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Growth responses in Swedish boreal coniferous forests after addition of nitrogen as sewage sludge pellets

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ABSTRACT

Every year, large amounts of municipal sewage sludge are produced worldwide. Most of the sludge ends up on landfills, garbage dumps and incineration plants, and only small part is utilized as a fertilizer in agriculture and forestry. Sewage sludge contains a lot of nutrients, especially nitrogen. In boreal forests, a lack of available nitrogen limits the growth, and therefore sewage sludge could be applied into forests to increase the growth. Sewage sludge pellets might offer a good alternative for liquid and dewatered sludge or even for inorganic fertilizers in fertilizing forests. The aims of this study were to investigate the effect of the addition of nitrogen as sewage sludge pellets on tree growth, the effect of dose size and the duration of the growth response.

The study consists of two experiments, Pilot and Åheden that had been fertilized with sludge pellets in 1996 and 1998, respectively. In the Pilot experiment two treatments, 0 and 4 tons sludge pellets ha^{-1} (ca. 100 kg N ha^{-1}), were applied in Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) stands. In the Åheden experiment, five treatments, 0, 3.3, 6.6 and 13.2 tons sludge pellets ha^{-1} (equalling 0, 100, 200 and 400 kg N ha^{-1}, respectively) and 200 kg N ha^{-1} as ammonium nitrate, were applied in a pine dominated stand. Ammonium nitrate had been applied in order to compare the effects of nitrogen from different sources on tree growth. The breast height diameter (DBH) was measured from the sample trees and cores samples taken with an increment corer.

The application of sludge pellets increased the diameter and basal area growth in comparison to control treatment in the Åheden experiment. In the Pilot experiment, addition of sludge pellets did not result in any significant change in basal area in comparison to control treatment, but the spruce stands tended to respond more clearly on sludge pellets addition than pine stands. The results were not statistically significant, however. In the Åheden experiment, the addition of 400 kg N ha^{-1} as sludge pellets increased the diameter and basal area growth nearly as much as when 200 kg N ha^{-1} of ammonium nitrate was applied. Additionally, the basal area growth tended to increase with the increasing amount of nitrogen added as sludge pellets. The increased basal area growth tended to last at least the first 5-year period after fertilization on the sludge treated plots in

Åheden experiment (and on the spruce stand in Pilot experiment) but these results were not however statistically significant.

The study showed that application of sludge pellets in boreal, Scots pine dominated forest increases the forest growth. Since the growth response to the highest dose of sludge pellets was nearly as good as from commercial fertilizer, ammonium nitrate, it seems that pellets do offer a reasonable and attractive alternative for inorganic fertilizers and could even replace them in the future forest fertilizations. However, more research about both environmental and growth effects is needed before sludge pellets can be taken in use in a large scale.

Keywords: Basal area; Growth response; Nitrogen fertilization; *Pinus sylvestris*; Sludge pellets

SAMMANFATTNING

Stora mängder avloppsslam produceras i världen varje år. Största delen av slammet deponeras på avfallstippar, används som anläggningsjord eller bränns på förbränningsanläggningar och bara en liten del används som gödsel på jordbruksmark eller på skogsmark. Slammet innehåller stora mängder växtnäring, särskilt kväve. I boreala skogar begränsar brist av kväve ofta skogens tillväxt och därför kan avloppslam spridas på skogsmark för att öka skogsproduktion. Pelletterat slam som skogsgödsel kan vara ett bra alternativ till obehandlant slam eller till konstgödselmedel.

Denna studie består av två försök, Pilot och Åheden, som gödslades med pelletterat avloppsslam 1996 respektive 1998. I Pilot-försöket hade 0 och 4 ton pelletter per hektar (motsvarar ca 100 kg N ha^{-1}) spridits i tall- (*Pinus sylvestris* L.) och granbestånd (*Picea abies* (L.) Karst.). Åheden-försöket, ett talldominerat bestånd, hade fem behandlingar som bestod av 0, 3.3, 6.6. och 13.2 ton pelletter ha^{-1} (motsvarar 0, 100, 200 och 400 kg N ha^{-1}, respektive) och ytterligare 200 kg N ha^{-1} som ammonium-nitrat. Försöksledet ammonium-nitrat inkluderades för att kunna jämföra effekter av kväve från slam och konstgödselmedel på trädens tillväxt. Brösthöjdsdiameter (DBH) av provträd var mätt och borrad med en årsringsborr för att få kärn prov.

Spridning av slampelletter till skogen i Åheden-försöket ökade diameter och grundyttillväxten i jämförelse med kontrollbehandlingen. I Pilot-försöket gav slampelletter ingen generell ökning i grundyta i jämförelse med kontrollen. Granbestånden verkade emellertid ha en tendens för att reagera mer positivt på tillförseln av slampelletter än tallbestånden. Resultaten hade i alla fall ingen statistisk betydelse. I Åheden-försöket, behandlat med 400 kg N ha^{-1} som slampelletter ökade diameter- och grundyttillväxten nästan lika mycket som när 200 kg N ha^{-1} som ammoniumnitrat hade använts. Grundyttillväxten verkade ytterligare ha en tendens att öka med ökande mängder kväve som tillsatt med slampelletter. Resultaten visade ökad grundyttillväxt på gödslade provytor fem år efter behandlingen i Åheden-försöket och på gödslade granprovytor i Pilot-försöket.

Den här studien visade att tillförsel av slampelletter i boreala, talldominerad skog ökar skogens tillväxt. Eftersom den högsta slamnivå medförde nästan lika hög tillväxtreaktion som konstgödselmedel, ammonium nitrat, kan slampelletter ge ett rimligt alternativ till oorganiskt gödselmedel och kunde även ersätta dem vid skogsgödslingar i framtiden. Naturligtvis behövs mera undersökningar för att utröna noggrant slampelletters effekter på miljö och skogens tillväxt innan skogsgödslingar med pelletter kan införas i stor skala.

Nyckelord: Grundyta; Kvävegödsling; Pelletterat slam; *Pinus sylvestris*; Tillväxt-respons

1 INTRODUCTION

1.1 Background

1.1.1 The nitrogen balance in boreal coniferous forest

Boreal upland forests are usually characterized by a deficiency of available nitrogen (Aaltonen, 1926 *ref.* Mälkönen, 1990; Chapin et al., 1993). Therefore it is one of the most important growth limiting factors (Tamm, 1991; Mäkipää, 1995; Smolander et al., 1998). The shortage of available nitrogen (N) is due to nitrogen being bound in organic components (e.g. in soil organic matter). According to the traditional view of N cycling, trees take up mainly inorganic nitrogen, e.g. ammonium (NH_4^+) and nitrate (NO_3^-), and therefore the nitrogen compounds of organic material thus first have to be converted into inorganic forms (ammonium-ions, NH_4^+) through ammonification (Turner et al., 1993; Hallet et al., 1999). In subsequent process, i.e. nitrification, the ammonia (NH_3) is oxidized to nitrite and further to nitrate (Hallet et al., 1999). Since decomposition of organic material and hence also mineralization (ammonification and nitrification) are slow processes in boreal forests, nitrogen is released relatively slowly (Brockway, 1983; Mäkipää, 1995) and therefore often not in sufficient amount for trees (Mälkönen, 1990).

Nitrogen additions into forest ecosystems increase forest growth (Mälkönen and Kukkola, 1991). Moreover, nitrogen fertilizations may induce long-term improvement in the availability of N in forest soil through the recycling of the added nitrogen in the litter (Prescott et al., 1993) and hereby ameliorate site quality (Bennet et al., 2003). The growth response to fertilization is largely dependent on the amount and the form of added nitrogen (Westman, 1973). Nitrogen fertilizations have been carried out by using commercial N-fertilizers. In acid forest soils urea-N can be quickly converted to ammonium nitrogen (NH_4^+), which is readily taken up by trees and other vegetation (Tamm, 1991). There is a risk however that inorganic-N is lost from the soil system through leaching as nitrate (NO_3^--N) due to its good solubility. Nitrogen can also be lost through volatilization (under basic conditions, $pH \geq 7$) and through surface-runoff (Preston et al., 1990).

Due to the risk of nutrient-leaching related to inorganic fertilizers, alternative ways are needed to carry out forest fertilizations in a more environmentally sustainable way. Several studies have concluded that not only commercial inorganic fertilizers but also amendments of municipal sewage sludge result in significantly increased forest growth (e.g. Zasoski et al., 1984; Bastian, 1986; Henry et al., 1993; Henry et al., 1994; Prescott and Blevins, 2005). Hence, it might be plausible that inorganic fertilizers could be successfully replaced by municipal sludge.

1.1.2 Municipal sewage sludge without a use?

Every year large amounts of municipal and industrial waste are produced worldwide, and the annual production rates are rising, whereas the reutilization of sludge is decreasing. In Finland, for example, the annual production of municipal and industrial waste in 2003 was approximately 2.3 and 12 million tons, respectively (SYKE, 2003). The annual production (in 2003) of municipal sewage sludge was approximately 150 000 tons (dry weight) (SYKE, 2003). In Sweden, the corresponding figure was ca. 240 000 tons dry weight in 2000 (Hultman et al., 2000). It should be pointed out, however, that there is a clear distinction between municipal waste and municipal sewage sludge. Municipal waste usually encompasses different kind of mixed waste, i.e. car wreckages, scrap metal as well as organic waste, wood and cardboards among others. Sewage sludge, in part, is that liquid or solid particles containing residue separated from various types of waste waters during the waste treatment processes. In this study, with municipal sewage sludge is meant the latter definition.

Municipalities and industry are faced with managing these large and increasing quantities of residuals from wastewaters (Henry et al., 1993). A major proportion of the sludge ends up on landfills, garbage dumps or incineration plants (Kelty et al., 2004). During the past decades, demands are raised to increase the utilization rates of sludge. Fees set for dumping sludge into landfills, increased regulatory scrutiny for incineration, EU-directive (Directive 1999/31/EC) for decreasing the amount of organic waste ending up on garbage dumps, and international protocol set to prohibit ocean dumping (IMO, 1996) have in part contributed to find out other alternatives to utilize sludge. Despite that beneficial reuse of sludge has become increasingly attractive and a popular option in recent years (Magesan and Wang, 2003), still only less than half of the amount of sewage sludge produced is usually recycled and utilized in agriculture and forestry. At present, for example in Finland, forest fertilizations are not practiced in a large extent and in 2003 only approximately 23 000 hectares of forest were fertilized with commercial nitrogen fertilizers (Anon., 2005). In Sweden, the area of forest fertilizations is approximately the same (Skogvårdstyrelsen, 2002).

