Swedish University of Agricultural Sciences
Department of Forest Ecology
Graduate Thesis in Soil Science 1999

The Effects of Pelleted Sewage Sludge on Norway spruce Establishment and Nitrogen Dynamics

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Supervisors: Reiner Giesler and Urban Nilsson*
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Abstract

In Sweden there is a big resource in unutilised sewage sludge. Studies have shown that application of municipal sewage sludge can improve forest productivity and planting environment. This study is examining the effects of two types of pelleted sewage sludge (pure sludge and a mixture of sludge and domestic wastes compost) on nitrogen turnover. Large differences were found in the fertilisation effect of the different treatments. The pure sewage sludge pellets treatment showed significant increases for NH_4-accumulation, nitrification and NO_3-leaching in the top 10 cm of the soil. Uptake of nitrogen was increased in spruce plants and vegetation. The mixed sludge/domestic waste pellets treatment showed indications of a minor initial release of nitrogen. This is seen as a small but significant initial increase in soil nitrification. These results suggest that the pure sewage sludge pellet is an adequate nitrogen fertiliser. The mixed sludge though is inadequate at leased in the short run.

Introduction

The utilisation of sewage sludge as an agricultural fertiliser is widely spread. There are however some doubts about the sludge negatively affecting food quality (Pettersson 1992). Due to this and possibly high transport cost for the wet sludge only part of the produced sludge is used. In 1994 only 60 Gg dw of 200 Gg dw produced in Sweden were used and most of that as agricultural fertiliser (SCB 1996). This alone makes alternative utilisation interesting since the option is deposition, which is not free of costs. Many studies have been made regarding sewage sludge as a forest fertiliser. In *The Pack Forest Sludge Research Program* (Henry, Cole and Harrison 1994) it was concluded that sludge could be used to improve long-term productivity of coniferous forests with no reasonable hazard to the environment. These results mostly origin from 60-years old Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) stands in Washington studied for 18 years. However others such as Sutton (1995) has come to the opposite conclusion that sludge fertilisation has no long-term effect, in his case over a period of 30 years in white spruce (Picea glauca (Moench) Voss).

An alternative use of sewage sludge is as fertiliser in forest establishment. Short-term studies have shown that inorganic fertilisers can be of value in forest establishment. Early growth is often limited by planting check (i.e. stresses affecting the roots on planting, especially for bare root plants). Burdett, Herring and Thompson (1984) showed that growth was enhanced through fertilisation in the first but mostly in the second growing season after plantation for two North American spruce species. Payandeh and Sutton (1989) also saw growth enhancement over four years after plantation for moderate fertilisation on various spruce species in North America. Similar results using sewage sludge as fertiliser was shown by McDonald et al. (1994). They showed that growth was enhanced by sludge fertilisation in the 9 years following planting in a stand with western red cedar (Thuja plicata).
Positive effects have been shown when planting with Sitka spruce in as extremely problematic environments as in competition with *Calluna sp.* or *Gaultheria shallon* (Dutch and Wolstenholme 1994, Weetman et al. 1993).

In the previous studies wet sludge has been used as fertiliser. Alternatively the sewage sludge can be pelleted, i.e. pressed together and dried. The pelleting of sludge makes it possible not only to more easily handle the sludge and reduce transport costs due to reduced water content but also store it without major effect on quality.

The objective of this study is to compare the effects of two different kinds of pelleted sludge on the establishment of Norway spruce (Picea abies. L.) on arable land. The hypothesis is that sludge pellet fertilisation will increase the fluxes and pools of nitrogen in soil, plants and vegetation.

Materials and methods

Site description

The study is located at Hjuleberg (56°58'N, 12°43'E, 40-45 m a.s.l.) 10 km east of Falkenberg in the southwestern part of Sweden. The sea influences the climate and the growing season is approximately 190 days with a mean temperature of 12.6 °C. The mean annual precipitation is 1150 mm. The climate during the study period is presented in table 1.

Table 1. Climate of study site during the vegetation period of 1998 (Lars Lövdahl pers. com.).

Month	Monthly mean temperature (°C)	Precipitation (mm)	Soil temperature at 15 cm (°C)
April	4.6	15.4	4.3
May	11.5	17.3	9.2
June	12.8	172.9	11.0
July	14.1	209.2	12.2
August	13.8	110.3	12.8
September	13.1	93.7	12.0
October	7.5	226.1	8.4

The land that the study is located on has been used for agricultural purposes in late time and has a cultivation depth of 25 cm. The texture of the parent material was loamy silt.

Sludge pellets

Two types of sludge pellets are used in this study. One is produced from pure sewage sludge and the other from a composted mix of sewage sludge and domestic waste.
Biopell (Muab, Stockholm, Sweden) is made from pure sewage sludge in a process using lime to make the pellets easy to handle and dryable. The pellet thus contains small amounts of lime although most of it is recycled after drying. The nitrogen content at the beginning of the study was 2.7% (dw). Plant nutrition pellet (Rondeco Scandinavia AB, Nynäshamn, Sweden) is made from a composted mix of sewage sludge and domestic waste in the approximate proportions of 2:1. This compost is pelleted to make the product easy to handle and to dormatise the mineralising microorganisms. The nitrogen content at the beginning of the study was 1.7% (dw).

Experiment

The study was designed as a randomised block study (Fig 1) with five treatments and four replicates, which gives a total of 20 parcels with an area of 5x5 m each. The treatments were control with intact vegetation (control), patch scarification (Sc), patch scarification with Plant nutrition pellet (ScVNP), Plant nutrition pellet without scarification (VNP) and Biopell without scarification (BP). In the scarification parcels 3x3 plants were planted at a distance of 2 m in between and in the others 4x4 plants at 1 m. The plant material were 3 years old bareroot stock Norway spruce (Picea abies. L.) plants originating from the seed orchard Maglehem. Planting was made 15 May. Fertilisation was carried out 2 June for VNP and 9 June for BP. 3 kg pellets were applied to each plant. At application the pellets were confined within an open cylinder with 30 cm diameter so that the sludge were evenly distributed around the plants. The cylinder was then removed.

