ANNA-MARIA VEIJALAINEN

Sustainable Organic Waste Management in Tree-Seedling Production

Doctoral dissertation

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Department of Environmental Science
University of Kuopio

ABSTRACT

Organic waste formed in tree-seedling production mainly consists of culled tree seedling and their growing media (low-humified Sphagnum peat), as well as weeds, grass clippings and fallen leaves. According to the Finnish waste legislation, wastes should be treated and recycled as materials near to their source if it is technically and economically feasible. Thus, the aim of the present study was to find sustainable management practices for the organic waste formed in tree-seedling production on-site in forest nurseries. The limited resources of the tree-seedling producers to implement organic waste treatment were taken into consideration in this study.

The composting process, organic matter (OM) decomposition and nutrient leaching, as well as the effect of composting on the survival of nursery pathogens and microbial hygiene indicators, were studied in small-scale compost bins and nursery-scale windrows. The physical and chemical properties of growing media mixtures of Sphagnum peat and compost were studied in order to assess the usability of compost in tree-seedling production. The suitability of the compost as a component in peat-based growing medium for container seedlings of Norway spruce [Picea abies (L.) Karst.], and the effect of these growing media on the out-planting performance of the seedlings, were also studied.

The results indicated that the organic waste formed in tree-seedling production is not ideal for composting. It decomposes slowly and is an acidic material with a low initial content of OM, nutrients and easily available C compounds. A suitable management practice for forest nursery waste composting is the addition of horse manure, or other materials, which provide nutrients, neutralizing agents, microbes and easily available C compounds to the process. Together with forced aeration, they ensure a sufficiently high rise in temperature for the hygienization of the material. In contrast, forest-nursery waste composting in windrows without additives is a feasible method of organic waste management in accordance with the legislation. The compost is not necessarily totally hygienized, and it is therefore recommended for use e.g. in lawns, parks or for landscaping. Uninucleate Rhizoctonia sp. was successfully used as a test organism to validate the efficacy of the process during forest-nursery waste composting.

Nutrient addition, together with an unsuccessful composting process, increased nutrient leaching during composting. This can pose an environmental contamination risk if the compost is piled at the same site for many years without a leachate collection system. Therefore, optimization of the process, the use of a water-tight floor and water circulation systems, as well as covering the compost, are proposed as a means of avoiding an extra nutrient load on the environment.

This work demonstrated that composted forest-nursery waste can be mixed into peat at around 25% by volume to produce viable Norway spruce seedlings for forest planting. If the growing medium contains more compost it is unfavourable for seedling growth due to the fine texture, increased bulk density and possible problems associated with aeration, wettability and water availability under the nursery-culture practices currently in use. Therefore, the irrigation regime and fertilization practices should be specifically designed for compost mixtures. Further research is also needed in order to gain a better understanding of how the physical conditions in the compost media can be improved by mixing a coarse-textured constituent into these container media.

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CAB Thesaurus: waste management; organic wastes; sustainability; forest nurseries; seedlings; composting; decomposition; organic matter; lignocellulose; nutrient content; horse manure; urea; plant pathogens; Rhizoctonia; eradication; leaching; nutrients; environmental impact; growing media; peat; utilization; maturity; Picea abies; planting; irrigation
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Anna-Maria Veijalainen
ABBREVIATIONS

CO₂ carbon dioxide
C/N ratio carbon/nitrogen ratio
Db bulk density (g cm⁻³)
DM dry matter
Ds particle density (g cm⁻³)
EC electrical conductivity (mS m⁻¹)
H₂O( qa) liquid water
H₂O( q) water vapour
K potassium
N nitrogen
NH₃ ammonia
NH₄-N ammonium nitrogen
NOₓ nitrogen oxide compounds
N₂O dinitrogen oxide
NO₃-N nitrate nitrogen
O₂ dioxygen
OM organic matter
P phosphorus
Tp total porosity (% by volume)
WRC water retention capacity

Compost materials in 300 litre, small-scale composts
HM1 Horse manure and forest-nursery waste during the 1st summer in 1999
W1 Forest-nursery waste during the 1st summer in 1999
P1 Sphagnum peat during the 1st summer in 1999
U2 Urea and forest-nursery waste during the 2nd summer in 2000
MU2 Methylene urea and forest-nursery waste during the 2nd summer in 2000
W2 Forest-nursery waste during the 2nd summer in 2000
HM3 Horse manure and forest-nursery waste during the 3rd summer in 2002

Compost materials in windrows
N99 Forest-nursery waste compost piled in 1999
U00 Urea and forest-nursery waste compost piled in 2000
H01 Horse manure and forest-nursery waste compost piled in 2001
N01 Forest-nursery waste compost piled in 2001
H02 Horse manure and forest-nursery waste compost piled in 2002
HA02 Horse manure and forest-nursery waste compost with aeration piled in 2002

Growing-medium mixtures (% by volume)
100P 100% Sphagnum peat
75P25C 75% Sphagnum peat and 25% composted forest-nursery waste mixture
50P50C 50% Sphagnum peat and 50% composted forest-nursery waste mixture
100C 100% composted forest-nursery waste
LIST OF ORIGINAL PUBLICATIONS

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GENERAL INTRODUCTION

1.1 Tree-seedling production in Finland

1.1.1 Tree-seedling production for forest planting

Planting is currently the most widely used artificial regeneration method in Finland. In 2005 ca. 88 000 ha of the artificially regenerated area (119 000 ha) was planted, while the rest was seeded almost totally with Scots pine (Pinus sylvestris L.) (Finnish Forest Research Institute 2006). Annual tree-seedling production has been around 150 million seedlings in Finland since the mid-1990s. Norway spruce [Picea abies (L.) Karst.] (66%) and Scots pine (30%) were the main tree species produced for planting in 2006 (http://www.evira.fi/...). The rest consisted of silver birch (Betula pendula Roth) (3%), downy birch (Betula pubescens Ehrh.) and some other tree species. Almost all (99.6%) of the produced seedlings were container seedlings, although some bare-rooted seedlings, mainly Norway spruce, were still being produced. In addition to domestic production, ca. 12 million seedlings were imported from other EU countries in 2005, whereas only 3 million seedlings were exported from Finland in the same year (Finnish Forest Research Institute 2006).

About 88% of the tree seedlings are currently produced by 19 large- and medium-scale nursery units (production area more than 5000 m²), each of which produce on average ca. 6.9 million seedlings annually (http://www.evira.fi/, K. Koivula, Evira, personal communication). The remaining 12% of the seedlings are produced by 55 local, mainly family-owned, small-scale forest nurseries (production area less than 5000 m²), each producing on average 340 000 seedlings per year. Forest nurseries are usually located in rural areas with long distances to community services e.g. landfills and other solid-waste treatment plants (Poteri 2003), and frequently on groundwater aquifers and/or near lakes and rivers (Jaakkonen & Sorvari 2006).

Low-humified Sphagnum peat is almost exclusively used for the growing medium of container-tree seedlings in the Nordic countries, and also globally in other plant-production systems (Juntunen & Rikala 2001, Clarke 2005). The physical and biological properties of low-humified Sphagnum peat provide favourable growth conditions for container seedlings during greenhouse cultivation (Puustjärvi 1991). Peat is virtually free from plant pathogens and pests, and it has also been reported to contain microbes, which have the capacity to suppress the growth of fungal pathogens (Tahvonen 1982). Most Finnish forest nurseries use commercial Sphagnum peat, which is limed and fertilized to give suitable pH (4.0 – 6.0) and nutrient concentrations (16% N, 8% P, 16% K and micronutrients) for tree seedlings (Juntunen & Rikala 2001).

The technology and growing practices used in tree-seedling production have become highly developed during the past decades. The change from bare-rooted seedling production to seedling production in hard-plastic containers has enabled the adoption of automatic filling, seeding and packing machines (Tervo 1999, Rikala 2002) and automated irrigation and fertilization in plastic greenhouses (Juntunen & Rikala 2001). This, together with the severe competition in this sector, has brought about a need for larger production units and lower production costs (including labour costs). Consequently, the number of forest nurseries has been decreasing. There are also fewer personnel available to take care of e.g. waste management, even though it is important to ensure good nursery hygiene. For these reasons, organic waste management practices in tree-seedling production should be inexpensive and easy to implement technically.
1.1.2 Organic waste management in forest nurseries

The organic waste generated in tree-seedling production includes culled tree seedlings, which have not met the size and shape requirements or have been affected by plant diseases or pests, as well as weeds, grass clippings and fallen leaves from the nursery yards. Out-graded container seedlings also include root plugs, which consist mainly of Sphagnum peat-based growing media, whereas the roots of bare-rooted seedlings and weeds may include sand or peat depending on the soil type of the field. The annual amount of organic waste produced in Finnish forest nurseries varies, but the average amount per nursery was ca. 50 m³ at the end of the 1990’s (Veijalainen et al. 1999).

According to a questionnaire (Juntunen & Rikala 2001), tree-seedling producers find organic waste management problematic (unpublished data). Abandonment, uncontrolled disposal or burning of organic waste in forest nurseries is not allowed by the Finnish Waste Act (1072/1993). Burning is only allowed at specifically designed plants and a license for waste combustion at high temperatures is needed because these wastes may contain pesticides (Jaakkonen & Sorvari 2006). Neither is the transportation and dumping of organic waste in landfills possible because this has been prohibited since 2005 by a Finnish Council of State Decision concerning landfills (861/1997).

Finnish waste legislation primarily requires a reduction in the amount of waste produced. Waste which is subsequently generated should be recycled primarily as raw materials, and secondarily as energy if this is technically and economically feasible (Finnish Waste Act 1072/1993, 6§). In addition, according to the proximity principle of the waste policy, wastes should be treated near to their source, and the waste management should not cause any harm to health or the environment (Finnish Waste Act 1072/1993). In the case of tree-seedling production this means that the priority has to be given to recycling organic wastes as raw materials in the forest nurseries. Thus the most practical solution for tree-seedling producers would be to compost the organic wastes on-site and reuse the composted material in tree-seedling production. However, there is no information available about the composting and utilization of organic wastes from tree-seedling production. In addition, more information is needed about the possible harmful environmental impacts of composting in compliance with the principle of preventing and minimizing any harmful effects, as stated in the Finnish Environmental Protection Act (86/2000).

In general, an environmental permit is not needed for the windrow composting of organic wastes formed in tree-seedling production because the amount of organic waste is small and the wastes are not considered hazardous (Finnish Environmental Protection Decree 169/2000). However, according to the Finnish Environmental Protection Act (86/2000), soil and groundwater pollution is absolutely prohibited. Since many forest nurseries are located on groundwater aquifers and/or near lakes and rivers (Jaakkonen & Sorvari 2006), the need for an environmental permit has to be evaluated case-specifically, especially if nutrient-rich materials such as horse manure are added to the windrows. Therefore, an official announcement of the composting must be sent to the municipal environmental authority, who supervises waste management and issue permits if needed.

The Fertilizer Product Act (539/2006) regulates the treatment process and the use of produced compost if the compost is used in container tree-seedling production or if it is sold or even given free of charge for use outside the forest nursery in Finland. An operator must give written notification to the Finnish Food Safety Authority (Evira) regarding the
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commencement of operations no later than one month prior to the start of operations. The Finnish Food Safety Authority (Evira) will issue an approval if the composting process and produced compost fulfill the requirements of the legislation (Fertilizer Product Act 539/2006, Finnish Ministry of Agriculture and Forestry Degrees No. 12/07 and 13/07).

1.2 Composting

1.2.1 Composting process

Composting can be defined as the aerobic decomposition of organic waste by microorganisms under controlled conditions (Gray et al. 1971a, Golouke 1991). It is a commonly used method for the treatment of organic waste formed in agriculture, the food and forest industries and municipalities in order to simultaneously obtain a soil-improving agent (Haug 1993, Koivula et al. 2000, Paredes et al. 2000, Parkinson et al. 2004). However, the composting methods and prerequisites for a successful process are probably not as well known among the tree-seedling producers. This lack of knowledge may lead to a failure in the treatment process and increases the risk of spreading pests when the compost product is used e.g. in seedling production.

At the beginning of the composting process, the heterogenous organic waste contains a mixed population of mesophilic and thermotolerant microorganisms originating from the raw materials and environment. These microorganisms will grow, multiply and start the decomposition process if the abiotic factors such as temperature, water content, pH, oxygen and nutrient concentrations are favourable (Gray et al. 1971a, Poincelot 1974). However, composting is a flexible process, and thus it can occur over a broad range of conditions.

Abiotic factors

Microbial decomposition occurs most rapidly in the thin liquid films around solid particles. Water provides the medium for chemical reactions, transports the nutrients and metabolism products, and allows the microbes to move (Rynk 1992). A water content of 30 - 40 mass-% has shown to be the lower limit for the decomposition process by inhibiting microbial activity (Gray et al. 1971b); below this value the microorganisms become dormant or die (Ryckeboer 2001). At a water content of above 65 - 70 mass-%, water displaces too much of the air in the pore spaces of the waste material, leading to hypoxic conditions (Gray et al. 1971b). The optimum water content is strongly dependent on the porosity and absorbency of the organic material and on the composting method selected. For example, woody and fibrous materials, such as straw and bark, retain their structure well in wet conditions, and they can therefore be composted at water contents of 75 - 85 mass-% (Golouke 1991). The water content in mechanically-agitated systems with forced aeration can be higher than that in static windrows with passive aeration (Gray et al. 1971b).

