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Nordic Environmental Co-operation

The Nordic Environmental Action Plan 2005-2008 forms the framework for the Nordic countries' environmental co-operation both within the Nordic region and in relation to the adjacent areas, the Arctic, the EU and other international forums. The programme aims for results that will consolidate the position of the Nordic region as the leader in the environmental field. One of the overall goals is to create a healthier living environment for the Nordic people.

Nordic co-operation

Nordic co-operation, one of the oldest and most wide-ranging regional partnerships in the world, involves Denmark, Finland, Iceland, Norway, Sweden, the Faroe Islands, Greenland and Åland. Co-operation reinforces the sense of Nordic community while respecting national differences and similarities, makes it possible to uphold Nordic interests in the world at large and promotes positive relations between neighbouring peoples.

Co-operation was formalised in 1952 when *the Nordic Council* was set up as a forum for parliamentarians and governments. The Helsinki Treaty of 1962 has formed the framework for Nordic partnership ever since. The *Nordic Council of Ministers* was set up in 1971 as the formal forum for co-operation between the governments of the Nordic countries and the political leadership of the autonomous areas, i.e. the Faroe Islands, Greenland and Åland.

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Preface

In the society development towards increased ecological sustainability, decreasing landfill and increasing reuse of sewage sludge are of high priority. Within the European Union, a revision of the regulations for reuse of sewage sludge in the Sewage Sludge Directive 86/278/EEC is in progress. From a Nordic point of view, it has been considered that sludge fertilization of conifer forests might be an important option for sewage sludge nutrient reuse. Therefore, the PA-group under the Nordic Council of Ministers has commissioned the Swedish University of Agricultural Sciences, Department of Silviculture, Umeå, to make a compilation of existing research results from sewage sludge fertilization of conifer forests in the Nordic countries and in North America, for determination of the possibilities for the use of sludge as forest fertilizer, and as an input to the elaboration process of the new Sludge Directive.

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Umeå, November 2004

Kenneth Sahlén

Summary

Sewage sludge, containing all essential nutrients for tree growth, might be a valuable fertilizer for increased tree growth in conifer production forests in Sweden, Norway, Denmark and Finland. This would facilitate an increased supply of renewable wood raw material for forest industrial production and for substitution of fossil fuels with tree biomass based energy sources, being of great economical significance in this region of Europe, where the forest sector constitutes a substantial part of the economy.

Other effects might be reduction of the greenhouse effect through increased forest carbon accumulation, decreased methane emissions from sludge landfill and decreased net carbon dioxide emissions from energy production, and increased reuse of sludge nutrients. Such effects would be in line with a desired society development towards increased ecological sustainability. Besides positive tree growth effects, forest sludge fertilization may also be associated with environmental concerns regarding possible negative health effects to humans and wildlife of nitrate leaching or sludge heavy metals, synthetic organic substances or pathogens.

In a research program, where the Swedish University of Agricultural Sciences (SLU) cooperates with Swedish Polytechnic and the Finnish Forest Research Institute in Finland, development of methods for conifer forest sludge fertilization is in progress. The program is financed by the Regional Development Fund of the European Union and national sources, and includes sludge nutrient composition, application technique and tree growth and environmental effects. In North America, research on sludge forest fertilization has been carried out for several decades.

In this literature review, research results from conifer forest sludge fertilization experiments in the Nordic countries and in North America are compiled for determination of the possibilities for the use of sludge as forest fertilizer, and as a base for elaboration of regulations for sewage sludge reuse in the new Sludge Directive of EU.

The results show that tree growth is generally increased by 15-70% after sewage sludge applications of 300-2000 kg N/ha for most conifers in the Nordic countries and in North America. The duration of the growth promoting effect of sludge fertilization probably exceeds 15 years, i.e., much longer than for mineral fertilizers. Fertilization increases the soil nitrogen pool and humus layer pH and ammonium concentration. Humus layer C/N ratio may remain lowered for more than a decade after sludge application. Nitrification and nitrate leaching is common after high application rates, in excess of the assimilation capacity of the ecosystem, and may be accompanied by leaching of base cat ions. It is expected that soil

or ground water nitrate-N peak concentrations will not exceed drinking water standards (<10 mg/l), if an upper application rate limit of about 1000 kg N/ha for dewatered sludge (20% dry matter content), is applied. Humus layer concentrations of P, Ca and Mg may by elevated for several years after application. The risk for contamination of surface water sources adjacent to fertilized sites through surface nutrient runoff is believed to be small.

Sludge heavy metals are retained in the sludge or in the organic layer in the uppermost soil horizon, and are not leached downwards in the soil profile, even after very heavy sludge applications and during at least 15 years. Heavy metal concentrations may be elevated in forage plants, but no toxic levels have been found in deer, mice, shrews and woodcock, feeding on sludge fertilized sites. Increased concentrations of cadmium is found only in kidney and liver from shrews, deer and woodcock and therefore, it is concluded that no health risk is associated with consumption of meat from game animals. Possible health risks will be even further reduced, with the use of modern sludge with Cd concentrations being less than 5% of that in most cited investigations here, and with lower application rates. No elevated cadmium content was recorded in berries or fungi on Swedish forest sites, fertilized 2001 and 2003 with dry sludge pellets and granules.

The effects of sludge synthetic organic compounds, such as PCB and PAH, on the forest ecosystem, are not much investigated. However, since they are immobile in soil and almost not taken up by plants, human or wildlife health risks are estimated to be very small.

Survival time in the forest environment after sludge application is less than one year for most pathogen indicator organisms. No downward movement of pathogens in the soil to lower water sources is expected, and aerosol pathogen dispersal is limited in closed forest. Access to fertilized sites should be prohibited during one year after application of potentially pathogen containing sludge, and a buffer zone without appli-cation should be kept towards adjacent surface water sources. Sludge application should be avoided on sites with domestic water wells. These precautions are not required if the sludge is subjected to effective pathogen killing treatments.

It is concluded from the literature review and the results from the ongoing research program in Sweden and Finland, that it is possible to elaborate practically applicable methods for conifer forest fertilization with sewage sludge in the Nordic countries, resulting in:

- considerably increased tree growth during at least 15 years
- no health risks for humans or wildlife caused by nitrate leaching, sludge heavy metals, synthetic organic substances or pathogens.

Forest sludge use should not be more hazardous than the already permitted use for food production on agriculture land, but still more results from forest fertilization experiments are required before sludge fertilization may be introduced into practical scale.

The forest fertilization option for sewage sludge use is ecologically sound from a wide perspective, contributing to reduced greenhouse effect and increased reuse of the sludge nutrient resource. It is also economically beneficial through increased tree growth and reduced municipality costs associated with sludge incineration and landfill.

Sammanfattning

Avloppsslam, som innehåller alla nödvändiga näringsämnen för trädtillväxt, skulle kunna vara ett värdefullt gödselmedel för ökad trädtillväxt i produktionsbarrskogar i Sverige, Norge, Danmark och Finland. Detta skulle möjliggöra en ökning av tillgången på förnyelsebar skogsråvara för industriell förädling och för ersättning av fossila bränslen med trädbiomassabaserade energikällor, och därmed även vara av stor ekonomisk betydelse i denna region av Europa, där skogssektorn svarar för en avsevärd del av samhällsekonomin.

Andra positiva effekter skulle vara minskad växthuseffekt via ökad kolackumulering i skogsekosystemen, via minskade metanutsläpp från slamdeponier och via minskade nettoutsläpp av koldioxid vid energiframställning, samt ökad återanvändning av näringsämnen från avloppsslam. Sådana effekter skulle vara i överensstämmelse med en önskad samhällsutveckling mot ökad ekologisk hållbarhet.

Förutom positiva tillväxteffekter på träd, kan skogsgödsling med slam eventuellt medföra oönskade negativa miljöeffekter för djur och människor orsakade av nitratutlakning, tungmetaller, syntetiska organiska ämnen eller patogener.

I ett forskningsprogram, där Sveriges Lantbruksuniversitet (SLU) samarbetar med Svenska yrkeshögskolan och Skogsforskningsinstitutet i Finland, pågår utveckling av metoder för gödsling av barrskog med avloppsslam. Programmet finansieras av EU:s regionala utvecklingsfond och nationella offentliga medel, och behandlar näringsämnessammansättning i slam, spridningsteknik, trädtillväxt och miljöeffekter. I Nordamerika har forskning om slamgödsling av skog bedrivits under flera tiotals år.

I denna litteraturgenomgång har forskningsresultat från försök med slamgödsling av barrskog i de nordiska länderna och Nordamerika sammanställts, för ställningstagande till möjligheterna att använda slam som skogsgödsel, och som en bas för utformning av regler för återanvändning av slam i EU:s nya slamdirektiv.

Försöksresultaten visar att trädtillväxten vanligtvis ökar med 15-70 % efter tillförsel av avloppsslam motsvarande 300-2000 kg N/ha i de nordiska länderna och i Nordamerika. Den positiva tillväxteffekten består sannolikt under mer än 15 år, dvs mycket längre än för mineralgödselmedel. Efter gödsling ökar kväveförrådet i marken liksom ammoniumkoncentrationen och pH i humustäcket. C/N-kvoten kan förbli sänkt under minst 10 år efter gödsling. Nitrifikation och nitratutlakning är vanlig efter mycket höga gödseldoseringar, då kvävet inte kan assimileras av ekosystemet, och kan även resultera i utlakning av baskatjonerna K, Ca och Mg. Mark- eller grundvattnets maximala halt av nitratkväve kommer sannolikt

inte att överstiga gränsvärdet för dricksvatten, (~10 mg/l), om en övre doseringsgräns för avvattnat slam (20 % ts) på 1000 kg N/ha, tillämpas. Halterna av P, Ca and Mg kan vara förhöjda i humustäcket under flera år efter gödsling. Risken för kontaminering av näraliggande vattendrag via ytavrinning från slamgödslad barrskog bedöms vara mycket liten.

Slammets innehåll av tungmetaller utlakas ej och transporteras ner till djupare jordlager eller grundvatten, utan stannar kvar i slammet eller återfinns i humustäcket eller i mineraljordens ytskikt, även efter mycket höga slamdoseringar, och under minst 15 år.

Halterna av ett fåtal tungmetaller kan bli förhöjda i vissa skogliga foderväxter, men inga giftiga tungmetallhalter har uppmätts i hjortar, smågnagare, näbbmöss och morkulla, som levt på slamgödslade områden. Hos hjort, morkulla och näbbmöss har förhöjda halter av kadmium bara uppmätts i lever och njure, och det anses därför helt riskfritt att äta kött från jaktbart vilt som lever på slamgödslade områden. Hälsoriskerna kommer dessutom att vara avsevärt lägre vid användning av dagens avloppsslam med kadmiumhalter på mindre än 5 % av de halter som använts i de här citerade undersökningarna, och med lägre dosering. I svenska gödslingsförsök med torra slampellets och slamgranuler 2001 och 2003 har ingen förhöjd kadmiumhalt uppmätts i bär och svamp.

Effekter på skogsekosystemet av syntetiska organiska föreningar i slam som PCB och PAH, är mycket litet undersökta. Eftersom dessa ämnen ej är mobila i marken och i stort sett ej tas upp av växter, bedöms hälsoriskerna för människor och djur som mycket små.

Överlevnadstiden i skogsmiljön är mindre än ett år för de flesta patogenindikatorerna i slam. Ingen vertikal transport av patogener i marken till lägre beläget markvatten, kan förväntas, och patogenspridning via aerosoler är mycket begränsad i sluten skog. Vid gödsling med slam som inte säkert är patogenfritt, bör grundvattentäkter undvikas, en ogödslad buffertzon lämnas mot närliggande vattendrag och tillträdesförbud råda under ett år. Dessa försiktighetsåtgärder är inte nödvändiga, om det slam som används är behandlat med metoder som effektivt avdödar patogener.

Slutsatsen av litteraturgenomgången och resultaten från det pågående svens-finska forskningsprogrammet vid SLU, är att det är möjligt att utforma praktiskt användbara metoder för skogsgödsling av barrskog med avloppsslam i de nordiska länderna, vilket skulle kunna resultera i:

- avsevärt ökad skogstillväxt under åtminstone 15 år
- inga negativa hälsoeffekter för människor eller djur förorsakade av nitratutlakning, tungmetaller, syntetiska organiska ämnen eller patogener.

Användning av avloppsslam i skog borde inte betraktas som mera riskabelt än den redan nu tillåtna användningen för livsmedelsproduktion på jordbruksmark. Ytterligare forskningsresultat från skogsgödslingsförsök krävs dock innan slam-gödsling kan introduceras för användning i praktisk skala. En introduktion av gödsling i praktisk skala bör åtföljas av ett miljökontrollprogram under de första fem åren.

Alternativet att utnyttja avloppsslam för skogsgödsling är ekologiskt sunt utifrån ett vidare perspektiv, genom att bidra till minskad växthuseffekt och ökad återanvändning av växtnäringsresursen i avloppsslam. Det är också ekonomiskt fördelaktigt genom ökad trädtillväxt och minskade samhällskostnader för slamförbränning och deponering.

Introduction

Nordic forestry practice

The typical and traditional management practice during a rotation period in Nordic conifer production forests, dominated by Scots pine and Norway spruce, includes natural or artificial regeneration of indigenous conifers, followed by several selective thinnings and a final felling. The rotation period is long (70-120 years), and the trees are so far mainly harvested as saw timber and pulpwood. Swedish production forest area is about 23 million hectares and the annual cut is more than 80 million cubic meters of wood. Forests cover up to more than 50% of the land area in the Nordic countries, and the forest area per inhabitant is about 40000 m^2 in Finland, compared to, e.g.,1000 m^2 in Germany. The forest sector is of great economic importance, accounting for an annual export surplus of about 10 billion € in Sweden, which is much more than any other sector. In rural areas, especially in the north, the forests are the most important raw material resources for employment and economy.

Experiences of nitrogen fertilization

Nitrogen is the most important nutrient for tree growth of the boreal conifers, and considerable growth increases are generally achieved on most low to medium fertile sites after application of N-containing fertilizers. Therefore, forest fertilization with mineral nitrogen fertilizers as ammonium nitrate and urea have been used in practical forest management for increased wood production of mainly Scots pine since the 60-s in Sweden. Totally about 3.4 million hectares have been fertilized so far, with application rates of 150 – 300 kg N/ha. The results show that an increased volume growth of in average15-20 m^3/ha totally, during a 10-year period after fertilization, is achieved.