In agriculture, municipal sewage sludge is a commonly used fertilizer, where it has been used in fact already since antiquity (Zasoski et al., 1984). Since the 1970s, sludge has been applied into forest ecosystems for site improvement purposes (e.g. Zasoski et al., 1983; Henry et al., 1994; Hånell et al., 1996; Henry and Cole, 1997; Thornton et al., 2000; Kelty et al., 2004). Municipal sludge contains essential plant nutrients, especially nitrogen and phosphorus. Most of the nitrogen, 70-80 % is however bound in organic matter (Kelty et al., 2004). With regard to nitrogen content, sewage sludge would be an excellent fertilizer in boreal mineral soil forests (Tamm, 1991).

The amount of organic material in sewage sludge is high, which can in part improve the soil physical characteristics such as soil structure and porosity (Henry, 1986; Wolstenholme et al., 1992; Adegbidi et al., 2003) when mixed into the soil. Application of sewage sludge contributes to the soil's organic matrix which immobilizes nutrients but also heavy metals. Hence, sludge additions may improve the nutrient holding capacity (Henry, 1986; Outwater and Tansel, 1994; Bramryd, 2001) and further increase the site quality (Prescott et al., 1993). This relates, however, mainly to considerably high application rates of sludge (Miller, 1981 *ref.* Prescott et al., 1993). Several studies have shown that sludge has remarkable growth-increasing effects in different type of forests with regard in age and species (e.g. Cole et al., 1984; Zasoski et al., 1983; Brockway et al., 1986; Henry et al., 1993; Henry et al., 1994; Prescott and Brown, 1998; Kimberley et al., 2004; Prescott et al., 2005). The growth responses are often related to the nitrogen and phosphorus added with the sludge (Kimberley et al., 2004). Further, liquid sludge has been found to increase the forest growth faster than dewatered sludge due to its higher inorganic-N content (Bramryd, 2001).

Some researches have concluded that the long-term improvements in site quality and productivity caused by municipal sludge might even exceed those of chemical fertilizations due to e.g. prolonged mineralization of nutrients (Brockway et al., 1986; Henry et al., 1993; Prescott and Blevins, 2005). Nonetheless, there are also studies that found no growth response or even a decline in growth after application of sewage sludge. Similarly, the findings on environmental effects of sludge applications have been controversial (e.g. McKee et al., 1986; Hånell et al., 1996; Thornton et al., 2000; Kelty et al., 2004). Magnusson and Hånell (2000a) stated (based on literature review) that when the sludge dose was applied at a rate of ca. 15-20 tons per hectare, there were no substantial harmful effects, such as nitrate leaching, on the surrounding environment.

Sludge seems to be a good alternative for conventional fertilizers when properly applied (Wolstenholme et al., 1992). Almost all sludge applications in forests ecosystems have been carried out either by spreading dewatered sludge (water content 70-80 %) before planting or by spraying liquid sludge (water content (water content >90 %) under the canopy of established stands (Henry et al., 1994). However, public acceptance has been a major challenge for applying sludge in to forests (Henry et al., 1993) and there are several factors that set limits to the utilization rates of liquid and dewatered sludge; for example bad smell, several years of limited access to the fertilized site after the treatment, high transportation costs, and difficulties in storing and handling of sludge (Magnusson and Hånell, 2000b). Furthermore, concerns have aroused on the heavy metal concentrations in sludge, uncertainty of the fate of contaminants, nutrient (especially N) leaching, and occurrence and spread of infectious pathogens, viruses and parasite eggs, thus possessing a plausible risk for contaminating the human food chain (Zasoski et al., 1984; Hånell et al., 1996). The chemical composition and amount of contaminants vary depending on e.g. the source of the sludge (e.g. municipal vs. industrial) and stabilization treatments (Bramryd, 2001). The quality of sludge, in terms of contaminants and physical properties, has improved during the past years through better treatments and other sanitation processes (Thornton et al., 2000). It is now possible to reduce the amounts of pathogens into insignificant levels through heating treatment (Hånell et al., 1996).

1.1.3 Sludge pellets - more applicable form of sludge

Before sewage sludge can be used as a fertilizer in forest ecosystems, it needs to be stabilized and sanitized (i.e. destruction of the pathogens). The most common methods are liming (with CaO or $Ca(OH)_2$), anaerobic digestion (rotting), aerobic digestion (composting), drying, long-time storing and pasteurizing (Naturvårdsverket, 2003). However, difficulties with the use of liquid and dewatered sludge have brought about a need to develop new technologies to produce more usable forms of sewage sludge. Pelletizing dewatered sludge has received lot of interest and research experiments have been undertaken (e.g. Hånell and Magnusson, 1996).

Previously, attempts to pelletize sludge have mainly failed due to the high water content of sludge and because most of the water is bound inside to the cells from where it is difficult to release. Mechanic dewatering has been inadequate and therefore pellets have stuck together and formed clumps of different sizes which have made it impossible to dry them enough for storing. The new technical possibilities for pelletizing sludge eliminate the practical obstacles that so far have complicated a sound use of sludge. With the new technique (Biopell^{TM}), fine calcium powder is continuously sprayed on pellets in an extruder. The lime prevents the pellets from sticking together, and instead the pellets are strengthened and made easier to cut into various sizes (Hånell et al., 1996). The pellets are dried to approximately 90 % dry matter content and sterilized by heating (100 °C) during the drying process (Magnusson, 2001). One of the most important benefits of this heating process is that it effectively kills all infectious substances (Hånell et al., 1996; Kelty et al., 2004). Furthermore, the pellets do not have a bad smell, and yet the nutrients are remained. Dry sludge pellets are as easy to handle as conventional fertilizers, and easily stored (Hånell et al., 1996). However, in the initial dewatering process prior to the heating most of the soluble constituents are lost in the drainage water (Bramryd, 2001). Pellets contain little inorganic nitrogen and organic-N can even constitute as high as 98 % of the total nitrogen. Thus, nitrogen in pellets is not in a form immediately available for trees (Kelty et al., 2004). Despite of the positive prospects of pelletized sludge, there are not many studies made concerning the growth effects from pelletized sludge. Thus, it is important to examine thoroughly the possibilities related to pellets.

It seems that pelletized sludge may indeed offer an excellent alternative for liquid/dewatered sludge and maybe even for commercial fertilizers (Thornton et al., 2000). The benefits of sludge are multiple. Recycling of waste products contributes to the sustainable resource management, nutrient cycling becomes more efficient and nutrient deficiencies on mineral soils can be eliminated. Furthermore, tree growth can be enhanced without remarkable harmful effects on the surrounding environment (cf. liquid and dewatered sludge). Another positive effect is that the amount of sewage sludge deposited on landfills would decrease. Fertilizing forests with pelletized sewage sludge is however a relatively new measure and only few studies on environmental and growth effects are reported (e.g. Hånell et al., 1996; Kelty et al., 2004). Several aspects, e.g. magnitude and duration of the growth response, need to be further investigated so that the suitability and profitability of pellets in large-scale forest fertilization can be evaluated (Dickens et al., 2002). Yet, it seems that forests are becoming even more important links in the cycling of waste by-products (Magnusson and Hånell, 2000b).

1.2 Aims and hypotheses

The present study concerns the growth effects of pelletized sewage sludge in a boreal forest. The aims of this study were to i) determine whether or not amendments of sludge pellets as forest fertilizer result in a positive tree growth response, ii) estimate the suitable dose size, and iii) estimate the duration of the growth response from sludge pellet and ammonium nitrate (AN) applications.

The main hypothesis was that sludge pellets have a positive effect on growth. It was also expected that growth response increases with increasing amounts of sludge used, i.e. the higher the dose the greater the growth response. Another hypothesis was that the highest dose of pelletized sludge would have at least as good growth effect as commercial fertilizer (here ammonium nitrate).

2 MATERIAL AND METHODS

2.1 Site descriptions

The present study was a part of a larger project, “Sewage sludge to forest land” (Hånell and Magnusson, 1996) investigating the impacts of pelletized sludge. The project was established in 1996 and has been running since. The experimental sites are located in

Svartberget and Kulbäcksliden Experimental Forests in Vindeln (64°12'N, 19°44'E), 50 km NW of Umeå, in the county of Västerbotten in Northern Sweden (Fig. 1). The study at hand consists of two experiments, the Pilot experiment and the Åheden experiment, established in 1996 and 1998, respectively. The climate is cold temperate with an annual mean temperature of 1 °C. Annual precipitation in the area is around 600 mm of which one third falls as snow. Furthermore, snow cover lasts for six months from late October till early May (Alexandersson et al., 1991).

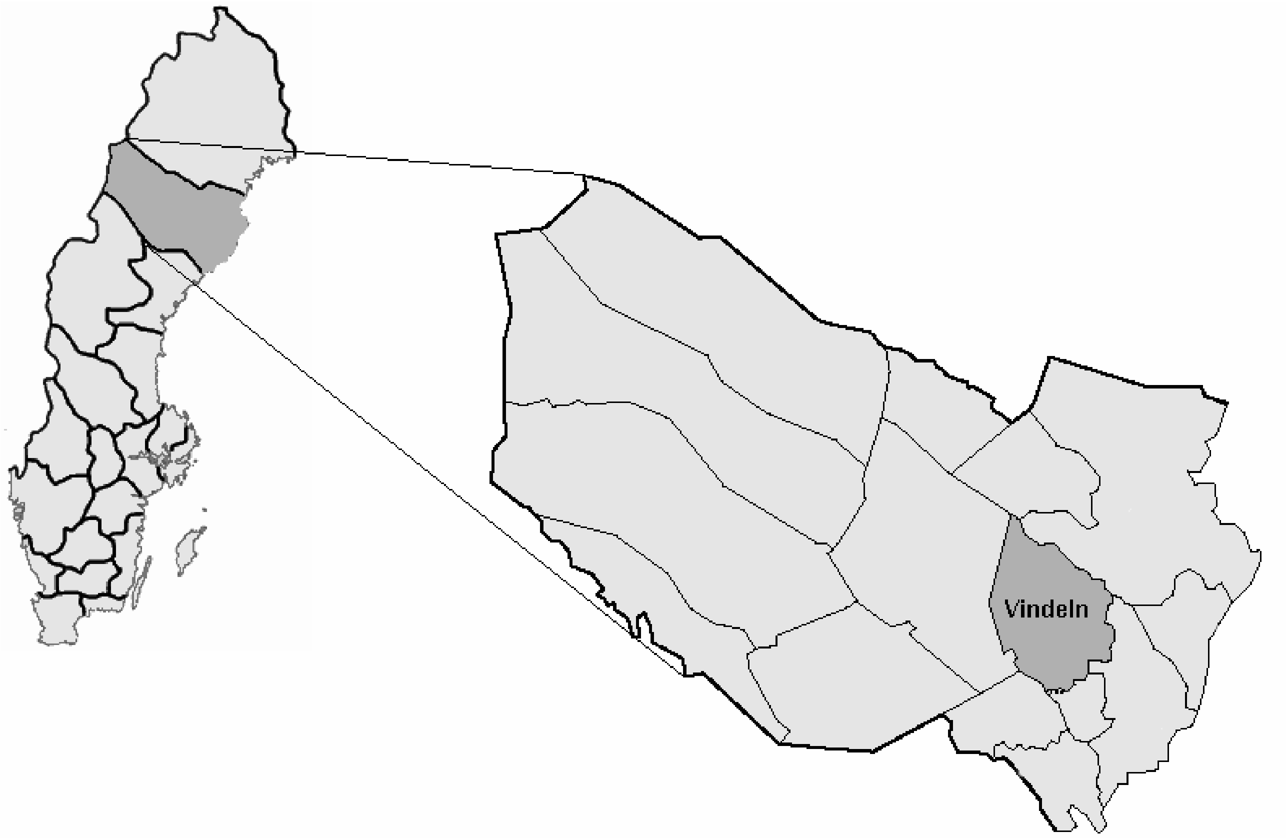

Figure 1. The location of the study area in the municipality of Vindeln in the county of Västerbotten, Northern Sweden.