Availability of oxygen is essential for efficient microbial decomposition. A minimum oxygen concentration of 5% within the pore space of the compost is required (Rynk 1992). As a result of intensive microbial metabolism, the oxygen consumption is highest during the thermophilic phase (> 40 °C) of composting (Haug 1993). Adequate aeration can be achieved by forced aeration, turning the compost, or even by natural aeration if the material is coarse enough to
assure sufficient porosity (Gray et al. 1971b, Fernandez & Sartaj 1997). In addition to providing oxygen, aeration removes excessive heat, water vapour, CO₂ and other gases trapped within the organic waste (Fig. 1). Inadequate aeration has been reported to decrease the decomposition rate and lead to hypoxic metabolism, with end products such as methane, organic acids and hydrogen sulphide (Rynk 1992). On the other hand, excess aeration also retards the decomposition process by cooling it down and decreasing the water content of the waste material (Gray et al. 1971b).

Microorganisms can tolerate a wide pH range and therefore pH adjustment is usually not required. The optimum pH range for most bacteria is 6.0 - 7.5, whereas for fungi it is between 5.5 and 8.0 (Golouke 1991). An initial lag in the decomposition rate has been reported if the pH is below 4.5 or above 9.0, although an excessively high or low pH is normally buffered back to within the neutral range as the composting process proceeds (Haug 1993).

Nitrogen (N), phosphorus (P) and potassium (K) as macronutrients and certain trace elements are needed for microbial growth and reproduction. Carbon (C) compounds in organic waste serve primarily as an energy source for microorganisms, although a part of the C is also used for new cell synthesis. The optimum C/N ratio for microbial decomposition is reported to be 25 - 40, depending on the type of organic material to be composted (Gray et al. 1971b, Finstein & Morris 1975). If a significant proportion of the C compounds are only slowly

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**Figure 1.** Schematic diagramme of the composting process.
available for microbes (e.g. lignocellulosic material), the C/N ratio can be higher than expected, even though biological activity has reported to diminish if there is excess C over N (Golouke 1991). In contrast, excess N is usually lost from the compost as NH$_3$ gas or through NO$_3$ leaching (Parkinson et al. 2004). Gray et al. (1971b) suggested that optimization of the P concentration in organic waste material would also be advantageous, resulting in faster decomposition and a higher nutrient value of the final product.

**Microbial succession**
Under optimal conditions the decomposition process leads to changes in the composition of microbial populations i.e. microbial succession, which depends on the properties of the raw material, composition of the OM at a particular time, changes in abiotic factors, and the interactions between microbial populations (Golouke 1991). As a result of microbial succession, the composting process proceeds through four phases: i) the mesophilic phase (temperature 20 - 40 °C), which usually lasts for a few hours up to several days, ii) the thermophilic phase (temperature above 40 °C) lasting for a few days to a few months, iii) the cooling phase when the temperature gradually declines to ambient air temperature due to the decline in microbial activity, and iv) the maturation phase, which can last for several months or even years (Crawford 1983).

Information about the number of different microorganisms involved during the different phases of composting is variable. In general, the more heterogeneous the material, the more diverse is the microbial population (Golouke 1991). The approximate numbers of dominant microorganisms in compost according to the review by Crawford (1983) are: $10^8 - 10^9$ bacteria, excluding $10^5 - 10^8$ actinomycetes and $10^4 - 10^6$ fungi per gram dry compost material. Also algae, viruses, protozoa and macroorganisms, such as worms, beetles, spiders and centipedes, are present in the later phases, although to a lesser degree (Finstein & Morris 1975).

Bacteria thrive better than fungi in the rapidly changing compost conditions during the meso- and thermophilic phases. The competitive advantage of bacteria is based on their short generation time, ability to produce a wide range of enzymes to degrade a variety of organic compounds and high surface/volume ratio, which allows rapid utilization of substrates (Ryckeboer 2003). When the temperature rises above 40 °C mesophilic organisms are partially destroyed or are present in resting stages, whereas thermophilic and thermotolerant bacteria including actinomycetes and fungi become abundant. Finstein & Morris (1975) found that the optimum temperature for thermophilic fungi and actinomycetes is 40 - 55 °C and 50 - 55 °C, respectively. At temperatures above 60 °C, the activity of thermophilic organisms also begins to be inhibited, and mainly some spore forming thermophilic bacteria can survive. At this point, the rate of decomposition slows down (Gray et al. 1971b, Ryckeboer 2003). During the cooling and maturation phase, thermotolerant and mesophilic bacteria, including actinomycetes and fungi, will re-appear either from heat-resistant spores or through re-invasion from outside (Gray et al. 1971a). These later phases of the composting process favour the growth of fungi and actinomycetes due to their ability to degrade natural complex C compounds and their preference for moderate to low N concentrations (Ryckeboer 2003).

### 1.2.2 Organic matter decomposition

Organic waste mainly consists of carbohydrates (mono-, di- and polysaccharides, such as starch, cellulose and hemicellulose), proteins, lipids and lignin (Gray et al. 1971a, Haug 1993). However, the waste material may also contain synthetic and mineral material such as
plastics, glass, metal or sand and gravel (Gray et al. 1971b), which may affect the composting process or the quality of the end product. During composting, the organic waste is decomposed and converted into a humus-like compost product and new microbial biomass (Fig. 1). The main end products of the aerobic metabolism are CO2, H2O and heat, and some volatile compounds may also be released during the process.

The degradability of an organic waste depends on the chemical composition of its organic fraction (Haug 1993, Bernal et al. 1998). The heating-up and decomposition rate are rapid in organic materials, such as animal manure (Paumala & Sarin 2000), sewage sludge (Strauch 1991) and kitchen biowaste (Koivula et al. 2000), which contain nutrients and a high proportion of easily available and degradable compounds such as monosaccharides and starch. Lipids and proteins are also relatively easily broken down during the first two phases of composting (Poincelot 1974). For instance, Koivula et al. (2000) found that temperatures of 55 to 65 °C (even a peak temperature of 80 °C) can easily be reached within two weeks and last for a month in kitchen-biowaste windrows.

However, not all biological materials decompose rapidly or even completely. Composting studies conducted with materials including carbon-rich plant materials, such as straw, sawdust, yard waste, wood or peat, have shown that the decomposition rate is slower and the maximum temperature may also be lower than when materials such as manure or sludge are used. Several authors have emphasized that this is due to the high initial C/N ratio and high amount of lignocelluloses in the organic material to be composted (Churchill et al. 1995, Bernal et al. 1998, Eiland et al. 2001). In this respect, these materials have some similarities with the organic waste formed in connection with tree-seedling production, the decomposition of woody tree seedlings and Sphagnum peat being of major concern. However, there is only limited information available about the behaviour of this kind of organic waste alone during composting.

Decomposition of peat

Sphagnum peat, which consists of decomposed Sphagnum moss fibres (stems and leaves), has natural physical and biological properties which create favourable conditions for plant growth. Therefore the decomposition of peat, which is used in growing medium, is not necessary during forest-nursery waste composting. In fact, the bulk density of peat moss increases along with an increase in the degree of decomposition, and this reduces the total porosity and more importantly the volume of air-filled pores (Puustjärvi 1991). However, the growing medium used in tree-seedling production may contain plant pathogens, which must to be destroyed in order to ensure the safe end use of the compost.

The behaviour of peat (alone) in a compost environment has not been investigated widely. However, peat is commonly used as an amendment in manure (Vuorinen & Saharinen 1998, 1999, Airaksinen et al. 2001), organic household waste (Eklind & Kirchmann 2000), sewage sludge and city refuse composting (Garcia et al. 1991) to improve the structure, absorb excess liquid, and to counteract the normally high N concentration of the raw materials. The results of these composting studies demonstrate that the characteristics of the bulking agent greatly influence the composting process and the quality of the compost product.

Vuorinen & Saharinen (1998, 1999) found that dairy cattle and pig manure can be successfully composted with Sphagnum peat in a continuously working horizontal drum. Hygienization, as determined by the absence of faecal streptococci, was mostly reached during a six-day drum composting period. However, the use of peat led to low processing
temperatures (42 - 45 °C), which was accompanied by a low increase in ash content (less than 10%) and low composting efficiency (measured as total average loss of C). They concluded that composting a mixture of manure and peat was slower than composting a mixture of manure and straw in the same system.

Similarly, Eklind & Kirchmann (2000) reported that the decomposition rate was influenced by the type of bulking agent during 590 days’ composting of organic household waste. According to their study, the loss of dry matter was 68, 66 and 39% and of organic C 34, 15 and 8% in straw, softwood (Pinus sylvestris and Picea abies) shavings and Sphagnum peat, respectively. In addition, the initial lignin concentration, which was the highest in the peat compost, was found to be the most important factor determining biodegradability during the composting period (Eklind & Kirchmann 2000). The same conclusion, i.e. that peat is highly resistant to decomposition in a compost environment, can be drawn from the study of Garcia et al. (1991), which showed that decreases in the amounts of individual carbon fractions were the lowest when sewage sludge or city refuse was composted with peat for seven months. Despite the stable nature of peat, the study of Airaksinen et al. (2001) showed that horse manure, which was composted with peat bedding, was ready for further use in plant production after one month’s composting.

Decomposition of lignocelluloses

In woody material, such as tree seedlings, over 90% of the dry mass can consist of lignocelluloses. The polymeric composition of lignocelluloses varies between wood species, and consists of approximately 40 - 45, 20 - 30 and 20 - 30% of cellulose, hemicelluloses and lignin, respectively (Eriksson et al. 1990). In plant cell walls, hemicelluloses are cross-linked with lignin, which has a water insoluble and heterogeneous aromatic structure (Glazer & Nikaido 1998). Together they form a matrix that surrounds the cellulose microfibrils, thereby enhancing the stability and strength of the cell walls.

Lignocellulosic materials are highly resistant to microbial degradation (Eriksson et al. 1990, Haug 1993, Bernal et al. 1998), although the rate and extent of microbial degradation can be greatly influenced by the composition of lignocelluloses (Blanchette 1995). The large molecules of cellulose, hemicelluloses and lignin cannot penetrate through the cell walls of the microorganisms to be metabolised. Thus, microorganisms have to secrete extracellular enzymes, which degrade these polymers into smaller units (Crawford 1983). For the degradation of cellulose, only enzymes hydrolyzing 1,4-β-glucosidic bounds are required. Since hemicelluloses have a branched and variable structure, a larger range of enzymes is needed for their hydrolysis (Eriksson et al. 1990).

Microorganisms obtain energy from the degradation of cellulose and hemicelluloses. In contrast, lignin degradation is dependent on an additional C source (cometabolic degradation), and thus fewer microorganism species can degrade lignins than cellulose or hemicelluloses (Haider 1992). Moreover, the complex structure of lignin requires a wide spectrum of enzymes in the degradation process, and thus the biodegradation rate is much lower than for either cellulose or hemicelluloses (Atlas & Bartha 1998). Lignin also decreases the bioavailability of other cell-wall components by acting as a physical barrier and decreasing water permeation across the cell wall, thereby reducing the surface area available for enzymatic penetration and activity (Eriksson et al. 1990, Atlas & Bartha 1998). However, the order and proportion in which these lignocellulosic compounds are decomposed is not
uniform and there is considerable variation according to the type of microorganism responsible for degradation in specific conditions (Eriksson et al. 1990, Atlas & Bartha 1998).

Basidiomycetous white- and brown-rot fungi are the most effective at degrading lignocelluloses in wood (Eriksson et al. 1990, Atlas & Bartha 1998). White-rot fungi are able to degrade all the cell-wall components, including lignin (Blanchette 1995). They appear to attack wood components either selectively or simultaneously, depending on the fungal species (Blanchette 1995, Atlas & Bartha 1998). Brown-rot fungi efficiently degrade cellulose and hemicelluloses, but not lignin (Blanchette 1995). However, they are able to modify lignin molecules by the demethylation of phenolic and non-phenolic units (Glazer & Nikaido 1998). Soft-rot fungi such as Ascomycota and Deuteromycota are also able to degrade all lignocellulosic compounds, especially in wet conditions (Blanchette 1995), although the decomposition rate is slower than that of Basidiomycetes (Eriksson et al. 1990).

In addition to fungi, several anaerobic and aerobic bacteria including actinomycetes are also capable of degrading lignocelluloses (Eriksson et al. 1990, Blanchette 1995). They are often found in conditions which do not support fungal growth, such as in wet or hypoxic conditions, or in wood with a high phenolic or other extractive content (Blanchette 1995). Bacterial populations alone attack wood slowly. Thus lignocelluloses are normally degraded by synergistic consortia of microorganisms, bacteria mainly participating in the degradation of polysaccharides (Eriksson et al. 1990).

In the compost environment, the degradation process of lignocelluloses differs from that in natural conditions due to the widely fluctuating environmental conditions and complex interactions between mixed populations of microorganisms. The majority of white-rot fungi and other Basidiomycetes do not survive the thermophilic phase and therefore cannot play a significant role in the degradation of lignocelluloses in high temperature composts (Tuomela et al. 2000). However, the importance of Basidiomycetes as lignocellulosic fungi may increase during the cooling down and maturation phases. On the other hand, according to a review by Tuomela et al. (2000), thermophilic or thermotolerant Ascomycota and Deuteromycota have been reported to decompose lignocelluloses in a compost environment. Actinomycetes such as species of Streptomyces and Nocardia, which can tolerate higher temperatures and higher pH, are also potential degraders of lignocelluloses during the thermophilic and maturation phases (Crawford 1983). Similarly to the case in natural conditions, lignocelluloses are probably degraded by dynamic synergistic consortia of microorganisms occurring in a compost environment.