In field research experiments, with totally 480-2400 kg N/ha applied (i. e. up to eight times the recommended quantity during a rotation period) in the easy soluble form of ammonium nitrate during a 15-year period, there is:

- no enduring change in the species composition of the ground vegetation
- no enduring reduction in the quantity of base cat ions in the soil
- no enduring increase in nitrogen leaching

In research scale, with annual applications of nitrogen-based fertilizers with well-balanced nutrient composition, growth increases of about 300% have been achieved in Norway spruce forests in northern Sweden, without leakage of nutrients to the soil water below the root zone.

Towards ecological sustainability

The progressive development of the society towards increased ecological sustainability includes reuse of waste matter, such as sewage sludge, and reduction of carbon dioxide emissions, through substitution of fossil fuels with renewable energy sources.

In this context, the Nordic conifer forests might play an important role, providing raw material for renewable energy production. Already, extraction of harvesting residues for energy production is practised. However, it is believed that this will not, of technical, economical and ecological reasons, be sufficient to meet an expected increased raw material demand for bio fuel use. Therefore, it will be necessary to use whole trees for energy production, preferably from early thinnings, with small tree dimensions. This new merchantable assortment, fuel wood, will contribute to an improved profitability for the forest owner, but also to some extent compete with pulpwood for the traditional forest industry.

An increased harvest of biomass, including nutrient containing branches and needles, may cause nutrient losses and lowered site productivity. This is believed to require compensation by mineral plant nutrients. Therefore, the Government Authority, the Swedish National Board of Forestry, at present recommends such a nutrient compensation, e.g., with wood ash, after fuel wood extraction, if the whole trees are harvested. The main objective of this compensation is to add the basic cat ions Ca^{2+}, K^{+} and Mg^{2+}. However, this wood ash compensation fertilization does not compensate for the most important nutrient nitrogen.

High quality sewage sludge, containing all necessary nutrients for tree growth, might be an even better nutrient resource for maintaining productivity after bio fuel extraction, since it also contains nitrogen. Sludge could also replace mineral nutrients as a general fertilizer for increasing tree growth. This would increase the amount of potentially harvestable tree biomass, and thus lower the risk of raw material shortage for the forest industry, in a situation of increased demand for forest biomass. Increased growth will also result in reduced carbon dioxide content in the atmosphere, through increased carbon accumulation in the forest ecosystem. The use of recycled instead of industrially produced mineral nutrients for forest fertilization would also be more in accordance with the ecological sustainability goals.

Consequently, utilization of sewage sludge as forest fertilizer might substantially contribute to a society development towards increased ecological sustainability and also be economically beneficial for the Nordic forest sector, through a sustained high wood production in the forests. However, sludge use may also be associated with health risks to humans and wildlife from nitrate leaching and sludge heavy metals, synthetic organic compounds or pathogens. Therefore, quantification and assessment of these potential risks are important elements in the process of method development for sludge fertilization in practical scale.

Sludge nutrient use in conifer forests

Conifer forest fertilization with sludge nutrients has been tested in a few European countries, Japan, Australia, New Zealand, USA and Canada since the beginning of the 70-s. Most of the research activities have been carried out in USA and mainly concentrated to the states of Washington, Michigan and South Carolina. Based on results from extensive research activities since 1973 at the University of Washington, College of Forest Resources, and from biosolid (sludge) applications made by King County since 1987, a Biosolid Forestry Program is launched. The program is a partnership of private and public interests, and the objectives are to preserve and enhance forests in the Interstate-90 road corridor and to improve water quality and tree growth by recycling biosolids as forest fertilizer. Biosolid application started 1995, and today about 6500 solid tons of sludge is annually used as forest fertilizer. All biosolid applications are subject to a monitoring program of environmental (soil, water) and tree growth effects.

In Europe, sludge forest fertilization is not practiced in operational scale. It is even prohibited in countries as Austria, Germany and Switzerland, but not in the Nordic countries. In a literature review, sludge forest fertilization was not recommended from an Austrian point of view (Mayr 1998). Sludge fertilization experiences are rather limited in the Nordic countries, with only a few field experiments established before 1990.

Sludge forest fertilization research program

Even if there are similarities between the conifer forest ecosystems in North America and the Nordic countries and the basic relationships between fertilization and tree growth and environmental impacts should be applicable under similar conditions, North American experiences and operational guidelines for practical forest fertilization are not directly transferable to the Nordic conditions. Furthermore, sludge pollutant concentration has been substantially reduced during the last decades, and new advanced sludge treatment methods have been introduced. These changes have reduced the possible environmental concerns associated with forest use of sludge, but also call for new investigations of fertilization effects.

Therefore, a research program was started seven years ago at the Swedish University of Agricultural Sciences (SLU), with the objective to develop methods and guidelines for the practical use of sewage sludge nutrients for conifer forest fertilization. At present, SLU cooperates with Swedish Polytechnic and the Finnish Forest Research Institute in Finland, and several municipalities and private companies. The activities are financed from Swedish and Finnish national sources and the Regional Development Fund of the European Union, through the Objective 1 and Interreg Kvarken-MittSkandia development programs. The research program includes research on sludge nutrient composition, application technique and tree growth and environmental effects. So far, five field experiments with sludge fertilization are established in northern Sweden. Several of them are quite recently established, and a thoroughly evaluation of the results will be carried out within the next 2-3 years.

This investigation – objective and scope

The work with elaborating a new sludge directive for the European Union, regulating the future use of sewage sludge, is planned to be finished during 2005. The PA group under the Nordic Council of Ministers has considered research results and experiences from forest sludge fertilization to be important input to this process, and has initiated this investigation. The objective is to make a compilation of existing research results, regarding tree growth and environmental effects of sludge fertilization in established conifer forests in the Nordic countries and North America, as a base for judgement of the potential use of sludge as forest fertilizer. Documentation is searched for in international scientific publication databases and in other sources, and is delivered by the Forest Library at the Swedish University of Agricultural Sciences in Umeå, having provided excellent service. However, some of the older North American documentation has not been possible to achieve through the ordinary library channels, and is therefore missing. This is not believed to be of significance for the drawn conclusions. In some cases, especially for the most recently established Swedish fertilization experiments, also not yet published results are presented.

The paper is organized with a first section, describing the forest fertilization experiments, from which most of the results are achieved. This information is also summarized in an appendix at the end of the paper. In the following sections, fertilization effects on tree growth and nutrient status, soil nutrients and heavy metals, heavy metals in ground vegetation and fauna, effects of synthetic organic compounds and hygienic effects, are described. After each section, the results are summarized in a conclusion. In a last section, the final conclusions about the potential use of sewage sludge nutrients for forest fertilization in the Nordic conifer forests, are drawn.

Conifer forest sewage sludge fertilization experiments[1]

Sweden

In central Sweden, a fertilization experiment was established 1976 in a 50 year old stand of Scots pine (*Pinus sylvestris* L.) on a sandy sediment soil (haplic podzol) (Bramryd 2001). Two aerobically treated municipal sludge types with dry matter content of 4 (196 kg NH_4^+-N/ha, totally 898 kg N/ha) and 20% (58 kg NH_4^+-N/ha, totally 864 kg N/ha), respectively, were used. Application rate was 20 tons dw/ha and nitrogen content about 4%. The effects on tree growth, uptake of nutrients and heavy metals in needles and lingonberry leaves and content of C, N and heavy metals in the humus layer and the mineral soil down to 50 cm, were investigated during a period of 11 years.

A series of five fertilization experiments, located from south (56° 46' N) to north (67° 51' N), were established in middle aged Scots pine stands on sandy sediment soils (haplic podzols) in 1976 (Bramryd 2002). Dewatered aerobically stabilized sludge from different wastewater treatment plants with dry matter content of about 20% was used. Application rate was 20 ton dw/ha, corresponding to 588-870 kg N/ha, of which 30-80 kg was ammonium nitrogen, and the rest was organic N. Nutrient content in needles, lingonberry leaves, humus layer and mineral soil were investigated after 3 and 11 years. In the same experiments, also the effects on tree growth, pH, C, N and content of nitrate and ammonium in humus and mineral soil down to 50 cm, was investigated (Bramryd 1994). The effects of sludge application rate on the same properties were also studied in an additional experiment in Mora in central Sweden, where 20 (780 kg N/ha), 40 (1560 kg N/ha) and 80 tons/ha (3120 kg N/ha) were applied.

Six stands of Scots pine and Norway spruce in Västerbotten in northern Sweden, were fertilized 1996 with 4 tons of dry sludge pellets (about 3% N content) from Umeå municipality (Magnusson and Hånell 2000; Sandström 2000). In 1998, another field experiment with 3.3-13.2 tons/ha of the same pellet type was established in a Scots pine stand in the same area. The effects on ground vegetation nitrate reductase activity and heavy metal content was investigated after two months and two years.

In Hjuleberg in south-western Sweden, an experiment on former agriculture land was established 1998 with fertilization of planted three year

[1] See also Appendix 1 at the end of the paper.

old Norway spruce seedlings. Each plant received 8 kg of pelletized sewage sludge with a nitrogen content of 2.7%, corresponding to 139 kg N/ha (Johannesson 1999) . Nitrogen content in sludge, tree needles, shoots and ground vegetation and pH and content of nitrate and ammonium in the topsoil were determined during 4.5 months after fertilization.

In 1997, a wastewater fertilization experiment was established in a 60 year old Scots pine forest on sandy sediment soil in Vindeln in northern Sweden (Sahlén *in prep* a). Raw wastewater is pumped through pipes and sprinklers from the primary sedimentation pond, before which the largest particles are removed in a screen and a grit chamber in the nearby located wastewater treatment plant. Wastewater average N content is about 25 g/m^3 (26% organic N and 73% ammonium N) but varies with precipitation. Application is carried out between June and August annually, and the target application rate is about 100 kg N/ha annually. For comparison, the experiment also includes mineral fertilizer (100 kg N/ha, annually) and pure water (the same amount as in wastewater) treatments. Fertilization effects on tree growth and nutrient composition in needles and soil water and heavy metals in ground vegetation are investigated, as well as dispersal and survival of pathogenic indicator micro organisms.

Ash/sludge pellets from Lycksele wastewater treatment plant was used in a fertilization experiment, established 2001 in a 36 year old Scots pine forest (Sahlén *in prep* b). Application rates were 5.8-23.1 tons dw/ha, corresponding to 63,5-254 kg N/ha. Mineral fertilizer at a rate of 150 kg N/ha, was also used. Treatment effects on tree growth and chemical composition in tree needles, ground vegetation, humus layer, soil water (50 cm depth) and heavy metals in small mammals (autumn 2001) are under investigation.

A field fertilization experiment was established in June 2002, in a mixed (pine, spruce, birch) stand in Movattnet in northern Sweden (Sahlén *in prep* c).Treatments are septic sludge (target N application rates 50, 100 and 200 kg N/ha, annually), calcinated sludge (3 and 6 tons dw/ha) and mineral fertilizer (100 kg N/ha, annually). The septic sludge is collected from private wells and small wastewater treatment plants in the region around the experiment site with a tank lorry and is unloaded into a roadside container through a grid for removal of bigger particles. The sludge is then pumped into the adjacent forest through a system of pipes and sprinklers. Dry matter content of the sludge varies between 0.04 and 3%, and average N content is about 3% dw (about 45% ammonium nitrogen). Investigation objectives include determination of treatment effects on tree growth and chemical content in needles, ground vegetation, humus layer and soil water (50 cm depth) and dispersal and survival of pathogenic indicator micro organisms.

In May 2003, a fertilization experiment with anaerobically digested sludge granules (Himmerfjärden wastewater treatment plant, 139 och 419 kg N/ha) and sludge pellets from Umeå WWTP (202, 242 and 606 kg

N/ha) was established in a 60 year old Scots pine forest on a sandy till (Sahlén *in prep* d). Effects on tree growth and chemical content of needles, ground vegetation, humus layer and soil water are to be investigated.

Norway

In Hedmark (60° 5' N), a sandy sediment soil dominated by *Cladonia* ssp, *Calluna vulgaris* and *Vaccinium vitis-idaea*, was fertilized with dewatered undigested sludge 1979 after prescribed burning and before planting of Scots pine (Solbraa 1999). Sludge was applied to a depth of 5 cm, which was estimated to about 2500 kg N/ha. Mineral fertilizer treatments were also included in the experiment. Tree growth was measured annually until 1997 and nutrient content in applied sludge, tree needles, humus layer and mineral soil (0-20 cm) was investigated 1990. In humus and sludge, also some trace metals were analysed.

Denmark

A 75 year old Norway spruce stand on sandy podzolic soil in Denmark was fertilized 1974 with 800 m^3/ ha (51 tons dry weight, 6% dry matter content) corresponding to1300 kg N/ha of anaerobically digested municipal sewage sludge (Olesen, Lundberg et al. 1979; Grant and Olesen 1984). During an investigation period of 6.5 years, the chemical composition of applied sludge, tree needles, humus layer, mineral soil and soil (50 cm depth) and ground water (2-3 m depth) were measured. Tree growth was measured after 4.5 years.

In 1987/88, the trees were cut (clear-cut and shelterwood) and replaced with plants of Norway spruce, Abies sp and Larix (Mark and Clausen 1993). The content of nutrients and heavy metals in the ground water were studied until 1992. During the first two years, needle nutrient content and plant heights were also measured.

USA

In Florida, fertilization was conducted 1974 with digested sludge (2.6% dw, 3.6% N) after planting of one year old Pinus ellottii on extremely sandy soil (Lutrick, Riekerk et al. 1986; Riekerk and Lutrick 1986). Application rates were 20-100 dry tons/ha (730-3650 kg N/ha). Tree growth was measured after 9 years, and nutrient content in needles and soil down to 90 cm depth were determined during eight years.

Anaerobically digested liquid sewage sludge (0.1-3.1% dw) application of 12.7 and 27 tons dw/ha was done 1974-75 in a mixed hardwood forest in Pennsylvania (Sidle and Kardos 1977). Applied metal amounts were: Cu, 11-25kg/ha (800 ppm); Cd, 0.11-0.25 kg/ha (13 ppm) ; Zn, 12.6-28.5) (1000 ppm). Soil water (15 and 120 cm depth) and soil sample (0-7.5, 7,5-15, 15-30, 30-60, 60-120 cm) content of heavy metals was determined until March 1976.

Pathogen indicator survival was investigated in a clear-cut and a Douglas fir stand after application of up to a 15 cm thick layer of anaerobically digested dewatered sewage sludge during1972-75 (Edmonds 1976).

In Pack Forest,100 km south of Seattle, Washington, a sludge fertilization experiment was established 1975 on extremely coarse-textured outwash soil (Harrison, Henry et al. 2000) . This soil type was chosen in order to maximize the potential for adverse effects (leaching, acidification, metal toxicity). Anaerobically digested sludge (500 tons/ha, 2.6% N) was spread and disked into the surface layers to a depth of about 30 cm before planting of Douglas fir and Ponderosa pine. The applied amounts were : C=91700, N=13100, P=9000, Ca=13200, K=7800 and Mg=175 kg/ha. In another field experiment, nine different sites were fertilized with the same sludge type at application rates 25-50 tons/ha. The distribution of heavy metals and pH and nutrients in the soil down to 135cm depth was investigated after 15 years.