2.1.1 The Åheden experiment

The Åheden experiment was established in a Scots pine stand on an alluvial delta plain. The experimental design consisted of three blocks with five plots (50 m x 50 m) in each, allowing five treatments replicated three times (Fig. 2). The net plot area was 40 m x 40 m, leaving a 10 m untreated buffer zone around each side of the net plots. The soil texture was fine sand to coarse silt. Forest was dominated by coniferous trees, mainly Scots pine (*Pinus sylvestris* L.), and the relatively open field layer is a mixture of blueberry (*Vaccinium myrtillus*), lingonberry (*Vaccinium vitis-idaea*) and short grasses, mainly Wavy Hair-grass (*Deschampsia flexuosa*). The bottom layer was dominated by feather mosses (*Pleurozium schreberi* and *Hylocomium splendens*). When the experiment was establishment, the average stand density was ca. 930 stems ha^{-1} and the average basal area was 22 m^2 ha^{-1}. At the time of data collection (May 2005), the stand age (average of three blocks) was 63 years measured at breast height.

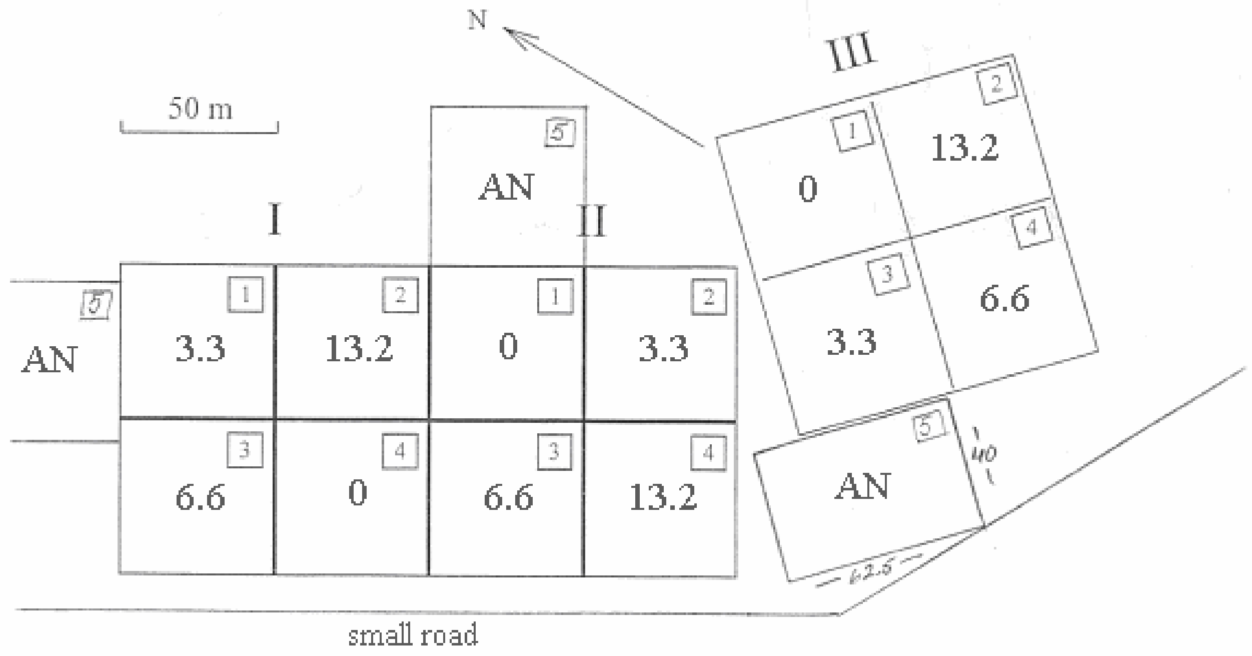

Figure 2. Experimental design of the Åheden experiment. The numbers inside the small squares indicate plot numbers within blocks (I-III). The numbers 0, 3.3, 6.6, and 13.2 inside the plots 1-4 describe the dose of sludge pellets applied in metric tons, and correspond to ca. 0, 100, 200, and 400 kg N ha^{-1}, respectively. Label AN (plot 5) indicates the addition of 200 kg N ha^{-1} as ammonium nitrate.

Sludge pellets were spread on the plots by a tractor in June / July 1998 and ammonium nitrate June 1999. Some trees were removed on all treatments including the untreated control in order to allow the tractor to follow parallel strips with a 20 m interval. The following treatments were applied:

(1) Control, no nutrient additions
(2) Fertilization with 3.3 t (dry weight; dw.) sludge pellets per hectare (ca 100 kg N ha^{-1})
(3) Fertilization with 6.6 t (dw.) sludge pellets per hectare (ca. 200 kg N ha^{-1})
(4) Fertilization with 13.2 t (dw.) sludge pellets per hectare (ca. 400 kg N ha^{-1})
(5) Fertilization with commercial fertilizer, ammonium nitrate 200 kg N per hectare

Later in the text, the treatments are abbreviated as follows: CONTROL, SLUDGE100, SLUDGE200, SLUDGE400, and AN200. The sludge pellets used in both experiments were produced from municipal sewage sludge with the Biopell^{TM} method. The pelletization process involves some additions of finely ground lime. Furthermore, the batches produced in 1996 were made from lime-treated sludge. The pellets were sterilized by heating and dried to ca. 90 % dry weight. The chemical characteristics of pellets are presented in table 1.

Table 1. Concentrations of carbon and macronutrients (%), and pH (in water) and C/N ratio of sludge pellets spread in the Åheden experiment (1998) and in the Pilot experiment (1996).

Experiment	**C %**	**N %**	**P %**	**K %**	**Ca %**	**Mg %**	**S %**	**C/N**	**pH (H_2O)**
Pilot trial	30	2.6	1.2	0.22	13.7	0.28	0.39	7.6	11
Åheden dose trial	34	3.0	1.8	0.21	6.8	0.31	0.36	6.8	11

2.1.2 The Pilot experiment

The Pilot experiment included six paired plots (control and treatment) without replications. The plot size was 225 m^2 (15 x 15 m). The plots were laid out in three Scots pine (*Pinus sylvestris* L.) and three Norway spruce (*Picea abies* (L.) Karst.) stands. The age of the stands varied between 45 and 105 years. All soil types are podzols on till soils. The field layer was dominated by Ericaceous shrubs (mainly *Vaccinium myrtillus* and *Vaccinium vitis-ideae*, *Empetrum*, and *Calluna* sp.) whereas feather mosses (especially *Pleurozium schreberi* and *Hylocomium splendens*) dominated the bottom layer. Stand characteristics are presented in table 2. Dried sludge pellets were applied in June 1996 at dose of 4 tons ha^{-1} (dw.) corresponding approximately to 100 kg N ha^{-1}.

2.2 Field measurements

Field measurements were done on both experiments in the beginning of May 2005. Prior to this study, sample trees had been chosen systematically, that is selecting the first tree in each diameter class and thereafter every fifth tree. The sample trees were numbered randomly on each plot. The amount of sample trees was not constant on the plots in the Åheden experiment but varied from 27 to 43 being approximately 35 sample trees per plot on average. In the Pilot experiment there were 10 sample trees on each plot. The diameter of each sample tree (all together ca. 630 trees) was measured at breast height ($D_{1.3}$, mm) crosswise with a calliper and the tree species was also registered. In order to measure the ring widths, core samples were taken with an increment corer at breast height from all sample trees. The core samples were put in cartridges for storing and further analyses. On each plot, four of the sample trees in the Åheden experiment and two of the sample trees in Pilot experiment were additionally cored to the pith for assessment of the average stand age. These trees were chosen systematically by selecting every seventh in the Åheden experiment and every fourth tree in the Pilot experiment.

Table 2. Stand characteristics of the forests on the Pilot trial in means of average diameter ($D_{1.3}$, cm), stem density (stems ha^{-1}), basal area (m^2 ha^{-1}), mean stand age (yrs), stand vegetation, soil type, soil moisture conditions and slope at the time of stand establishment in 1996.

Forest	**$D_{1.3}$, cm**	**Average stand density, stem ha^{-1}**	**Basal area, m^2 ha^{-1}**	**Mean stand age, yrs ***	**Vegetation**			**Soil type**	**Soil moisture conditions**	**Slope**
					Main tree species	**Field layer**	**Bottom layer**			
1	17	2100	33	105	*Picea abies*	*Vaccinium myrtillus*	Feather mosses	Slightly washed sandy loam till	Mesic	Flat
2	17	1400	21	61	*Pinus sylvestris*	*Vaccinium vitis-idaea, Empetrum hermaphroditum*	Feather mosses and lichens	Sandy loam till	Dry to mesic	Flat
3	13	2200	23	51	*Pinus sylvestris*	*Vaccinium vitis-idaea, Empetrum hermaphroditum, Calluna vulgaris*	Feather mosses and lichens	Glacifluvial medium to fine sand	Dry	Flat
4	16	1600	30	47	*Pinus sylvestris*	*Vaccinium myrtillus, Vaccinium vitis-idaea*	Feather mosses	Sandy loam to silt loam till	Mesic	Short slope 15 %
5	20	1400	30	91	*Picea abies*	*Vaccinium myrtillus*	Feather mosses	Sandy loam till of hummocky moraine	Mesic	Flat
6	15	1800	23	41	*Picea abies*	*Vaccinium myrtillus*	Feather mosses	Washed sandy loam till	Mesic to moist	Long slope 10 %

*) Mean age is the average age measured from the two sample cores bored in May 2005.