Block 1.	Control	ScVNP	VNP	Sc	ScVNP	Sc	Block 2.
	Empty	BP	Sc	BP	Empty	VNP	
Block 3.	Sc	ScVNP	BP	VNP	ScVNP	BP	Block 4.
	VNP	Empty	Control	Empty	Control	Sc	

N ↑

Figure 1. Overview of the study site

Incubation

To assess nitrogen turnover in the topsoil an in situ incubation method, described by Raison et al. (1986), was used. The incubation study was carried out during three incubation periods, 12 June to 9 July, 10 July to 24 August and 26 August to 19 October. For each incubation period a start sample was taken with a 10 cm diameter soil auger in the area of pellet cover. The upper 10 cm of soil was collected. The soil samples were sieved through a 2 mm mesh sieve to remove course fragment and homogenise the sample All samples were placed in polyethylene bags and stored in a freezer until further analysis. Two 5 cm diameter PVC-tubes were inserted in the area of pellet cover. The tubes were 50 cm long and inserted to a depth of 30 cm. The 5 mm walls of the tubes were sharpened before inserting. One of the tubes was cover by a lid to shut out precipitation. The tubes were removed at the end of each incubation period and the top 10 cm of soil was sampled. The samples were stored in a freezer until further analyses

A subsample of the soil was separated to measure water content. The soil was dried at 105 °C for 24 h and the dry weight was calculated for each sample. The soil was analysed for KCl extractable ammonium and nitrate. Fresh soil was weighed in corresponding to 10 g dw and extracted in 30 mL 1.0 M KCl-solution giving a soil:solution ratio of approximately 1:3.6. After 2 h of shaking the samples were filtered (00H Munktell filter paper, STORA AB, Grycksbo, Sweden), and the filtrate was collected for further analyses. A 4 ml sub sample of the filtrate from each start sample from the second incubation period was collected for pH measurement.

Nitrogen fluxes were calculated as follows:

$$\text{Nitrification} = [NO_3^-]_{lidded} - [NO_3^-]_{start}$$
$$NO_3^-\text{-leaching} = [NO_3^-]_{lidded} - [NO_3^-]_{open}$$

Ammonification $=[NH_4^+]_{lidded} - [NH_4^+]_{start}$
NH_4^+-leaching $= [NH_4^+]_{lidded} - [NH_4^+]_{open}$

The nitrification and ammonification is assumed to be the amount of nitrate or ammonium released in the tubes. The leaching is assessed as the largest possible leakage when no root uptake is present. Negative values for nitrification or ammonification denotes immobilisation and negative values for leaching denotes accumulation.

Pellets were sampled at four occasions. The first three of them were taken from the start samples taken by the soil auger and the forth one from the open incubation tube at the end of the third incubation. The pellet samples were put in polyethylene bags and stored in freezer until further analysis. The pellets were dried in 70 °C for 48 h and ground in a mill before nitrogen measurements.

Sampling

At two sampling occasions (9-10 July and 19-20 Oct) two spruce plants were sampled from each parcel. The plants were carefully dug up with long and thin spade to avoid losses of fine roots. To get as wide size distribution as possible the plants were divided into rows so that sampling at each occasion was made from one row. From block 1 and 3 the two plants with the smallest diameter at planting were sampled and from block 2 and 4 the ones with the largest. After sampling the plants where divided into C-shoots (i.e. current year shoots), older shoots, and roots. The roots where placed in polyethylene bags and the shoot parts where placed in paper bags before storing in freezer until further analyses.

Before nitrogen analysis the spruce plants were thawed, the roots where washed and all parts where dried for 48 h in 70 °C. The dry weight for each plant part (i.e. C-shoots, older shoots and roots) were measured after drying (Fig 2). One plant from each parcel and sampling occasion was further separated into C-needles, C-shoot axis, older needles and a bulked sample containing older shoots and roots (Fig 2). The older shoot and root samples were further bulked to one sample per sampling occasion and treatment (Fig 2). The samples where ground in a mill, before analyses of nitrogen.