In 1976, 500 tons of sewage sludge was disked into the soil surface (20 cm) on a site in Pack forest (Zazoski 1983). After 4 years, the heavy metal (Cd, Cu, Zn, Ni, Pb) content in the soil/sludge layer down to 120 cm depth was determined.

Heavy metal (Cd (45 ppm), Cu (1000 ppm), Ni (90 ppm), Pb (900 ppm), Zn (1700 ppm) mobility was investigated in Pack Forest, Washington after application of anaerobically digested sewage sludge 1980 (20% dw, pH 8) at layer thicknesses of 10, 20 and 40 cm (McKane 1984). Leachate water from beneath the sludge was collected during a 16 month period.

Heavy metal content in fungal sporocarps and soil was investigated in five sludge fertilized forest (four with Douglas fir and one with shrubs and hardwood) sites and six unfertilized sites (three in rural and three in suburban areas) in the state of Washington 1982-83 (Zabowski, Zasoski et al. 1990). Sludge fertilization had been carried out between 1977 and 1981 at application rates between 12.5 and 125 tons dw (0.5-6.2 kg Cd/ha).

A 60 year old Douglas fir stand on a coarse gravelly outwash soil in Pack Forest, Washington USA, was fertilized with anaerobically digested and dewatered sludge 1977 (95 tons dw/ha) and 1980 (47 tons dw/ha), corresponding to totally about 6000 kg N/ha (Cole, Rinehart et al. 1984). Tree growth and wood density were investigated during the subsequent six years. Litter fall, decomposition, nitrogen mineralization and supply of N och P to the forest floor were investigated after 10 years (Prescott, McDonald et al. 1993).

In 1977, a 55 year old Douglas fir stand was fertilized with 47 tons of anaerobically digested sludge (Henry, Cole et al. 1993). Fertilization was repeated 1980 with 95 tons, resulting in a total nitrogen load of 6000 kg/ha. Volume growth was measured after 12 years. Volume growth was also evaluated after 14 years in a 45 year old stand, fertilized with 4000 kg N/ha. In 1981, young (8-11 years) Douglas fir stands on three sites of different productivity, (site class II-IV) were sludge fertilized with 47 tons dw/ha, corresponding to 2000 kg N/ha (of which 450 kg available N). Effects on height growth until 1990 were determined. Another 65 year old stand was fertilized 1985 with the same sludge amount and tree volume growth was evaluated after 6 years.

Christmas tree plantations with three year old Abies grandis and Douglas fir on sandy textured outwash soil, located 100 km north of Seattle, were sludge fertilized 1981 with 300 tons dw/ha, corresponding to 8000 kg N/ha (2.6% N) (Harrison, Henry et al. 1994). In 1989, needle and mineral soil samples (down to140 cm) were analysed for chemical composition, after which some plots were fertilized with $MgSO_4$ and dolomite. The analyses were repeated one year later.

Fertilization experiments with anaerobically digested and dewatered (18% dry matter content) sewage sludge (3.9% organic and 0.7% ammonium nitrogen) were established 1981-83 in three Douglas fir stands of ages 1, 15 and 50 years and located 100 km S Seattle (Henry, Cole et al. 2000). The soils were well drained, ranging in texture from sand to gravelly sand. Application rates were 47 tons dw/ha corresponding to 2180 kg N/ha one year, two consecutive years or three years. Soil water concentrations of nitrate and ammonium at 50 cm depth were investigated.

A mature (70 year old) Pinus ponderosa stand was fertilized 1989 with inorganic fertilizers (220 kg N/ha) and sewage sludge (11.4 tons dw, 6.5% solids, total N content 6.5%, resulting in 240 kg available N content/ha) (Zabowski and Henry 1994). Soil water and soil and needle samples were analysed for nutrients on several occasions until 1993. Tree diameter growth was measured 1993.

Three 2-3 year old Douglas fir stands were fertilized with 17-19 tons dw of sewage sludge in 1991, and tree growth was measured during the subsequent 4 years (Harrison, Turnblom et al. 2002).

Application of sewage sludge (13.5 tons dw /ha, 20% solid, 5.3% N, 3.6% P, 700 kg N and 500 kg P/ha) to a steep (up to 60%) 18 year old Douglas fir watershed in Pack Forest (annual precipitation 1200 mm of which 50% Oct.-Jan., maritime climate), was made 1997 (Grey and Henry 2002). A 20 m buffer zone along a creek was left unfertilized. Nitrogen and phosphorus were analysed in monthly water samples from the creek between November 1995 and November 1998.

Dry sludge pellets with a nitrogen content of 4.4% was applied to a 50 year old red pine stand on a stony sandy loam in Massachusetts 1991 (Kelty, Menalled et al. 2004). Application rate was 200-800 kg N/ha. Tree growth, needle nutrient content and soil water nitrogen content at 60 cm depth was recorded during three years after fertilization.

A sludge fertilization experiment was established 1976 in two 36 year old plantations of Pinus strobus and Pinus resinosa on a well-drained sandy soil in NW Michigan (Brockway 1983; Brockway and Urie 1983). The understory was composed by Pteridium, Vaccinium, Carex, grasses, mosses and lichens, as well as several hardwood seedlings. Application rates were 4.8, 9.7 and 19.3 tons dw/ha of anaerobically digested sludge (N= 6%, C:N 13:1) with a solid content of 6%. Nitrogen loadings were from 287 to 1160 kg N/ha. Soil (1.2 m depth) and ground water (3 m) were sampled and analyzed for nitrate until November 1980 (Brockway and Urie 1983). In addition, samples were taken from the mineral soil down to 120 cm depth, from the forest floor, from the understory vegetation and from the tree needles in the autumn 1976 and 1977 (Brockway 1983). These samples were analyzed for nutrients, trace elements and heavy metal content. Needle weight and tree and understory growth was also measured.

In northern Michigan, a research/demonstration project was conducted, with sludge fertilization of four different sites, of which three were occupied with hardwood, and one with a mixture of 50 year old red pine (*Pinus resinosa* Ait.) and Jack pine (*Pinus banksiana* Lamb.) (Brockway 1988). The pine site had a sandy outwash soil type of high permeability. Sludge application was conducted 1981-82 with anaerobically digested sewage sludge. The sludge was sprayed on the forest floor from a tank equipped terrain vehicle. Sludge dry matter content was 2.6% and application rate 8 tons dw/ha, corresponding to 379 kg N/ha. During a four year period, effects on needle nutrient content, tree growth, ground vegetation composition and chemical composition of forest floor, soil water (120 cm) and ground water was investigated. In addition, heavy metal uptake in earthworms, small mammals, woodcock and white-tailed deer, was investigated.

In another experiment in South Carolina, an 8 year old Pinus taeda stand was fertilized with liquid (2.5% solids) anaerobically digested sludge at application rates corresponding to 400 and 800 kg N/ha in 1981 (Dickens, Miller et al. 1998). Tree growth was measured during 12 years, and nitrate concentration in soil water (1 m depth) and ground water (3 m depth) was analyzed until 2 years after application.

Liquid anaerobically digested sewage sludge was applied to four (ages 1, 3, 9 and 28 years) Pinus taeda stands on well-drained, moderately permeable clayey to sandy sediment soils in S Carolina in 1981, at rates 400 and 800 kg N/ha (Wells, Murphy et al. 1986). Soil water concentrations of nitrate, ammonium, base cat ions, and trace elements from 0.5 and 1 m depths, were analysed until 1984. Needle nutrient content and tree growth were measured 1983 (Wells, McLeod et al. 1984).

Wood properties were investigated on logs from the 9 and 28 year old stands 1981-84 and 1990-93 (Lee, Chen et al. 1999). The fertilization effect on the population density of soil mesofauna was investigated until 1983.

A 10 year old Pinus taeda plantation in South Carolina was fertilized 1992 with aerobically digested sewage sludge (15% solids, 5.7% dw N content) at application rates 12.2 and 25.5 tons dw/ha (728 and 1460 kg N/ ha, of which 200 and 400 kg available N/ha, respectively) (Dickens, Outcalt et al. 2002). Tree growth was measured during 7 years after application.

In South Carolina, two longleaf pine stands (9 and 32 years old) on sandy soil, were fertilized with lime stabilized sewage sludge (22% agricultural lime value, 4.9 and 7.9 tons dw/ha, 58 and 94 kg available N/ha,146 and 235 kg tot N/ha) and inorganic fertilizer (168 kg N/ha) in May 1995 (Dickens and Haywood 1999). Tree growth (2 years) and litter production (4 years) was measured.

Canada

In western British Columbia, an eight year old plantation with Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Pacific silver fir (*Abies amabilis* (Dougl.) Forbes) and Western red cedar (*Thuja plicata* Donn), was fertilized with dewatered anaerobically digested sewage sludge (N-content 3% dw) from Vancouver (Weetman, McDonald et al. 1993). Application rate was 500 kg N and 133 kg P/ha. The effects on tree growth, needle weight and nutrient content were evaluated after one growing season.

On northern Vancouver Island, fertilization with anaerobically digested sewage sludge, pulp sludge, fish silage and ammonium nitrate was compared in a 9 year old stand of western red cedar (*Thuja plicata* Donn ex D. Don) (McDonald, Hawkins et al. 1994). The soil was a Ferro-Humic podzol on unconsolidated morainal and fluvial outwash material. Application rate was 69 tons/ha with a solid content of 26%, corresponding to 542 kg N/ha (3% N dw) for sewage sludge, and 225 kg N/ha for ammonium nitrate. Needle nutrient status and tree growth was evaluated after two years.

Concentrations of total and faecal coliforms in 5 cm deep forest soil samples were investigated during 34 weeks after application of biological and dephosphatation sewage sludge (21-181 tons/ha) on two sites in Quebec in autumn 1993 (Vasseur, Cloutier et al. 1996).

Effects on tree nutrient status and growth

Sweden

Three years after fertilization with dewatered sludge (588-870 kg N/ha) of five Scots pine sites on sandy sediment soils located from south to north, needle concentrations in trees on treated plots were increased for Ca, Mg and N, but not for K and P for the northernmost three sites (Bramryd 2001; Bramryd 2002). After 11 years, only the nitrogen concentration was still elevated in two of the northern sites. The K/N but not P/N and Mg/N ratios were lower at fertilized plots after three and eleven years for the northernmost three sites. However, the ratios were close to or above the desired values for optimal nutrient balance. One locality in the south showed a P/N and K/N ratio after sludge fertilization below the target value. There was no difference in needle nutrient content between liquid (898 kg N/ha) and dewatered sludge at the site located in mid-Sweden (Jädraås). In Mora, needle concentration increased with increasing application rate for N (1.8% for 80 tons dw/ha), P, K, Ca and Mg after three and 11 years (Bramryd 1994). K/N (27 for 80 tons/ha), but not Mg/N and P/N ratio decreased with increasing application rate.

Tree growth was increased by between 1 and 14 (maximum about 50% basal area increase) m^3/ha during five years after fertilization with about 800 kg N from dewatered sludge (Bramryd 1994). Growth reaction was fastest for the three southernmost localities, but the growth increase was lowest (1-2.5 m^3 increase) at the two southernmost sites. For the two northern localities with a more slow growth reaction (2-4 m^3 increase), there was still a remaining fertilization effect after 5 years. In Mora, in mid-Sweden, a doubled application rate resulted in a three times higher growth increase (15 m^3) during 5 years. Liquid sludge showed a faster growth reaction, but dewatered sludge seemed to have a more prolonged effect. However, there were no difference in total five year growth increase between the sludge types in Jädraås (Bramryd 2001).

Nitrogen content in three year old Norway spruce plant needles increased by 75% during the first growing season after fertilization with 8 kg /plant (139 kg N/ha) of pelletized sewage sludge in a field experiment in south-eastern Sweden 1998 (Johannesson 1999). However, needle or whole plant biomass growth was not influenced.

In the wastewater fertilization (100 kg N/ha annually) experiment on a sandy sediment soil in Vindeln, Scots pine one-year needle length was increased from 36 mm (control) to 43 mm (mineral fertilizer) and 52 mm (wastewater) after three growing seasons (Sahlén *in prep* a). Needle weight was increased by fertilization with 75% for mineral fertilizer and 160% for wastewater after the 2002 growing season. Nitrogen content was almost doubled by wastewater (from 1.1 to 2.0%), and concentrations of the macronutrients P, K, Ca and S were significantly higher. Similar differences occurred also at later sampling occasions. Stem volume growth between 1997 and 2002 was about 70% higher for trees treated with wastewater or mineral fertilizer than for unfertilized trees.

Norway

Scots pine needle concentrations were higher for N (1.7 versus 1.2%) , P (0.22 versus 0.16%) and K (0.63 versus 0.5%) ín Scots pine seedlings fertilized with sewage sludge (2500 kg N/ha) 11 years earlier (Solbraa 1999). No such effect was found for Ca, Mg and S. Tree height was 5.7 m on sludge fertilized plots, 4.7 m on mineral fertilized plots (6 x 136 kg N/ha) and 2.3 m on unfertilized plot after 18 years. The height growth curves indicated a continued increasing growth difference between fertilized and unfertilized trees at that time.

Denmark

Needle nitrogen content of 75 year old Norway spruce was 2% (control=1.5%) one year after sludge fertilization 1973/74 with 1300 kg N/ha (Olesen, Lundberg et al. 1979; Grant and Olesen 1984). The difference decreased thereafter, and no significant fertilization effect on needle N content remained after 7 years. For phosphorus, the concentration was significantly elevated on fertilized plots during 7 years, whereas no difference was found for K, Ca, Mg, Zn, Ni and Cu. Sludge fertilization increased basal area growth with 40% during a three-year period. Growth increase was about 2 m^3/ha during the third year. The nitrogen release from the sludge is estimated to continue for more than 10 years.

There was no difference in plant needle content for N, P, K, Cu, Mn and Ca after clear cut or shelter in the above experiments in December 1990 and 1991 (2-3 years after planting) (Mark and Clausen 1993). Plants on previously fertilized plots showed higher content of P, Ca and K but not of N. Seedling heights on fertilized plots were 15-50% higher than on control plots 4 years after planting (Mark and Clausen 1993).