1.2.3 Organic matter hygienization

Factors affecting eradication

Hygienization of waste material, i.e. the eradication of plant, animal and human pathogens, pests and other undesirable biological agents such as weed seeds and roots, is necessary for the safe end-use of the compost in agri- or horticulture. In forest-nursery waste composting special attention has to be paid to the survival of plant pathogens, such as species of Pythium, Rhizoctonia, Phytophthora, Botrytis and Fusarium etc., which commonly cause economically significant damage in tree-seedling production (Lilja et al. 1997). Inactivation of weed seeds and roots is also necessary, if weeds are present in the compost feedstocks.

However, if animal excrements are used as an additive material in forest-nursery waste composting, the eradication of faecal microorganisms must also be taken into account. The
Recently published Finnish Ministry of Agriculture and Forestry Decree No. 12/07 requires that a compost product has to be free of Salmonella, and the number of *Escherichia coli* should be less than 1000 colony forming units/g, which is reached if the number of faecal coliforms is less than 1000 cfu/g. In previous studies, faecal coliforms, coliphages (*Escherichia coli*), enterococci and faecal clostridia have been commonly used as indicators to ensure that faecal microorganisms are eradicated during the treatment processes, i.e. anaerobic digestion, in-vessel composting, using quicklime and disinfection (Carrington 2001, Heinonen-Tanski & Savolainen 2003, Vuorinen 2003). Therefore, these microorganisms were used as hygiene indicators in this thesis during the windrow composting studies conducted with horse manure and forest-nursery waste in 2002.

The growth and survival of pathogens, pests and weeds in the compost environment is determined by a number of physicochemical factors, such as temperature, pH, nutrients and presence of toxic compounds (Atlas & Bartha 1998). Exposure to temperatures above the growth range of the organism is considered to be the major determinant of the hygienization of waste material (Bollen 1984, Hoitink & Fahy 1986, Haug 1993). The mechanisms involved in the thermal death of the cells include enzyme and protein denaturation, as well as the destruction of cell membranes (Haug 1993, Atlas & Bartha 1998). The temperature needed for the destruction of the organisms depends on the duration of the exposure, characteristics of the species and the number of pathogens originally present in waste material (Haug 1993, Atlas & Bartha 1998). If the duration of the exposure increases, the temperature required for hygienization decreases (Fig. 2, Strauch 1991). However, there is always a species-specific threshold temperature, which should be exceeded in order to ensure eradication of the organism (Haug 1993).

Many authorities have concluded that a temperature of above 55 °C is generally needed for the hygienization of waste material. The European and Mediterranean Plant Protection Organization (2006) has set the requirement that compost material should be exposed to a temperature of 55 °C for a continuous period of two weeks, and that the water content should be at least 40% during this period, in order to ensure the elimination of plant pests. According to the Canadian Council of Ministers of the Environment (Composting Council of Canada 1999), the windrow temperature should be above 55 °C for 15 days and the windrow shall be turned at least 5 times during the high temperature period. However, if a static aerated pile is used as a composting method, the waste material will be hygienized in three days. In this case it is advised that the pile be covered with insulating material, such as cured compost or wood chips. Carrington (2001) concluded that sewage sludge should be maintained at a temperature of at least 55 °C for at least 4 hours between each turning. The number of turnings for a windrow should be at least three. In the European Commission’s Working Document on the Biological Treatment of Biowaste (2001), it is proposed that a temperature of 55 °C for 14 days and 5 turnings during this period should be attained for windrow composts. These time-temperature requirements are mainly based on the eradication of human pathogens in municipal waste and sewage sludge or animal pathogens in slurries, all of which have been studied widely (Haug 1993, Strauch 1991).
In reality, the elimination of a desired organism during composting is often a consequence of the interaction of several factors (Bollen 1984, Atlas & Bartha 1998). In addition to the heat generated during composting, such factors include: i) toxic compounds e.g. organic acids and ammonia, which are formed during the decomposition of organic material (Bollen 1984, Chun & Lockwood 1985); ii) microbial antagonism including the production of antibiotics and other antimicrobial substances and parasitism (Yuen & Raabe 1984, Atlas & Bartha 1998); iii) competition for resources (Celar 2003) are involved in the eradication of pathogens. Moreover, if an organism is living in suboptimal environmental conditions, e.g. at too high a temperature or there is a lack of nutrients, it is even more vulnerable to the effect of these factors. Microbial interactions and toxic substances are also advantageous in restricting pathogen re-growth during maturation (Pullman 1981, Haug 1993). It is thus rather complicated to precisely define the eradicating factor in complex environments such as compost.

**Eradication of plant pathogens**

The survival of plant pathogens during composting has not attracted as much interest as that of human pathogens (Bollen 1984, Lopez-Real & Foster 1984, Ryckeboer 2001). This may be partly due to the assumption that the temperatures needed for the eradication of human pathogens ensure that most plant pathogens and seeds are also destroyed, because the optimum temperature for the growth of plant pathogens may be lower than that of human pathogens (Haug 1993). However, plant pathogens are capable of producing resistant resting stages, such as spores, sclerotia and cysts, which may survive at higher temperatures than the...
vegetative cells of the same organism. Plant pathogenic bacteria are known to be non-spore forming, and thus they are easily eradicated at the elevated temperatures achieved during composting (Bollen 1984), whereas many soil-borne fungal plant pathogens, e.g. *Rhizoctonia*, *Phytophthora* and *Pythium* species, are capable of forming heat-resistant sclerotia or chlamydospores (Lilja et al. 1997).

For this reason, the management of the plant health risks of biowaste of plant origin has recently attracted increasing worldwide attention (Ryckeboer 2001, Noble et al. 2004, European and Mediterranean Plant Protection Organization 2006). Great efforts have been made to find indicator microorganisms of plant origin for the verification of the hygienization effect of a composting process. The heat resistant *Tobacco mosaic virus* and *Plasmodiaphora brassicae*, which can survive in the soil only as dormant cysts for up to 6-8 years without the presence of a host, have shown potential for use as indicators. In Europe, the research has focussed on quarantine pests, which are not common in Finland, and therefore there is need to find national indicators to avoid the risk of spreading new diseases in the area.

Moreover, specific production sectors, such as forest nurseries, require their own indicators, which would specifically indicate plant pathogens causing economically significant damage in tree-seeding production. Therefore, the uninucleate *Rhizoctonia* (teleomorph *Ceratobasidium bicorne* J. Erikss. et Ryvarden) was chosen as a model pathogen to validate the efficacy of the composting process to eliminate plant pathogens commonly found in forest nurseries. It is a root pathogen that occurs in Finnish forest nurseries and infects *Picea abies* and *Pinus sylvestris* seedlings (Lilja et al. 1997, Hietala et al. 2001). The pathogen has shown to be genetically very uniform, and thus it may be a new species with a low divergence and host specificity (Hietala et al. 2001).

The eradication of different plant pathogens during composting has been studied in disparate composting systems (Hoitink et al. 1976, Yuen & Raabe 1984, Noble et al. 2004). It is rather difficult to make broader conclusions about the time-temperature relationships needed for eradication of a specific plant pathogen or even to extrapolate the results to cover other plant pathogens based on the literature (Table 1). The conditions inside composts are highly variable (e.g. moisture content and pH) due to the differences in the materials being composted and the variety of techniques used, and therefore the ability of the composting process to hygienize waste material varies (Grundy et al. 1998, Ryckeboer 2001).
### Table 1. Temperature-time relationships needed for the eradication of some plant pathogens during composting.

<table>
<thead>
<tr>
<th>Pathogen</th>
<th>Temperature a</th>
<th>Time b</th>
<th>Inoculum</th>
<th>Compost material</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Armillaria mellea</td>
<td>Above 45 °C (Max 70 °C)</td>
<td>10-14 days</td>
<td>Cherry branches</td>
<td>Green waste</td>
<td>Yuen &amp; Raabe (1984)</td>
</tr>
<tr>
<td>Botrytis cinerea</td>
<td>40 – 60 °C</td>
<td>10-12 weeks</td>
<td>Geranium shoots</td>
<td>Hardwood bark</td>
<td>Hoitink et al. (1976)</td>
</tr>
<tr>
<td>Fusarium oxysporum</td>
<td>Above 50 °C (Max 70 °C)</td>
<td>5 days</td>
<td>Tomato plants</td>
<td>Green waste</td>
<td>Noble et al. (2004)</td>
</tr>
<tr>
<td>Phytophthora cinnamomi</td>
<td>40 – 60 °C</td>
<td>10-12 weeks</td>
<td>Rhododendrons</td>
<td>Hardwood bark</td>
<td>Hoitink et al. (1976)</td>
</tr>
<tr>
<td>Pythium irregulare</td>
<td>40 – 60 °C</td>
<td>10-12 weeks</td>
<td>Rhododendrons</td>
<td>Hardwood bark</td>
<td>Hoitink et al. (1976)</td>
</tr>
<tr>
<td>Rhizoctonia solani</td>
<td>40 – 60 °C</td>
<td>10-12 weeks</td>
<td>Sugarbeets</td>
<td>Hardwood bark</td>
<td>Hoitink et al. (1976)</td>
</tr>
<tr>
<td>Verticillium dahliae</td>
<td>Above 45 °C (Max 70 °C)</td>
<td>10-14 days</td>
<td>Millet seeds</td>
<td>Green waste</td>
<td>Yuen &amp; Raabe (1984)</td>
</tr>
<tr>
<td></td>
<td>Above 45 °C (Max 70 °C)</td>
<td>10-14 days</td>
<td>Rose stems</td>
<td>Green waste</td>
<td>Yuen &amp; Raabe (1984)</td>
</tr>
</tbody>
</table>

a Temperature inside the compost.  
b Total exposure time above the given temperature.

Consequently, laboratory incubations are commonly used to control the factors affecting the destruction of pathogens. However, the plant materials and conditions that are used in laboratory studies are also variable (Table 2). Thus, the results obtained in the laboratory are not directly applicable to full-scale composts, and the literature must be interpreted carefully (Noble & Roberts 2004).

There are also some studies which demonstrate that the eradication of plant pathogens may be caused by the presence of toxic compounds or microbial antagonisms. Chun & Lockwood (1985) found in a field study that *Pythium ultimum* was sensitive to the urea added to a sandy soil. The reduction in the *P. ultimum* population was attributed to the increased concentrations of ammonia, which was generated by the hydrolysis of urea. High soil temperatures increased the toxicity of ammonia. Eradication of pathogens by microbial antagonism is reported in the study of Yuen & Raabe (1984), in which *Sclerotium rolfsii* sclerotia were eliminated when exposed to sublethal temperatures in mesh bags placed in the corners of the compost bins. The inactivated sclerotia were colonized by bacteria that produce fungitoxic substances. However, other tested pathogens, *Armillaria mellea* and *Verticillium dahliae*, survived inside woody tissues under similar conditions. Thus, the results suggest that pathogen eradication by microbial antagonism or toxic substances requires direct contact with the pathogen (Yuen & Raabe 1984, Chun & Lockwood 1985).
Table 2. Time-temperature relationships needed for eradication of some plant pathogens during laboratory incubation.

<table>
<thead>
<tr>
<th>Pathogen</th>
<th>Temperature</th>
<th>Time</th>
<th>Inoculum</th>
<th>Incubation system</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Botrytis cinerea</em></td>
<td>40 °C</td>
<td>3 weeks</td>
<td>Geranium stems</td>
<td>Heat incubator</td>
<td>Hoitink et al. (1976)</td>
</tr>
<tr>
<td></td>
<td>50 °C</td>
<td>1 week</td>
<td>Geranium stems</td>
<td>Heat incubator</td>
<td>Hoitink et al. (1976)</td>
</tr>
<tr>
<td><em>Fusarium oxysporum</em></td>
<td>46 °C</td>
<td>1 week</td>
<td>Propagules mixed with talc</td>
<td>Flasks filled with green waste in water baths</td>
<td>Noble et al. (2004)</td>
</tr>
<tr>
<td></td>
<td>52 °C</td>
<td>1 week</td>
<td>Propagules mixed with talc</td>
<td>Empty flasks in water baths</td>
<td>Noble et al. (2004)</td>
</tr>
<tr>
<td><em>Phytophthora cinnamomi</em></td>
<td>40 °C</td>
<td>1 week</td>
<td>Rhododendrons</td>
<td>Heat incubator</td>
<td>Hoitink et al. (1976)</td>
</tr>
<tr>
<td><em>Phytophthora ramorum</em></td>
<td>55 °C</td>
<td>1 hour</td>
<td>Pathogen in agar medium</td>
<td>Heat incubator</td>
<td>Garbelotto (2003)</td>
</tr>
<tr>
<td></td>
<td>55 °C</td>
<td>1 week</td>
<td>Oak wood chips and stems</td>
<td>Heat incubator</td>
<td>Garbelotto (2003)</td>
</tr>
<tr>
<td><em>Pythium irregulare</em></td>
<td>40 °C</td>
<td>1 week</td>
<td>Rhododendrons</td>
<td>Heat incubator</td>
<td>Hoitink et al. (1976)</td>
</tr>
<tr>
<td><em>Pythium ultimum</em></td>
<td>39 °C</td>
<td>12 days</td>
<td>Pathogen in agar medium</td>
<td>Plates in water baths</td>
<td>Pullman et al. (1981)</td>
</tr>
<tr>
<td></td>
<td>50 °C</td>
<td>0.5 hours</td>
<td>Pathogen in agar medium</td>
<td>Plates in water baths</td>
<td>Pullman et al. (1981)</td>
</tr>
<tr>
<td></td>
<td>50 °C</td>
<td>3 days</td>
<td>Propagules mixed with chopped potato and soil</td>
<td>Flasks filled with green waste in water baths</td>
<td>Noble et al. (2004)</td>
</tr>
<tr>
<td></td>
<td>52 °C</td>
<td>1 week</td>
<td>Propagules mixed with chopped potato and soil</td>
<td>Empty flasks in water baths</td>
<td>Noble et al. (2004)</td>
</tr>
<tr>
<td><em>Rhizoctonia solani</em></td>
<td>39 °C</td>
<td>2 weeks</td>
<td>Pathogen in agar medium</td>
<td>Plates in water baths</td>
<td>Pullman et al. (1981)</td>
</tr>
<tr>
<td></td>
<td>40 °C</td>
<td>7 weeks</td>
<td>Barley grains</td>
<td>Heat incubator</td>
<td>Hoitink et al. (1976)</td>
</tr>
<tr>
<td></td>
<td>50 °C</td>
<td>10 minutes</td>
<td>Pathogen in agar medium</td>
<td>Plates in water baths</td>
<td>Pullman et al. (1981)</td>
</tr>
<tr>
<td></td>
<td>50 °C</td>
<td>1 day</td>
<td>Barley grains</td>
<td>Flasks filled with green waste in water baths</td>
<td>Noble et al. (2004)</td>
</tr>
<tr>
<td></td>
<td>50 °C</td>
<td>1 week</td>
<td>Barley grains</td>
<td>Heat incubator</td>
<td>Hoitink et al. (1976)</td>
</tr>
</tbody>
</table>
1.2.4 Environmental considerations