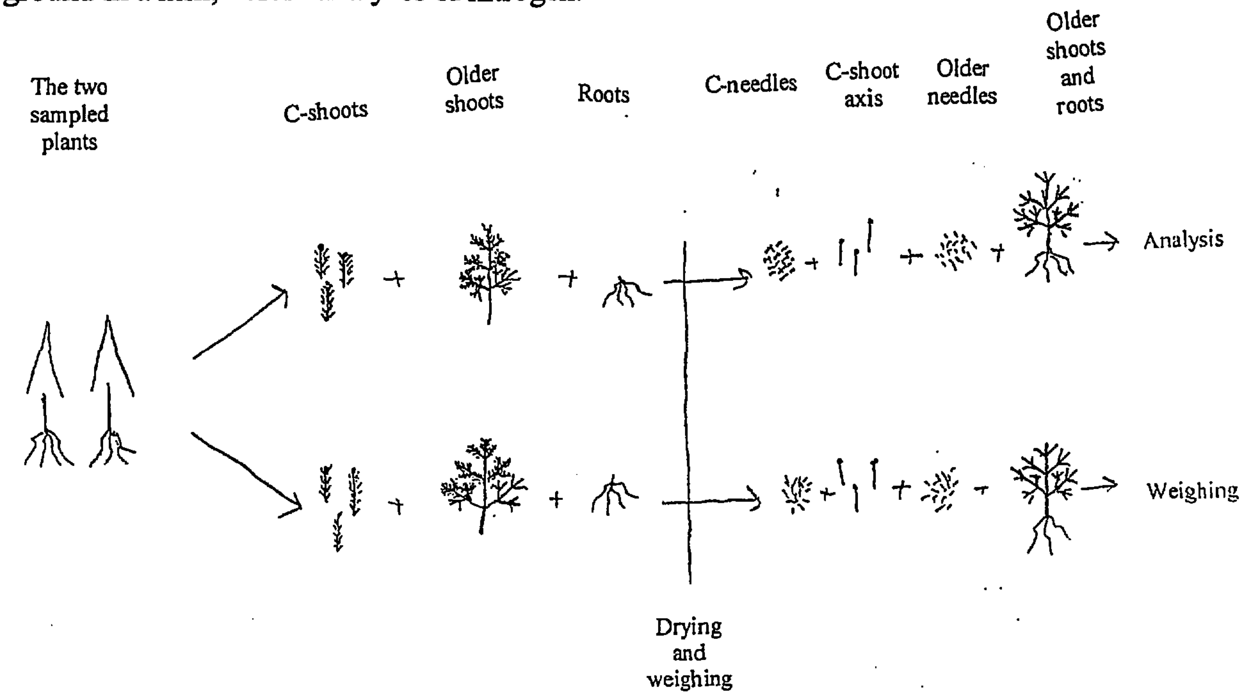

Figure 2. Treatment of the sampled spruce plants.

The analysed samples were not weighed. To assess the weight of the analysed samples the remaining plants were separated in the same manner as the analysed (Fig 2). The samples were weighed and linear regression was made correlating the initial sample weight with the weight of the new sample configuration. The regressions were then used to calculate the weight of the analysed samples (Tab 2).

Table 2. Equations used to calculate weights of the analysed samples.

Sampling occasion	Equation	r^2
1	C-needles = 0.8961 x C-shoot - 0.0564	1.00
1	C-shoot axis = 0.1451 x C-shoot + 0.030	0.94
1	Older needles = 0.2867 x older shoots and roots – 0.2664	0.87
1	Other parts = 0.7133 x older shoots and roots + 0.2664	0.98
2	C-needles = 0.7506 x C-shoot - 0.1853	0.99
2	C-shoot axis = 0.2494 x C-shoot + 0.1853	0.92
2	Older needles = 0.1229 x older shoots and roots – 0.4849	0.69
2	Other parts = 0.8771 x older shoots and roots + 0.4849	0.99

Vegetation was sampled 26th Aug so that all above ground vegetation was cut, with gardening scissors, within 15 cm around the control plants. On the other treatments the same area was sampled but around the pellets (i.e. 15 cm to 20.8 cm from the plant) since there was nothing growing on the pellets. The scarification plots where sampled at the same distance from the plants as the fertilised plots.

Analyses

Total nitrogen in pellets, vegetation and plant material was determined using a Carlo Erba NA1500 elemental analyser (Carlo Erba Strumentazione, Milan, Italy). Total carbon in pellets was analysed on an elemental analyser coupled to an isotope ratio mass spectrometer (ANCA-NT coupled to a Model 20-20 IRMS, Europa Scientific Limited, Crewe, England). Ammonium and nitrate in KCl-extracts were determined spectrophotometrically with a flow injection analyser (5020 Analyser, Tecator, Höganäs, Sweden). pH in KCl-extracts was measured with an Orin research Model 601/digital analyser and an Orion 8103 SC Ross combination electrode (Orin Research, Cambridge, Massachusetts, USA).

Statistics

For statistical comparison of nitrogen concentrations and content and biomass a randomised block analysis of variance without replication (df=3) was used. Multiple comparison in variance analyses were performed with a Tukey's test. The statistical limit of significance used was $p < 0.050$ Statistical analysis was performed using SYSTAT statistical software (SYSTAT Evanston, Illinois, USA).

Results

Pellets

Nitrogen concentrations decreased significantly in the BP pellets during the study period according to the equation $\%N = 2.799 + 0.0125 \times day + 0.000035 \times day^2$ ($r^2=0.85$ and $p<0.001$, fig 3). Both VNP treatments showed no significant decrease in pellet nitrogen concentrations (Fig 3).