USA

Slash pine needle nitrogen and phosphorus content increased from 0.8 to 1% and from 0.09 to 0.11%, respectively, four years after planting and fertilization with 80 tons dw/ha of sewage sludge (Lutrick, Riekerk et al. 1986). After eight years, no such difference remained. Concentration of K and Mg decreased with increasing application rate after 4 and 8 years, whereas Zn showed an opposite trend. Tree volume, nine years after planting and sludge fertilization, increased with increasing application rate up to 60 tons/ha (2190 kg N/ha), for which the volume was doubled.

Tree volume growth increase was 53% and height increase was 61% six years after fertilization with totally 142 tons dw/ha of anaerobically digested sewage sludge (Cole, Rinehart et al. 1984). Growth increase commenced during the second year, and the growth curve indicated a continued growth increase after six years. Wood density was 10-15% lower after fertilization, which was considered as normal in view of the achieved site productivity improvement.

Twelve years after sewage sludge fertilization with 142 tons dw/ha of a 55 year old thinned Douglas fir stand, the total growth increase was about 45% higher after fertilization (Henry, Cole et al. 1993).

Basal area growth increase in a 45 year old Douglas stand, thinned and fertilized 1977 with 95 tons dw/ha, was for thinned and fertilized trees 648, 430, 229 and 126% after 14 years for tree crown classes suppressed, intermediate, co-dominant and dominant trees, respectively (Henry, Cole et al. 1993). The corresponding growth increase for only thinned trees was 229, 201, 155 and 86%. All trees within each crown class had about the same diameter 1977. There were no signs of declining growth at the end of the 14-year period. This long-term effect deviates from the normal effect of mineral fertilizers, with a maximum duration of 7 years.

Height growth during 9 years for 10 year old Douglas fir was 72% (SiteClass IV), 14% (Site Class III), and 2% (Site Class I) higher after sewage sludge fertilization with 47 tons dw/ha (2000 kg N/ha) (Henry, Cole et al. 1993).

In two 65 year old Douglas fir stands, sludge fertilized 1985 with 47 tons dw/ha, volume growth during six years after fertilization was increased by 65% (site class IV) and 40% (site class II) (Henry, Cole et al. 1993).

Needle concentrations of Mn, Zn, Ni, Cd and Cr were elevated (but below toxic levels) in sludge fertilized Abies grandis och Douglas fir trees 8 years after fertilization with sewage sludge corresponding to 8000 kg N/ha. In contrast, the concentration of Mg was only ¼ of that for control trees (Harrison, Henry et al. 1994). The needles of fertilized trees were chlorotic with necrotic patches and spots, probably a result of the Mg-poor site and Mg-leakage. No significant effect of fertilization was found for N, P, K, Ca, S. Six months after fertilization with $MgSO_4$ + dolomite1989, the needles were non-chlorotic with considerably elevated Mg concentrations. Needle concentrations of Ni, Cd, Cr and Zn were not influenced by the second fertilization.

Pinus ponderosa needle nitrogen content was significantly elevated 5 years after sludge fertilization with 740 kg N/ha (Zabowski and Henry 1994). Ammonium nitrate fertilizer increased N concentration after 1 and 2 years. There was no significant treatment effect on basal area growth during 5 years after fertilizer application. The lack of fertilization effect was supposed to be caused by water limitations, or some other nutrient deficiency or too low N application.

Volume growth during 4 years for two to three year old Douglas fir seedlings, was increased (7-61%) by sludge fertilization, but not statistically significant (Harrison, Turnblom et al. 2002). It was apparent that growth increase continued during the last two years, which supports the assumption that the fertilization effect is long lasting.

Needle nitrogen content in red pine was significantly elevated for applications 400 and 800 kg N/ha, one (1.1%, control ; 1.4-1.9%, sludge) and two (1.4% versus 1.7-2.3%) years after fertilization with sludge pellets in 1991 (Kelty, Menalled et al. 2004). Concentrations of P, K, Ca and Mg were not influenced at any application rate. This resulted in decreasing N/nutrient ratios with increasing application rate and time after treatment. There was no positive tree growth effect of the 200 and 400 kg N/ha applications, and growth during year 2 and 3 after fertilization was 50% lower for the highest application 800 kg/ha. Based on previous fertilization results for red pine, it was believed that the negative growth reaction was caused by mainly the lowered K/N ratio. Red pine is known to be very sensitive to potassium deficit.

Red and white pine needle nitrogen content increased with increasing application rate from 1.2% (control) to 1.7% for 1160 kg N/ha after 14 months in northern Michigan (Brockway 1983). Assimilation of other nutrients and heavy metals were unrelated to fertilization treatments. Needle weight was increased by 50% for the highest application for red pine, but not for white pine. Radial growth was increased up to 47% by fertilization for white pine, whereas no positive growth reaction was achieved for red pine. It was believed that growth reaction will appear later for red pine.

In another sludge fertilization experiment in the same area, needle nitrogen content was 1.5% (Pinus banksiana) and 1.1% (Pinus resinosa) four years after sludge fertilization (379 kg N/ha) in 1982 and 0.9% for unfertilized trees (Hart and Nguyen 1986). P content was also significantly raised by fertilization. Basal area growth increased by 36% for the thinning and fertilization treatment.

Douglas fir (older stands, 37-59 years) volume increment increase 1977-1981 was 40-60% for sewage sludge (2.3% N) application of 5 (102 ton/ha) or 7.5 (153 ton/ha) cm thickness on low productivity sites in Pack Forest, but lower on high productivity sites (Zasoski, Cole et al. 1983). In young Douglas fir plantations (5-10 years old), fertilized with a 2.5 cm thick layer (51 tons/ha) of sludge, basal area growth increase during the first year varied from – 18 to +328%. Growth acceleration and response duration seemed to exceed that of mineral fertilization.

In a simulation of the growth response to sludge fertilization of a Douglas fir plantation in Pack Forest, the results indicated that repeated applications of 5 or 10 tons dw, results in increased aboveground biomass production during a 100 year rotation period (Luxmoore, Tharp et al. 1999). Single applications of 10, 20 and 40 tons dw/ha is estimated to increase production by 18, 36, and 71%, respectively. Fertilizer dose response is estimated to be higher for repeated applications of 5 or 10 tons/ha. The simulations indicate that the positive effects on production are more extended, than the current experience from field experiments.

Canada

Biosolid application increased Pinus taeda volume growth with about 20% during the first 6 years after treatment for application rates 400 and 800 kg N/ha (Dickens, Miller et al. 1998). Later until year 12, the effect ceased.

Needle N concentration in a 28 year old Pinus taeda stand 18 months after fertilization, was elevated from 1.26% for no sludge application to 1.5% and 1.8%, respectively, for application of 400 and 800 kg N/ha of sewage sludge (Wells, McLeod et al. 1984). Volume growth increased by 48% for both application rates until the second year after application. Growth increase in a 9-year stand was 40%, and there were no significant effects of fertilization on modulus of elasticity and rupture, compression strength, shear strength or wood density (Lee, Chen et al. 1999)

In a 10 year old Pinus taeda plantation in South Carolina, accumulated growth during 7 years after application of sewage sludge 1992, was increased by 30 and 35%, respectively, for application rates 728 and 1460 kg N/ ha (Dickens, Outcalt et al. 2002).

Pinus palustris needle production (litter layer weight) was significantly increased (50-90%) by fertilization during years 2-4 in a 32 year old stand. The effect was in proportion to the amount of added N for biosolids, but highest for inorganic fertilizer (Dickens and Haywood 1999). In a younger stand, similarly treated, the positive growth effect of fertilization (28-97%) was interrupted after three years, due to bend-over caused by heavy crowns. Two-year volume growth increase was 11 and 36% in the young and older stand, respectively after inorganic fertilization. Only the highest biosolid application (235 kg N/ha) resulted in increased diameter growth by 25%.

Needle weights one year after sludge fertilization (500 kg N/ha) of eight year old Abes amabilis, Thuja plicata and Tsuga heterophylla in western British Columbia were increased by 25-300% (Weetman, McDonald et al. 1993). Nutrient concentrations also increased for N, S and Ca, but not for K, Mg, Mn, Fe, Cu and Zn. Height growth increase was between 50 and 300% for fertilized trees after one year.

Nine year old Thuja plicata needle concentrations of N, P, K, Ca and Mg, increased one year after sludge fertilization with 542 kg N/ha (McDonald, Hawkins et al. 1994). After two years, only the N (1.3% sludge, 1% control) and P (0.24% sludge, 0.17% control) concentrations were elevated. At the same time, heights of fertilized trees were 30% (mineral fertilizer) and 23% higher (sludge) than that of control trees. The result was similar for diameter growth. The growth effect was impaired if sewage sludge was mixed with pulp sludge.

Conclusions-tree nutrient and growth effects

Sludge application results in an immediate response, with increased nutrient content in the tree needles already the first year after fertilization. Nitrogen concentration is elevated from about 1.0% to almost the double for Scots pine in Sweden, fertilized with wastewater or sludge and for mature Norway spruce trees in Denmark and spruce seedlings in Sweden. An elevated nitrogen concentration may remain for at least 11 years after Scots pine fertilization in Norway and at sites in northern Sweden , indicating a long-term increased nitrogen supply. Similar effects is also commonly achieved after sludge fertilization of pines in north America after 1-5 years, but N concentrations are in general lower, (1-1.8%), even for heavy sludge applications. The effects of sludge fertilization on needle content of other nutrients are more irregular. Phosphorus concentration tends to increase with time after application, with generally elevated concentrations later than three years after fertilization. Elevated P concentrations may occur in Norway spruce seedlings, planted as late as 18 years after application in Denmark. Base cat ion concentrations show a temporary increase within a couple of years, especially after fertilization with dewatered sludge. Concentrations of K, Mg and Ca may remain elevated after more than 10 years under Nordic conditions. Heavy nitrogen applications may cause Mg and K deficiency in the needles. Needle growth is positively influenced by sludge fertilization, with increased needle weights of 50-300% and a total needle production with up to 90%.

Sewage sludge fertilization generally has a significant tree growth promoting effect. Volume growth increases of 15 to 65% during up to 14 years may be achieved in 40-60 year old Douglas fir stands after application of more than 2000 kg N/ha in western USA. Growth increases are significant also in young stands and for lower application rates. Similar effects are also expectable for other conifers in eastern USA and Canada, with sludge applications between 250 and 2000 kg N/ha. Red pine seems to be an exception, showing decreased growth after fertilization, probably caused by K deficiency. Sewage nutrient fertilization results in increased tree growth also in the Nordic countries. On low to medium fertile Scots pine sites, volume growth in mature stands may be increased by 15-70%, during a 5-10 year period, and height growth increases of 80% are obtainable in young stands. Similar growth effects are probably achievable also for Norway spruce. The experiences from both North America and the Nordic countries show that the duration of the growth promoting effect of sludge fertilization probably exceeds 15 years, i.e., much longer than after treatment with mineral fertilizers. Wood properties are not changed in trees subjected to sewage sludge fertilization to a greater extent than what corresponds to the improved site fertility effect.

Effects on soil nutrients and heavy metals

Sweden

Total nitrogen content in the humus layer increased at all six Scots pine sites one year after fertilization with 20 tons/ha of dewatered sewage sludge (588-870 kg N/ha) (Bramryd 1994; Bramryd 2001; Bramryd 2002). Increased levels remained during 11 years at the northernmost three sites, but not at the two southern sites. C/N decreased after fertilization at all sites (at the two southern localities from 35 to ca 15 and in the north from up to 60-70 to 15-40 after 11 years). In Mora, C/N in the humus layer decreased with increasing application rate after one year from 61 to 21 and13, respectively, for application rates 20 and 80 tons/ha. After 11 years, corresponding C/N values were 29 and19. C/N in the uppermost 10 cm of the mineral soil showed great variations between sites, but with no remaining effect of sludge fertilization after 11 years, irrespective of application rate. The effect on soil C/N in humus or mineral soil was not significantly different between liquid and dewatered sludge.

Humus layer pH increased after fertilization with dewatered sludge and reached a peak value with an increase of 0.5 to1 unit (max from 4.2 to 5.4) during the first 2-4 years after fertilization of five Scots pine sites in Sweden (Bramryd 1994). After 11 years, the pH values were still somewhat elevated. Mineral soil pH increased with increasing depth down to 50 cm below surface, but was not influenced by fertilization on almost all sites. Extractable ammonium-N concentration in the humus layer increased to between 60 and 100 mg/kg at the three southernmost sites the first year after fertilization, from an original level of close to zero. For the two northernmost sites, the peak was both less pronounced (15 mg/kg) and appeared a couple of years later. After 11 years, the concentrations were back at original levels. A marked ammonium-N peak value (5-7 mg/kg) appeared after one year in the surface mineral soil (0-10 cm) at the two southernmost sites. At the other sites, the peak was lower and occurred after 4 years. After 11 years, ammonium-N concentrations again approached background levels. Extractable nitrate-N showed the same pattern as ammonium-N, but the levels were much lower (< 1 mg/kg) and the concentration was in some cases somewhat elevated also after 11 years. In Mora, humus layer pH increased from 4.2 to 5.2 (40 tons/ha) and 5.7 (80 tons/ha) the year after application. A raised pH level remained also after 11 years for all application rates. Surface mineral soil pH was not influenced by application rates, but ammonium and nitrate-N concentrations after one year was considerably increased for the 80-ton application.

Ammonium and nitrate-N concentrations decreased with increasing mineral soil depth, and was increased by fertilization in the mineral soil down to 30 cm depth two years after fertilization at most localities. At that depth, the concentrations were < 0.5 and < 0.2 mg/kg, respectively, for ammonium and nitrate-N.

Ammonium-N concentration and pH in the humus layer increased more rapidly for dewatered than for liquid sludge and was significantly higher during the first three years after application. After 11 years, no such difference remained. In contrast, liquid sludge showed a significantly higher nitrate-N concentration in both the humus layer and the surface mineral soil and a higher surface mineral soil ammonium-N concentration than dewatered sludge after one year. Concentrations thereafter rapidly decreased, with no remaining differences between sludge types at later sampling occasions. First year mineral soil concentrations were significantly elevated for dewatered sludge at 10 cm (ammonium-N) and 10-30 cm (nitrate-N) depths. For liquid sludge, concentrations were significantly increased at all depths between 10 and 50 cm and higher than for dewatered sludge at 10-50 (ammonium-N) and 40-50 cm (nitrate-N).

Humus layer concentrations of P, Ca and Mg were higher on fertilized plots after 3 and 11 years on most sites. Similar differences were found also in the surface mineral soil layer after three years for P, K, Ca and Mg, but after 11 years only for Ca. In Mora, P, K, Ca and Mg increased in humus and mineral soil with increasing application rate. Concentrations of the heavy metals Cr, Cu, Ni and Zn were elevated in the humus layer after three and 11 years and concentrations varied between in average 0.6 (Cd) and 75 (Zn) mg/g. Corresponding concentrations in the mineral soil were 0.03 (Cd) and 1 (Zn) mg/g dw. In general, fertilization did not cause an increased heavy metal content in the mineral soil after 3 or 11 years on most sites.