Concern about the quality of groundwater and the eutrophication of watercourses or surface waters is worldwide. In Finland, approximately 60% of the total water supply distributed by waterworks consists of groundwater. One of the major threats of groundwater contamination is the nutrient losses from agriculture (Britschgi 1997). The threat is greatest in sand and gravel areas, which readily permeate water and are therefore easily polluted. However, the depth of the water table and soil characteristics also influence the risk of groundwater contamination (Mälkki et al. 1988). According to Council Directive (98/83/EU), drinking water which contains more than 11.3 mg L\(^{-1}\) NO\(_3\)-N is considered unsuitable for human use (European Communities 1998).

Eutrophication of the water bodies is caused by the increased availability of nutrients, mainly P and N, which are the main factors limiting the growth of vegetation. Increased turbidity and growth of algae and aquatic plants are signs of eutrophication. Finnish surface waters are vulnerable to such changes due to their small water volume, low nutrient concentrations and low buffering capacity (Kauppi et al. 1993). According to Rekolainen et al. (1997), eutrophication of surface and coastal waters in the Nordic countries is mainly caused by nutrient losses from agricultural land and manure management.

The risk of nutrient leaching and surface run-off, as well as N volatilization, has found to be considerable in composting systems, which are supplemented with nutrients to accelerate decomposition, or consist of naturally nutrient-rich materials such as grass clipping or manure (Richard & Chadsey 1990, Dewes 1995, Parkinson et al. 2004). Relatively high nutrient concentrations in the leachates from manure compost indicate that nutrient leaching may be a pollution risk to water resources, particularly on highly permeable soils and near lakes or rivers (Martins & Dewes 1992, Ulén 1993, Parkinson et al. 2004). Composting may represent a local risk of environmental contamination by nutrients, pesticides and other harmful substances also in forest nurseries, because the nurseries are usually located on groundwater aquifers and/or near lakes and rivers (Jaakkonen & Sorvari 2006). However, relatively few studies have been carried out on the environmental impacts of forest-nursery waste composting.

Water is formed as a result of microbial metabolism during aerobic decomposition (see Fig. 1). On the other hand, especially during the thermophilic phase, the water will be lost by evaporation and the risk of water percolation and run-off, and concurrently nutrient leaching, therefore increases as the compost temperature decreases. Excess wetness of the waste material also increases run-off and the percolation potential of a compost windrow, as well as the odours through hypoxic conditions (Haug 1993). Moreover, Dewes (1995) observed that the amount of percolation water was increased by precipitation in the case of uncovered manure windrows, especially during the later period of the process. Berner (1989) reported that 40% of the rainfall leached out as percolate, the rest of the rainfall being evaporated or retained by straw during 177 days of manure composting. Accordingly, he suggested that nutrient losses can be reduced by optimizing the composting process and covering the windrow compost with a water-proof material during the maturation phase. However, opposite results have been reported by Dewes (1995), who found that the amount of percolation water could not be markedly reduced by covering the windrow.

Several studies have suggested that gaseous N losses are higher than the leaching losses of N (Martins & Dewes 1992, Puumala & Sarin 2000). For example, Martins & Dewes (1992)
found that 47 - 77% of the initial N was lost by NH₃ volatilization, including small amounts (<5%) of NOₓ, but only 10 - 20% of the N was leached during manure composting. According to Dewes (1995), gaseous losses of NH₃ are high if N-rich compost is well-aerated and the material is or turns alkaline (pH > 7). Moreover, NH₃ volatilization is promoted by turning during the thermophilic phase of composting as a result of the enhanced NH₃ vapor pressure, as has also been reported elsewhere (Ulén 1993, Puumala & Sarin 2000, Parkinson et al. 2004). Parkinson et al. (2004) reported that N₂O emissions followed the same pattern as NH₃ emissions, although the emission rates of N₂O were very much lower than those of NH₃. Puumala & Sarin (2000) concluded that NH₃ volatilization can be reduced by covering the manure compost with an approx. 10 cm layer of Sphagnum peat. Maintaining the C/N ratio above 30 in the initial waste material also decreases N losses and odour problems (Richard & Chadsey 1990). Paredes et al. (2000) and Sánchez-Monedero et al. (2001) emphasized the importance of using lignocellulosic materials as bulking agents to reduce N losses during manure composting.

1.2.5 Quality and utilization of the compost product

Quality assessment
The quality of the compost product depends on the chemical, microbiological and physical properties of the composting materials, the composting method and the functionality of the composting process (Rynk 1992, Haug 1993). In addition, the degree of stability and maturity of the compost have a great impact on the successful utilization of the compost product in agri- and horticulture (Raviv 2005). Stability is related to the degree of decomposition and it is a function of the microbial activity, i.e. the O₂ consumption and CO₂ production (Haug 1993), whereas maturity is associated with phytotoxicity, i.e. plant growth potential and compost utilization (Zucconi et al. 1981). However, these terms are often inter-related, because phytotoxic compounds are mainly present or produced in unstable composts. Therefore, in this study, maturity is considered to be a parameter that includes stability.

The maturity of the compost product has been studied comprehensively using many biological, chemical and physical methods. The studies have mainly been conducted on municipal solid waste and sewage sludge (Zucconi et al. 1981, Jiménez & Garcia 1989, Haug 1993), although some studies have also been carried out with other types of waste, such as yard waste (Brewer & Sullivan 2003) and mixtures of manure and lignocellulosic waste (Bernal et al. 1998). The results vary among the compost materials and thus the proposed criteria and parameters cannot be generalized to apply to compost made from other types of organic waste. Consequently, in the review by Mathur et al. (1993) it is proposed that a combination of methods is probably needed for the maturity assessment depending on the type of the organic waste in the compost.

From the viewpoint of forest nurseries and other farm-scale composting systems, the methods should be economically feasible and simple to carry out. Monitoring of the composting process is a useful way to predict the quality of the compost product, including the maturity (Levanon & Pluda 2002). Monitoring consists of subjective estimation of physical properties, e.g. temperature, colour and odour, determination of some chemical and biological parameters, such as changes in OM content, C/N and NH₄-N/NO₃-N ratios and germination tests during the composting (e.g. Jiménez & Garcia 1989, Bernal et al. 1998).

Temperature development during the composting process reflects the activity of the microbial populations responsible for the organic matter decomposition (Finstein & Morris 1975). Thus,
the gradual decrease in temperature after thermophilic phase is a sign of increasing compost stability (Jiménez & García 1989). However, according to Haug (1993), the decrease in temperature may also be caused by inadequate aeration, which must be excluded by turning the windrow. Microbial activity can also be determined directly by measuring the formation of CO₂ in the laboratory (Jiménez & García 1989). The subjective assessment of odour and colour are inaccurate and therefore their usefulness is considered to be limited (Rynk 1992). However, after a sufficiently long period of maturation, the unpleasant odours disappear following turning, and the colour of the material becomes dark brown (Jiménez & García 1989, Haug 1993).

The decrease in the C/N ratio and NH₄-N concentration, and the increase in the NO₃-N concentration, have been proposed as an indicator of maturation for many types of compost (Bernal et al. 1998, Sánchez-Monedero et al. 2001, Parkinson et al. 2004). Bernal et al. (1998) proposed that a C/N ratio of <12 and an NH₄-N/NO₃-N ratio of <0.16 can be used as maturity indices of composts that contain lignocellulosic materials. In addition, these values provide valuable information about the chemical characteristics of the compost product. On the other hand, if a part of the organic C is in a resistant form (i.e. lignin), then the C/N ratio may be well above 20 in relative mature compost (Jiménez & García 1989).

Seed germination tests are often used to evaluate compost maturity. These tests are usually conducted with fast growing plant species, such as cress (Lepidium sativum, L.) or curly kale (Brassica oleracea var sabellica), (Zucconi et al. 1981, Jiménez & García 1989). Seed germination is sensitive to the presence of phytotoxic substances, such as NH₃ and low molecular weight organic acids (acetic, propionic and butyric acids), which are formed in the initial phases of composting (Zucconi et al. 1981). In addition to the information about compost maturity, these tests provide information about the usefulness of the compost. However, the test results cannot be generalized to species other than those tested, because the plant growth requirements may vary.

Compost utilization
The research and use of growing-media materials other than peat has increased considerably during the past decades (Carlile 2005). For example, in Central and Southern Europe, the intensive exploitation of peatlands has raised pressures to control the extent of peat extraction (Gaudig & Kamermann 2005). In addition, these local types of peat are often dark and highly humified, and thus not as good as light, low-humified Sphagnum peat for plant growth (Puustjärvi 1991). In general, the biological treatment of biowaste has increased the need for the reuse of composted materials in agri- and horticulture.

The beneficial effect of compost utilization on plant growth has been reported in many greenhouse- and nursery-crop production systems, although there is only limited information about the use of compost in container tree-seedling production. For example, Holopainen et al. (2002) found that composted horse manure (including peat bedding) was a slow-release fertilizer for greenhouse vegetables such as tomatoes, cucumbers and sweet peppers, giving higher yields and better growth than the commercial organic fertilizers used as a control. Wilson et al. (2002) reported that compost derived from sewage sludge and yard waste and mixed with peat provided suitable growing media for container perennials such as Gloxinia, Justicia or Lysimachia, although the effect of the compost application rate on plant growth and development varied with the plant species. In the study of Bugbee (2002), woody ornamental shrub species, such as Juniper and Lilac, grew better in composted hardwood chips and sewage sludge (3:1 by volume) than in the control medium, which consisted of
softwood bark, peat and sand (3:1:1 by volume). The positive effect of compost addition on plant growth was probably due to the increased amount of plant-available nutrients. Also Raviv (2005) concluded in his review that compost addition is beneficial because it improves soil fertility by increasing the amount of soil organic matter, thus activating the soil biota, or directly by adding nutrients. Moreover, the application of compost may improve the physical properties of container media or soil, such as porosity, water-holding capacity and bulk density (Jiménez & Garcia 1989).

Mature composts suppress soilborne plant pathogens in compost-amended soils or growing media. According to Hoitink & Fahy (1986), the disease suppressiveness is clearly linked to the active microflora found in the composts, although some other factors such as chemical inhibitors or low pH are also important. For example, Trichoderma spp. is found to be an effective fungal antagonist of Rhizoctonia solani in bark-compost amended growing media (Nelson et al. 1983, Hoitink & Fahy 1986). However, the composition of the organic waste and the composting process used have an impact on the microflora present in the compost product, and thus the disease suppressiveness of the composts varies (Hoitink et al. 1997). In the study of Kuter et al. (1983), for example, hardwood bark composted outdoors was colonized by a greater variety of microbial species than the same material composted in an in-vessel system. Moreover, excessively decomposed organic matter may lose its capability to suppress diseases due to the inadequate activity of antagonistic microorganisms (Raviv 2005).

Nevertheless, negative influences of compost utilization, i.e. decreased plant growth or yield, have also been reported. According to the review by Jiménez & Garcia (1989), the use of insufficiently mature compost is the most frequent reason for failure during utilization. The lack of maturity cause phytotoxicity, immobilization of N and a decrease in the soil O2 concentration due to the increased microbial activity. On the other hand, some chemical and physical properties of composts may also be disadvantageous to plant growth. High soluble salt and heavy metal concentrations have been typical problems in the utilization of municipal waste and sewage sludge compost (Simpson 1985, Klock-Moore & Fitzpatrick 2000, Wilson et al. 2002). For example, Simpson (1985) suggested that the high heavy metal concentration in woodwaste-sewage sludge compost had an adverse effect on the germination and growth of Douglas fir and white spruce seedlings. However, heavy metal concentrations in sewage sludge have subsequently decreased owing to the pre-treatment of wastewaters in industrial plants and stringent discharge limits for these metals (Vihersaari 2002). Wilson et al. (2002) concluded that reduced root growth of salt-sensitive Justicia was probably caused by too high salinity (>4 dS cm−1) and/or bulk density, together with media compaction, in peat-based growing media that contained 75% or more sewage sludge and yard-waste compost. In addition, the presence of excessive amounts of fine particles (less than 0.1 mm), which clog the pores, increase the non-available water-holding capacity and decrease the air-filled porosity, are problems associated with the utilization of green-waste compost (Spiers & Fietje 2000). According to a review by Raviv (2005), many sewage sludge and municipal solid-waste composts have a high bulk density and low total porosity and therefore can be used only as minor ingredients in potting mixes. Consequently, growing media have to be formulated specifically for the plant requirements and the growth practices used.
1.3 Aims of the study

The main aim of this thesis was to find sustainable management practices for the organic waste formed in connection with tree-seedling production on-site in the forest nurseries. The limited resources of the tree-seedling producers to implement organic waste management were taken into account during this study.