2.3 Methods

2.3.1 Data processing

From the bored increment cores, the last 18 and 20 year rings were measured from the samples of the Åheden and Pilot experiment respectively. The ring widths were measured by using a special ring width measuring system, WinDENDRO (Regent Instruments Inc. 1998), which included an image analysis programme specifically designed for tree-ring measurement and analysis. The programme automatically calculates the ring widths from scanned tree core samples. In Åheden experiment there were 15 birch (*Betula* sp.) sample trees. The ring widths of the birch cores were measured manually with a gadget with a magnifying glass since WinDENDRO-program was not able to detect the faintly distinguishable year rings.

2.3.2 Calculations

In this study, the basic data comprised the current diameter ($D_{1.3}$, mm) and the annual ring width increments for all sample trees. This data was used as the basis for the calculations of the basal area increment of each individual tree. Since the annual growth had not yet begun when the field measurements were done, the latest diameter and ring width increment was considered that of year 2004. The effect of fertilization on ring width development in Åheden and Pilot experiment are presented in Appendix I.

On the basis of this data, the current breast height diameter (DBH, $D_{1.3}$, mm) under bark of each sample tree was first calculated by subtracting the calculated bark thickness (formula 1) from the measured DBH. Second, annual backward DBH under bark of each sample tree in previous years was calculated by stepwise subtracting the annual diameter increments (i.e. double ring widths) from the DBH of each sample tree. Third, the annual diameter on bark of each sample tree was calculated by adding corresponding bark thickness (formula 1) to respective diameter. Finally, corresponding annual basal areas of individual trees were calculated from the DBH data. Thus, basal areas for each year for the 10-year observation period were calculated for each sample tree. Due to the high variation in sample tree size, annual average tree DBH and basal area were calculated for each sample plot on the basis of the individual sample tree data for DBH and basal area in order to be able to compare plots with each other more reliably.

The increase in basal area (BA) was calculated for the 5-year period (I_{BA}) after the fertilization. The periods were in the Åheden experiment 1999-2003 on sludge treatments and 2000-2004 on treatment AN200, and in the Pilot experiment 1997-2001. The effect of added amount of nitrogen on growth was tested by calculating block-wise the difference in basal area increment during the 5-five year period after fertilization (DIFF I_{BA}) between treated plots and corresponding control plot, and further plotting this difference against the added amount of nitrogen (N). A logarithmic regression model was fitted to describe the relation. The duration of the growth response was examined by comparing the annual basal area increment (I_{BA}) of the sludge treatments with the annual basal area increment of the control treatment (% yr^{-1}).

Double bark (DB) regression model

$$DB\ (mm) = b_0 + b_1 * D_{1.3} \qquad (1)$$

where b_0 is a constant and b_1 is the coefficient for the breast height (1.3 m) diameter over bark (subtraction function) or under bark (addition function). The model was based on all sample trees. Separate models were used for pine, spruce and broadleaved trees (Table 3). Models were used in the prediction mode for the calculation of retrospective double bark thicknesses in the basal area increment calculation procedure.

Table 3. The coefficients for the different tree species used in the double bark (DB) regression model.

	Coefficients	
Tree species	**b_0**	**b_1**
Pinus sylvestris	6,906	0,944
Picea abies	6,286	0,589
Betula sp.	-0,128	1,108

2.3.3 Statistical analyses

In order to examine the effect of fertilization in Åheden experiment, the increases in sample plot average tree breast height diameter (DBH) and basal area (BA) five years after the fertilization treatment were first compared and differences among the treatments were tested (only I_{BA}) with the analysis of variance (Univariate General Linear Model) with treatment and block as fixed factors. Examining the residuals of the linear model showed that the assumptions were met. The effect of sewage sludge nitrogen (200 kg N ha^{-1}) was compared to the effect of ammonium nitrate nitrogen (200 kg N ha^{-1}) separately by t-test (one-way ANOVA). The control treatment was used as a comparison. Concerning the Pilot experiment, the effect of fertilization (100 kg N ha^{-1}) was examined by comparing the I_{BA} during five years after the fertilization of the treated and untreated plots and within the three species. The differences were tested with the analysis of variance and both treatment and tree species were used as factors. In both experiments, Tukey's multiple comparison test was used to determine whether the treatments differed significantly from each other. The differences were considered statistically significant when $P < 0.05$.

The effect of the amount of sewage sludge on the increase in the plot average basal area, BA (DIFF I_{BA}, dm^2 5 yr^{-1}), was analysed graphically from scatter plots (the growth increase in relation to the amount of nitrogen) and by fitting a curve logarithmic line. Finally, the duration of the effect of sewage sludge addition on growth of sample plot average tree was analysed graphically by plotting annual basal area increment in relation to control (% yr^{-1}) on a time scale that covered the ten years observation period (1993-2003 in the Åheden experiment and 1991-2001 in the Pilot experiment). All the statistical analyses were made using SPSS analytical software (version 13.0; SPSS Inc. 2004).

3 RESULTS

3.1 Growth response to application of sludge pellets

During five years after the fertilization (i.e. 1999-2003) the basal area and breast height diameter increased more on the sludge treated plots than on the CONTROL in the Åheden experiment (Table 4). The differences between the treatments were however small. Furthermore, the increases in basal area of the average tree did not differ significantly from each other (Table 5). Thus, the sludge fertilization did not have statistically significant effect ($p = 0,26$). The block was neither a significant factor ($p = 0,73$). Nonetheless, as is shown in table 4, the trend was that adding nitrogen within sludge pellets resulted in bigger growth after the fertilization than when no additions were made. The same trend could be seen when examining the increases in the breast height diameters of the average trees. Within the treatments in different blocks there was a lot of variation, however, even already before the fertilization.

The different treatments in the Åheden experiment were not fully comparable as regarding the diameter (at breast height) and the basal area increase (Table 4) since the tree stands varied in terms of breast height distribution and abundance of different tree species and thus the rate of the annual basal area increment was dependent on the DBH distribution. When comparing the annual basal area increments after the sludge treatments with the corresponding increment in the control plots, the basal area increased with nearly 42 % (average) more on SLUDGE400 (13.2 t pellets ha^{-1}) than on CONTROL. The increase was somewhat smaller on the other sludge treatments, i.e. 25 and 29 % on the treatments SLUDGE100 and SLUDGE200, respectively.

In comparison to CONTROL plot, addition of ammonium nitrate at a rate of 200 kg N ha^{-1} clearly increased average tree basal area growth during the 5-year period after fertilization (2000-2004). The statistical analyses, with basal area growth (I_{BA}) as a dependent variable, showed that the difference between treatments AN200 and CONTROL was statistically significant ($p = 0,05$) (Table 4) whereas treatment (200 kg N ha^{-1} as sludge pellets or as ammonium nitrate) as a factor was not ($p = 0,06$) (Table 5). When comparing treatments AN200 and SLUDGE200 with each other, it was clear that 200 kg N (ha^{-1}) added as ammonium nitrate increased the basal area increment (I_{BA}) more than equal amount nitrogen added in sludge pellets (Table 4). The difference was not statistically significant. However, the addition of 400 kg N per hectare as sludge pellets enhanced the diameter and basal area growth nearly as much as when 200 kg N per hectare as ammonium nitrate was applied.

In the Pilot experiment, the addition of sludge pellets at rate of ca 4 tons per hectare did not result in any general significant change in basal area growth in comparison to control treatments ($p = 0{,}70$) (Table 5). However, when dividing the plots between pine (*Pinus sylvestris* L.) and spruce (*Picea abies* (L.) Karst.) stands, there were clear differences in the basal area increases between the tree species. The spruce plots tended to respond more clearly to the sludge pellet addition than pine stands. The increase in basal area during five years after fertilization (i.e. 1997-2001) on treated plots was nearly 2 cm^2 bigger than on untreated plots. The corresponding difference between treated and untreated pine plots was not significant. Tree species was not a statistically significant factor ($p = 0{,}58$), however.

Table 4. The increase in breast height diameter (cm) and in the basal area (dm^2) of the average plot trees during five years after fertilization on each treatment in the Åheden and Pilot experiments. In the Åheden experiment, the values were based on the averages of three replicates. In the Pilot experiment the values were averages for treatments and tree species. Standard deviation (SD) describes the distribution from the mean value.

Treatment	**I_{DBH}***	**SD_{DBH}**	**I_{BA}***	**SD_{BA}**
ÅHEDEN EXPERIMENT				
0 N	0,56	0,11	0,16	0,03
100 N	0,65	0,07	0,19	0,01
200 N	0,70	0,10	0,19	0,03
400 N	0,79	0,24	0,22	0,05
200 AN	0,94	0,12	0,22**	0,02
PILOT EXPERIMENT PINE STANDS				
0 N	0,84	0,028	0,11	0,01
100 N	0,83	0,104	0,11	0,04
PILOT EXPERIMENT SPRUCE STANDS				
0 N	0,84	0,331	0,11	0,06
100 N	0,99	0,19	0,13	0,03

*) Periods in Åheden experiment: CONTROL , SLUDGE100, SLUDGE200, and SLUDGE400 2003-1999, 200 AN 2004-2000; periods in Pilot experiment: 2001-1997.

**) The difference in basal area growth (IBA) between AN200 and CONTROL was statistically significant (p = 0,05).

Table 5. The results of the statistical tests for the Åheden and Pilot experiments showing the Type III Sum of Squares, degrees of freedom (df), Mean Square, F value and significance (Sig.).

Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
ÅHEDEN EXPERIMENTS - SLUDGE TREATMENTS					
Corrected model	,008(a)	5	,002	1,166	,422
Intercept	,439	1	,439	334,832	,000
Treat	,007	3	,002	1,725	,261
Block	,001	2	,000	,326	,734
Error	,008	6	,001		
Total	,455	12			
Corrected total	,016	11			
ÅHEDEN EXPERIMENT - AN TREATMENT					
Between groups	,007	2	,003	4,606	,061
Within groups	,004	6	,001		
Total	,011	8			
PILOT EXPERIMENT					
Corrected model	,001(b)	3	,000	,201	,839
Intercept	,156	1	,156	111,374	,000
Treat	,000	1	,000	,160	,699
Species	,000	1	,000	,330	,581
Treat*Species	,000	1	,000	,113	,745
Error	,011	8	,001		
Total	,168	12			
Corrected total	,012	11			

a R Squared = ,439 (Adjusted R Squared = ,070); b R Squared = ,070 (Adjusted R Squared = -,279)

3.2 Effect of the dose size

In the Åheden experiment, the basal area increment (I_{BA}) during the 5-year period after fertilization was consistently higher on all treated plots compared with the CONTROL plot except for one case (Fig. 3). On the SLUDGE200 plot in block 1 the basal area increment was smaller than on the corresponding CONTROL plot. Basal area increment tended to increase with increasing amount of nitrogen added (Fig. 3). Calculated per kilogramme of N added, the basal area increment tended to increase with higher amount of N added (the relationship between the amount added and I_{BA} was non-linear). However, the first 100 kg N ha^{-1} added increased the basal area growth relatively more than the subsequent additions of 100 kg N ha^{-1}, i.e. the regression line evens out with the increasing amount of nitrogen added.

