻¹ | 40.5a          | 10.6a         | 51.1a               |

† Within columns, different letters indicate significant differences at \( P < 0.05 \) (Tukey test).

---

**Fig. 4. Changes in the concentrations of the macronutrients in needles of *Pinus radiata* throughout the study period. Changes over time were tested by analysis of repeated measurements. When this test revealed significant differences for the whole period, the monthly mean values were compared by Tukey means test at \( P < 0.05 \). Asterisks indicate significant differences between the months compared.**
ations of these elements did not increase after treatment. The vector diagrams seem to indicate that the lower needle N concentration was due to a dilution effect resulting from higher tree growth rates.

Ground vegetation, which included shrubs and grasses, was affected by the brushing performed in 1998 (just before treatment) and in 2001 (Fig. 7). The treatment did not affect the ground vegetation biomass. However, the application of DDFS led to a lower biomass of shrubs and higher biomass of grasses and thereby affected biomass distribution.

Discussion

Effects on Soil Chemical Properties and Tree Nutrition

The slight increases in soil pH were attributed to the alkaline character of the DDFS and were associated with increases in soil-extractable Ca and Mg (the initial concentrations of which were particularly low) and parallel decreases in exchangeable Al. The effects on Ca were significant 6 yr after DDFS application, which indicates good retention of this element in the soil. Similarly, Bramryd (2001) reported dewatered sludge to have more pronounced long-term effects than liquid sewage sludge.

As is typical in acid soils (Fölster and Khanna, 1997), the plantation studied was mainly limited by availability of P, Mg, and Ca. The increases in tree foliar levels of N, P, Ca, and K recorded in all types of plots (control and treated) from 2001 onward coincided with brushing and chopping of the ground vegetation performed in 1998 (just before treatment) and in 2001 (Fig. 7). The treatment did not affect the ground vegetation biomass. However, the application of DDFS led to a lower biomass of shrubs and higher biomass of grasses and thereby affected biomass distribution.

Ground vegetation, which included shrubs and grasses, was affected by the brushing performed in 1998 (just before treatment) and in 2001 (Fig. 7). The treatment did not affect the ground vegetation biomass. However, the application of DDFS led to a lower biomass of shrubs and higher biomass of grasses and thereby affected biomass distribution.

Discussion

Effects on Soil Chemical Properties and Tree Nutrition

The slight increases in soil pH were attributed to the alkaline character of the DDFS and were associated with increases in soil-extractable Ca and Mg (the initial concentrations of which were particularly low) and parallel decreases in exchangeable Al. The effects on Ca were significant 6 yr after DDFS application, which indicates good retention of this element in the soil. Similarly, Bramryd (2001) reported dewatered sludge to have more pronounced long-term effects than liquid sewage sludge.

As is typical in acid soils (Fölster and Khanna, 1997), the plantation studied was mainly limited by availability of P, Mg, and Ca. The increases in tree foliar levels of N, P, Ca, and K recorded in all types of plots (control and treated) from 2001 onward coincided with brushing and chopping of the ground vegetation. This indicates that these nutritional limitations were also due to competition between trees and ground vegetation, as suggested in other studies (Rose and Ketchum, 2002). The stand was also deficient in Cu, and the treatment may have helped to overcome this. However, the analysis of soils and needles did not reveal any evidence of increased availability of this element.

In spite of the large inputs of N through application of DDFS, the increases in soil-extractable N and foliar levels were modest. Such effects have also been described for treatment with sewage sludge under similar conditions (Egiarte et al., 2005). In other forest ecosystems limited by N, however, the concentration of foliar N increased (Wang et al., 2004). In the present study, vector analysis showed a dilution effect for these two elements as a consequence of the increased tree growth. The lower rate of N mineralization (Table 2), along with the lower N concentrations in ground vegetation (Table 4), suggest decreased availability of this element after treatment with DDFS.

In contrast, the response of the plantations as regards K, Ca, Mg, and P was somewhat affected by the strong competition between trees and ground vegetation. Thus, decreased tree foliar K/N ratios have occurred as a consequence of the higher concentrations of NH4 among treatments. It is also possible that antagonistic reactions occurred as a consequence of the higher concentrations of NH4 during the first year. Thus, decreased tree foliar K/N ratios have been reported after application of sludge (Bramryd, 2001). On the other hand, the vector analysis showed a dilution effect for these two elements as a consequence of the increased tree growth. The lower rate of N mineralization (Table 2), along with the lower N concentrations in ground vegetation (Table 4), suggest decreased availability of this element after treatment with DDFS.