The more detailed objectives of the individual studies were:

1. To study the composting process, organic matter decomposition and environmental contamination risk posed by nutrient leaching during the composting of organic waste formed in tree-seedling production with and without nutrient additions in small-scale composts (Chapter 2) and nursery-scale windrows (Chapter 4).

2. To determine whether nursery pathogens can be eradicated during the composting of organic waste formed in tree-seedling production in order to attain a hygienic compost product for further use. Uninucleate Rhizoctonia (teleomorph Ceratobasidium bicorne), which is able to produce heat-resistant sclerotia, was selected as a model pathogen to test the survival of nursery pathogens during composting (Chapter 3).

3. To assess the suitability of the produced compost as a component of peat-based growing medium for container tree-seedling production. The physical and chemical properties of growing media mixtures of Sphagnum peat and compost, as well as the growth and early out-planting performance of container seedlings of Norway spruce [Picea abies (L.) Karst.], were evaluated (Chapters 5 and 6).
Chapter 1

References


Chapter 1


Chapter 1


CHAPTER 2

COMPOSTING OF FOREST NURSERY WASTE AND NUTRIENT LEACHING


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Composting of Forest Nursery Waste and Nutrient Leaching

ANNA-MARIA VEIJALAINEN 1,2, MARJA-LIISA JUNTUNEN 1, ARJA LILJA 3 AND LEO TERVO 1
1The Finnish Forest Research Institute, Suonenjoki Research Unit, FI-77600 Suonenjoki, Finland, Email. Anna-Maria.Veijalainen@metla.fi; tel. +358 10 211
2The Finnish Forest Research Institute, Vantaa Research Unit, PL 18, FI-01301 Vantaa, Finland


Abstract

The properties of forest nursery waste from the viewpoint of composting are not well known. The objective of the study was to clarify the properties of the forest nursery waste in order to get the thermophilic composting process going on. The composting process and nutrient leaching during composting was also studied. Forest nursery waste including tree seedlings and their growing media (Sphagnum peat), weeds, fallen leaves and grass clippings was composted in 300-litre experimental bins for three months. In the first summer, forest nursery waste was composted with and without horse manure, and during the second summer with and without urea or methylene urea fertilizer. Temperature, volume reduction, pH, water and the organic matter content, nutrient concentrations, water percolation and nutrient leaching were monitored during the composting. Horse manure was the only additive material, which ensured the thermophilic composting process. All additives increased the nitrogen leaching, and horse manure also increased the phosphorus leaching. The results suggest that additive material, such as horse manure, is needed to improve the heating process in forest nursery waste composting. However, the nutrient rich additive material may pose risk for the environment.

Key words composting, forest nursery waste, horse manure, nutrient leaching, methylene urea, nitrogen, organic matter, phosphorus, potassium, thermophilic process, urea

Introduction

Approximately 150 million forest seedlings are delivered for planting annually in Finland. About 90% of the forest seedlings are produced by seven nursery companies that own a total of 24 nurseries. The remaining 10% of the produced seedlings are grown in small, family-owned forest nurseries, comprising a total of 60 to 70 nurseries. Nowadays, about 90% of the production is container seedlings, although bare-root seedlings are also still produced (Poteri 2003).

If seedlings are affected by plant diseases or pests, or they do not meet the size and shape requirements, then they should be culled off before selling (Rikala 2000). Thus forest nursery biowaste includes e.g. culled coniferous and deciduous tree seedlings and their growth media (Sphagnum peat), weeds, grass clippings and fallen leaves. The annual amount of biowaste produced in Finnish forest nurseries varies, but the average amount per forest nursery is about 50 m³ (Veijalainen et al. 1999).

According to a questionnaire (Juntunen and Rikala 2001), forest nurseries find the handling of biowaste problematic (unpublished data). The Finnish Waste Act (1072/1993) does not allow the heaping up or burning of biowaste in an uncontrolled fashion in the forest nursery fields. Disposal of biowaste by landfilling is not a solution, because the number of landfills is decreasing and the regulations governing the use of landfills have been tightened (European Communities 1999). Moreover, from the environmental point of view, it is not a good policy to transport biodegradable material from one site to another. Owing to the increasing political and economical pressures on minimising the generation of waste, there is a need to study composting as one solution to recycle the organic, rejected material produced in forest nurseries to a reusable material.

Composting is one of the oldest solid waste treatment methods, and the principles of the composting process are well known (Gray et al. 1971a, Poincelot 1974, Crawford 1983, Haug 1993). The composition of the waste material affects the composting process, and optimization of the process parameters has to be specific to the type of waste material to be treated in order to get the temperature rise high enough to kill weeds seeds and plant pathogens (Haug 1993, Grundy et al. 1998). As the composting of organic waste produced by forest nurseries has been a relatively neglected subject, it is necessary to investigate it in more detail.

Since the Finnish forest nurseries are of small size and have limited resources to carry out composting, the composting method should be cheap and easy to
implement technically without negative environmental impacts. Composting can also represent a local risk of environmental contamination by nutrients, pesticides and other harmful substances because some of the forest nurseries are located on groundwater aquifers and/or near lakes and rivers (Jaakkonen and Sorvari 2006). Concern about the eutrophication of watercourses or surface waters and the quality of groundwater is worldwide. As a result, the leaching of nitrogen and phosphorus from manure compost has been studied in many countries (Martins and Dewes 1992, Ulén 1993, Parkinson et al. 2004). However, there is no information available about forest nursery waste composting and nutrient leaching.

The aim of our study was to clarify the composting of the forest nursery waste. The main objective was to ensure the thermophilic composting process and show the possible nutrient leaching during composting. Small-scale composting experiments, reported here, were done in addition to large-scale windrow composting (Veijalainen et al. 2007) in order to produce the best management practices for the handling of forest nursery waste on-site in the forest nurseries. In the first summer, forest nursery waste was composted in bins with and without cutter chip bedded horse manure in order to find out is additive material, such as horse manure, needed to get the thermophilic composting process going on. During the second summer, the study focused on the question of whether it is possible to replace manure with urea or methylene urea fertilizer, both of which are easier to handle than horse manure.

**Materials and methods**

**Preparation of the composts**

The experiment was carried out in two parts during the summers of 1999 and 2000. In both years, the compost material consisted of typical forest nursery waste, such as tree seedlings birch (Betula pendula Roth), Norway spruce (Picea abies (L.) Karst.), Scots pine (Pinus sylvestris L.) and their growing media (low-humified Sphagnum peat), weeds and grass clippings. In the first summer (1999) the forest nursery waste was composted unchopped without additive material in W1 bins (n=4), and chopped with cutter chip bedded horse manure (one-third of total volume) in HM1 bins (n=4). Horse manure was chosen as an additive material, because it is drier, and thus, manageable when compared to manure from cattle and pigs. During the second summer (2000), forest nursery waste composted with 420 g of urea (Kemira Corp., Finland) in U2 bins (n=4), with 450 g of slow-release methylene urea (Kemira Corp., Finland) in MU2 bins (n=4) and chopped without additive material in the W2 bins (n=4).

Composting was performed in wooden, heat-insulated 300 litre bins (60 cm high, 70 cm deep and 70 cm wide). The sidewalls of each bin were insulated with 6 cm thick styrofoam sheets. The bottom of the bins were raised above the ground and consisted of galvanized netting to keep the composts well aerated. The bins were placed uncovered in two rows on an open field. All the treatments had four replicates and the location of the treatments was randomized. In both years, the waste material was piled in the bins after the middle of June, and water was added to the bins to give a water content of 50 – 70 mass-% (Gray et al. 1971b). In order to raise the temperature of the W1 composts, weed residues were added to the bins and the content of the bins was turned over after four weeks of composting. The composting process (temperature, volume reduction, pH, water and the organic matter content and nutrient concentrations), water percolation and nutrient leaching were monitored during the 12 weeks’ composting period.

**Physical and chemical analyses**

The temperature in the compost material in the central part of the composts was measured three times a week for the first month, and after that once a week. Volume reduction of the composting material was monitored weekly by measuring the height of the piles. Five subsamples (200 g composite sample) were collected weekly from each compost. The samples were pre-treated (ISO 11464 1994) and the pH was measured on a pH meter (model 3020, Jenway, England) at a ratio of 5:1 distilled water to material (vol/vol) (ISO 10390 1994). The water content was determined by gravimetric analysis (ISO 11465 1993). Organic matter (OM) was determined by loss of mass on ignition of oven-dried samples at 550 °C to constant mass. Carbon (C) and nitrogen (N) concentrations in the compost materials were determined on a LECO CHN-600 analyzer (Leco Co, St Joseph USA). The phosphorus (P) and potassium (K) concentrations were determined, following dry digestion (350 °C, extraction of the ash with 2 M HCl) (Halenen et al. 1983), by inductively coupled plasma atomic emission spectrophotometry (ICP/AES, ARL 3800). The C, N, P and K concentrations were determined at the beginning and end of the composting period.

**Water percolation and nutrient leaching**

The percolation water was collected weekly in 1999 and every second or third week in 2000 (depending on the amount of rainfall). The collection vessels located under each bin were smaller than the bottom
of bins in order to avoid the collection of the water flowing directly down the inner walls of the bins (not percolated through the composting material). The volume of the percolation water was measured after each collection period. The samples were stored frozen and filtered through Schleicher & Schuell 589/2 filter paper before the nutrient analysis. Total soluble N, ammonium (NH₄-N) and nitrate + nitrite (NO₃-N + NO₂-N) concentrations were analysed by FIA (flow injection analysis) (Tecator 5012, Foss, Sweden and QuikChem 8000, Lachat Instruments, USA). Total P was analysed by inductively coupled plasma atomic emission spectrophotometry (ICP/AES, ARL 3580, Switzerland). The amount of leached N and P (g m⁻²) was calculated by multiplying the nutrient concentration (g L⁻¹) by the volume of the percolation water (L m⁻²).

Statistics
The differences in N, P and K concentrations, the OM content, pH (tested as [H⁺]), C/N and C/P ratio between the initial composting materials were tested with one-way analysis of variance (SPSS 14.0 for Windows). One-way ANOVA was also used to test the difference in the total volume reduction between composts at the end of the 12 weeks’ composting period. For each variable, the homogeneity of variances among composts was tested with Levene’s test. In order to equalize variances, values of the OM contents were transformed to square root values, C/N ratios to squared values and P concentrations to reciprocal values before analysis. Means were compared for significant differences at p<0.05 by Tukey’s test. The change in N, P and K concentrations, OM content, C/N and C/P ratio within each compost type during the 12 weeks’ composting was tested by paired-samples t-test. Multivariate analysis of variance was used to test the differences in time course of temperature between composts, using temperature as a repeated factor. Independent-samples t-test was used to test the differences between weekly mean air temperatures in 1999 and 2000.

Weather conditions
Ambient air temperature and precipitation were recorded at a meteorological station located about 500 m from the composting site. Weekly mean air temperature did not vary considerably between the test years during the 12 weeks’ composting. The temperature was different between years only in 4th, 9th and 12th week (p<0.05) (Table 1). Thus we assume that ambient air temperature had no effect on the heating process inside the compost bins. Weekly mean precipitation varied between the years during the 12 weeks’ composting (Table 1).

Table 1. Weekly mean air temperatures (°C) and precipitation (mm) at experimental site in 1999 and 2000 during the 12 weeks’ composting

<table>
<thead>
<tr>
<th>Week</th>
<th>Temperature, °C</th>
<th>Precipitation, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>21</td>
<td>7.0</td>
</tr>
<tr>
<td>2nd</td>
<td>19</td>
<td>31.8</td>
</tr>
<tr>
<td>3rd</td>
<td>17</td>
<td>12.2</td>
</tr>
<tr>
<td>4th</td>
<td>21 *</td>
<td>26.3</td>
</tr>
<tr>
<td>5th</td>
<td>18</td>
<td>31.4</td>
</tr>
<tr>
<td>6th</td>
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<td>2.8</td>
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<td>7th</td>
<td>15</td>
<td>3.1</td>
</tr>
<tr>
<td>8th</td>
<td>13</td>
<td>2.6</td>
</tr>
<tr>
<td>9th</td>
<td>12 *</td>
<td>5.4</td>
</tr>
<tr>
<td>10th</td>
<td>13</td>
<td>14.0</td>
</tr>
<tr>
<td>11th</td>
<td>15</td>
<td>1.0</td>
</tr>
<tr>
<td>12th</td>
<td>13 *</td>
<td>8 *</td>
</tr>
</tbody>
</table>

* Mean weekly temperatures are significantly different (p<0.05) between years. Independent-samples t-test.