There were small differences between sludge types in humus and mineral soil content of P, K, Ca, Mg and heavy metals.

In forest fertilization experiments with 3.3-13.2 tons/ha of sewage sludge pellets, Nitrate Reductase Activity (NRA) in *Deschapsia flexuosa* increased with increasing sludge application rate after two months, indicating a nitrate increase in the humus/soil layer (Sandström 2000). Two years after fertilization with 4 ton pellets/ha, NRA was elevated on fertilized plots but only significantly higher than on control plots for two of six sites. NRA levels were considerably lower than after fertilization with 100 kg /ha of mineral fertilizer and not higher than after clear-cut or than average values for similar stand types. It was concluded that there is no risk for nitrate leaching after application of up to13 tons of sludge pellets/ha.

Ammonium accumulation, pH, nitrification and nitrate-N leaching increased in the topsoil (10 cm) during the growing season (4.5 months), after fertilization of Norway spruce seedlings with sludge pellets (139 kg N/ha) in southern Sweden (Johannesson 1999). During the same time, sludge pellets N concentration decreased from 2.7 to about 1.8%.

In the fertilization experiment in Vindeln with wastewater irrigation (about 100 kg N/ha, annually), soil water (50 cm depth) nitrate-N concentrations were typically elevated to 10-20 mg/l (control < 0.1 mg/l) during the irrigation period June-August (Sahlén *in prep* a). In spring, before irrigation start, nitrate-N levels were in general < 10 mg/l.

In Lycksele, where fertilization was made with ash/sludge pellets (up to 250 kg N/ha) in spring 2001, no elevated nitrate-N concentrations were recorded in the soil water on sludge fertilized plots during summer 2001, 2002 or 2003 (Sahlén *in prep* b). However, nitrate-N concentrations were temporarily increased to 8 mg/l in autumn 2001 on plots fertilized with 150 kg N/ha of mineral fertilizer. Soil water concentration of cadmium was elevated on plots fertilized with pellets or mineral fertilizer from control values 0.02 to 0.13 μg/l in autumn 2001, but still well below the drinking water standard limit of 5 μg/l.

In Movattnet, soil water nitrate-N concentration was increased to about 5 mg/l by septic sludge fertilization (up to 200 kg N/ha) in summer 2002, whereas mineral N fertilization (100 kg N/ha) resulted in a nitrate-N concentration of 12 mg/l (Sahlén *in prep* c). In spring 2003, nitrate-N concentrations approached background levels on sludge plots, but was still elevated (5 mg/l) on mineral N fertilized plots.

In Umeå, no soil water nitrate-N concentration increase was detectable two weeks or 4 months after fertilization of a Scots pine stand with sludge pellets and granules at rates up to 600 kg N/ha in spring 2003. However, nitrate-N was elevated to 4.6 mg/l after two weeks on plots fertilized with 150 kg/ha of mineral nitrogen (Sahlén *in prep* d).

Norway

Eleven years after fertilization with a 5 cm thick layer of dewatered sludge on a burnt area, sludge nitrogen content had decreased from 2500 to 2000 kg/ha (Solbraa 1999). Concentrations of most nutrients, heavy metals and pH were considerably higher in the remaining sludge layer on the ground than in the humus layer. Nutrient concentrations in the uppermost 20 cm of the mineral soil did not significantly differ between sludge fertilized and control plots.

Denmark

Sludge organic matter content was mineralised from 54% to 40% after 1.5 years and 38% after 3.5 years, following fertilization of a Norway spruce stand with 45 tons (1300 kg N) of dewatered sewage sludge 1974 (Grant and Olesen 1984). It was estimated that 850 kg of sludge nitrogen remained in the sludge, 250 kg was immobilised in the humus layer, 100 kg was leached and 100 kg was taken up by the trees after 3.5 years. A subsequent annual nitrogen release of 30-60 kg N/ha from the sludge was expected. Inorganic P (plant available) and organic P in applied sludge had deceased by about 50%, of which all was found in the humus layer and uppermost mineral soil. In water at 50 cm soil depth, concentrations of nitrate-N and ammonium-N increased to >30 and 40 mg/l, respectively, during the first year after fertilization. One year later, ammonium-N concentration was close to zero and nitrate-N concentration less than 10 mg/l. Nitrate-N concentrations in the ground water were occasionally until 1977 above 10 mg/l, whereas no increased phosphorus or heavy metal concentrations were detected. Most of these metals remained in the sludge or in the humus layer after 3.5 years. An increased concentration of Zn, close to the detection limit, was detected in the ground water also after 6.5 years, but the level was well below WHO drinking water limits. This was probably a result of the very high (9600 ppm) Zn concentration in the applied sludge. As a consequence of the nitrate-N leakage, it is recommended that application rate should not exceed 25 tons/ha with this sludge type.

Groundwater nitrate-N concentration increased from 1 mg/l to >8 mg/l 1.5 years after clear-cut of the fertilized site in1988 (Mark and Clausen 1993). The nitrate-N concentration was in average 2 mg higher on fertilized than on control plots. The increase was faster on clear-cut area than where a shelterwood was left, reaching peak values of ca 7 mg/l after 3.5 years. The differences between control and fertilization plots were similar to clear-cut/shelterwood differences. Nitrate-N values were back at original levels after about 4 years for all treatments. Ammonium-N concentrations increased from 0.01 mg/l to 0.4 mg/l 3 months after clear-cut on control plots, higher than after fertilization (0.3 mg/l) and shelter (0.05 mg/l control; 0.2 mg/l fertilization). In average for 1988-1992, there were no significant differences between control and fertilized plots for groundwater concentration of ammonium-N, phosphorus and several heavy metals. It was concluded that 50% of the sludge organic fraction is expected to be mineralized within 4-10 years after application. The duration of the positive nitrogen fertilization effect in this experiment is estimated to >10 years.

USA

Two years after liquid sludge fertilization of an one-year old slash pine plantation on an extremely sandy soil, pH in the mineral soil decreased with increasing application rate (730-3650 kg N/ha) down to 90 cm depth (Lutrick, Riekerk et al. 1986; Riekerk and Lutrick 1986). Mineral soil concentration of K, Ca and Mg decreased significantly with increasing application rate after 4 years, but P, Zn and Cu increased. After eight years, the differences still were the same for P, Mg, Zn and Cu. It was concluded that soil acidity increase with increasing application rate was most probably caused by the H^+ produced by nitrification of excess nitrogen. This was accompanied by a decrease of cat ions caused by proton production and nitrate accompanied cat ion leaching.

Less than 0.5% of Cu, 3% of Zn and 3,6-6.6% of Cd moved out of 120 cm depth 6 months after application of 12.7-27 tons dw/ha of liquid sludge in a mixed hardwood stand in Pennsylvania (Sidle and Kardos 1977). All sampled soil water concentrations were well below drinking water standards.

Application of 500 tons/ha of biosolids, resulted in an increased concentration of the

heavy metals Cd, Cu, Ni, Pb and Zn after 15 years, but only in the surface layer (0-30 cm), in which the sludge was mixed with mineral soil through disking (Harrison, Henry et al. 2000). No significant effect on metal concentration of biosolid existed below this level. In other experiments, with surface application rates of 25 and 50 tons/ha, no influence on heavy metal concentration were detected in the mineral soil. The results indicate that trace metals are immobile downwards (0-30 cm). Very low amounts of the metals were water soluble (Cu 0.1%, Zn 0.3%). Exchangeable, and possibly available for plants and micro organisms, amounts were about 25% for Cd, Ni and Zn and < 1% for Cu and Pb. Organic, Al- and oxide bound metal forms were the dominating 75-85% for Cd, Cu and Pb. Element concentration in the uppermost (0-7 cm) soil layer was higher for C (double), N (4 times) and P (7 times) after sludge fertilization then for control plots (Harrison, Xue et al. 1994). Thus, C:N ratio was reduced from 20:1 to 12:1. Concentrations of Ca and Mg were higher after fertilization at all depths down to 135 cm. Much of the Ca, Mg and K added with the biosolid amendment were leached from the surface soil horizons. Soil pH in the uppermost 30 cm was 4.9 after fertilization and 5.9 without, which indicates nitrification. Similar pH differences were recorded at greater depths. Cat ion exchange capacity increased in the uppermost 30 cm, most likely caused by the added biosolid organic matter supply. About 30% of supplied N was believed to be lost through nitrification. It was concluded that the biosolid application objective of increasing nutrient content in the tree rooting zone, extended at least 15 years after application.

Heavy metal (Cd, Cu, Zn, Ni, Pb) content in the soil/sludge layer remained at the original level four years after sludge mixing with the uppermost 20 cm of the mineral soil in Pack Forest 1976, even if pH was lowered from 5.8 to a lowest value of 4.5 in the mineral soil down to120 cm depth. Most of the metals remained in the upper soil layers and it was concluded that metals are not being leached out of the soil over a 4 year period (Zazoski 1983).

Nitrogen supply to the forest floor through needle litter fall and decomposition rate in a 70 year old Douglas fir stand 10 years after treatment, was increased by sludge fertilization (6000 kg N/ha) (Prescott, McDonald et al. 1993). However, nitrogen turnover in litter was not influenced, and it was therefore concluded that sludge fertilization does not result in a long-term increase of site productivity through increased nitrogen turnover.

Heavy metal concentrations in leachate water from beneath the sludge were extremely low throughout a 16 month study period after application of anaerobically digested sewage sludge 1980 (20% dw, pH 8) at layer thicknesses of 10, 20 and 40 cm in Pack Forest, Washington (McKane 1984). It was concluded that metals remained in immobile forms in the sludge over at least the time span of the study. Some small metal concentration increases were associated with the peak of leachate pH decrease to 5.9 as lowest. The original sludge pH value of about 7 was almost approached at the end of the study.

A Christmas tree plantation with Abies grandis and Douglas fir, was fertilized with sewage sludge at an application rate of 8000 kg N/ha (Harrison, Gessel et al. 1996). Base cat ion exchange capacity, pH, and the concentration of exchangeable base cat ions Ca^{2+}, K^{+} and Mg^{2+} were lowered 8 years after fertilization. In contrast, concentrations of the acid cat ions Al and Fe, as well as Cd, Cr, Ni, Mn and Zn was higher on fertilized than on unfertilized plots . The differences were greatest (sevenfold) for Mg^{2+} in the uppermost (0-20 cm) mineral soil layer and decreased with increasing depth to 140 cm. The chemical effect of fertilization was considered typical for the acidification and leakage of the base cat ions and mobilisation of the acid cat ions Al, Fe that is a result of great nitrification.

Nitrate-N concentration in the soil water at 50 cm depth increased from 0.8 to 26 (1 year old stand), 43 (55 year old stand) and 13 mg/l (15 year old stand) during the first year after one sludge application of 2180kg N/ha (Henry, Cole et al. 2000). This was estimated to correspond to a nitrogen leakage of 116, 479, and 73 kg N/ha. Nitrate-N concentration showed a great decrease on single application plots during the second year for the one and 15 year old stands (from 38 to 6 mg/l and from 13 to 1 mg/l, respectively, close to background levels), but increased in the oldest closed stand from 39 to 71 mg/l). For repeated applications, nitrate-N concentrations were high (40-60 mg/l) but approached background levels the second year after the last application. No increased soil water ammonium-N concentrations were recorded. There was a delay between sludge application and increased soil water nitrate-N concentration, which probably was a result of slow nitrification during low winter temperature conditions, or anaerobic conditions in the sludge. It was assumed that the high nitrate concentrations in the closed stand (in comparison to the open stands) was caused by low understory uptake, volatilization and denitrification due to lower temperature and wind velocity, and a lower N uptake due to the already closed canopy.

All fertilizers (biosolids, urea, ammonium nitrate) applied to a 70 year old Pinus ponderosa stand, increased extractable soil nitrogen, but only during the first year after application, and not always significantly (Zabowski and Henry 1994). The levels decreased to those of the control soil by year 2. Soil water nitrate-N concentration was not elevated for the biosolid treatment in any soil horizon, but was increased in the BC horizon for the inorganic fertilizers, indicating some nitrate-N leaching. Soil pH was elevated in the O horizon for biosolids and urea. Soil solutions showed increases in ammonium and nitrate-N in the upper profile, but increases in solution N at the base of the soil profile were found only with the urea treatment.

No change in ammonium-N (0.01-0.07 mg/l) was recorded any time in a creek adjacent to a steep (up to 60%) slope with 18 year Douglas fir during 1.5 years after fertilization with sewage sludge 1997 (13.5 tons dw /ha, 20% solid, 5.3% N, 3.6% P ; 700 kg N and 500 kg P/ha) (Grey and Henry 2002). Much higher peak values are commonly recorded after urea fertilization (1.5 mg/l after one day). Nitrate-N concentration in the creek increased from 0.05-0.5 mg/l to a peak value of 1.5 mg/l. It was concluded that phosphorus and ammonium direct runoff to the creek did not occur, and total phosphorus seems to be immobile. Nitrate-N runoff losses were estimated to less than 1% of applied N.

Soil water nitrate concentration was not influenced for application rates 200 and 400 kg N/ha during three years after fertilization with sludge pellets (Kelty, Menalled et al. 2004). A peak value of close to 10 mg nitrate-N/l, was recorded after the second growing season for the 800 kg N/ha application, but background level was again approached one year later.

Forest floor content of N, P, Zn, Cd, Cu, Cr, Ni, Pb and pH were significantly increased 14 months after sludge fertilization of two stands (red and white pine) with 4.8-19.3 tons of sewage sludge (Brockway 1983). Organic matter dry weight increased by 72% for the highest application rate. Surface mineral soil (0-5 cm) content of total nitrogen and ammonium-N were not elevated by fertilization, whereas nitrate-N (peak value 9 mg/l) and phosphorus were significantly increased after 19 tons/ha application. Micronutrient and heavy metal concentrations, base cat ions, cat ion exchange capacity (CEC), pH, and C:N ratio in the mineral soil were not influenced by fertilization. Below 5 cm, soil nitrate-N and ammonium-N, but not total N, were somewhat elevated for the 19 ton rate. It was believed that nitrate-N leached rapidly through the coarse sand and that lower soil layers having generally lower CEC (0.2 to 5), were less able to adsorb supplemental nutrients. Thirteen months after application, a great portion of the applied nutrients remained in the still only partially decomposed sludge layer in the forest floor. Nitrate-N concentration in the soil water at 1.2 m depth was significantly elevated during 2.5 years (but not thereafter) after sludge fertilization with 1160 kg N/ha (19.3 tons dw), with a maximum value of 15 mg/l (control < 1 mg/l) one year after application (Brockway and Urie 1983). Application rates 580 kg N/ha or lower did not result in any significant increased nitrate-N changes (< 5 mg/l nitrate-N concentration). It was suggested that nitrate-N concentrations > 10 mg/l at 1.2 m depth did not mean that potable water standards necessarily were exceeded, since denitrification and dilution may reduce water nitrate concentration before reaching ground water. A calculated regression showed that pine plantations could be sludge fertilized with up to 16 tons (990 kg N/ha), without producing peak soil water nitrate-N concentrations above 10 mg/l. However, appropriate application rates also depend on sludge and soil properties, water table depth, hydrologic conditions, vegetation type and stand age. The most vigorously growing forests should receive the highest rates.