Table 3. Heavy metal concentrations in Pinus radiata needles 1, 3, and 7 yr after application of sewage sludge (n = 4).

|                | Untreated | 3.1 Mg DDFS ha⁻¹ | 6.2 Mg DDFS ha⁻¹ |
|----------------|-----------|------------------|------------------|
|                | mg kg⁻¹   |  mg kg⁻¹         |  mg kg⁻¹         |
| Cd             | 1999      | 0.13             | 0.14             |
|                | 2001      | 0.12             | 0.14             |
|                | 2005      | 0.14             | 0.11             |
| Cr             | 2001      | 0.25ab           | 0.18ab           |
|                | 2005      | 0.12             | 0.09             |
| Cu             | 1999      | 3.2              | 3.3              |
|                | 2001      | 4.2              | 3.2              |
|                | 2005      | 3.9              | 2.9              |
| Ni             | 1999      | 0.44             | 0.39             |
|                | 2001      | 0.48             | 0.21             |
|                | 2005      | 0.37             | 0.35             |
| Pb             | 1999      | 0.065            | 0.057            |
|                | 2001      | 0.076            | 0.060            |
|                | 2005      | 0.101            | 0.080            |
| Zn             | 1999      | 21.4             | 23.1             |
|                | 2001      | 30.7             | 27.3             |
|                | 2005      | 23.0             | 23.0             |

† Within rows, different letters indicate significant differences at P < 0.05 (Tukey test).

Table 4. Chemical composition of the understory vegetation in samples (n = 4) collected 1 yr after the application of the sludge (November 1999).

|                | Untreated | 3.1 Mg DDFS ha⁻¹ | 6.2 Mg DDFS ha⁻¹ |
|----------------|-----------|------------------|------------------|
|                | mg g⁻¹   |                   |                   |
| Macronutrients |           |                   |                   |
| N              | 22.0a†   | 17.1b            | 19.0b            |
| S              | 2.22a    | 1.69b            | 2.0b             |
| P              | 0.11a    | 0.39b            | 0.44b            |
| Ca             | 0.59a    | 2.4b             | 2.6b             |
| Mg             | 0.35a    | 0.52ab           | 0.96b            |
| K              | 1.78a‡   | 3.25ab           | 5.81b            |

† Within rows, different letters indicate significant differences at P < 0.05 (Tukey test).
study showed that the effect on microbial activity of the single process (Guerrero et al., 2000). The results of the present study indicate that the soil microbial community was actively immobilizing at least part of the inorganic N into microbial biomass. However, N may also be immobilized by chemical reactions between NH$_4^+$ and organic matter (Dail et al., 2001). This process seems to be related to the concentration of soil N, which is more important in N-saturated soils (Johnson et al., 2000), such as the soil in the present study.

The low nitrification rates along with the low concentration of NO$_3^-$ suggest that the potential for leaching of NO$_3^-$ from the treated soil was low under the conditions of the study. Nevertheless, higher nitrification rates have been detected in less acid soils after application of sewage sludge (Wáng et al., 2003). In addition, Meiwes et al. (1998) have shown that continuous increases in the concentration of NH$_4^+$ as a consequence of repeated application of sludge may favor nitrification, even in acid soils.

The data obtained indicated that enhanced denitrifier activity, which represents accelerated transformation of NO$_3^-$, to gaseous N$_2$O and N$_2$, led to low annual losses of N (estimated at <50 mg N m$^{-2}$) compared with N input (2000 mg m$^{-2}$). This is consistent with the findings of Cameron et al. (2002). This process may also have contributed (to a lesser extent than immobilization) to the reduction in the amount of mineral N during the first months after DDFS application, as has been observed in other soils in the study region after amendment with cow slurry (Merino et al., 2004).

Heavy Metals

Marked changes in soil concentrations of heavy metals were not expected because of the low content of heavy metals in the residue applied. Although the analysis of soil or tree needles did not reveal any clear trend, the increased concentrations of Mn in ground vegetation reflect higher availability of these elements, which are the most abundant trace elements in the sludge. These results differ slightly from those of López-Mosquera et al. (2000), who did not find any increase in trace elements in the vegetation in a grassland subjected to repeated application of dairy sludge. The higher acidity of the soil used in the present study possibly enhanced the mobility of these elements.