Results

Composting process
The difference in time course of temperature was significant between composts (p<0.001). In the HM1 composts, composting reached the thermophilic phase (>40 °C) rapidly in two days, with temperatures of as high as 67±1 °C for two days, followed by temperatures above 40 °C for 1.5 weeks (Figure 1). The temperature was over 40 °C (maximum 42 °C) for three days in the U2 composts (Figure 1). However, the temperature did not rise above 40 °C in W1, W2 and MU2 composts, although nitrogen-rich weeds were added and the material was turned over in W1 composts after four weeks’ composting.

The volume of the composting material decreased rapidly during the first week (Figure 2a). During the whole composting period, the greatest loss occurred in the HM1 composts (31±2 %) due to the most inten-

Figure 1. Time course of temperature (°C) inside the composts during the 12 weeks’ composting. Bars indicate standard deviations.
sive decomposition (p<0.05). The loss was the smallest in the W1 composts (18±1 %), where forest nursery waste was not chopped. Chopping of the waste material increased the volume reduction, which can be seen in comparison between W1 and W2 composts (p<0.05) (Figure 2a).

The addition of horse manure increased the pH of the initial composting material (p<0.05) (Figure 2b). The pH remained neutral (6.8 – 7.2) in HM1 composts during the 12 weeks’ composting. The composting materials in all the other composts remained acidic (4.5 – 6.3) during the 12 weeks’ composting (Figure 2b). The mean water content was 50 – 68 mass-% in all bins during the 12 weeks’ composting. The OM content was initially higher in HM1 and W1 composts than in W2, U2 and MU2 composts (p<0.05) (Table 2). The OM content decreased in all composts during the 12 weeks’ composting, although the decrease was not significant in any compost (Table 2).

At the beginning of the process, the C/N ratio was below 40:1 in all other composts, except W1 (Table 2). The decrease in the C/N ratio was relatively small during 12 weeks’ composting, although it was significant in W1 and W2 compost. The initial C/P ratio was = 250 in all other compost, except W1, and thus favourable for microbial growth (Table 2). C/P ratio did not change significantly in any compost during the 12 weeks’ composting (Table 2). The initial N concentration was higher in HM1 and W1 composts than in W2, U2 and MU2 composts (Figure 3a). N concentration did not change significantly in any other compost than in MU2 during...

Table 2. Organic matter content (OM, % of DM), C/N ratio and C/P ratio in composting materials: HM1 = horse manure and chopped forest nursery waste, W1 = no chopped forest nursery waste, W2 = chopped forest nursery waste, U2 = urea and chopped forest nursery waste, MU2 = methylene urea and chopped forest nursery waste before and after 12 weeks’ composting. Mean of four replicates ± standard deviation

<table>
<thead>
<tr>
<th>Compost code</th>
<th>OM content, %</th>
<th>C/N ratio</th>
<th>C/P ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>before</td>
<td>after</td>
<td>before</td>
</tr>
<tr>
<td>W1</td>
<td>72 ± 14 (a)</td>
<td>59 ± 5</td>
<td>42 ± 3 (a)</td>
</tr>
<tr>
<td>W2</td>
<td>31 ± 1 (b)</td>
<td>35 ± 1 (b)</td>
<td>30 ± 1</td>
</tr>
<tr>
<td>U2</td>
<td>31 ± 1 (b)</td>
<td>25 ± 5</td>
<td>22 ± 1 (c)</td>
</tr>
<tr>
<td>MU2</td>
<td>31 ± 1 (b)</td>
<td>29 ± 5</td>
<td>21 ± 1 (c)</td>
</tr>
</tbody>
</table>

* Theoretical value calculated on the basis of the amount of added nitrogen and original N concentration in the forest nursery waste (W2).

Data followed by different letters (a, b, c) denote significant differences (p<0.05) between initial composting materials. ANOVA and Tukey’s test.

![Figure 2. Volume reduction (% of initial) (a) and pH (b) of the composting materials during the 12 weeks’ composting. Bars indicate standard deviations. Different letters (a, b, c) denote significant differences (p<0.05) in the final volume reduction (Figure 2a) and in the initial pH (Figure 2b) between composts. ANOVA and Tukey’s test. For compost codes, see Figure 1](image1)

![Figure 3. Total nitrogen (N) (a), phosphorus (P) (b) and potassium (K) (c) concentrations (g kg⁻¹ of dry matter) before and after 12 weeks’ composting. Bars indicate standard deviations. Different letters (a, b, c) inside columns denote significant differences (p<0.05) in the initial nutrient concentrations between composts. ANOVA and Tukey’s test. For compost codes, see Figure 1](image2)
Chapter 2

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COMPOSTING OF FOREST NURSERY WASTE AND NUTRIENT LEACHING

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the 12 weeks’ composting (Figure 3a). The addition of horse manure increased significantly the initial P and K concentration of the composting material (Figure 3b). The initial and final P concentration was higher in the HM1 composts than that in all the other composts \((p<0.05)\) (Figure 3b). The K concentration decreased significantly only in HM1 composts during the 12 weeks’ composting (Figure 3c).

Water percolation and nutrient leaching

Water percolation was generally small. The amount of percolation water was 16 – 76 L m\(^{-2}\) from all composts during 12 weeks’ composting, being 11 – 38 % of the precipitation during the experiments (Figure 5a). A decrease in the ammonium concentration, together with an increase in the nitrate concentration, was detected in the percolation water during the composting (Figures 4a & b). In the HM1 composts, the concentration of ammonium in the percolation water was highest (190 mg L\(^{-1}\)) during the thermophilic phase of the composting process (Figure 4a). As composting proceeded, the ammonium concentration decreased as a result of nitrification in HM1 composts. In U2 bins, the ammonium concentration was high (270-390 mg L\(^{-1}\)) in the percolation water during the whole 12 weeks’ composting period (Figure 4a). However, nitrate occurred at the later stages of the process as a result of nitrification also in the U2 composts (Figure 4b). In the MU2 composts, ammonium concentration increased later than in the U2 composts, being the highest (360 mg L\(^{-1}\)) after 4 weeks’ composting. The increase in nitrate concentration also occurred in the MU00 composts (Figure 4b). The concentrations of ammonium and nitrate were low in the percolation water of W1 and W2 composts where pure forest nursery waste was composted (Figures 4a & b).

Irrespective of the form in which the nitrogen was added, all the additive materials (horse manure, urea and methylene urea) increased the amount of leached N (Figure 5b). The total amount of leached N was the highest (54 g m\(^{-2}\)) in the U2 composts, being slightly higher than in the MU2 and HM1 composts (34 g m\(^{-2}\) and 27 g m\(^{-2}\), respectively). The total amount of leached

![Figure 4](image-url)

**Figure 4.** Ammonium (NH\(_3\)-N) (a) and nitrate + nitrite (NO\(_2\)-N + NO\(_3\)-N) (b) concentrations (mg L\(^{-1}\)) in percolation water during 12 weeks’ composting. Bars indicate standard deviations. For compost codes, see Figure 1

![Figure 5](image-url)

**Figure 5.** Total amount of percolation water (L m\(^{-2}\)) and the amount of water (%) of the precipitation (a), leached nitrogen (N, g m\(^{-2}\)) (b) and phosphorus (P, g m\(^{-2}\)) during the 12 weeks’ composting. Bars indicate standard deviations. For compost codes, see Figure 1
N was low in the W1 and W2 composts (less than 2 g m⁻²) where forest nursery waste was piled without additive material. The half of the leached N was in the form of NH₄-N in the U2 and W1 composts (Figure 5b). A total of 74 and 85 % of the leached N was organic in the HM1 and W2 composts, respectively. The proportion of NO₃-N was highest (65 %) in the MU2 composts. The highest initial P concentration of the material in the HM1 composts (Figure 5b) also resulted in the highest total amount of leached P (11 g m⁻²) (Figure 5c).

**Discussion and conclusions**

The thermophilic phase was reached only in composts with forest nursery waste and horse manure (HM1). The generation of sufficient heat in the composts is essential for the eradication of plant pathogens and weed seeds commonly found in many types of composts (Hoitink et al. 1976, Yuen and Raabé 1984, Eghball and Lesoing 2000). In our HM1 composts, as well as in other experiments (Paré et al. 1998, Eiland et al. 2001, Veijalainen et al. 2007), manure acted as the source of nutrients (N, P and K) that enable effective growth of the microbes responsible for OM decomposition and consequent rise in temperature. In addition, manure acted as a source of easily available C compounds and an inoculum of microbes that made the process more effective (Rynk 1992, Carisse et al. 2003, Raivio 2005).

According to Golouke (1991), the initial C/N ratios were theoretically suitable (25-40:1) for microbial activity in all the composts, except W1 composts. Despite this, the composting process in our study did not reach the thermophilic stage in most of the composts. The failure of the thermophilic process was probably the combination of several factors, such as lack of nutrients and easily available C, the low initial OM content and low pH (Haug 1993). Neither urea nor methylene urea contained any P or K, which are also important nutrients for multiplying microbes (Gray et al. 1971b). In this respect, ammonium phosphate had probably been a better admixture than urea or methylene urea because it contains both N and P (Haug 1993).

The decomposition of waste material begins with the metabolism of easily available C compounds in the presence of nutrients, leading to the initial heat production and thermophilic phase (Gray et al. 1971a, Haug 1993). In all other composts, except HM1, organic material was pure forest nursery waste, e.g. tree seedlings, in which the carbon is mainly in the form of cellulose, hemicellulose and lignin (Kaakinen et al. 2004). Cellulose is relative resistant to biodegradation especially when it is associated with hemicellulose and lignin as lignocellulose, and thus it requires a relatively long composting time (Eriksson et al. 1990, Haug 1993). Thus the decrease in the C/N ratio in all the composting materials was relatively small during the 12 weeks’ composting. Same phenomenon was noticed by Benito et al. (2003) in the composting of pruning wastes.

The low initial OM content (31 %) and consequently low C content in the waste material composted in 2000 was also responsible for the failure of the thermophilic composting process in these composts. On the other hand the thermophilic temperature was not reached in the large-scale forest nursery waste windrows with urea addition, although the OM content was 47 % at the beginning of the composting (Veijalainen et al. 2007). In our study, the low initial OM content was caused by the high amount of inorganic material e.g. sand in the forest nursery waste. The sand was stuck on the birch seedlings, which were kept in the sand bed during the winter. Also the roots of the weeds and bare-root seedlings, which were removed from sandy fields, brought inorganic material to the process. According to our study, the quality of the forest nursery waste material is heterogeneous, which makes the composting of forest nursery waste more complicated than expected.

The greatest loss in the volume of composting material occurred in the HM1 composts as a result of the intensive microbial decomposition (Inbar et al. 1993). The particle size reduction had probably positive effect on the composting process in HM1 composts by increasing the surface area of waste material (Crawford 1983, Haug 1993). However, composting material was only loosely compressed in the bins at the beginning of our experiment, and thus the volume reduction may be partly due to the increasing density of the material, i.e. mechanical compaction, as reported by Churchill et al. (1995).

Bacterial decomposers prefer a pH range of 6.0-7.5 and fungal decomposers 5.5-8.0 (Golouke 1991). Moreover, the thermophilic phase of composting is dominated by bacteria, which are generally not acid tolerant (Atlas and Bartha 1998). In our study, only horse manure neutralized the acidity in the composts and made forest nursery waste more suitable for microbial decomposition in the HM1 composts, as was also noticed in the windrow composting of forest nursery waste (Veijalainen et al. 2007). The composting materials in all the other bins remained too acidic probably mostly because of the high proportion of Sphagnum peat, which is acidic due to the presence of weak organic acids, particularly fulvic acids (Puustjärvi 1991). Thus pH adjustment e.g. with lime would be desirable if the material is both acidic and has a
low N content, e.g. forest nursery waste (Haug 1993). The water content was within the optimum range (50 – 70 %) in all composting material during the 12 weeks’ composting (Gray et al. 1977b).

The changes in the nitrogen forms of the percolation water indicate the stage of the composting process (Martins and Dewes 1992, Parkinson et al. 2004). At the beginning of the composting the increase in the NH$_4^+$-N concentration, due to the ammonification reactions resulting from the microbial activity, was clear in the percolation water of HM1 composts. However, high NH$_4^+$-N concentration in the percolation water of U2 composts was probably due to the hydrolysis of the urea into NH$_4^+$-N. In the MU2 composts, NH$_4^+$-N concentration increased later than in the U2 composts, presumably due to the slower dissolution and hydrolysis of urea. Despite this, the nitrogen from these sources was available more quickly than the carbon in the forest nursery waste, and thus the nitrogen compounds occurred in the percolation water of these composts (Rynk 1992). Gaseous losses of ammonia have hardly occurred in this study, because the volatilization of NH$_4^+$-N is not liable at acid or near neutral pH (Golouke 1991). As the composting proceeded, nitrification, i.e. the conversion of NH$_4^+$-N into NO$_3^-$-N was detected, when the temperature of the compost was below 40°C and the conditions aerobic, as has also been observed by Sánchez-Monedero et al. (2001) and Parkinson et al. (2004). The low concentrations of NH$_4^+$-N and NO$_3^-$-N in the W1 and W2 composts indicate that there is a lack of available nitrogen for effective microbial activity in the pure forest nursery waste.

The total amounts of the leached nutrients were ten times higher from the small units used in this study than from the large-scale windrows reported by Veijalainen et al. (2007). Thus there is no reason to make broader conclusions about the leaching results from this study as a direct measure of environmental contamination. According to our studies, caution should be used when the results of small-scale composting experiments are generalized to the prevalent usage. However, the comparison between the chemical compositions of the percolation water from the different composts is valid in this study. In this respect, the additional nutrient and microbial sources needed for effective composting might pose a risk to the environment if the compost is placed at the same site for a long time and water percolation is not prevented or the percolation water is not collected.