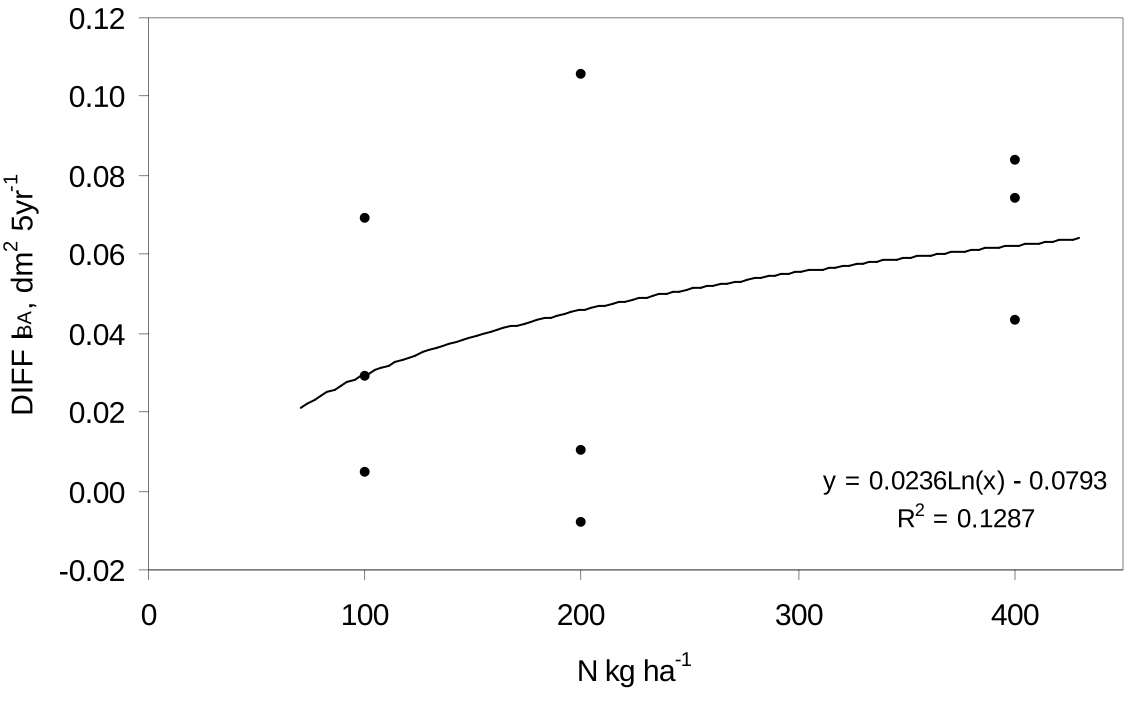

Figure 3. The difference in basal area increase (dm^{2} 5yr^{-1}) of the five year period after fertilization (1999-2003) between the sludge treated (100, 200 and 400 N) and the corresponding block control plots in the Åheden experiment. The three values of each treatment correspond to three blocks (I-III).

$$y = 0{,}0236\ \mathrm{Ln}(x) - 0{,}0793,\ R^2 = 0{,}1287 \qquad (2)$$

The coefficient of determination (R^2) of the regression equation was really low (formula) thus meaning that only 13 % of the variance in growth differences (DIFF I_{BA}) could be explained by the amount of nitrogen added. There was considerable variation within treatments (see also Fig. 4) and this was particular the case with the treatment SLUDGE200 where one plot even showed a negative effect (Fig. 3). On plots SLUDGE100, the basal area increments during the 5-year period after fertilization (I_{BA}) varied from 0,58 to 0,72, on plots SLUDGE200 from 0,58 to 0,75 and on plots SLUDGE400 from 0,51 to 0,96 dm^2 $5yr^{-1}$ (data not shown). On the CONTROL plots, the I_{BA} varied from 0,44 to 0,66 dm^2 $5yr^{-1}$ (data not shown).

3.3 Duration of the growth response

The annual basal area increment increased clearly on all plots after sludge fertilization when compared with the control treatment in the Åheden experiment (Fig. 4) and remained elevated throughout the first five years after fertilization. The basal area increments fluctuated on all treatments, and especially on SLUDGE200 after the fertilization. Before sludge application (in 1998) the basal area increments were smaller on treatment SLUDGE400 than corresponding increments on the CONTROL treatment. The growth response to the fertilization was immediate and considerable on SLUDGE400, and the annual basal area increments increased with nearly 60 % within the two subsequent years after the fertilization. In the year 2000 the basal area increment was 50 % greater than on the CONRTROL. After this, the annual increments decreased, with an exception in 2002.

Even though the response to fertilization on SLUDGE200 was smaller in magnitude than on treatment SLUDGE400, it was immediate. In contrast to SLUDGE400, the basal area increments on SLUDGE200 continued to increase till the end of the observation period except in the year 2003 when the annual increment dropped being only ca. 18 % bigger than that of CONTROL. On SLUDGE200, the annual increment was greatest (49 %) among the sludge treatments in year 2002. During 2004, the basal area increment was again considerable. On SLUDGE100, the annual basal area increments were bigger compared with the CONTROL already before fertilization. As opposed to the other sludge treatments, the annual increment decreased in the year following the fertilization. Hereafter, the basal area increments increased gradually with an exception in 2003.

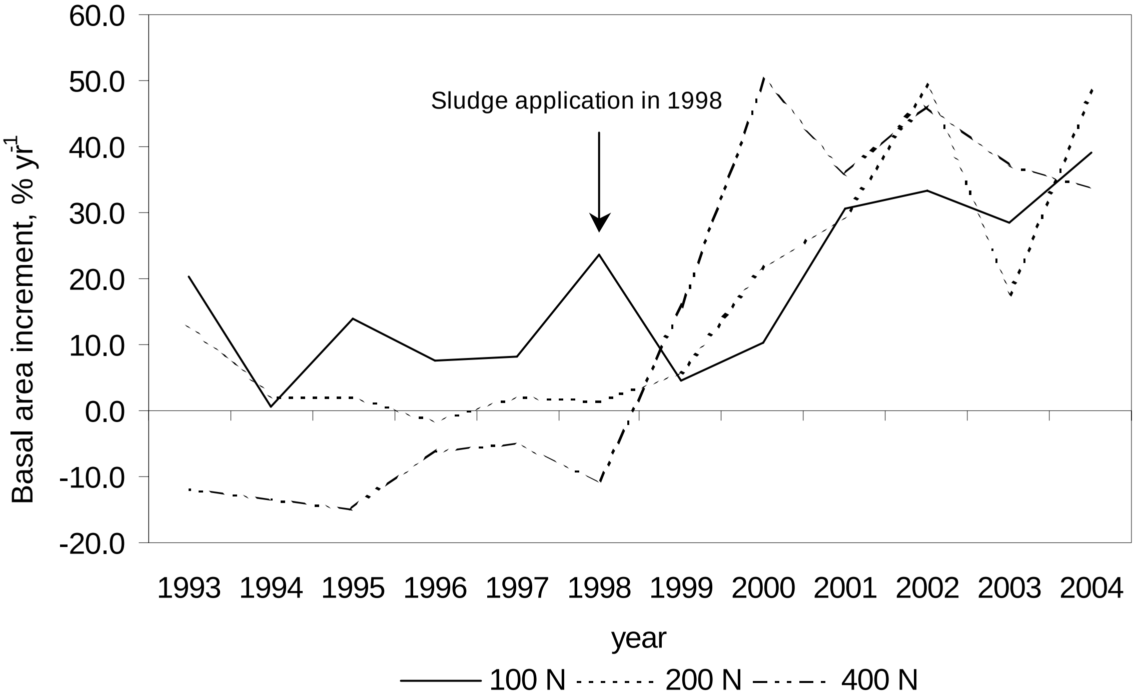

Figure 4. The annual basal area increment in relation to control (% yr^{-1}) of the sludge treatments in the Åheden experiment. The values were based on the averages of three replicates. The control is shown as horizontal line (y = 0).

In the Pilot experiment, there was a lot of fluctuation in the annual basal area increments within the fertilized pine and spruce stands during the whole observation period 1991-2001 (Fig. 5). On both pine and spruce stands, the annual basal area increments on the treated plots were decreasing in comparison to control at the time of fertilization in 1996. On the fertilized spruce plots, the basal area increments increased considerably few years after fertilization and continued increasing until the end of the first 5-year period after fertilization (2001). During the subsequent years, the annual basal area increments increased but in the last observation year (2004) the trend was decreasing again. On fertilized pine plots, the basal area increments tended to decrease during few years after fertilization but started to gradually increase in 1998. In the end of the first 5-year period after fertilization, the growth had started to decrease again. In the following years (2002-2004) the basal area increments fluctuated considerably. There was no clear positive response to the fertilization.