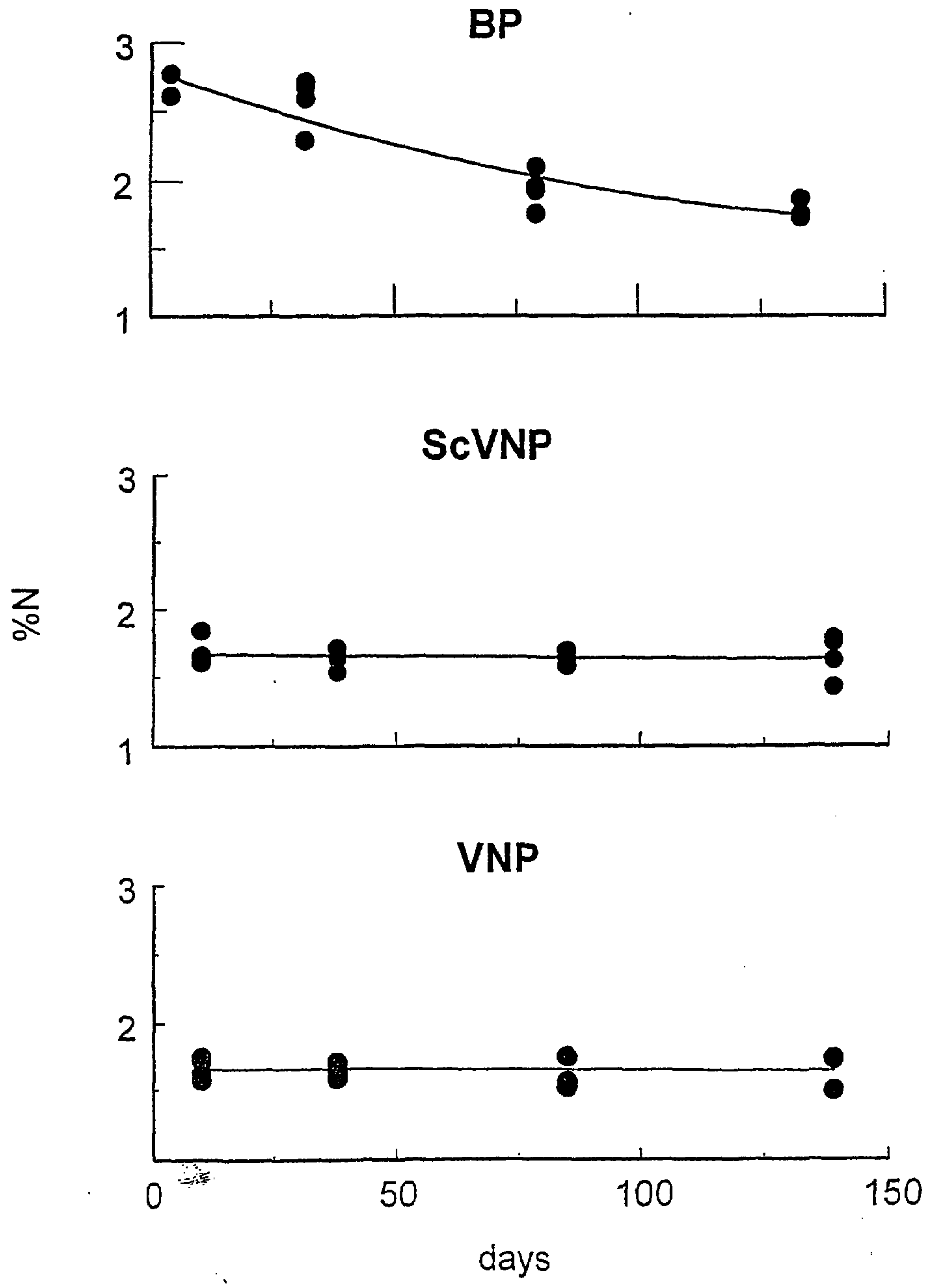

Figure 3. Changes in nitrogen concentrations in the pellets during the experiment.

Carbon content is decreasing in the BP pellets over the study period while the VNP pellets remain on approximately the same carbon concentration(Tab 3). The C/N ratios are almost the same at the start end the end of the study.

Table 3. Carbon concentrations and C/N ratios for Biopell and Plant nutrition pellet

Treatment	Day	%C		C/N	
		Mean	±se	Mean	±se
BP	4	35.7	0.7	13.1	0.6
	133	22.8	0.5	12.1	0.3
VNP	10	29.6	0.3	17.3	0.4
	139	29.1	0.3	16.4	0.6

Soil

Ammonium accumulation increased significantly in the BP treatment compared to the control ($p = 0.040$) during the first incubation period (Fig 4.). Nitrification showed a small but significant increase in the VNP treatments compared to the control ($p=0.008$ and $p=0.019$ respectively for VNP and ScVNP, fig 4). No changes in ammonification were found (Tab 4).

Table 4. P-values for analysis of variance of soil nitrogen fluxes.

	Ammonification	NH_4 leaching	Nitrification	NO_3 leaching
Period 1	p = 0.983	p = 0.010	p = 0.002	p = 0.025
Period 2	p = 0.582	p = 0.001	p < 0.001	p < 0.001
Period 3	p = 0.954	p = 0.751	p = 0.003	p < 0.001

Nitrification and leaching of nitrate were significantly greater for the BP treatment compared to the control ($p < 0.001$ for both) during the second incubation period (Fig 4). The increased ammonium accumulation was still evident ($p = 0.003$, fig 4). There were still indications of increased nitrification for the VNP treatments but only significantly greater than the control for the ScVNP treatment ($p=0.058$ and $p=0.007$ respectively for VNP and ScVNP, fig 4). Increased leaching of nitrate occurred from the VNP treatments although only significantly greater than the control for ScVNP ($p=0.362$ for VNP and $p=0.026$ for ScVNP fig 4). As before no changes in ammonification were found (Fig 4).

Leaching or accumulation of ammonium did no longer differ from the control in the BP treatment during the third incubation (Fig 4). However nitrification and nitrate leaching were still greater in the BP treatment compared to the control ($p = 0.005$ and $p < 0.001$ respectively, fig 4). Nitrification and leaching of nitrate in the VNP treatments were no longer showing any deviancies from the control (Fig 4). As before no changes in ammonification were found (Fig 4).

The Sc treatment was in no aspect showing any differences from the control (Fig 4).

The pH measurements indicate an increase in soil pH by both VNP and BP treatments (Tab. 5).

Table 5. pH values for the second incubation.

	Control		VNP		BP		P-value
	Mean	Se	Mean	Se	Mean	Se	
Start	4.14	0.08	4.54	0.13	4.34	0.08	0.017
Open	4.15	0.05	4.12	0.08	4.46	0.29	0.392
Lidded	4.20	0.04	4.20	0.03	4.35	0.06	0.105
All	4.16	0.03	4.29	0.07	4.38	0.09	0.092