Forest floor weight increased after liquid sludge fertilization (8 tons dw/ha, 379 kg N) from 31 to 41 tons/ha (Hart and Nguyen 1986) . Content of K, Ca, Mg, Cu, Zn, Ni and Cr in the forest floor was significantly higher for sludge fertilized than for unfertilized plots after three years. The humus layer was the main storage for nutrients and trace elements. The total amounts of heavy metals in the forest floor were very small, despite the significant differences between fertilized and control plots. In the surface mineral soil, only Ca and Mg showed somewhat increased levels. At greater depths, the chemical composition was not influenced by the fertilization (Brockway 1988). Three years after fertilization, < 50% of the applied macro nutrients and 50% of micro nutrients and heavy metals were retained in the forest floor (Hart and Nguyen 1986). One exception was Cd with only 11% retained in the forest floor. Therefore, Cd was considered as having a possible hazardous potential, through entrance into the food chain. The risk for water contamination was believed to be low, since few nutrients and none of the trace elements were detected as moving into the mineral soil or leaching to the ground water. Nitrate-N concentration increased from 1 to 13 mg/l during the first year after fertilization in the soil water at 120 cm depth, but decreased to background level already during the second year (Urie, Burton et al. 1986). A peak nitrate-N concentration of about 5 mg/l was recorded in the ground water at several meter depths1-2 years later than the peak value was measured in the soil water. No raised ammonium-N concentrations were recorded. Nitrate leaching caused an accompanying leaching of Ca, K and Mg with the maximum value occurring simultaneous with the peak for nitrate leaching and declining with lowered nitrate leaching. No leaching losses of Zn, Mn, Cd, B, Cu, Ni and Cr were recorded. These elements remained in the organic layer or were taken up by the vegetation.

Nitrate-N peak concentration at 1 m depth was about 5 mg/l, 6 and 12 months after liquid sludge application of 400 and 800 kg N/ha in an 8 year old Pinus taeda stand, and returned to background level thereafter for the 400 kg N/ha application (Dickens, Miller et al. 1998). For 800 kg N/ha, the peak nitrate-N value was 21 mg /l, occurring 15 months after application. Background levels were reached after 24 months. Average nitrate-N concentration in the groundwater at 3 m depth was 0.7 mg/l upstream and 1.8 mg/l downstream the fertilized site. No groundwater measurement exceeded 10 mg nitrate-N/l.

Nitrate-N concentrations in the soil water at 1 m depth was always below 10 mg/l in Pinus taeda stands with ages 3, 9 and 28 years for a 400 kg N/ha sludge application, whereas peak values of 50 mg/l was reached during the first year after application in an one year old stand (Wells, Murphy et al. 1986). Nitrate-N peak levels of 60 (1 year stand) and between 12 and 30 mg/l (3, 9 and 28 year old stands) was reached for the 800 kg N/ha application. Average nitrate-N concentrations year 1 and 2 were significantly elevated (4 to 27 mg/l) for the 800 kg N/ha application in all stands. For 400 kg N/ha, nitrate-N was increased only in the 1 year old stand and maximum value in the other stands was 4.2 mg/l. Leaching of nitrate-N during 18 months was estimated to between 7 and 22% for 800 kg N/ha and < 8% for 400 kg N/ha. Soil water ammonium-N concentration was in general not influenced by treatments. Cat ion leaching was significant, especially for Ca and Mg, and was related to nitrate-N levels and application rate. This was considered as a risk of cat ion depletion at higher soil horizons, after the higher N application rate. No P leaching was recorded. Heavy metal concentrations at 0.5 and 1 m depth were not significantly elevated for Zn, Cu, Pb, Cd, and Cr for any application rate.

General

Nitrification and nitrate leaching after sludge fertilization may be lower in young plantations subsequent to clear-cut than in a closed forest, due to higher ground vegetation uptake and higher nitrogen volatilization through increased temperature and wind velocity (Zasoski, Edmonds et al. 1984). The risk for nitrate leaching is lower in sludge with a high portion of the nitrogen in organic form (Andrew, Hart et al. 1990).

Heavy metal mobility in the humus layer is strongly pH-dependent, and is very limited at pH above 4 (Tyler 1978). Mobility is highest for Cd and Zn and lowest for Pb. Time for 10% reduction in the humus layer in a Swedish Norway spruce forest is about 20 years for Cd and > 100 years for Cu, Cr and Pb at pH 4. Metal mobility is also negatively correlated with soil cat ion capacity and organic matter content, which may limit plant uptake of Cd (Haghiri 1974; King and Dunlop 1982; Logan and Chaney 1983).

Exposure of trace elements to humans through groundwater appears unlikely at slow-rate land sludge application treatment sites (Kowal 1983). It is concluded that little risk to man or animal or animals is associated with land application of anaerobically digested sludge. It seems reasonable to conclude that cadmium is the only trace element likely to be of health concern to humans as a result of land application of sludge, with the exposure being through food plants or organ meats.

Conclusions-soil nutrients and heavy metals

Nutrients and pH

Forest sludge application increases the soil nitrogen pool in proportion to the application rate and sludge nitrogen content. Ammonium concentration rapidly increases in the humus layer through supply from the applied sludge and increased humus N mineralization, stimulated by increased pH and nutrient supply. Humus layer C/N ratio is lowered and pH may be elevated during more than 10 years after application. Nitrogen application in excess of the assimilation capacity of the ecosystem may result in nitrification and occasional soil acidification and nitrate leaching during 1-2 years after fertilization. Nitrification and nitrate leaching increases with increasing N application rate and is higher from liquid sludge, containing a higher proportion of inorganic nitrogen. Nitrification and nitrate leaching may be accompanied by leaching of base cat ions, replaced by hydrogen ions, if nitrification is extensive. Soil or ground water nitrate-N peak concentrations should not exceed 10 mg/l, if an upper application rate limit of about 1000 kg N/ha for dewatered sludge, is not exceeded. The application rate may be even higher for dry sludge pellets or granules, in which a high proportion of the nitrogen is in organic form, without causing undesirable nitrate leaching. Concentrations of P, Ca and Mg are generally increased in the humus layer after sludge fertilization, also after up to more than 10 years, if not depleted in association with nitrification. Surface mineral soil concentrations of Ca and Mg may also be elevated for some time. The risk for contamination of adjacent surface water sources through runoff of phosphorus, ammonium or nitrate after sludge application seems to be small, even at steep slopes.

Heavy metals

The gathered experience from many forest sludge fertilization experiments shows that heavy metals applied in sewage sludge are retained in the sludge or in the organic layer in the uppermost soil horizon, and are not leached downwards in the soil profile. This is true even for very heavy sludge applications of 500 tons/ha and throughout at least a 15 year period. Present operational sludge application rates will probably be less than 1/20 of that, and sludge heavy metal concentrations are substantially reduced (for Cd with more than 95%) since most of the cited investigations were carried out. Therefore, the risk for groundwater heavy metal contamination after forest sludge application is considered as very small.

Heavy metals in ground vegetation and fauna

Sweden

Cadmium concentrations were not elevated in lingonberry leaves after 3 or 11 years at any of four Swedish Scots pine sites, fertilized with 20 tons/ha of sewage sludge (Bramryd 1994). In contrast, Cu concentrations were higher at all sites after both 3 and 11 years. Concentrations were also in some cases elevated for Cr and Ni.

Heavy metal content two years after treatment, were not elevated in blue berry and lingonberry leaves or berries or in fungal fruit bodies by fertilization with 4 tons/ ha of pelletized sewage sludge (Magnusson and Hånell 2000). The number of fungal species was unchanged, but the number of individuals per species was changed after two months.

No heavy metal increase was detectable after one growing season in lingonberries and blueberry leaves two growing seasons after fertilization with up to 23 tons/ha of ash/sludge pellets in Lycksele 2001 (Sahlén *in prep* b). Concentration of most metals in liver and kidney was not elevated for *Sorex araneus,* captured after one growing season on plots fertilized with ash/sludge pellets. (Tord Magnusson, *pers comm*[2]).

Similar results were achieved in Umeå, with no significant difference in heavy metal content in blueberry leaves and berries and the fungus *Lactarius helvus*, between control plots and plots fertilized with up to 16 tons /ha of sludge pellets and granules (Sahlén *in prep* d).

USA

Heavy metal content in the forest floor on five sludge fertilized (12.5-125 tons dw; 0.5-6.2 kg Cd/ha) sites in Washington was 3-24 mg/kg for Cd and 890-8300 mg/kg for Cu, 2-4 years after application (Zabowski, Zasoski et al. 1990). Very few of the investigated fungal species were found on all (sludge vs control sites) sites, but average sporocarp metal concentrations were significantly elevated on fertilized sites (cap Cd content was 3.6 mg/kg for sludge and 2.6 mg/kg for control sites) for all metals. However, there was no correlation between soil and sporocarp metal concentration, mainly a result of the great variation in metal uptake between individual species.

[2] Tord Magnusson, SLU, Department of Forest Ecology, Umeå, Sweden

Understory biomass increased by 132% 14 months after sludge fertilization with 19 tons/ha of sewage sludge, and ground vegetation nitrogen and phosphorus content were significantly increased after 2 and 14 months (Brockway 1983). Content of Cr, Pb, Ni, fe, Mn, Zn, Cu were unaffected by fertilization, whereas Cd was significantly elevated from 0.5 to 2.8 mg/kg for the highest sludge application rate. A concen-tration of 1 mg/kg in the ground vegetation is considered as upper limit, to avoid potential problems with Cd build-up in the food chain (Baker, Amacher et al. 1977). It should be noted that, in this case, sludge Cd concentration was 440 mg/kg (more than 200 times the Cd levels in modern sludge), corresponding to 8.4 kg/ha.

Sludge fertilization (379 kg N/ha) of a pine stand in northern Michigan, resulted in an increased vegetation ground cover, both vertically and horizontally during the study period of three years (Haufler and Campa 1986; Haufler and Woodyard 1986; Woodyard and Haufler 1991). Species composition was not influenced. Increased biomass production was most pronounced for herbaceous species, and the protein content in the vegetation increased by 20-50%. Sludge fertilized plots were more heavily browsed by deer and elk. Annual ryegrass grown in sludge treated soil had higher concentrations of Cd (0.78 ppm, fertilized vs. 0.32 ppm, control), Cr (0.95 ppm vs. 0.47 ppm), Zn (60 ppm vs. 44 ppm) but not Cu (3 ppm vs. 3.6 ppm) and Ni (1.1 ppm). These concentrations were considered to be well below maximum safe levels at that time (Underwood 1977). Elevated metal concentrations in forage were only apparent the first year. Liver and kidney tissue from whitetail deer contained slightly elevated concentrations of cadmium and zinc, but well below toxic levels. The population of small mammals was doubled already within one year after fertilization, but declined after three years when the vegetation nutrition value had decreased. No toxic heavy metal levels were found in small mammals, and two-month mice feeding with grass pellets did not increase any metal content.

Earthworms are a possible metal transfer pathway to higher food chain levels as, e. g., woodcock (Woodyard and Haufler 1991). Seven cm sludge was applied and mixed with topsoil. The soil/sludge mixture contained elevated concentrations of Cd, Cr, Cu and Zn. Earthworms were added to the soil/sludge mixture for 30-90 days. Metal content of the earthworms was elevated for Cd (from 5 to 27 ppm), Cr (16-48 ppm), Cu (10-25 ppm), and Zn (21-117 ppm). A woodcock was subjected to a diet, entirely consisting of sludge living worms, during 30 days. The only significant metal concentration effect in the bird, was a doubled (45 ppm) cadmium content in liver and kidney. This was considered to be well below a lower level of 200 ppm for toxic effects. The conclusions from these investigations were that sludge use in forests does not present a metal toxicity problem to wildlife consuming vegetation or to higher trophic groups, at application rates used here. Neither is the consumption of meat from deer or game birds (excluding internal organs) a health risk. However, additional studies of animals consuming soil living organisms as, e. g., earthworms, may be required.

The effects on soil mesofauna of sewage sludge application (400 and 800 kg N/ha, 2.5% solids, 5.6-11.1 tons dw/ha and dewatered sludge 630 kg N/ha) 1981, was investigated in four Pinus taeda stands in South Carolina until 1983 (MacConnell, Wells et al. 1986) . Soil mesofauna was reduced until the end of 1982 on all sites for both liquid application rates, whereas the relative frequency of Collembola increased. Reduction was in general greatest for the higher application. In 1983, no differences remained. In contrast, mesofauna population density was significantly elevated throughout the investigation period, after application of dewatered sludge, without change in community structure. It was believed that the dewatered sludge improved living conditions for the mesofauna through supply of less decomposed organic matter, providing increased number of attachment sites and food availability.

Effects of sludge (anaerobically digested, 22% solids, 3.9% N content, 500 kg N/ha, about 12 tons dw/ha) application in November 1990 on small mammal populations, were investigated in a Douglas fir forest in British Columbia, Canada between May 1990 and October 1991 (Cheng, Kimmins et al. 1996). There were no detectable differences in abundance, recruitment, survival, species diversity or body weight of deer mouse, Oregon vole and chipmunks between fertilized and control areas. However, juvenile deer mice growth was significant higher on fertilised areas.

In 1982-85, kidney and liver concentrations of several metals in insectivorous shrews (two species) and granivorous mice were investigated in four sludge fertilized (1981, 50 tons/ha, 1200 ppm Pb, 900 ppm Cu, 50 ppm Cd, 2000 ppm Zn) and five control Douglas fir stands in Pack Forest, Washington (Hegstrom and West 1989). Kidney and liver concentrations were significantly elevated in fertilized stands for all metals in one of the shrew species. For the other species, only cadmium and lead concentrations were significantly higher. Only cadmium concentration was elevated after fertilization in mice kidney and liver, but the levels were only 1/20 of that in shrews. None of the species showed any sign of metal intoxication.