In conclusion, the waste material produced in forest nurseries is not ideal for composting. The quality of waste material is variable and the amount of mineral material may be unexpectedly large. According to our results, nutrient amendment seems to be necessary for reaching the thermophilic temperatures during composting of forest nursery waste. Horse manure was advantageous as a source of nutrients and neutralizing compounds that enable effective growth of the microbes responsible for OM decomposition and consequent rise in temperature. Urea and methylene urea did not promote the rise in temperature in an expected manner. Artificial fertilizers bring nitrogen to the process but they lack the other beneficial features typical of organic additives, e.g. horse manure. The composting process should be long-term than the monitoring period used in this study to enable the decomposition of slowly degradable woody tree seedlings. Chopping raw material and turning could be the ways to accelerate the process and to guarantee a uniform quality of the compost product. All additive materials increased the nitrogen leaching, and horse manure also increased the phosphorus leaching.

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Компостирование отходов в лесных питомниках и выщелачивание удобрений

А.-М. Вейялайнен, М.-Л. Юнтуен, А. Лилья и Л. Терво

Резюме

Свойства отходов в лесных питомниках, с точки зрения их разложения, ещё окончательно не изучены. Целью этой работы является установить свойства отходов лесных питомников для ускорения термофильного процесса разложения отходов. Также изучался процесс компостирования и выщелачивание удобрений. Отходы лесных питомников, в составе которых входили сеницы и субстрат их выращивания (сфагновый торф), сорняки, листва и трава были компостированы в течение трёх месяцев в ящиках объёмом 300 литров. Во время первого вегетационного периода отходы лесных питомников компостирулись с лошадиным навозом и без него, а во время второго - с мочевиной или метилен-мочевиной и без внесения удобрений. Темпераутура, уменьшение объёма, кислотность, количество воды и органических веществ, концентрация удобрений, прокачиваемость воды и выщелачивание удобрений измерялись во время компостирования. Лошадиный навоз являлся единственным веществом, способствующим термофильному процессу компостирования. Все прибавки способствуют выщелачиванию азота, а лошадиный навоз также увеличил выщелачивание фосфора. Полученные результаты показывают, что прибавки, такие как лошадиный навоз, необходимы для увеличения температуры во время компостирования отходов лесных питомников. Однако, богатые удобрениями прибавки могут создавать угрозу окружающей среде.

Ключевые слова: компостирование, отходы лесных питомников, лошадиный навоз, выщелачивание удобрений, метилен-мочевина, азот, органическое вещество, фосфор, калий, термофильный процесс, мочевина.
CHAPTER 3

SURVIVAL OF UNINUCLEATE *RHIZOCTONIA* SPECIES DURING COMPOSTING OF FOREST NURSERY WASTE


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Survival of uninucleate *Rhizoctonia* species during composting of forest nursery waste

ANNA-MARIA VEIJALAINEN¹, ARJA LILJA² & MARJA-LIISA JUNTUNEN¹

¹Finnish Forest Research Institute, Suonenjoki Research Station, Suonenjoki, Finland, and ²Finnish Forest Research Institute, Vantaa, Finland

Abstract

Forest nursery waste was composted with and without different nitrogen sources in 300 litre composts. Uninucleate *Rhizoctonia* (teleomorph *Ceratobasidium bicorne*) was selected as a model pathogen for testing the survival of pathogens during composting. Hyphal culture of the pathogen was mixed with waste material and buried in nylon mesh bags in the composts. Temperature, water content, pH and volume reduction were monitored during the composting period. Carbon, nitrogen and phosphorus concentrations were determined in the initial compost materials. After composting, the pathogen was baited with Norway spruce seedlings, and damping-off due to uninucleate *Rhizoctonia* was recorded. None of the seedlings showed any symptoms of damping-off in the treatment in which forest nursery waste was composted with cutter-chip bailed horse manure, indicating eradication of the pathogen. The survival of the test pathogen in the other treatments is a risk for the future use of the composted material in forest nurseries.

Keywords: Eradication, forest nursery, fungal pathogens, horse manure, methylene urea, urea.
CHAPTER 4

FOREST NURSERY WASTE COMPOSTING IN WINDROWS WITH OR WITHOUT HORSE MANURE OR UREA – THE COMPOSTING PROCESS AND NUTRIENT LEACHING


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In order to find the best management practices for forest nursery waste composting, organic waste was composted without or with horse manure or urea in six windrows for two years. The windrows were built in four consecutive years during 1999–2002. In 1999, no extra-nutrients were added to the windrow (N99). In 2000, urea fertilizer was used as a nitrogen source (U00). Despite this, the process did not function properly. In 2001, two windrows were built, one (H01) with and the other (N01) without horse manure. Horse manure slightly accelerated the heating process. Consequently, two windrows with more horse manure were built in 2002. One was aerated passively (H02) as earlier windrows, and the other was aerated forcedly (HA02). Horse manure and forced aeration were needed to keep the temperature above 55°C for long enough to ensure microbial hygiene of the material. The degradation of cellulose was greater during the curing stage. Nutrient leaching was low, although the additives increased leaching in conjunction with the inefficient process. The results showed that forest nursery waste alone is ineffective at raising the temperature of the compost, and degrades slowly due to its low nutrient and easily available carbon content. The best management practice for forest nursery waste composting is to use horse manure and aeration to ensure the heating process. Environmental contamination can be avoided by collecting the leachates. Further research is needed to evaluate the usability of the compost.

Keywords: microbial hygiene, lignocellulose, nutrients, organic matter decomposition, temperature, tree seedling waste, waste management

Addresses: Veijalainen (corresp.), Juntunen, Tervo: Finnish Forest Research Institute, FI-77600 Suonenjoki, Finland; Lilja: Finnish Forest Research Institute, PO Box 18, FI-01301 Vantaa, Finland; Heinonen-Tanski: Univ. of Kuopio, Dept. of Environm. Sc., PO Box 1627, FI-70211 Kuopio, Finland

E-mail anna-maria.veijalainen@metla.fi

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CHAPTER 5

TREE-SEEDLING COMPOST AS A COMPONENT IN SPHAGNUM PEAT-BASED GROWING MEDIA FOR CONIFER SEEDLINGS: PHYSICAL AND CHEMICAL PROPERTIES


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Tree-seedling compost as a component in Sphagnum peat-based growing media for conifer seedlings: physical and chemical properties

Veijalainen, A.-M.¹), Heiskanen, J.¹), Juntunen, M.-L.¹) & Lilja, A.²)

¹) Finnish Forest Research Institute, Suonenjoji Research Unit, FI-77600 Suonenjoji Finland
²) Finnish Forest Research Institute, Vantaa Research Unit, P.O.Box 18, FI-01301 Vantaa, Finland

Abstract

Approximately 150 million forest tree seedlings are delivered for planting annually in Finland. The seedlings affected by plant diseases or pests, or not meeting the quality requirements, as well as the used growing media, weeds, clipped grass and fallen leaves comprise the biodegradable waste formed in forest nurseries. Currently there is an increasing political and economical pressure on minimizing the generation and landfilling of waste materials. A practical solution for forest nurseries would be composting of biodegradable waste on-site, and then using the compost as a component of growing media for seedling production. Before this, the suitability of composted tree-seedling waste for growing media in tree-seedling production needs to be assured. In this study growing-media mixtures were (by volume): 100% light sphagnum peat (100P), 100% tree-seedling compost (100C) and peat mixtures with 25 or 50% of compost (75P25C and 50P50C, respectively). Particle-size distribution, bulk density, water-retention capacity, particle density, loss on ignition, pH, electrical conductivity, total and plant available nitrogen (N), phosphorus (P) and potassium (K) concentrations, as well as the germination capacity of Norway spruce were studied. The tree-seedling compost was found to have a relatively fine texture and high density compared with peat. These physical properties may lower the air-filled porosity and oxygen-diffusion rate, and thus have a negative effect on the germination and growing in the mixtures with a high compost content. The results indicate that tree-seedling compost has a potential to be used as a minor component in growing media in tree nurseries, although the irrigation and fertilizer requirements need further studies.

Keywords: density, forest nursery, germination, nutrients, organic matter, particle-size distribution, water-retention capacity

Introduction

Approximately 150 million forest seedlings are delivered for planting annually in Finland. Scots pine (Pinus sylvestris L.), Norway spruce (Picea abies (L.) Karst.) and European silver birch (Betula pendula Roth) are the main tree species produced by forest nurseries. At present, about 95% of the production is container seedlings, the rest being bare-root seedlings (Finnish Forest Research Institute, 2004). If tree seedlings are affected by plant diseases or pests, or not meeting the size and shape requirements, they are discarded before selling. The biodegradable waste produced by nurseries therefore includes discarded tree seedlings and their growing media, as well as weeds, clipped grass and fallen leaves.

Currently there is increasing environmental, political and economical pressure on minimizing the generation and landfilling of wastes. In addition, transportation of biodegradable wastes from one site to another is not good policy, involving energy consumption during transport frequently over long distances in Finland. The Landfill Directive 1999/31/EC encourages composting of biodegradable wastes with the utilization of produced compost for agricultural benefit or ecological improvement. The practical solution for forest nurseries would be to compost biodegradable wastes on-site, and use the composted tree-seedling waste as a component of growing media in the seedling production.

Composting and the use of compost product in horticulture and agriculture have been researched widely (e.g. Gouin, 1977; Haug, 1993; Marfà et al., 2002): such studies have involved the treatment of easily degradable material with a high nitrogen (N) content. Tree-seedling waste, in contrast, has a low N content, and it contains cellulose associated with hemicellulose and lignin as lignocellulose, which is relative resistant to biodegradation and requires relatively long composting time, because lignin serves as a physical and chemical barrier to enzymatic degradation of wood polysaccharides (Eriksson et al., 1990; Kaakinen et al., 2004). Many studies have shown the beneficial effect of compost utilization on greenhouse and nursery-crop production systems (e.g. Fitzpatrick et al., 1998; Bugbee, 2002). However, the composition of the biodegradable waste and composting method will influence the quality of the compost product. In addition, the properties of the growing medium have a special role in container-plant production, where the roots of the plant are restricted to a small volume (Bunt, 1988). The optimal amount of the compost used in container media depends upon the specific plant species to be grown (Wilson et al., 2002). Therefore, the evaluation of the basic chemical and physical properties of the compost is necessary in order to determine the suitability of composted tree-seedling waste as a constituent of growing media in tree-seedling production. The objective of this study was to evaluate these properties of growing-media mixtures of peat and composted tree-seedling waste and the effect of mixtures on the germination of Norway spruce (Picea abies (L.) Karst.).

Materials and methods

Growing-media mixtures were prepared volumetrically by hand using a 10 L bucket. The mixtures were peat (P) to compost (C) ratios (% by volume): 100/0 (100P), 75/25 (75P25C), 50/50 (50P50C) and 0/100 (100C). The peat was unfertilized but limed (2 kg m$^{-3}$) light sphagnum peat (Finnpeat M02, Kekkilä, Finland). The compost for inclusion in media was taken from a four-year-old (1998-2002) stacked compost made of rejected bare root- and container-tree seedlings (with peat in containers) and weeds at Suonenjoki forest nursery in
Chapter 5

the Central Finland. The compost medium was sieved through a mesh size of 4 mm before mixing to remove coarse, undegraded woody twigs.

The gravimetric particle-size distribution of mixtures was determined with mechanical dry sieving (Retsch Corp., Germany). The air dried sample of 0.3 dm³ was sieved through standard sieves of 10, 5, 1 and 0.1 mm diameter for two minutes (Puustjärvi, 1977; Heiskanen, 1993). Bulk density (Db, g cm⁻³) was determined as the ratio of dry mass (dried at 105 °C for 24 hours) to saturated volume (Heiskanen, 1993). Particle density (Ds, g cm⁻³) was measured using a liquid pycnometer method (Heiskanen, 1992). Total porosity (Tp, by volume) was estimated as (Ds - Db) / Ds. Volumetric water-retention capacity (WRC) of the mixtures was determined at desorption (from -0.1 to -100 kPa) by using a pressure plate apparatus (Soilmoisture Equipment Corp., USA). The test cylinders were filled with a mixture to the same bulk density as the mixture used to fill containers in practice (Heiskanen, 1993).

The amount of organic matter (OM, % DM) of the mixtures was determined as loss of mass on ignition at 550 °C for 3 hours. The pH was measured with a pH meter (model 3020, Jenway, England) at a ratio of 5:1 distilled water to air dried and ground material (by volume). The Electrical conductivity (EC, mS cm⁻¹) was measured using a conductivity meter (Radiometer Copenhagen CDM-80) at the same ratio as the pH.

The total N concentrations of the mixtures were determined with a CHN analyzer (CHN-600, Leco Co, St Joseph, USA), and the total phosphorus (P) and potassium (K) concentrations were determined following dry digestion (550 °C, extraction of the ash with 2 M HCl) (Halonen et al., 1983), by inductively coupled plasma atomic emission spectrophotometry (ICP/AES, ARL 3800). Total soluble N was analyzed from the extract of 1M KCl by flow injection analysis (Quikchem 8000 FIA-analyzer, A83200, Lachat). Plant-available exchangeable K and soluble P were analyzed from the extract of acidic (pH 4.65) 1 M ammonium acetate by inductively coupled plasma atomic emission spectrophotometry (ICP/AES, ARL 3800). The number of germinating Norway spruce seeds was counted 7, 14 and 21 days after sowing (Leinonen, 1998).