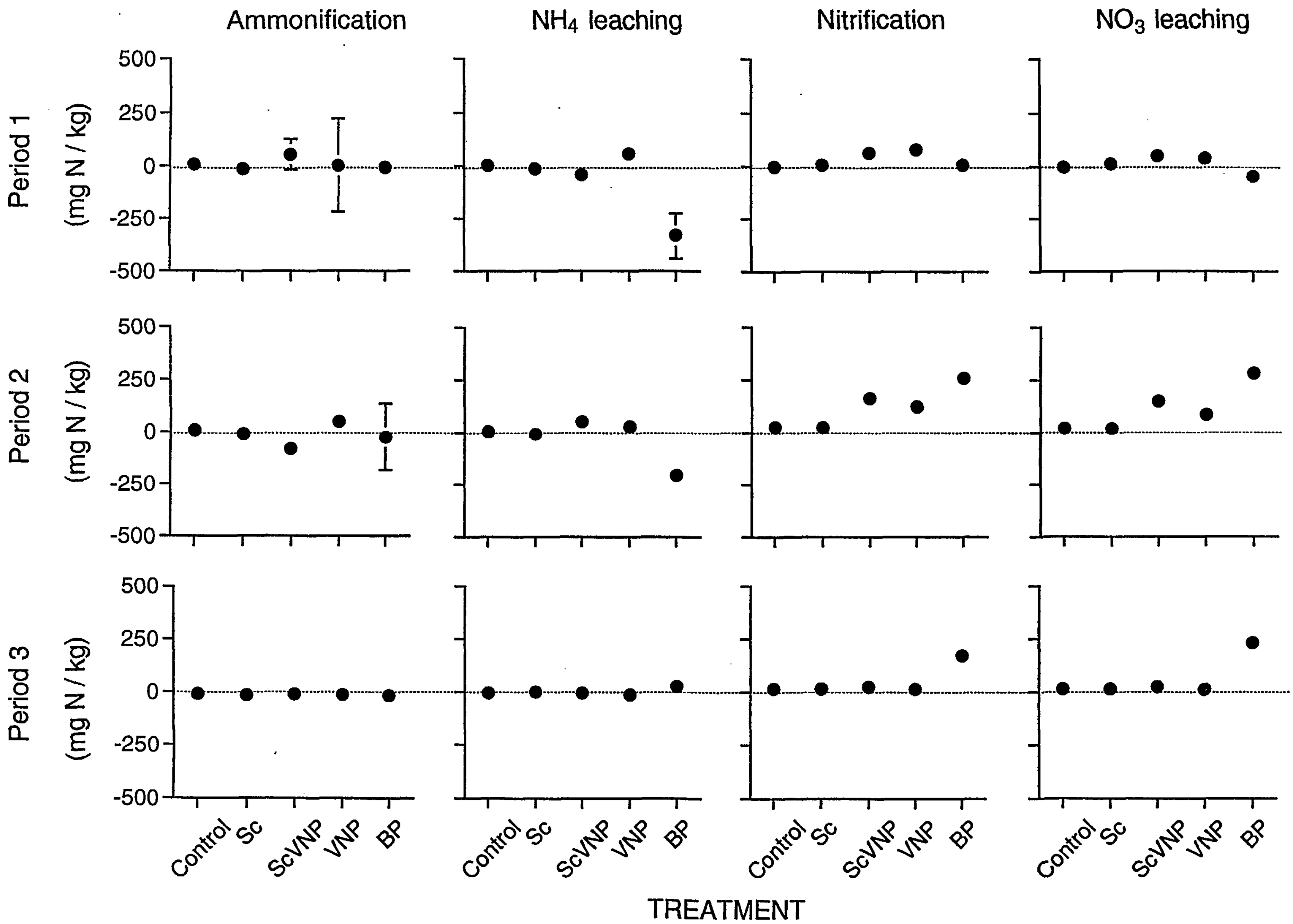

Figure 4. Nitrogen turnover in the top 10 cm of the soil.

Vegetation

Nitrogen concentration and biomass (dw) of the vegetation was significantly higher only in the BP treatment compared to the control (Fig 5).

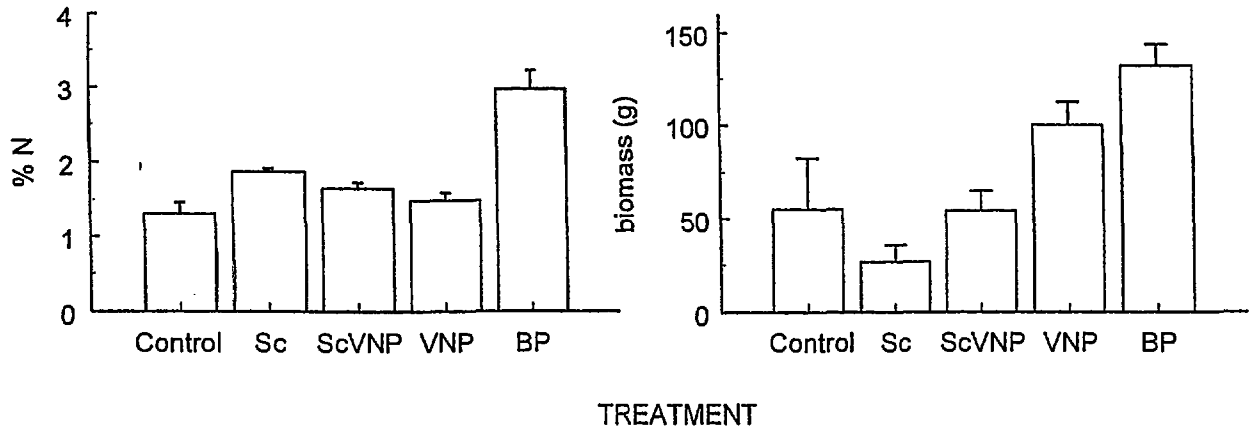

Figure 5. Nitrogen concentrations and biomass (dw) of vegetation surrounding spruce plants the 26 August.

Spruce plants

No differences in nitrogen concentrations or biomass were found in the C-shoots at the first sampling occasion (Tab 6).

Table 6. P-values for analysis of variance of spruce plant nitrogen content and total spruce plant biomass (dw).

	C-needle biomass	C-shoot axis biomass	C-needle concentration	C-shoot axis concentration	Total spruce plant dry weight
9-10 July	p = 0.102	p = 0.102	p = 0.150	p = 0.152	p = 0.030
19-20 Oct	p = 0.170	p = 0.170	p = 0.002	p = 0.162	p = 0.483

The nitrogen concentration of the C-needles was significantly higher in the BP treatments compared to the control (p = 0.007, Tukey's multi. comp.) at the second sampling occasion (Fig 6). The nitrogen concentrations of the C-shoot axis samples were found to have no significant differences (Fig 6). The C-shoot biomasses were found to have no significant differences (Tab 6). The nitrogen concentrations and biomasses of the C-shoots in VNP treatments and scarification treatment showed no deviancies from the control (Fig 6).

The nitrogen concentration in the bulked older needles sample was markedly higher in the BP treatment compared to the control at the first sampling occasion (Fig 7). Also the VNP treatments showed somewhat higher nitrogen concentration than the control (Fig 7). The old shoots with roots samples showed the same pattern although not as accentuated (Fig 7). At the second sampling occasion the nitrogen concentration of the older needles was still higher in the BP treatment but lower in the VNP treatments compared to the control (Fig 7). The same pattern was obvious for the older shoots and roots (Fig 7).