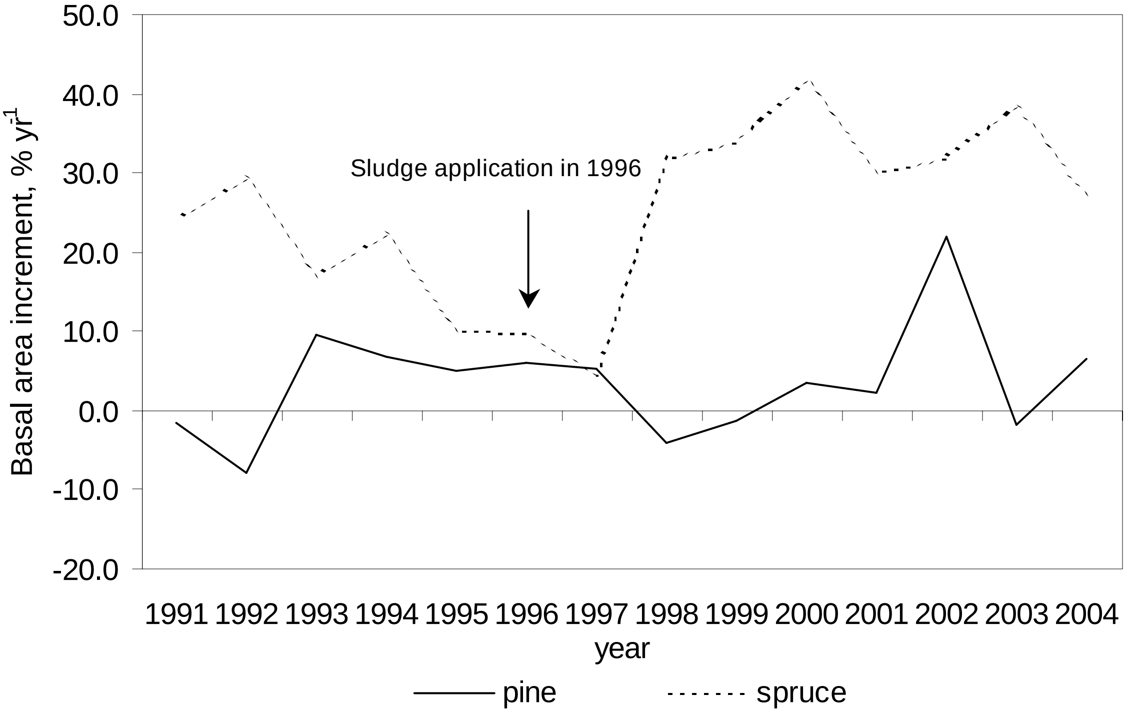

Figure 5. The basal area increment (% yr^{-1}) of the fertilized pine and spruce stands in relation to corresponding control plots in the Pilot experiment. The values are based on the averages of three plots. The control is shown as horizontal line (y = 0).

4 DISCUSSION

4.1 Effect on tree growth

Application of pelletized sewage sludge increased the basal area growth of a pine (*Pinus sylvestris* L.) dominated boreal forest. However, a positive growth response was evident only on one experiment site, namely in the Åheden experiment, whereas in the Pilot experiment no general significant increase in the basal area increments occurred on the treated plots. Amendments of organic fertilizers have increased forest growth both in young plantations (e.g. Zasoski et al., 1983; McKee et al., 1986; Dutch and Wolstenholme, 1994; Harrison et al., 2002; Kimberley et al. 2003; Prescott and Blevins, 2005), and older stands (Zasoski et al., 1983; McKee et al., 1986; Henry et al., 1993; Prescott et al., 1993; Bramryd, 2001) as well as in stands with different tree species (e.g. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Scots pine, Western red cedar (*Tsuga plicata* Donn ex D. Don), Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Amabilis fir (*Abies amabilis* (Dougl.) Forbes)). The characteristics of the sludge, application rates, tree species and reported growth effects in such studies are presented in table 6.

The basal area increment of the average tree during the five year period after fertilization detected in this study was about the same as or somewhat smaller than reported in other studies. In this study, the basal area increments of the sludge treated plots were approximately 25-42 % higher compared with the control treatment in the Åheden experiment, whereas in a mature Douglas-fir stand, for example, the basal area increase was as high as 40-60 % when liquid sludge was applied at rate corresponding ca. 470-700 kg N ha^{-1} (Zasoski et al., 1983). The absolute amount of nitrogen was not given by Zasoski et al. and was therefore calculated here with an assumption that the given percentage of nitrogen (2,3 %) was measured from the dewatered sludge (20 % dw.). Harrison et al. (2002) reported (on average) 28 % higher basal areas in a young Douglas-fir stand after application of liquid sludge at rate of 17-19 t ha^{-1} compared with untreated sites. Prescott and Blevins (2005) reported notable growth enhancements (cf. table 6) on sludge treated plots compared to untreated plots in Western red cedar, Western hemlock and Amabilis fir stands as response to 69 tons ha^{-1} sludge (equivalent ca. 540 kg N ha^{-1}). In a Monterey pine (*Pinus radiata*) stand treated with liquid sludge, the basal area increased significantly when compared to growth of untreated trees (Kimberley et al., 2004). Additionally, in a heath land planted with Sitka spruce (*Picea sitchensis* (Bong.) Carr), sludge was found to notably increase the height growth (Dutch and Wolstenholme, 1994).

Table 6. The background information and results from previous studies concerning sludge applications in different type of forests.

Tree species	**Sludge type**	**Dose, t ha^{-1}**	**Amount of N, kg ha^{-1}**	**Stand age, yrs^{5}**	**Years after treatment**	**Other treatments**	**Growth response**	**Reference**
Douglas-fir (*Pseudotsuga mentziesii*)	Dewatered^{1} (ca. 20 % dw.^{2})	102-153	2.3 %	37-59	4	Thinning	Increase in basal area with 40-60 %	Zasoski et al., 1983
Conifers, e.g. Loblolly pine (*Pinus taeda*)	Liquid^{1}	5.5 and 11.1 od.^{4}	402 and 804	1-28	4	-	Increase (46 % in BA in older stand with higher amount of N)	McKee et al., 1986
Douglas-fir	Dewatered	47 and 142 dw.	-	55 and 65	13	Thinning on some of the stands	Increase	Henry et al., 1993
Douglas-fir and Sitka spruce (*Picea sitchensis* (Bong) Carr.)	Dewatered^{1}	142 dw. / 3 yrs	total 6000	0.5-1	0.5-1	-	No	Prescott et al., 1993
Sitka spruce	Liquid^{3}	13 and 26 dw.	445 and 893	Planting one year after fertilization	8	Heath control	Increase (in height)	Dutch and Wolstenholme, 1994
Lombardy poplar (*Populus nigra 'Italica'* (L.)), Douglas-fir, Ponderosa pine (*Pinus ponderosa*)	-^{1}	400-600	ca. 13 100 (26.2 mg/g)	At the time of planting	15	Disking sludge into the soil, ploughing on control plots	Elevated soil nutrient levels	Harrison et al., 1994

Tree species	**Sludge type**	**Dose, t ha^{-1}**	**Amount of N, kg ha^{-1}**	**Stand age, yrs^{6}**	**Years after treatment**	**Other treatments**	**Growth response**	**Reference**
Scots pine	Liquid^{6} and dewatered^{6} (4 and 20 % dw., respectively)	20 dw.	40 g N kg^{-1}	50-60	5	-	Increase (60-80 % cf. with control)	Bramryd, 2001
Western red cedar, Western hemlock, Amabilis fir	Dewatered^{1} (26 % dw.)	69	540	9	5	Site burned before plantation	Increase (in height)	Prescott and Brown, 1998
Douglas-fir	-	17-19	-	2-3	3	-	Increase (stem BA 2.9-50.7 %)	Harrison et al., 2002
Willow-clone (*Salix dasyclados*)	Lime-stabilized	130 od. (one year after planting)	1200	1	3	Ploughing; addition of herbicides one year before planting	Increase (biomass production 30-38 %)	Adegbidi et al., 2003
Red pine (*Pinus resinosa* Ait.) plantation	Pelletized^{3}	4.8, 9.7, and 19.4	200, 400, and 800	51	3	Thinning one year before treatment	No or decline	Kelty et al., 2004
Monterey pine (*Pinus radiata* D. Don)	Liquid	-	300 and 600 (application two times)	6	5	Pruning trees	Increase	Kimberley et al., 2004
Western red cedar, Western hemlock, Amabilis fir	Dewatered^{1} (26 % dw.)	69	540	9	11	-	Increase (36-81 % DBH)	Prescott and Blevins, 2005

[1] anaerobically digested; [2] dry weight; [3] undigested; [4] oven dry; [5] age at the time of the sludge application; [6] aerobically digested

Contradicting results to current study were found in a study of Kelty et al. (2004) where sludge pellets were applied into a thinned red pine (*Pinus resinosa*) plantation at rates of 4.8 tons (200 kg N ha^{-1}), 9.7 (400 kg N ha^{-1}) t and 19.4 t (800 kg N ha^{-1}) per hectare. It appeared that no (stem) growth response occurred with application levels of 4.8 and 9.7 tons of sludge pellets per hectare and that the growth rate even declined significantly a few years after application of 19.4 t pellets ha^{-1}. Kelty et al. (2004) considered the growth depression to result from the sensitivity of red pine to imbalance between concentrations of N and other nutrients. Hence, the results of Kelty et al. (2004) should be regarded with certain caution. Nonetheless, the macronutrient concentrations (N, P, K) of sludge pellets were nearly the same in the study of Kelty et al. (2004) than in the study at hand only the concentration of N was slightly smaller (1.5 %) in the latter one. However, Thornton et al. (1999) did not either find increased growth after application of containerboard sludge. The reason for decreased growth was thought to be a significant immobilization of N (Thornton et al., 1999).

The plausible explanation for higher growth increments found in previous studies can be explained by the type of sludge used in those studies. Namely, earlier experiments have mainly comprised liquid (dry weight < 10 %) and dewatered sludge (dry weight < 30 %) where higher proportion of the nitrogen (in total 20-30 %) is inorganic nitrogen whereas in sludge pellets the corresponding amount is only a few percent (Kelty et al., 2004). Hence, more nitrogen is readily available for trees' uptake (Tamm, 1991) and thus also the growth effect can be expected to be more immediate. Organic fraction of nitrogen has to be first transformed into inorganic forms (Hallet et al., 1999). The mineralization of the nitrogen from liquid sludge occurs generally faster than from pelletized sludge (Wattiez, 2000). Since mineralization and nitrification are slow processes in boreal forests, the extent of growth effect from pelletized sludge is likely to be smaller (within a short time period) compared with liquid sludge. Hence, one could assume that the increased growth also persists longer after sludge pellets application.

Compared with a commercial fertilizer (ammonium nitrate), 200 N kg ha^{-1} resulted in a higher increase in average tree DBH and basal area (I_{DBH} and I_{BA}) when applied as ammonium nitrate than as sludge pellets. Furthermore, the double amount of nitrogen, i.e. treatment SLUDGE400, did not result in a higher basal area increment compared with AN200 but rather an increment of nearly the same magnitude. This supports the conclusions of Prescott and Brown (1998) as well as Prescott and Blevins (2005) that sewage sludge does not result in a greater growth response than conventional N-fertilizer, but that the increase in many cases is smaller or at most equal. The inorganic and organic forms of nitrogen might explain why the subsequent growth after an application of chemical fertilizer exceeded those resulted from sludge pellet application. Nevertheless, in contrast with these results, Dutch and Wolstenholme (1994) reported better growth responses from a single application of liquid sewage sludge (26 t dw. ha^{-1}) compared to conventional fertilizers. Similar results were found also by Zasoski et al. (1983) and Henry et al. (1993). Zasoski et al. (1983) found, for example, that the volume growth increment after municipal sludge (mixed industrial-domestic) addition was (40-60 %) higher than those resulted from commercial fertilizer (23 %). However, the applications of sludge and a chemical fertilizer were made on sites of different fertility, and are not therefore fully comparable with each other. Furthermore, the discovered growth increase on control sites, yet small, in the Åheden experiment might be due to increased nutrient and light availability after the removal of trees from the roadway at the time of spreading of the pellets (in 1998).