Cadmium concentrations were investigated in kidney of mice (*Peromyscus*) and shrews (three *Sorex* species), captured late winter 1992 in previously sludge fertilized Douglas fir stands in Washington (Nickelson and West 1996). In Snoqualmine Tree Farm (TF), 80 km east of Seattle, four sites with 25-38 year old stands were fertilized (19 and 46 tons/ha,15 mg Cd/kg) four years earlier. In Pack Forest (PF), 100 km south of Seattle, fertilization was made 11 (50 tons/ha, 51 mg Cd/kg, three sites, same sites as in the above paper) and 15 (500 tons/ha, 51 mg Cd/kg) years earlier. Kidney Cd content was much higher in shrews (25-50 mg/kg) than in mice (about 2 mg/kg) and was also significant elevated for shrews after fertilization on all sites (applied with 0.7-25.5 kg Cd/ha) in contrast to mice, with no effect of dose. An exception was 19 tons sludge application (=0.3 kg Cd/ha) in TF, for which no elevated shrew kidney Cd was apparent. Cadmium concentration in soil A horizon 1991 was 18 mg/kg for 500 tons/ha in PF, and 3.5 mg/kg on the other fertilized sites, whereas control values were 3.2 and 1.9 mg/kg, respectively for PF and TF. The 50 tons/ha PF treatment kidney Cd levels were about the same for both species as 1983 (two years after application). It is discussed that biomagnifying of Cd is higher for insectivorous shrews being at a higher trophic level than omnivorous mice. It is not known at which Cd level renal damages are caused for shrews. Even if the kidney Cd contents were statistically significant, it is believed that they are not biologically significant. Population data, from TF, showing that no specie had lower population on fertilized sites, but some, including shrews and mice, had higher populations supports this conclusion. This is possibly caused by improved living conditions after fertilization. It is concluded that high Cd levels may exist in insectivores and may be amplified by biosolid application, but data about toxicity levels are lacking. However, it seemed that cadmium concentration was not elevated in shrew kidney when cadmium application was as low as 0.3 kg/ha. Cadmium loads would be even lower with sludge of today.

Conclusions-heavy metals in vegetation and fauna

Sludge fertilization may result in a temporary improvement of the habitat for both mammals and ungulates, due to increased growth and nutrition value of the ground vegetation, resulting in an increased population size. Even if heavy metal levels may be elevated in forage plants, toxic levels in animals are not reported in any case for municipal sludge. Increased cadmium concentrations may occur only in kidney or liver from ungulates, and meat from game animals may be consumed without any risk. Kidney and liver cadmium concentrations may also be elevated in woodcock, feeding on earthworms with elevated cadmium content after sludge application. However, concentrations are well below toxic levels, and Cd levels in meat are not influenced. No increased metal content is expected in omnivorous mice, but insectivorous shrews may accumulate cadmium in kidney and liver during several years after application, if high amounts of cadmium are applied with the sludge. However, no intoxication effects are expected at now practiced sludge application rates. Soil mesofauna population density or species composition is not negatively influenced by sludge fertilization on long term basis. Since no increased metal concentrations are recorded in berries or fungi after fertilization with up to 23 tons/ha (up to 0.13 kg cadmium/ha) of dry sludge pellets or granules, human consumption of berries and mushrooms may not be restricted.

Synthetic organic compounds

Much of the sludge organics are quite different from those native in the soil. A great number of synthetic compounds may be found in sludge, with the main groups being polychlorinated biphenyls (PCB), polynuclear aromatic hydrocarbons (PAH), ftalates and nonylphenoles. After application, they may be decomposed by micro organisms in soil or sludge, chemically or photo chemically degraded or adsorbed and immobilized in the soil or be lost from the soil through volatilization, plant uptake or leaching (Kowal 1985).

Synthetic organic compounds are concentrated to the sludge, since they decay slowly in the wastewater treatment process, have low water solubility and are attached to the sludge organic matter (Strand 1991) These properties also make them stable and immobile when applied to soil. Less then 1% of applied synthetic organics are leached to groundwater. PCB and phthalates show the highest concentration in sludge and most concerns of trace synthetic organics are focused on PCB. For PCB, less than 0.1% is leached annually after land application. Only a few percent of PCB degrade in soil, and degrading rate is lower for highly chlorinated PCB:s. Half-life times are 100 (2-Cl) and 2300 (4-Cl) days. Plant uptake of synthetic organics is very small. Less than 1% of PCB applied to a forest soil was found in spruce needles and less than 1% of applied dioxin and less than 3% of ftalates were taken up by some agricultural plants.

The effects on the forest ecosystem of sludge synthetic organic compounds are not much investigated. Only one investigation is found in literature (Hanson 1978). A 37 year old Douglas fir stand on a loamy sand was applied with 0.25 to 0.75 inches of sewage sludge during two years. The results showed that there were small differences in ether extractable organic leachate extracts in the B horizon between sludge and control. There were no major detectable low molecular weight organic constituents moving through the soil from the applied sludge. No pentachlorfenol moved from horizon A to B. Total organic carbon (TOC) in soil water was higher in B (36 mg/l) and C (34 mg/l) profiles for sludge than for control, 17 and 14 mg/l, indicating downwards movement of organics. TOC in profile C increased with increasing application rate, and the amount of low molecular weight organics was higher in both litter and at 160 cm depth, indicating an increase of soluble C, as a result of increasing mineralization after sludge application. No organic carbon reached the groundwater.

According to a literature review, mainly referring to agricultural conditions, most of the synthetic organic compounds supplied with sludge are attached to the soil organics, and are decomposed by C-requiring micro organisms (Couillard and Grenier 1990). Sludge organic matter stimulates microbe activity. The abiotic factors (hydrolyse, neutralisation, oxidation, photolysis, volatilisation) contributes to the degradation of certain substances (PAH, volatiles, phenolic compounds), but these mechanisms are not much studied. In general, most organic substances are decomposed. There is almost no plant uptake of organics, and consequently, the risk for a food chain entrance is rather small, except for leaf surface deposition.

From a laboratory study of PAH decomposition in forest soil, it was found that low-molecular-weight (< 4 rings) PAH were subjected to abiotic degradation and that PAH:s with higher ring numbers were biologically degraded (Wild and Jones 1993). It was concluded that sludge organic compounds probably are tightly bound to the soil organic matter and that the microbial population is capable of degrading PAH, with an average halftime of about six months under laboratory conditions.

In a risk assessment of forest sludge application, based on a literature study and actual data from sludge applications in Washington, the quantities of food, water and soil that could be consumed from a sludge-amended forest without exceeding an excess lifetime cancer risk of 1/100 000, was calculated (Munger 1986). For PCB, daily consumption should be less than 10g of sludge/soil litter, 200 g of blackberries or 20 g of deer fat, and for *benzo(a)pyrene* (PAH) the corresponding quantities were 1g and 300 g for sludge/soil and blackberries. Daily surface water consumption from the site, should not exceed 6 litres.

Conclusions-synthetic organic compounds

The effects on the forest ecosystem of sludge synthetic organic compounds, are not much investigated. However, present knowledge about the chemical behaviour of these substances, indicate that the health risk associated with a possible entrance into the food chain through plants or water sources is minimal. Sludge substances of great environmental concern, as PCB:s and PAH:s, are very immobile in sludge and soil, with almost no uptake in plants or leakage through the soil profile to water sources at greater depth. The possible risk is also further reduced by the decreasing trend of synthetic organic concentrations in modern sludge.

Hygienic effects

Human pathogens, that may be found in sewage sludge, are of the three categories bacteria, viruses and parasites (protozoa and helminths) (Sorber and Moore 1987). Levels and types of sludge pathogens depend on population health status and sludge treatment. Pathogens are reduced during sludge treatment by e.g. high temperature and pH, drying and long time storage. Pathogen survival after sludge application varies a lot and is influenced mainly by soil temperature, moisture, pH and occurrence of antagonistic indigenous micro organisms (Edmonds 1976; Yaeger and Ward 1981). Several researchers conclude that land application of properly digested sewage sludge is not associated with a health risk for humans. (Munger 1983; Kowal 1985).

For bacteria and viruses, field survival may vary from 4 to more than 280 days (Kowal 1985). In a mature Norway spruce forest in Denmark, survival of eight *Salmonella* bacterial species was less than 5 months after application of slaughter-waste containing sludge (Grant and Olesen 1984). Maximum survival time of Helminth ova was 15 months at the same site. Parasite survival times of up to 15 years have been recorded in rare cases for *Ascaris* (Munger 1983). Pathogen movement in soil depends on soil moisture, texture, organic matter content, pH, permeability and temperature (Ibibele and Inyang 1986). In general, most pathogens are retained in the uppermost 15 cm of the soil. Viruses are strongly attached to soil particles and are, in contrast to bacteria, not leached by soil water (Bitton, Davidson et al. 1979). A soil with high cat ion exchange capacity, has a high viral retention capacity, whereas a lowered soil pH reduces the number of exchange sites and viral retention time (Funderburg, Moore et al. 1981). Parasites are in general not moved through the soil because of their bigger size (Sorber and Moore 1987).

Pathogen indicator micro organism concentrations in wastewater sprayed into a Scots pine forest in Vindeln in northern Sweden 1999 were 10^4 CFU/g dw for faecal coliforms (*Escherichia coli*), and about 10^3 for faecal enterococci (*Enterococcus faecalis*), *Clostridium perfringens* and Coliphages (Anneli Carlander, *pers comm*[3]; (Sahlén *in prep* a). Micro organism concentrations on the forest moss layer were very close to the detection limit in May 1999, after application of about 6500 m^3/ha of untreated wastewater during June-August 1998. An exception was Clostridium, with a concentration of 10^5 CFU/g. No indicators were detected in the soil water at 50 cm depth during the application period. Two weeks after termination of irrigation in August 1999, concentrations were re-

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duced by 99.9% for faecal coliforms, 90% for faecal enterococci, whereas the occurrence of *Clostridium perfringens* and Coliphages were unchanged.

In another investigation in August 2001, faecal coliform concentrations were reduced from 10^6 CFU/g DW to below the detection limit within two weeks after wastewater application at the same site (Åström 2002). The reduction of verified faecal enterococci in general reached the detection limit within one week after application. The initial levels of coliphages in raw wastewater were lower than 10^4 PFU/g DW and the detection limit was reached within one week after application.

Pre-application moss surface concentrations of faecal coliforms, faecal enterococci *Clostridium* and colifages were close to zero in the experiment in Movattnet, where septic sludge was applied through PVC pipes with drilled outlet holes and with centrifugal sprinklers (Åström and Sahlén 2003). In contrast, total coliforms showed a count of 10^3 CFU/g. Three days after application, micro organism concentrations were 10^4-10^5 CFU/g within 1 m distance from the pipe outlet holes, whereas no micro organisms were detected at 2 m distance. No micro organisms were detected on the moss surface at a distance of 10 m or more from centrifugal sprinklers immediately after application, whereas concentrations were about 10^5 CFU/g for faecal coliforms and faecal enterococci and 10^4 PFU/g för coliphages within 5 m distance from the sprinkler. Faecal coliforms were reduced by 99.9% after 12 days and faecal enterococci by 90% after 6 days. No significant occurrence was detected later than after 24 days. Colifages were reduced by more than 99% within 6 days and were not detectable after 20 days. In the beginning of June the subsequent year, faecal coliforms and enterococci and coliphages were not detectable in the surface moss layer, whereas total coliforms and clostridium counts were 10^3-10^4 CFU/g.

Pathogen survival was investigated in a clear-cut and a Douglas fir stand after application of up to a 15 cm thick layer of anaerobically digested dewatered sewage sludge (Edmonds 1976). A faecal coliform reduction of 99%, from an initial concentration of 10^5 CFU/g, was reached after about 130 days after winter application and 230 days after summer application. Reduction was more rapid in clear-cut than in the closed stand. Within 12 months, die-off had reduced micro organism occurrence to background levels. Faecal coliform concentrations in the surface mineral soil (5 cm) reached a highest count level of about 10^3 (i.e. < 0.1% of the original counts in the sludge) after two months. Background levels were approached after less than 200 days. Groundwater concentration of faecal coliforms was not significantly elevated as a result of the sludge application.

In another investigation in the same area, Salmonella or enteroviruses were not detected in soil water or groundwater during 6 months after sewage sludge fertilization (Zasoski, Edmonds et al. 1984). It is suggested that coliform movement is limited by mechanical soil filtering and adsorption to soil particles. Pathogens are supposed to pose little health hazard, particularly if site access is limited some time after application.

Aerosol dispersal of coliform bacteria may occur from applied sludge surface immediately after application at high wind speeds and clear-cut (Edmonds and Littke 1978). In Pack Forest, Washington, a maximum count of about 10^4 CFU/m^3 air was detected shortly after application. Aerosol dispersal of coliform bacteria was also detected at 50, but not 100 m distance from the source after liquid sludge spraying (several meters height) in a mature Douglas fir stand (Edmonds and Mayer 1981).

Concentrations of faecal coliforms (sludge concentration 3-9 $x10^3$ CFU/g) and faecal streptococci (sludge concentration 3-4 $x10^3$ CFU/g) in 5 cm deep forest soil samples were in general unrelated to application rate (0-181 tons/ha and time after application (0-34 weeks) of biological and dephosphatation sludge on two sites in Quebec in autumn 1993 (Vasseur, Cloutier et al. 1996). These results suggest that the micro-organisms died rapidly during the first two weeks after application. Total coliforms (sludge concentration 3.3 $x10^4$ CFU/g) showed a greater survival, with in several cases increased concentrations after 4 and 34 weeks. With some exceptions, total coliform concentrations were reduced to background levels after 106 weeks. It is therefore suggested that access should be denied to sludge fertilized sites for two years after application in this region.

According to (Edmonds 2000) , forest biosolid application can be made with minimal risk to human health, if sludge treatment is pathogen-reducing and site is properly managed. The conclusion of a literature review and a questionnaire about health risks associated with sewage sludge fertilization, sent to the most important health authorities and researchers in the world, was that no documented case of pathogen dispersal caused by sludge dispersal, could be found (Stenström and Carlander 1999).

Conclusions-hygienic effects

Reported pathogen indicator micro organism survival in forest conditions varies a lot, from a few days to a couple of years. Total coliforms and Clostridium has shown the highest survival. However, since these may also occur naturally in the forest ecosystem, even without sludge application, results are more difficult to interpret and their value as indicators has been questioned (Stenström 1996; Åström and Sahlén 2003). The forest organic layer and the mineral soil are very effective in retaining micro organisms, and the risk for ground water contamination of sewage pathogens seems to be very small. Aerosol pathogen dispersal is rather limited in closed forest after application with low (< 1 m high) centrifugal sprinklers or with hole-equipped pipes. To keep human health risks at an acceptable low level after forest application of potentially pathogen containing sludge, access should be prohibited for at least one year. Application should be avoided in proximity of domestic water sources. To minimize the potential risk for pathogen dispersal through surface run-off, a buffer zone without application should be kept towards adjacent surface water sources. If sludge is subjected to effective pathogen killing treatments (temperature, pH, drying) before application, such precautions should not be required of hygienic reasons.