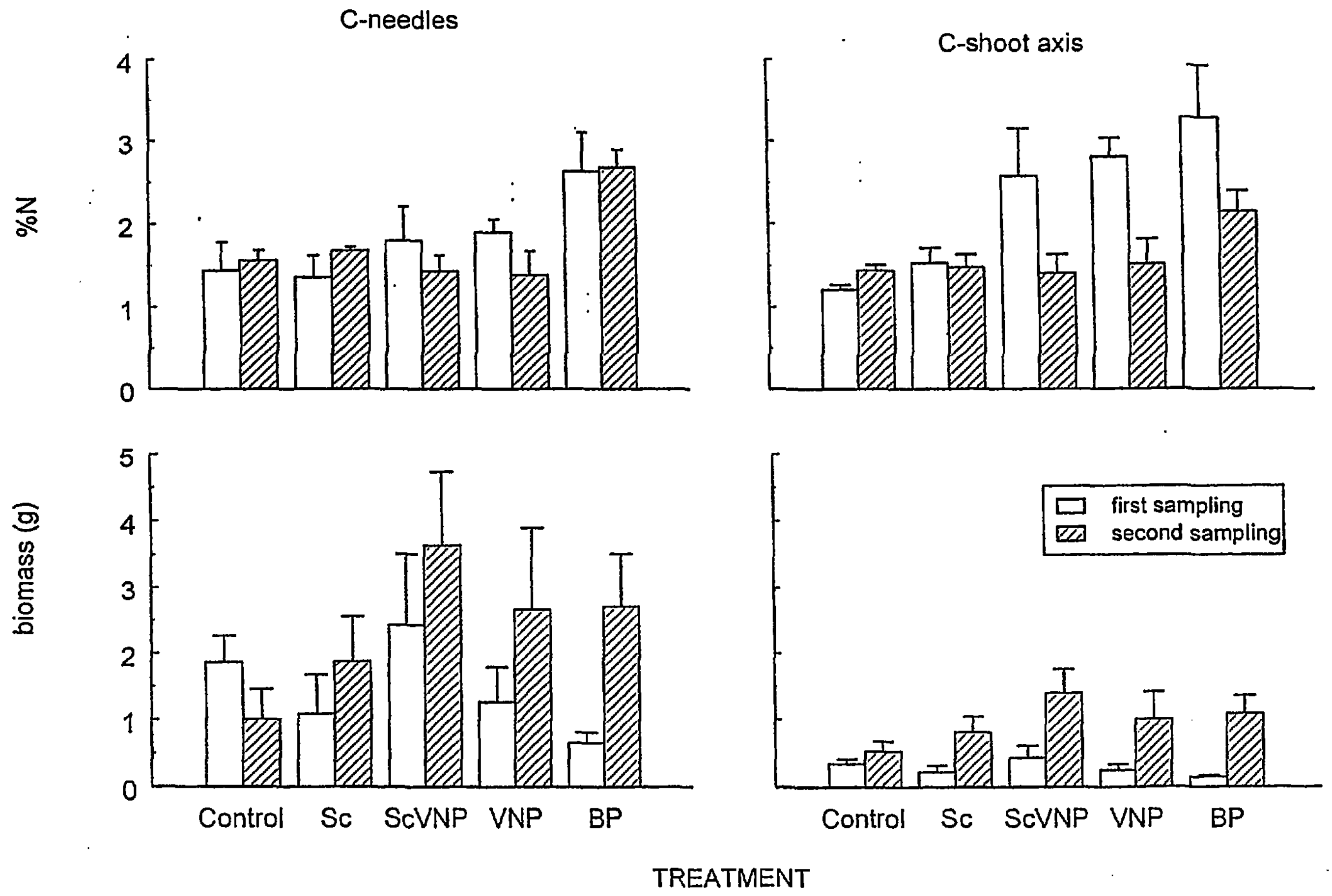

Figure 6. Nitrogen concentrations and biomass of the C-needles and C-shoot axis.

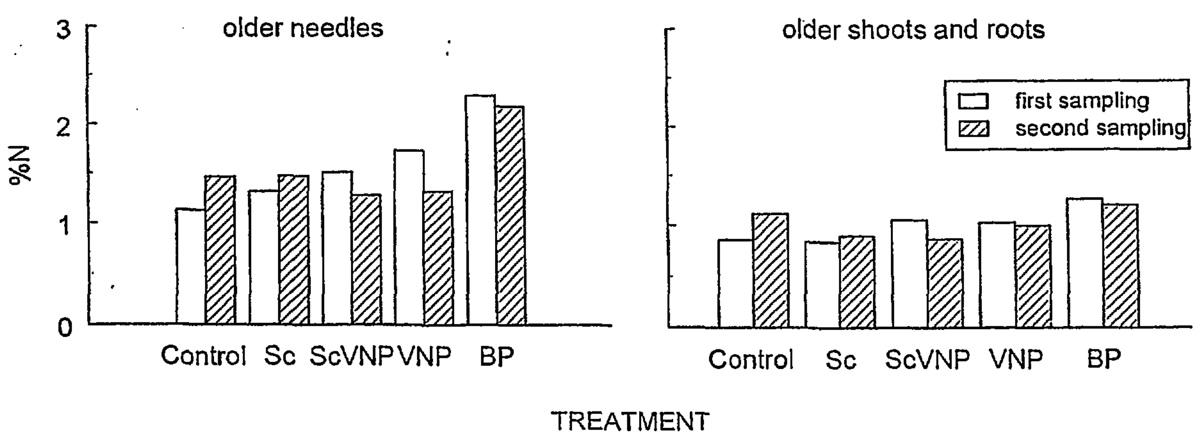

Figure 7. Nitrogen concentration of the bulked samples of older needles and older shoots and roots.