In the Pilot experiment, the basal area growth during five years following fertilization (100 N kg ha^{-1} as sludge) was nearly the same on the treated and untreated plots in pine stands but was slightly higher in treated (100 N kg ha^{-1}) spruce stands than on the control plots. A weaker and more incoherent growth response found in the Pilot experiment compared with the Åheden experiment (considering only treatment SLUDGE100) is a somewhat surprising result since the sludge pellets used in both experiments were nearly the same in characteristics. Several reasons could explain the lack of positive response. First, the higher calcium concentration (13.7 %) in pellets used in the Pilot experiment compared to those used in the Åheden experiment (Ca 6.8 %) might have caused differences in soil conditions. Application of substantial amounts of calcium (e.g. liming) elevates the soil pH and increases the soil microbial activity (Andersson and Lundqvist, 1989) thus increasing the decomposition rate of pellets and mineralization of nitrogen (Sandström, 2000). In micro-sites, this may further lead to a temporary deficiency in N due to microbial competition or increased nitrification, which can further cause readier nitrate (NO_3^-) leaching (Matzner et al., 1983). For instance, Derome et al. (1986) reported reduced volume growth in both pine and spruce stands as a result of liming (at rate of 2000 to 6000 kg limestone ha^{-1}).

4.2 Suitable application rate of sludge pellets

The forest sludge applications aim, by adding nutrients to the site, to achieve the highest possible growth increase without causing any significant adverse effects on the surrounding environment. Such effects are e.g. the increased leaching of nutrients, the contamination of groundwater (Zasoski et al., 1984; Hånell et al., 1996) and decline in growth. These undesired effects bring about the question over the most applicable sludge dose.

It was hypothesized that higher amount of sludge pellets would induce greater growth response among the sludge treatments and control. The results of the five years' basal area increase concerning the Åheden experiment support this assumption. The highest dose of sludge pellets induced greatest increase in basal area growth when the sludge treatments were compared to control (Fig. 4). Hence, one could further assume that the higher the amount of nitrogen added, the better the subsequent growth. Even though the effect of the amount of sludge pellets on forest growth could not be statistically proven, the trend is nonetheless clear. These results from the Åheden experiment support the ones reported by Kimberley et al. (2004) that higher amount of sludge (300 vs. 600 kg N ha^{-1}) increase basal area growth more than a smaller amount. However, McKee et al. (1986) reported opposite results suggesting that the increase of basal area was greater after application of 5.5 t (oven dry) liquid sludge per hectare (ca. 400 kg N ha^{-1}) than when double amount was applied. The study concerned a 28-years old loblolly pine (*Pinus taeda* L.) stand. What is interesting is that in that same study, but in a younger stand, the growth increase was greater (four years after the sludge treatment) when bigger amount of sludge was applied in comparison with lower amount (11.5 and 10.3 m^2 ha^{-1}, respectively). The differences were not statistically significant in either of the stands.

It seems to be evident that applications with higher amount of sludge, and hence also higher amount of nitrogen, cause more nitrate leaching than smaller amounts of sludge (e.g. Zasoski et al., 1984; Brockway et al., 1986). This is due to the plausible exceeding of the forests' capacity to immobilize nitrogen (e.g. into soil and plants) (Aber et al., 1989). Nitrogen leaching into groundwater is considered as the most important restraint on sludge forest applications (Zasoski et al., 1984; Dutch and Wolstenholme, 1994). Sludge application rates varying from ca. 100 to 600 tons per hectare (Zasoski et al., 1984;

Harrison et al., 1994) caused substantial leaching of nitrate but also cations (Harrison et al., 1994). This high amount of sludge is, however, not environmentally sustainable and also questionable from economical point of view. With remarkably lower sludge application rates, equalling ca. 400-500 kg N per hectare, nitrate leaching did not occur in a harmful extent (Brockway et al., 1986). Similar results were found in a study of Hallet et al. (1999) with 14.5 tons of liquid sludge (nearly 800 kg N ha^{-1}). These results are in agreement with findings of Dutch and Wolstenholme (1994) that leaching of nitrate and other nutrients do not occur in a harmful extent when liquid sludge is applied in an amount supplying up to 900 kg N ha^{-1}. On the other hand, in a modelling study (Crohn, 1995) it was stated, however, that the maximum application rate would be only 200-300 kg N ha^{-1} (within sludge) in order to keep nitrate leaching within an acceptable range, i.e. tolerable nitrogen concentration in drinking water (< 10 mg/L).

Kelty et al. (2004) suggested that a single application of pelletized sludge should not exceed the rate of 19.4 t per hectare (ca. 800 kg N ha^{-1}) because it caused a decline in tree growth. A somewhat smaller dose sizes were proposed by Larsson (2000) who suggested that a realistic pelletized sludge dose in commercial forests could be approximately 7 tons per hectare (ca. 250 kg N ha^{-1}) at the establishment phase and later decreased down to 3-4 tons per hectare (ca. 100-150 kg N ha^{-1}) till the end of rotation period (calculated for five year periods from the original annual values). Furthermore, Magnusson and Hånell (2000a) concluded (review based on previous studies) that the highest sludge dose would be between 15 and 20 tons per hectare (equalling ca. 500-1000 kg N ha^{-1}). In contrast to these results, 4 tons of sludge pellets were obviously too little on Pilot experiment to result in any growth increases. This was in fact in accordance with Brockway et al. (1986) who proposed that no significant growth response could be expected with sludge application levels equalling less than 800 kg N ha^{-1}.

Since most of the nitrogen in sludge pellets is in organic forms and mineralization of organic-N occurs slowly, one could assume that the single application rate of pelletized sludge might be higher than with the additions of liquid and dewatered sludge. Considering only the effects on growth, the results ($I_{BA\ 5\ yr}{}^{-1}$) gained in this study indicated, however, that sludge pellets could be applied into a 60-years old stand (Åheden experiment) at a rate between 6.6 and 13.2 t ha^{-1} (ca. 200-400 kg N ha^{-1}). Concerning the Pilot experiment, undisputable estimations over the most applicable dose size could not be made since there was no other amount of sludge pellets applied.

It has been suggested that the site productivity should be taken into account when planning suitable application rates. Sludge fertilizations appear to have a greater impact on tree growth on poorer sites than on more fertile sites (Henry et al., 1993; Kimberley et al., 2004; Prescott and Blevins, 2005). Different forests vary in their capacity to recycle nutrients (Brockway et al., 1986). Furthermore, the suitability of sludge additions depends also on the soil characteristics since they determine how easily trace metals can be carried on within the soil profile (Richards et al., 2000). The chemical composition (e.g. heavy metal and nutrient concentrations) of applied sludge is also an important aspect to consider since it is not fully known how heavy metals will affect forest ecosystems (Larsson, 2000). Furthermore, it is also questionable if it was more profitable to apply sludge pellets at earlier stage of the rotation period (cf. 60 years old forest in current study) when the growth rate is generally faster than in older stands.

4.3 Duration of the growth effect

The results from the Åheden experiment showed that the increase in basal area increments was elevated on all sludge treatment plots still five years after the sludge application in comparison to the control treatment. This was accordance with Kimberley et al. (2004) who reported elevated growth as a response to liquid sludge application five years after the application compared with an untreated site. Similar results were found also by Zasoski et al. (1983) as well as Harrison et al. (2002) who both reported the growth response to last at least three to four years. Harrison et al. (2002) further concluded that the growth even may continue to increase over time. These suggestions for prolonged increased growth are supported by Henry et al. (1993) who in part reported that the positive growth response continued as long as 13 years. In that study, sludge was applied in a relatively high amount (up to 140 t dw. ha^{-1}). Nearly equally long duration (11 years) of increased growth was found also in a Douglas-fir stand (Prescott and Blevins, 2005). Nonetheless, the results of the study at hand showed that annual increase in basal area had started to decline slightly on plots treated with the highest amount of sludge pellets already few years after fertilization, i.e. the maximum basal area increase was reached approximately three years after treatment. Similar observation was done by Bramryd (2001) when liquid sludge was applied in a Scots pine stand. On the sludge fertilized pine stands in the Pilot experiment, the fertilized plots varied considerably within tree species which made it difficult to make generalizing conclusions over the duration of the growth response.

One could assume that the duration of the positive growth response might be relatively long, e.g. longer than five years as in this study, after application of sludge pellets. The mineralization of nutrients occurs more slowly in pelletized sludge than in liquid/dewatered sludge or in inorganic fertilizers (Hånell et al., 1996; Bramryd, 2001; Kelty et al., 2004) because nitrogen in pellets is mostly bound in organic matter and therefore it becomes more successively available for trees on pellet treated sites, hence prolonging the increased growth effect. This is supported also by Prescott and Brown (1998) who concluded that nutrient supply of dewatered sludge diminished already few years after the sludge applications. The diminishing of the nutrient supply could be explained by the fast consumption of the inorganic nitrogen compounds, NH_4-N and NO_3-N, in liquid/dewatered sludge which increases the growth in a short time interval but also indicate a shorter duration of increased growth response. Furthermore, the fertilization history of a forest stand may also influence on the duration of growth effect. Namely, in already fertilized forests the decomposition of litter is often more rapid than in unfertilized stands due to the quality of litter produced. Hence, the decomposition of high quality litter (in fertilized forests) releases more nitrogen and thus prolongs the fertilization effect (Prescott et al., 1993). According to Kelty et al. (2004) also the physical structure of dry sludge pellets could explain the slower inorganic-N release.

4.4 Implications of sludge pellet applications

It has been suggested that the forest type should be considered, i.e. which kind of forests have the best prerequisites for pelletized sludge applications: production forests, production and recreational forests, or forests for bioenergy production in order to gain the best possible results from sludge applications (e.g. McKee et al., 1986; Wolstenholme et al., 1992; Henry and Cole, 1997; Magnusson and Hånell, 2000b) and furthermore to enlarge the scale of forest fertilization with sludge. Especially in forests that are grown for bioenergy production (Adegbidi et al., 2003) sludge pellets could offer an attractive tool to increase the profitability by higher biomass production during a shorter rotation period. According to Magnusson and Hånell (2000b) "environmentally sound, relatively large amendments of pellets could be made in areas selected for intensive forest production (pulpwood, fuel) whereas smaller pellet dozes could favour timber assortments in forests stands which are reaching the end of the rotation period". In the light of the information gained in the study at hand, fertilization with municipal sewage sludge is a measure to be reckoned with.