Effects on Ground Vegetation and Trees

Certain shrubs species in the stand, such as Ulm sp., Erica sp., and Halimium sp., are indicators of low soil pH and low concentrations of extractable P, Ca, and Mg (Zás and Alonso, 2002). Although the data are not conclusive, the treatment seems to have a suppressive effect on the biomass of these species. In the present study, the slight decrease in shrubs was concomitant with increases...
in grass species, such as *Pseudorocheherum longifolium* and *Agrostis stolonifera*, which may indicate greater competition from grass species at the expense of shrubs. Different studies (e.g., Kellner, 1993) have also shown that liming and greater amounts of available nutrients in forest soils convert the vegetation into a more grass-rich type. Similar effects have also been found to be brought about by the application of municipal sewage sludge (Mosquera-Losada et al., 2001) or of alkaline waste, such as wood ash (Arvidsson et al., 2002).

As a result of the competition between trees and ground vegetation, the response of trees in terms of growth was rather low during the first 3 yr. From 2002 onward, the greater tree growth in the treated plots was attributed to combined effects of ground vegetation control and the better status of trees in terms of Ca content. This supports the findings of other investigators, who found that response to fertilization may be lower than the response to weed control (Rose and Ketchum, 2002).

**Conclusions**

Application of dewatered alkaline sludge from the dairy industry may be a suitable way of replenishing nutrients in intensively managed forest plantations. The use of dewatered sludge involves lower risk of ground water contamination than use of liquid sludge. In addition, this type of amendment is suitable for maintaining soil nutrient reserves in the long term.

Because the response of tree vegetation in terms of growth and nutritional status is strongly affected by competing vegetation, the control of ground vegetation favors the response of the stand to this type of treatment. The amendment performed, in combination with the ground vegetation control, improved the supply of limiting nutrients (P, Mg, and Ca) to the tree vegetation.

The main risk related to N was the increase in mineral N during the first months after application of the sludge. Although the N supplies

---

**Fig. 6.** Vector nomograms illustrating the effects of the dewatered dairy factory sludge treatment on nutrient foliar concentrations and contents and foliar biomass in 2003. The latter figure provides an interpretation of directional shifts. (A) Dilution. (B) Sufficiency. (C) Deficiency. (D) Luxury consumption. (E) Excess. (F) Further excess. Adapted from Timmer and Stone (1978).

**Fig. 7.** Ground vegetation biomass in the experimental plot throughout the study period. U, untreated plots; D1 and D2, 3.1 and 6.2 Mg of DDFS ha$^{-1}$, respectively.
exceeded the demand of plants, no evidence of detrimental effects, such as increased foliar N or nitrification, were observed. The study revealed that the system under consideration showed a high capacity to retain N through soil microbial uptake as well as through denitrification. Immobilization by abiotic mechanisms is also possible. However, the production of NO$_3^-$ may be increased in other soils with higher nitrification potential or after repeated application of sludge. Despite the low contents of trace elements in the sludge, the strong acidity of the soil enhanced the mobility of certain heavy metals, which may also restrict the repeated application of sludge.

Acknowledgments

Funding for the study was provided by the Ministry of Science and Technology of Spain and Regional Government (Xunta de Galicia). The English grammar of the text was revised by Dr. Christine Francis.

References

Anderson, T.-H., and K.H. Domsch. 1989. Maintenance of carbon requirements of actively metabolizing microbial populations under in situ conditions. Soil Biol. Biochem. 17:197–203.

Antoniadis, V., and B.J. Allaway. 2001. Availability of Cd, Ni, and Zn to ryegrass in sewage sludge-treated soils at different temperatures. Water Air Soil Pollut. 132:201–214.

Arvidsson, H., T. Vestin, and H. Lundkvist. 2002. Effects of crushed wood ash application on ground vegetation in young Norway spruce stands. For. Ecol. Manage. 161:75–87.

Borken, W., Y.J. Xu, and F. Bese. 2004. Ammonium, nitrate, and dissolved organic nitrogen in seepage water as affected by compost amendment to European beech, Norway spruce, and Scots pine forests. Plant Soil 258:121–134.

Beamley, T. 2001. Effect of liquid and dewatered sewage sludge applied to a deciduous woodland on the physical properties of a burnt forest soil in field experiments. Biol. Fertil. Soils 32:410–414.

Johnson, D.W., W. Cheng, and I.C. Burke. 2000. Biotic and abiotic nitrogen retention in a variety of forest soils. Soil Sci. Soc. Am. J. 64:1503–1514.

Kellner, O. 1993. Effects on associated flora of silvicultural nitrogen fertilization repeated at long intervals. J. Appl. Ecol. 30:563–574.

Li, Q., L. Allen, and C.A. Wilson. 2003. Nitrogen mineralization dynamics following the establishment of a loblolly pine plantation. Can. J. For. Res. 33:364–374.