The total biomass of the plants in the scarification treatment was significantly greater than the control at the first sampling occasion ($p = 0.049$, fig 8). The other treatments showed no significant growth effect, although the BP and the ScVNP treatments showed small increases compared to the control (Fig 8).

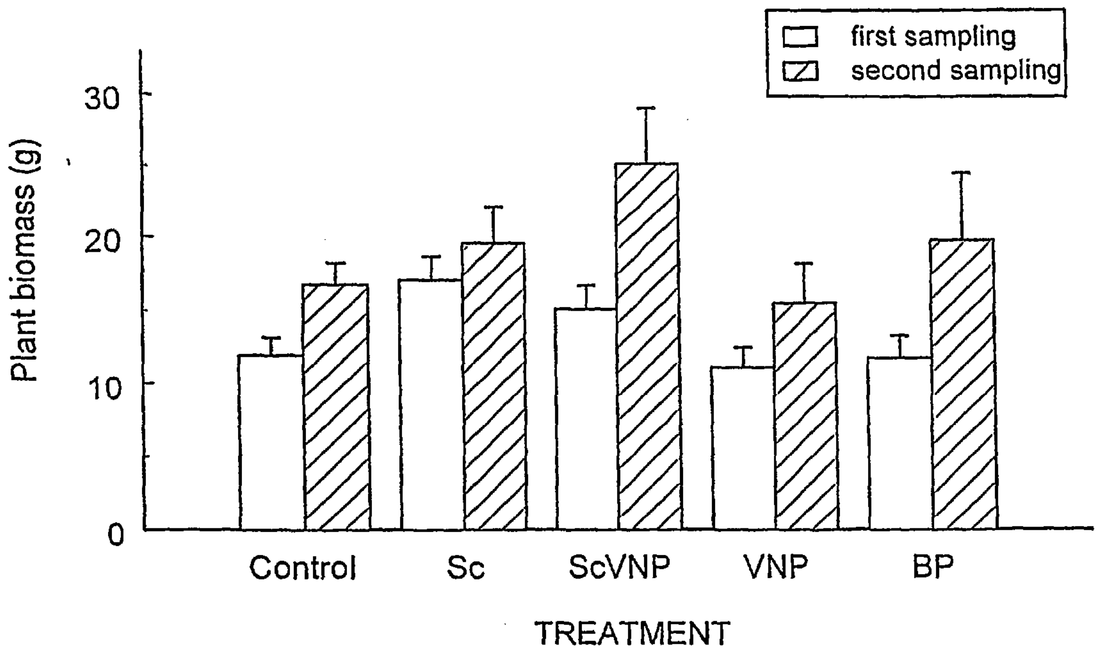

Figure 8. Total spruce plant biomass at the two sampling occasions.

No significant growth effects, assessed as total plant biomass (dw), were found, but the plants in the scarification treatments had a somewhat larger biomass than the other treatments at the second sampling occasion.

Budget calculations

A budget was calculated for the BP treatment (Fig 9). This budget shows that there is large input of nitrogen from the pellets to the soil (converted to nitrogen input over the parcel area 139 kgN/ha) but the spruce plants only take up a very small part of this. The vegetation takes up a much larger portion of the nitrogen input. There is a larger input to the top 10 cm of the soil then there is fluxes away from it.

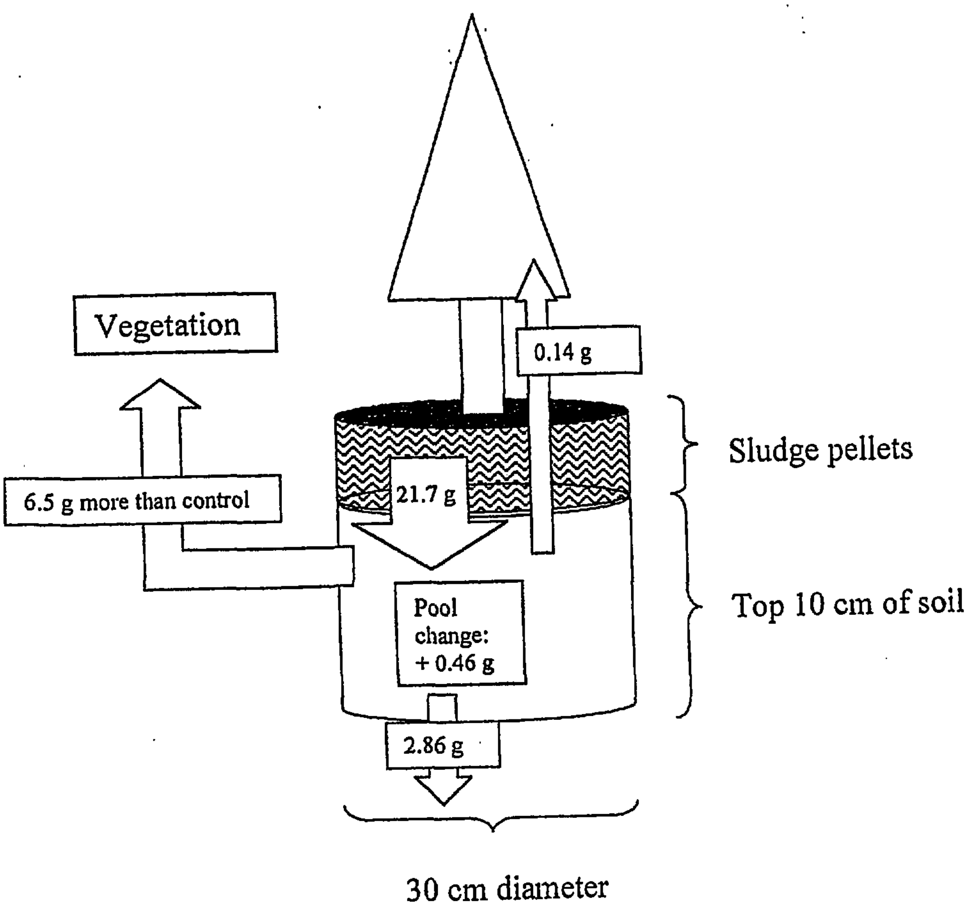

Figure 9. Nitrogen budget for the BP treatment. Fluxes and pools are expressed as gN. The calculations are based on a single treated plant and surrounding vegetation (soil bulk density: 0.750 kg/dm^3). Nitrogen leaching is expressed as maximum NO_3-N leaching without root uptake.