At present, the production of the sludge pellets is still small-scale. There are no existing markets yet for profitable utilization of sludge and therefore some sewage treatment plants processing (including also the pelletization procedure) give away sludge for free (Björn Hånell, Dep. of Silviculture, SLU; personal conversation 23.3.2006). Yet, the benefits of pelletized sludge are undisputable: it decreases dependence on chemical fertilizers, in part reduces incineration emissions (plausible contribution to greenhouse effect), increases forest growth and might shorten the rotation period, and contributes the sustainable resource and forest management.

4.5 Reflections to material and methods

There are few aspects that hamper the straightforward interpretation of the results. The variation within treatments and between the blocks was great in the Åheden experiment. This comes clearly out from the great differences observed in the increases in basal area on different blocks already before the fertilization. Hence, this non-uniformity made the generalization of the growth calculations (i.e. taking averages from the three replicates) and the comparisons disputable. The high variation that now occurred in the calculations would have been able to minimize e.g. by increasing the number of replicates. This would have further increased the trustworthiness of the results. In the Pilot experiment, there were no replicates at all which made the reliable comparison between the different paired plots difficult, if not even impossible. Furthermore, the plots varied a lot within treatments in both pine and spruces stands.

It is important to notice that most of the experiments done earlier are not directly comparable with the results gained in this thesis since the forms of sludge used have been either liquid or dewatered sludge which differ from sludge pellets in their effects on growth and surrounding environment. The study of Kelty et al. (2004) makes an exception as being the only other study using pelletized sludge.

5 CONCLUSIONS

This study shows that application of sludge pellets in boreal, Scots pine dominated forest increases the forest growth. The results were not statistically significant, however. An important finding of this study was that the growth at least did not decrease after the pellet applications. This indicated that pelletized sewage sludge could be applied in to boreal forest ecosystems without growth-decreasing effect. The results of this study further indicated that the growth remained elevated during at least the subsequent five years after the fertilization. It seemed that the most suitable dose, with regard in the highest growth increase, would be between 6.6 and 13.2 tons of pellets per hectare (equalling ca. 200-400 kg N ha^{-1}) when applied as a single-application.

Furthermore, the growth effect from the highest dose of sludge pellets was nearly as good as from commercial fertilizer, ammonium nitrate. Thus, in this respect, pellets do offer a reasonable and attractive alternative for inorganic fertilizers and could even replace them in the future forest fertilizations. Additionally, the quantity of sludge that ends up on e.g. landfills and incineration plants would decrease if the forest fertilizations with pelletized sludge were to become more common and extensive. However, if the scale of sludge applications enlarged, one should consider on which kind of forests have the best prerequisites for pelletized sludge applications, i.e. production forests, production and recreational forests or forests for bioenergy production.

It is self-evident, however, that more research about both environmental and growth effects is needed before sludge pellets can be taken in use in a large scale and wide public acceptance is gained. Future research projects need to thoroughly study the growth and environmental effects of even higher amounts of sludge pellets than were used in this thesis, and furthermore study the impacts over longer time period and with more replicates.

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APPENDIX I

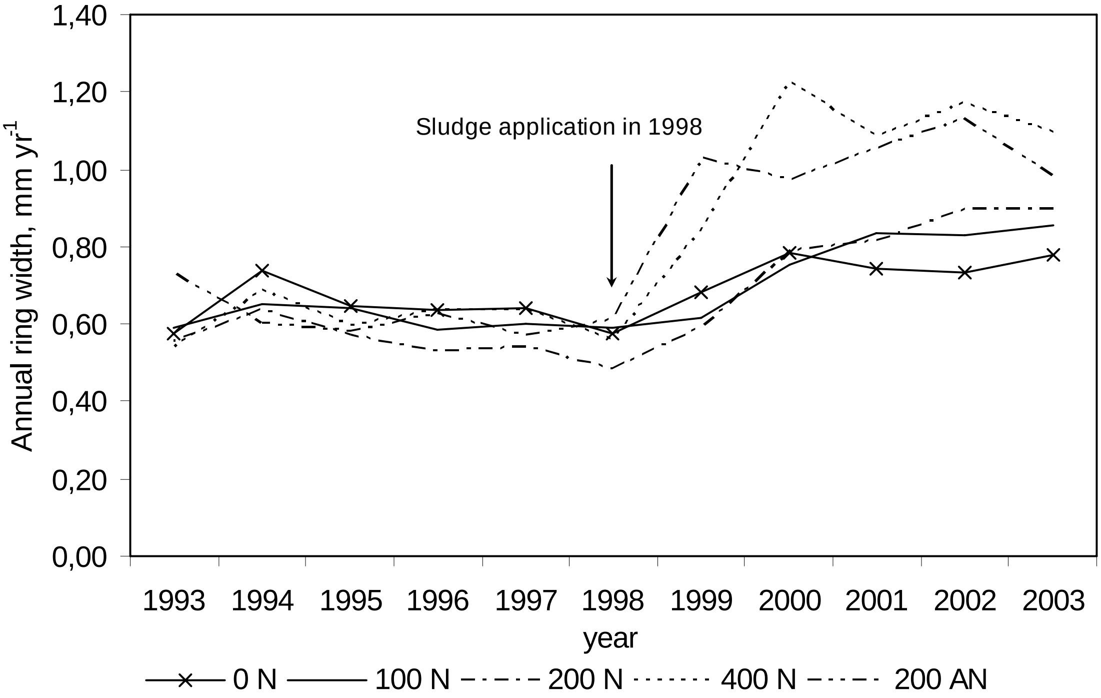

Figure 6. The annual ring width increments during five years before and after fertilization on control, sludge pellets and ammonium nitrate treatments in the Åheden experiment. The values are based on the averages of three replicates.

Web-sites

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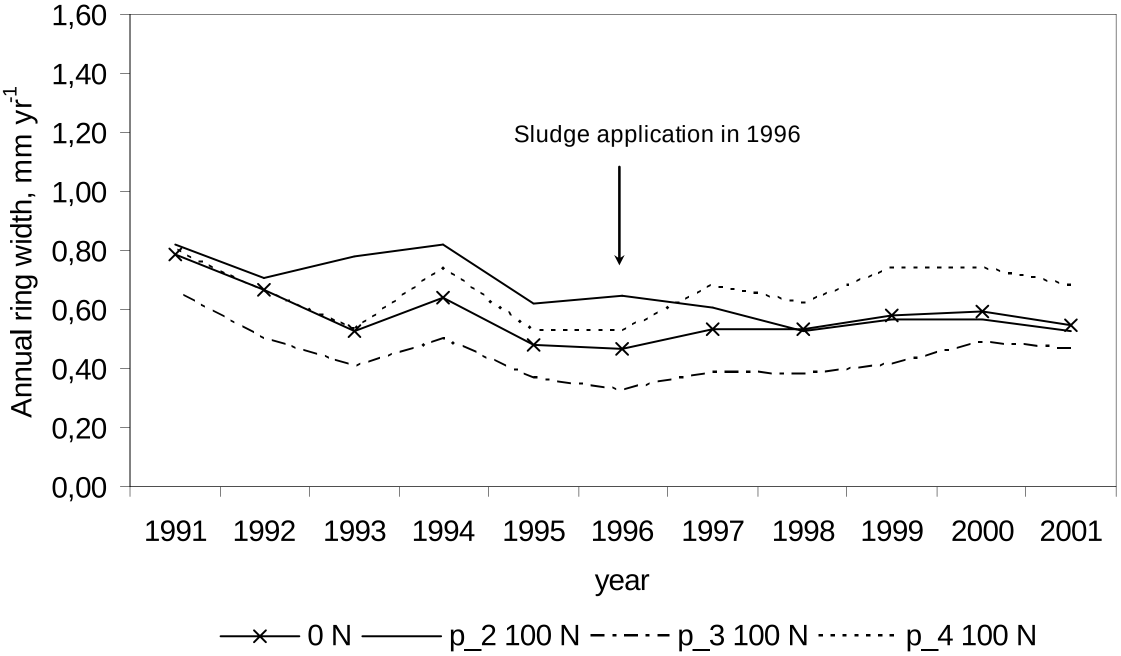
Pine stands



Spruce stands

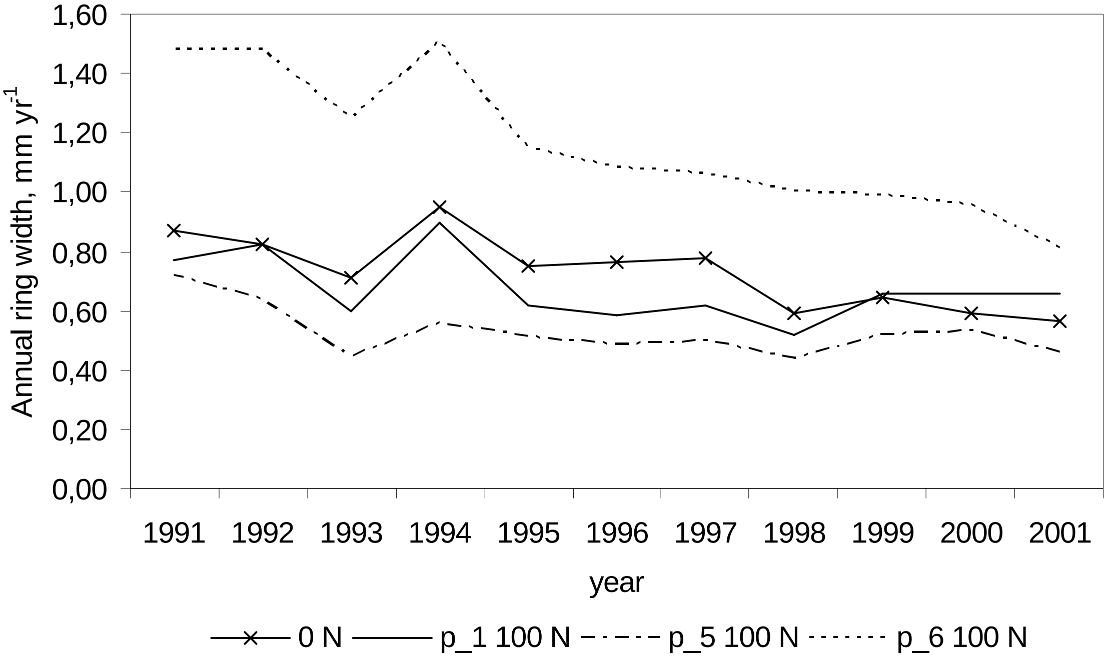


Figure 7. The annual ring width increments during five years before and after fertilization on treated plots (100 N) and on control plots (0 N) in both pine and spruce stands in the Pilot experiment. The control values are based on averages of three control plots.

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