Conclusions

Washington state risk assessment

In a risk assessment of forest fertilization with sewage sludge, made by Munger (1983), and reviewed by Seattle King County Health Department, Washington State Department of Social & Health Services, University of Washington College of Forest Resources and University of Texas, it was concluded that: ” Picking or eating of wild berries on a seasonal basis will not be limited as a result of sludge application. Occasional consumption of mushrooms from a sludge-amended site, should result in no increased risk. However, daily ingestion is not recommended. Hunting and eating game animals, which have grazed on sludge-amended forests, should cause no observable increased health risks. However, heavy metals are accumulated in animal liver and kidneys while PCB’s are concentrated in fatty tissues, not to be consumed daily. Normal play or recreational activities on a sludge-applied area after the one-year period of restricted access should result in no increased risk. Children and other persons with a propensity for eating dirt (pica), however, could be at risk on a sludge application site and should be supervised after site access is allowed. Any risk would depend on regularly (daily consumption) of sludge-soil by the most sensitive individual.”

Final conclusions

The reviewed research results from experiments with municipal sewage sludge fertilization of conifer forests in the Nordic countries and North America, show that it is possible to elaborate practically applicable fertilization methods, resulting in :

- considerably increased tree growth during at least 15 years
- no health risks for humans or wildlife caused by nitrate leaching or sludge heavy metals, synthetic organic substances or pathogens.

Furthermore, most of the municipal sewage sludge in the Nordic countries (for Sweden 90% year 2000) complies with quality requirements for use on agriculture land for food production. It seems reasonable to believe that the possible hazards, associated with sludge application, should not be higher on forest land.

However, continued research about tree growth and environmental effects of sludge application in Nordic conifer forest ecosystems is required, before guidelines for sludge application in practical scale may be elaborated. An environment-monitoring program should also accompany the introduction of forest sludge fertilization into practical scale.

The forest fertilization option for sewage sludge use is ecologically sound from a wide perspective, contributing to reduced greenhouse effect and increased reuse of the sludge nutrient resource. It is also economically beneficial through increased tree growth and reduced municipality costs associated with sludge incineration and landfill.

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Appendix 1. Summarized description of fertilization experiments

Reference	Site location	Start year	Tree species	Tree age	Sludge type	Application rate/ha		Duration	Tree growth	Needles	Organic layer	Mineral soil	Soil water	Ground vege-tation	Others
						kg N	tons dw								
(Bramryd 2001)	Jädraås, central Sweden	1976	P sylvestris	50	ae. sludge 4% dw 20% dw	 898 868	20	3, 11 y	volume 5 years	nutrients, heavy metals	C, N, heavy metals	C, N, heavy metals		heavy metals	
(Bramryd 2002) (Bramryd 1994)	several in Sweden as above + Mora	1976 " "	P sylvestris " "	50-60 " "	ae. sludge 20% dw " "	588-870 " 780-3120	20 " 20-80	3, 11 y " "	 volume 5 years "	nutrients	nutrients C, N, pH, ammo-nium, nitrate	nutrients C, N, pH, ammo-nium, nitrate			
(Magnusson and Hånell 2000; Sand-ström 2000)	Vindeln, northern Sweden	1996 1998	P sylvestris P abies P sylvestris	40-100 70	sludge pellets, 3% N	105 90-350	4 3,3-13,2	2 y 6-8 w	(volume)					heavy metals, fungal species compo-sition, nitrate reductase activity,	
(Johannesson 1999)	Hjuleberg, southern Sweden	1998	P abies	3	sludge pellets, 2.7% N	139	6	5,18 w 4.5 m	shoot and plant bio-mass	N, weight		pH, ammo-nium, nitrate		N	sludge C, N

Reference	Site location	Start year	Tree species	Tree age	Sludge type	Application rate/ha		Duration	Tree growth	Needles	Organic layer	Mineral soil	Soil water	Ground vege-tation	Others
						kg N	tons dw								
(Åström 2002) ; Sahlén, in prep a)	Vindeln, northern Sweden	1997	P sylvestris	60	waste-water	about 100, annually	nd	8 y	volume	nutrients, weight	(nutrients)		nutrients	(heavy metals)	pathogens
(Sahlén, in prep b)	Lycksele, northern Sweden	2001	P sylvestris	36	ash/sludge pellets, 1.1% N	64-254	5.8-23.1	4 y	(volume)	(nutrients, weight)	(nutrients)		nutrients, heavy metals	heavy metals	heavy metals in shrew

nd= no data available ; ae= aerobically digested ; an= anaerobically digested ;

(nn)= results not yet presented; dw= dry weight; y= years ; m= months ; w= weeks

Reference	Site location	Start year	Tree species	Tree age	Sludge type	Application rate/ha		Dura-tion	Tree growth	Needles	Organic layer	Mineral soil	Soil water	Ground vege-tation	Others
						kg N	tons dw								
(Åström and Sahlén 2003) ; Sahlén, *in prep* c)	Movattnet, northern Sweden	2002	P sylvestris P abies Betula sp	45	Septic sludge, 3% N, calci-nated sludge	50-200, annually	nd	3 y	(volume)	(nutrients weight)	(nutrients)		nutrients	heavy metals	pathogens
(Sahlén, *in prep* d)	Umeå, northern Sweden	2003	P sylvestris	63	sludge pellets and granules, ~ 3.5% N	139-606	4-16.1	2 y	(volume)	(nutrient, weight)	(nutrients)		nutrients	heavy metals	
(Solbraa 1999)	Hedmark, Norway	1979	P sylvestris	0, bur-ned	dewatered ae. sludge	2500	nd 5 cm thick-ness	18 y	height	nutrients, 1990	nutrients, pH, heavy metals, 1990	nutrients, pH, 1990			sludge pH, nutrients, heavy metals
(Olesen, Lundberg et al. 1979; Grant and Olesen 1984)	Denmark	1974	P abies	75	an. sludge 6% dw, 2.3% N	1300	45	6.5 y	basal area	nutrients	N, P, heavy metals	N, P, heavy metals	N, P, heavy metals		pathogens, N, P, heavy metals in sludge
(Mark and Clausen 1993)	Denmark	1974	several conifer seedlings	planted after cut 1988	as above	as above	as above	14-18 y	height	nutrients			nutrients, heavy metals		
(Lutrick, Riekerk et al. 1986; Riekerk and Lutrick 1986)	Florida, USA	1974	P elliottii	1	an. sludge 2.6% dw	730-3650	20-100	8-9 y	volume	nutrients		pH, nutrients, heavy metals			
(Sidle and Kardos 1977)	Pennsylvania, USA	1974	mixed hardwood	nd	an. sludge, 0.1-3% dw	700-1500	12.7-27	6 m				heavy metals	heavy metals		

nd= no data available ; ae= aerobically digested ; an= anaerobically digested ;

(nn)= results not yet presented; dw= dry weight; y= years ; m= months ; w= weeks

Reference	Site location	Start year	Tree species	Tree age	Sludge type	Application rate/ha		Dura-tion	Tree growth	Needles	Organic layer	Mineral soil	Soil water	Ground vege-tation	Others
						kg N	tons dw								
(Edmonds 1976)	Washington, USA	1972	clear-cut, P menziesii	45	an. sludge, 20-40% dw	nd	up to 15 cm deep	3 y							pathogens
(Harrison, Xue et al. 1994; Harrison, Henry et al. 2000)	Washington, USA	1975	P menziesii P ponderosa	nd	an. sludge, 2.6% N	13000 650-1300	500 25-50	15 y			pH, nutrients, heavy metals	pH, nutri-ents, heavy metals			
(Zazoski 1983)	Washington, USA	1976	nd	nd	an. sludge, 2.6% N	nd	500	4 y				pH, heavy metals			
(Zabowski, Zasoski et al. 1990)	Washington, USA	1977	P menziesii	nd	an. sludge, 18% dw	nd	12.5-125	2-4 y						heavy metals	
(Cole, Rinehart et al. 1984; Prescott, McDonald et al. 1993)	Washington, USA	1977	P menziezii hardwood	60	an. sludge 18% dw	6000	95, 1977 47, 1980	6, 10 y	volume, wood density		nitrogen turnover				
(Henry, Cole et al. 1993)	Washington, USA	1977	P menziesii	55	an. sludge, 18% dw	6000	47,1977 95,1980	12 y	volume						
(Henry, Cole et al. 1993)	Washington, USA	1977	P menziesii	45	an. sludge, 18%dw	4000	95	14 y	volume						
(Henry, Cole et al. 1993)	Washington, USA	1981	P menziesii	8-11	an. sludge, 18%dw	2000	47	9 y	height						
(Henry, Cole et al. 1993)	Washing-ton,USA	1985	P menziesii	65	an. sludge, 18%dw	2000	47	6 y	volume						
(McKane 1984)	Washington, USA	1980	nd	nd	an.sludge, 20% dw, 2.3% N	nd	10-40 cm thick-ness	16 m				pH, heavy metals			

Reference	**Site location**	**Start year**	**Tree species**	**Tree age**	**Sludge type**	**Application rate/ha**		**Dura-tion**	**Tree growth**	**Needles**	**Organic layer**	**Mineral soil**	**Soil water**	**Ground vege-tation**	**Others**
						kg N	**tons dw**								
(Harrison, Henry et al. 1994; Harrison, Gessel et al. 1996)	Washington, USA	1981	Abies grandis P. menziezii	3	an. sludge, 2.6% N	8000	300	9 y		nutrients, heavy metals		nutrients heavy metals			
(Henry, Cole et al. 2000)	Washing-ton,USA	1981-83	P menziezii	1, 15, 50	an sludge 18% dw	1-3x 2180	(1-3) x 47	0-4 y					ammo-nium, nitrate		

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(nn)= results not yet presented; dw= dry weight; y= years ; m= months ; w= weeks

Reference	Site location	Start year	Tree species	Tree age	Sludge type	Application rate/ha		Dura-tion	Tree growth	Needles	Organic layer	Mineral soil	Soil water	Ground vege-tation	Others
						kg N	tons dw								
(Zabowski and Henry 1994)	Washington, USA	1989	P ponderosa	70	sludge, 6.5% solid, 6.5% N	740, 240 "available"	11.4	5 y	basal area	N	N, ammonium, nitrate	N, ammo-nium, nitrate	pH, ammo-nium, nitrate		
(Harrison, Turnblom et al. 2002)	Washington, USA	1991	P menziezii	2, 3	nd	nd	17-19	4 y	height, diameter						
(Grey and Henry 2002)	Washington, USA	1997	P menziezii	18	an sludge, 20% dw, 5.3% N	700	13.5	1.5 y							ammonium, nitrate, phosphate, surface runoff
(Kelty, Menalled et al. 2004)	Massachu-setts	1991	P resinosa	50	sludge pellets, 4.4% N	200-800	4.8-19.4	3 y	basal area	nutrients	N, nitrate, ammonium		nitrate		
(Brockway 1983; Brockway and Urie 1983)	Michigan, USA	1976	P resinosa P strobus	36	an. sludge, 5.5% dw	287-1160, 28% as ammonium	4.8-19.3	14 m 5 y	dia-meter	nutrients, length, weight, heavy metals	N, P, pH, heavy met-als, weight	N, P, ammo-nium, nitrate, heavy metals, CEC	nitrate	N, P, heavy metals, growth	

Reference	Site location	Start year	Tree species	Tree age	Sludge type	Application rate/ha		Dura-tion	Tree growth	Needles	Organic layer	Mineral soil	Soil water	Ground vege-tation	Others
						kg N	tons dw								
(Hart and Nguyen 1986; Haufler and Campa 1986; Haufler and Woodyard 1986; Urie, Burton et al. 1986; Brockway 1988; Hart, Nguyen et al. 1988; Wood-yard and Haufler 1991)	Michigan, USA	1982	P resinosa P banksiana hardwood	50	an. sludge 2.6% dw	379	8	4 y	basal area	N, P	weight, nutrients, heavy metals	nutrients, heavy metals	ammo-nium, nitrate, base cat ions, heavy metals	species com-position, growth, protein content, heavy metals	heavy metal content in fauna

nd= no data available ; ae= aerobically digested ; an= anaerobically digested ;

(nn)= results not yet presented; dw= dry weight; y= years ; m= months ; w= weeks

Reference	Site location	Start year	Tree species	Tree age	Sludge type	Application rate/ha		Dura-tion	Tree growth	Needles	Organic layer	Mineral soil	Soil water	Ground vege-tation	Others
						kg N	tons dw								
(Dickens, Miller et al. 1998)	South Carolina, USA	1981	P taeda	8	an sludge, 2.5% dw, 7.2% N	400-800	5.6-11.1	12 y	height, dia-meter				nitrate		
(Wells, McLeod et al. 1984; MacConnell, Wells et al. 1986; Wells, Murphy et al. 1986; Lee, Chen et al. 1999)	South Carolina, USA	1981	P taeda	1, 3, 9, 28	an sludge, 2.5% dw 7.2% N	400-800	5.6-11.1	3 y	height, dia-meter, wood proper-ties	N			ammo-nium, nitrate, P, cat ions, heavy metals		soil meso-fauna
(Dickens, Outcalt et al. 2002)	South Carolina, USA	1992	P taeda	10	ae sludge, 15% dw, 5.7% N	728-1460, 224-448 “available”	12.2-25.5	7 y	height, dia-meter						
(Dickens and Hay-wood 1999)	South Carolina, USA	1995	P palustris	9, 32	lime stabi-lized sludge, 3% N	145-235	4.9-7.9	4 y	height, dia-meter	needle production					
(Weetman, McDonald et al. 1993)	Vancouver Island, Canada	1990	Abies amabilis, Thuja plicata, Tsuga hetero-phylla	8	an. sludge, 3% N	500	17	1 y	height	weight, nutrients					
(McDonald, Hawkins et al. 1994)	Vancouver Island, Canada	1990	Thuja plicata	9	an. sludge 26% dw, 3% N	542	18	2 y	height, diameter	nutrients					
(Vasseur, Cloutier et al. 1996)	Quebeck, Canada	1993	P resinosa hardwood	3	biological sludge, dephospha-tation sludge	35-329 ”available”	21-181	34 w							pathogens

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(nn)= results not yet presented; dw= dry weight; y= years ; m= months ; w= weeks