Discussion

Pellets

The nitrogen release was mostly from the BP treatment. The nitrogen released is most likely ammonium since ammonium accumulation is observed in the top soil. There could also be small releases of nitrate, which is masked by the nitrate leaching from the top soil. The C/N ratio remains more or less constant throughout the study, which indicates that the nitrogen released is from microbial activity.

The small increase in nitrification in the VNP treatments could be a sign that some very easily leachable ammonium was present and leached from the plant nutrition pellets before sampling. The reasons for the inert properties of the VNP pellet could be several. Mineralisation could be low if there is no easily digested carbon left in the material after composting. Heavy metals could be inhibiting mineralising micro biota. The high degree of compaction in the pelleting process could inhibit oxygen supply to aerobic micro biota.

Soil

The results are quite consistent in that BP is strongly affecting the nitrogen fluxes in the topsoil. Though this is not the case at the first incubation where the VNP treatments on the other hand has a small effect on nitrification. Since this effect is showing both with and without scarification it shouldn't be a mulching effect from covering the vegetation. Changes in soil temperature as well as soil water content and covering of the vegetation should also have been evident with the BP treatment. Therefore it seems that there must have been some easily leachable ammonium in the VNP even though this is not showing in the calculated NH_4-leaching. Perhaps this ammonium leakage occurred in the short time period between the distribution of the pellets and the start and the first incubation.

The increase in nitrification from the BP treatment is most certainly connected to the enrichment of ammonium. In the last incubation there is still an increased nitrification even though there is no increased ammonium enrichment. The ammonium concentration probably has reached some kind of steady state where leaching and nitrification is compensating for the input from the Biopell as the leaching potential is decreasing.

The pH increase could be due to several factors such as a higher pH, of the pellets or pH buffering of the decomposing vegetation under the pellets. Interestingly is the BP treatment not showing a lower pH than VNP even though the nitrification rate is higher. This could be an effect of the lime that is present in the Biopell.

Vegetation

The effects of the BP treatment on vegetation are the largest effects seen in this study. This is not surprising since the planted plants are subjected to planting check while the vegetation is vigorous. I also observed a marked effect on colour of the vegetation in the BP treatment parcels where the colour was shifting to darkgreen-bluish.

Spruce plants

Though not as large as for the vegetation there were some effects on the plants late in the study. Reallocation of nitrogen from older parts of the plant to the new shoots is probably the reason why fertilisation effects is not seen in the new shoots at the first sampling occasion. This is further indicated as the older parts of the fertilised plants show a fertilisation effect at the first sampling occasion. The possibility of an initial release of nitrogen from the plant nutrition pellets is further indicated as the fertilisation effect on the older needles has diminished at the second sampling occasion. The nitrogen from improved nitrogen status at the first sampling occasion is probably reallocated to the new shoots at the second sampling. That this is not the case fore the BP treatment clearly shows that those plants have access to plenty of nitrogen.

The Sc treatment apparently has some effect on growth and since this effect also is indicated for the ScVNP treatment the effect could be from lessened root competition. However this is dubious because the covering of vegetation in the other fertilised treatments should also exclude root competition. The only other reasonable explanation must be that the disturbance of the soil due to scarification has improved the planting environment even though the soil shouldn't be disturbed by an ordinary patch scarification.

Budget calculations

Since the nitrogen budget isn't balanced there must be other pathways of nitrogen removal from the topsoil. This excess nitrogen probably follows one of these pathways. Either it is leached through the soil as ammonium as only the net gain of ammonium in the soil is assessed. Another pathway is lateral diffusion, which is most likely to have happened since the vegetation was changed throughout the parcel area.

Conclusions

There is consistent evidence that Biopell is effectively fertilising the plants and soil with nitrogen. The results from the plant nutrition pellets are more doubtful even if some small effects were found. It is found that the plant nutrition pellet probably has small amounts of easily leachable ammonium but a study over a longer time period is required to properly evaluate the long-term effect of this treatment. Growth effects can probably not be evaluated in a short study like this since scarification is the only treatment that is showing any signs of growth effects.

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References

Burdett A. N., Herring L. J., and Thompson C. F., 1984. Early growth of planted spruce. Can. J. For. Res. Vol. 14. pp. 644-651.

Dutch J. and Wolstenholme R., 1994., The effects of sewage sludge application to a heathland site prior to planting with Sitka spruce. For. Ecol. and Man. 66:151-163

Henry C. L., Cole D. W. and Harrison R. B., 1994. Use of municipal sludge to restore and improve site productivity in forestry: The Pack Forest Sludge Research Program. For. Ecol. and Man. 66:137-149.

McDonald et al., 1994. Growth and foliar nutrition of western red cedar fertilized with sewage sludge, pulp sludge, fish silage and wood ash on northern Vancouver Island. Can. J. For. Res. Vol. 24, pp. 297-301

Payandeh B. and Sutton R.F., 1989. Modeling Early Plantation Performance: Identification of Critical Factors. Scan. J. For. Res. 4(1) pp. 75-86.

Pettersson, O., 1992. Avloppsslam som resurs och riskfaktor. SLU info rapporter nr 177.

Raison, R. J. et al., 1987. Methodology for Studying Fluxes of Soil Mineral-N *In Situ*. Soil Biol. Biochem. Vol. 19, No. 5, pp. 521-530.

SCB, 1996. Naturmiljön i Siffror. Red. Solveig Danell. Fifth publishment. Bulls Tryckeri AB Halmstad.

Sutton R. F., 1995. White spruce establishment: initial fertilization, weed control, and irrigation evaluated after three decades. New Forests 9:123-133.

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