López-Mosquera, M.E., C. Moirón, and E. Carral. 2000. Use of dairy-industry sludge as fertilizer for grasslands in northern Spain: Heavy metal levels in the soil and plants. Res. Conserv. Recycl. 30:95–109.

McBride, M.B., B.K. Richards, T. Stenhus, J.J. Russo, and S. Suave. 1997. Mobility and solubility of toxic metals and nutrients in soil fifteen years after sludge application. Soil Sci. 162:487–500.

Mehlich, A. 1984. Mehlich N. 3, extractant: A modification of Mehlich N. 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409–1416.

Meiwes, K.J., A. Merino, and F.O. Beese. 1998. Chemical composition of throughfall, soil water, leaves, and leaf litter in a beech forest receiving long term application of ammonium sulphate. Plant Soil 201:217–230.

Merino, A., M. Balboa, R. Rodríguez-Souileiro, and J.G. Álvarez González. 2005. Nutritional exports under different harvesting regimes in southern Europe. For. Ecol. Manage. 207:325–339.

Merino, A., P. Pérez-Batallón, and F. Macías. 2004. Responses of soil organic matter and greenhouse gas fluxes to changes in soil management and land use in a humid temperate region of southern Europe. Soil Biol. Biochem. 36:917–925.

Misson, L., G. du Bus de Warranne, and M. Jonard. 2001. Effects of fertilization on the vascular ground vegetation of European beech (Fagus sylvatica L.) and sessile oak (Quercus petraea (Matt.) Lieb.) stands. Ann. For. Sci. 58:829–842.

Mosquera-Losada, M.R., I. López-Díaz, and A. Riqueiro-Rodríguez. 2001. Sewage sludge fertilisation of a silvopastoral system with pines in northwestern Spain. Agrofor. Syst. 53:1–10.

Pérez-Batallón, P., G. Oyarzo, F. Macías, and A. Merino. 2001. Initial mineralization of organic matter in a forest plantation soil following logging residue management techniques. Ann. Sci. 58:807–818.

Raison, R.K., M.J. Connell, and P.K. Khanna. 1987. Methodology for studying fluxes of soil mineral-N in situ. Soil Biol. Biochem. 19:521–530.

Rose, R., and S. Ketchum. 2002. Interaction of vegetation control and fertilization on conifer species across the Pacific Northwest. Can. J. For. Res. 32:136–152.

Salas, A.M., E.T. Elliot, D.G. Westfall, C.V. Cole, and J. Six. 2003. The role of particulate organic matter in phosphorus cycling. Soil Sci. Soc. Am. J. 67:181–189.

Sánchez-Rodríguez, F., C. López, R. Rodríguez-Souileiro, E. Espiñol, and A. Merino. 2002. Influence of edaphic factors on the productivity of Pinus radiata D. Don plantations in NW Spain. For. Ecol. Manage. 171:181–189.

Timmer, V.R., and E.L. Stone. 1978. Comparative foliar analysis of young balsam fir fertilized with nitrogen, phosphorus, potassium and lime. Soil Sci. Soc. Am. J. 42:125–130.

Tisdale, H., W.I. Nelson, J.D. Beaten, and J.L. Havlin. 1997. Soil fertility and fertilizers. 5th ed. Prentice Hall, New York.

Vance, E.D., P.C. Brookes, and D. Jenkinson. 1987. Microbial biomass measurements in forest soils: Determination of Kc values and tests of hypothesis to explain the failure of the chloroform fumigation-incubation method in acid soils. Soil Biol. Biochem. 19:381–386.

Wang, H., M.O. Kimberley, and M. Schlegelmilch. 2003. Biodiesel-derived nitrogen mineralization and transformation in forest soils. J. Environ. Qual. 32:1851–1856.

Wang, H.L., G.N. Magesan, M.O. Kimberley, T.W. Payn, P.J. Wilks, and C.R. Fisher. 2004. Environmental and nutritional responses of a Pinus radiata plantation to biosolids application. Plant Soil 267:255–262.

White, C.S., S.R. Loftin, and R. Aguilar. 1997. Application of biosolids to degraded semiarid rangeland: Nine-year responses. J. Environ. Qual. 26:1663–1671.

Will, G.M. 1985. Nutrient deficiencies and fertilizer use in New Zealand exotic forests. For. Res. Inst. Bull. 97:1–53.

Zas, R., and M. Alonso. 2002. Understory vegetation as indicators of soil characteristics in northwest Spain. For. Ecol. Manage. 171:101–111.