The differences in particle-size distribution were tested with multivariate analysis of variance (SPSS 12.0.1 for Windows). Because the sum of the particle fractions within samples is 100%, the five particle-fraction classes were transformed to four new ones prior to analysis to obtain a distribution that is closer to multinormal. Transformations to four new variables were done according to equation: ln(y+1)-ln(x+1), where x is 0.1-1mm fraction and y represents separately other four fractions (Aitchinson, 1986). Multivariate analysis of variance was used to test the differences in WRC between mixtures, using matric potential as repeated factor. The differences in chemical and other physical properties and germination capacity (21 days) between growing-media mixtures were tested by one-way analysis of variance. For each variable, the homogeneity of variances among treatments was tested with Levene’s test. Total N and plant-available K concentrations were transformed to reciprocal values and germination data were arcsin transformed before the statistical analysis to equalize variances. Means were compared for significant differences at p<0.05 by Tukey’s test. The change in Ds, loss on ignition, pH (tested as [H⁺]) and EC within each growing-media mixture during the growing season was tested by a paired-samples t-test.

Results

The difference in particle-size distribution was significant between growing-media mixtures ($p<0.001$). The particle size in pure compost (100C) was relatively fine as it was dominated by particles <1 mm (>80%). In pure peat (100P), the respective proportion was notably lower (<50%) (Fig.1). Db increased significantly along with the proportion of compost in the growing medium (Fig. 1). Tp decreased significantly with the increasing proportion of compost in the growing medium (Fig. 2). WRC at desorption differed significantly between mixtures (Fig. 2). Water retention at near saturation (-0.3 kPa) was significantly less in 100C than in media containing peat, which suggests that finer pores predominate within the pore space in this compost (Fig. 2).

During the first growing season in seedling containers (PL-81F, Lännens Plant Systems, Finland), OM as determined by the loss on ignition decreased significantly in all growing-media mixtures except 100P (Fig. 3). The difference between growing-media mixtures remained significant during the growing season. Correspondingly, Ds increased significantly in all other mixtures except in 100P (Fig. 3). In 100C, however, this trend was reversed ($p<0.05$). Overall the pH increased significantly in all mixtures (Fig. 3). EC was initially high in 100C compared to other mixtures ($p<0.05$) (Fig. 3). During seedling growth, the EC slightly increased in 100P and 75P25C, while it decreased significantly in other media ($p<0.001$).

Total N concentration was significantly lower in 100C than in other growing-media mixtures (Table 1). However, the total plant-available N concentration did not significantly differ between 100C, 50P50C and 75P25C. Total P, total K and the plant-available K concentration increased along with the proportion of the compost in the growing medium. Despite that, the plant-available P concentration was the lowest in 100C ($p<0.05$) (Table 1). The germination capacity (21 days) of seeds in 100P, 75P25C and 50P50C was 92, 91 and 90%, respectively. In 100C the germination capacity was significantly lower (76%) than that of the other growing-media mixtures (Fig. 4).

Discussion

The tree-seedling compost was found to have a relatively fine texture and high density compared with peat. In addition, water-retention characteristics suggest that total porosity and the proportion of coarse pores are low. Therefore growing-media mixtures with high compost content have a lower air-filled porosity and thus lower oxygen diffusion rate, which may have a negative effect on root and shoot growth (Bunt, 1988). Correspondingly the proportion of small pores is high, and thereby the amount of the available water may be low, because the movement of the water from the inner small pores to the outer regions of the particles is slow in growing media with high compost content (Bunt, 1988).

During seedling growth, the peat-containing media tended to become compacted as the Ds increased, most probably due to degradation of the material into smaller particles (Ingram et al., 1991; Heiskanen, 1995). In 100C, however, the trend was reverse, because the daily movement of seedling containers and overhead irrigation caused loss and leaching of minerals, which obviously decreased Ds and slightly increased the loss on ignition (Ingram et al., 1991).
EC was initially high in 100C owing to concentration of the electrolytes during composting (Riviere and Milhau, 1983). During seedling growth, EC clearly decreased in 100C and 50P50C, probably due to leaching after irrigation and nutrient uptake by plants. The possible lack of colloids in the compost with low OM content may have promoted the leaching (Minnich and Hunt, 1979). The rise in pH was probably caused by the presence of bicarbonates in the irrigation water and dissolution of lime in peat-containing media (Bunt, 1988).

The nutrient concentrations were low in all studied growing-media mixtures compared to base-fertilized and limed sphagnum peat (Finnpeat M6, Keikkiä, Finland) commonly used for tree-seedling production in Finland (Juntunen and Rikala, 2001). Therefore, there is a need to optimize the specific level of each nutrient in the studied mixtures prior to or during seedling growth to achieve a balance of essential plant nutrients (Ingestad, 1979). Plant growth is better with balanced nutrient levels even at low fertility (Bunt, 1988). The lower germination capacity of Norway spruce seeds in pure compost cannot entirely be explained by the higher electrical conductivity of the compost, although high salinity has been reported to be detrimental to seed germination and subsequent growth and development (Bunt, 1988). Other factors, such as undetermined toxins, pre-emergence damping-off or higher density together with lower amount of the available oxygen in pure compost may have affected germination and primary root development (Bunt, 1988; Heiskanen and Rikala, 1998).

Conclusions

The tree-seedling compost used in this study showed potential for use as a minor component of growing media in tree nurseries, although properties of the growing-media mixtures e.g. irrigation and fertilizer requirements need further research. It is evident that the physical and chemical properties of growing media, such as aeration and availability of water and nutrients have a major effect on the growth of seedlings. Physical properties can be improved, e.g. by mixing tree-seedling compost with peat, vermiculite or other material, which provide space for air and water in growing media. Chemical properties can be adapted to optimal conditions by mixing specific level of nutrients to growing media mixture prior to or during seedling growth. On the other hand, there are also alternative uses for the compost, for example landscaping, lawns or as soil conditioners.

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Table 1. Total and plant-available nitrogen (N), phosphorus (P) and potassium (K) concentrations (mg kg\(^{-1}\) dry matter) in the growing-media mixtures: 100 % peat (100P), 75 % peat/25 % compost (75P25C), 50 % peat/50 % compost (50P50C) and 100 % compost (100C) before growing season.

<table>
<thead>
<tr>
<th>Growing medium</th>
<th>Nitrogen (N) (mg kg(^{-1}) DM)</th>
<th>Phosphorus (P) (mg kg(^{-1}) DM)</th>
<th>Potassium (K) (mg kg(^{-1}) DM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Soluble</td>
<td>Total Soluble</td>
<td>Total Soluble</td>
</tr>
<tr>
<td>100P</td>
<td>8800±820 a</td>
<td>170±10 a</td>
<td>220±20 a</td>
</tr>
<tr>
<td>75P25C</td>
<td>7220±1220 a</td>
<td>160±10 ab</td>
<td>470±30 b</td>
</tr>
<tr>
<td>50P50C</td>
<td>6070±1170 a</td>
<td>150±20 ab</td>
<td>530±30 c</td>
</tr>
<tr>
<td>100C</td>
<td>3080±1460 b</td>
<td>150±10 b</td>
<td>540±30 c</td>
</tr>
</tbody>
</table>

Different letters indicate significant difference (p<0.05, Tukey’s test).

Figure 1. Mean particle-size distribution (±sd) (n=3) and bulk density (±sd) (n=6) for the growing-media mixtures: 100 % peat (100P), 75 % peat/25 % compost (75P25C), 50 % peat/50 % compost (50P50C) and 100 % compost (100C) before growing season. Different letters indicate significant differences in bulk density (p<0.05 Tukey’s test).

Figure 2. Water-retention characteristics at desorption (mean+sd) (n=6) in relation to near-saturation volume (at -0.3 kPa) of the growing-media mixtures before growing season. Total porosity plotted at -0.01 kPa. Mean decrease in volume (shrinkage) in the upper (100 % at -0.3 kPa).
Figure 3. Means for loss on ignition, particle density, pH and electrical conductivity (EC) (±sd) (n=6) of the growing-media mixtures. Different letters indicate significant differences between growing-media mixtures and asterisks significant differences within variables between seasons (29th April and 17th September) (p<0.05, Tukey’s test).

Figure 4. Cumulative germination of Norway spruce (*Picea abies* (L.) Karst.) seeds (±sd) in the growing-media mixtures during 7, 14 and 21 days. Different letters indicate significant differences (p<0.05 Tukey’s test).
CHAPTER 6

GROWING PICEA ABIES CONTAINER SEEDLINGS IN PEAT AND COMPOSTED FOREST-NURSERY WASTE MIXTURES FOR FOREST REGENERATION


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Growing Picea abies container seedlings in peat and composted forest-nursery waste mixtures for forest regeneration


Anna-Maria Veijalainen\textsuperscript{1)}, Marja-Liisa Juntunen\textsuperscript{1)}, Juha Heiskanen\textsuperscript{1)} and Arja Lilja\textsuperscript{2)}

\textsuperscript{1)} Finnish Forest Research Institute, Suonenjoki Research Unit, FI-77600 Suonenjoki, Finland
\textsuperscript{2)} Finnish Forest Research Institute, P.O.Box 18, FI-01301 Vantaa, Finland

ABSTRACT

The suitability of using composted forest-nursery waste as a component in growing medium was studied. Norway spruce [Picea abies (L.) Karst.] seedlings were grown in containers filled with sphagnum peat (100P), forest-nursery waste compost (100C) and in peat mixtures containing 25 or 50\% compost by volume (75P25C and 50P50C, respectively). Morphological and chemical characteristics of the seedlings and the water and nutrient contents of the growing media were studied during 22-weeks’ nursery cultivation. The seedlings were out-planted the following spring, and the survival and growth were followed for three years. Compost additions decreased seedling height, diameter and shoot dry mass, but root dry mass was the same in 100P and 75P25C after nursery cultivation. Foliar nutrient concentrations were optimal in all the seedlings, although foliar N content was lower the greater the proportion of compost in the medium. Compost additions did not affect the root-egress potential tested before out-planting. The 100P-seedlings grew significantly more than the other seedlings during the first summer at the forest site. Thereafter, compost additions did not affect growth, but the final height and diameter were still the lowest in 100C. The results suggest that forest-nursery waste compost has potential to be used as a component of peat-based growing medium. However, specially adjusted nursery-cultivation practices need to be used for compost-containing media.

Keywords: biowaste, conifers, growing medium, recycling, out-planting

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CHAPTER 7

GENERAL DISCUSSION
GENERAL DISCUSSION

7.1 Decomposition process

The studies carried out in this thesis showed that the organic waste formed in tree-seedling production (forest-nursery waste) is not ideal for composting. Tree seedlings and their growing media (low humified Sphagnum peat) mainly consist of slowly decomposable and stable C compounds, which are highly resistant to microbial degradation, and consequently inefficient in rising the temperature during composting. The amount of easily decomposable constituents, such as grass clippings, weeds and leaves, was not high enough to ensure a high decomposition rate and subsequent rise in temperature. Moreover, the amount of OM was low (31 - 62% DM) in the initial forest-nursery waste, and substantially lower than that reported in composting studies conducted with agricultural and food wastes (> 75% DM) (Bernal et al. 1998, Koivula et al. 2000). This was obviously due to the presence of coarse sand, which was used to cover the growing media in the seedling containers, as well as the sand which was attached to the roots of the bare-rooted seedlings and weeds collected from the field and the birch seedlings which were kept in a sand bed during winter.

These results concerning the decomposition of OM are consistent with the results of Eklind & Kirchmann (2000a), who found that the loss of organic C is low (less than 15%) if organic household waste is composted with softwood shavings or Sphagnum peat. In addition, Vuorinen & Saharinen (1998, 1999) reported that decomposition is slow if peat is used as a bulking agent in manure composting. In the study of Vuorinen & Saharinen (1999), the temperature did not rise above 50 °C during the six-day drum composting periods. However, the material contained enough easily degradable constituents, because the temperature reached 65 - 70 °C for few days after the material was piled for curing.

Other characteristics of forest nursery waste were a low initial pH and low initial nutrient concentrations, although the initial C/N ratio was less than 40, and thus considered to be suitable for microbial growth (Golouke 1991, Rynk 1992). However, the total N concentrations (< 1.0% DM) were lower than those reported in other composting systems (>1.5% DM) (Bernal et al. 1998, Eklind & Kirchmann 2000b). Therefore, the results suggest that the lack of nutrients (N, K and P) also decreased the activity of the microorganisms responsible for OM decomposition (Chapter 2, Fig. 3; Chapter 4, Figs. 2 and 3). In addition, the initial pH of 4.8 - 5.3, which was caused by the high proportion of naturally acidic Sphagnum peat in the waste material (Puustjärvi 1991, Eklind & Kirchmann 2000b), was too low for effective microbial growth. Bacterial decomposers prefer a pH range of 6.0 - 7.5, whereas fungal decomposers grow best at pH 5.5 - 8.0 (Golouke 1991).

As a result, neither a high decomposition rate nor the thermophilic phase was attained in the small-scale composts (Chapters 2 and 3) or in the nursery-scale windrows (Chapter 4) if they contained only the organic waste formed in tree-seedling production. As demonstrated in the windrow-composting studies, OM was decomposed mainly during the first winter and second summer (Chapter 4, Table 2), and the degradation of cellulose in wood shavings placed in the windrows piled in 2002 occurred during the second year (Chapter 4, Fig. 4). Several other studies have also reported a slow decomposition of lignocellulosic materials (Churchill et al. 1995, Bernal et al. 1998, Eiland et al. 2001) and a decline in the decomposition rate due to low pH (Sundberg et al. 2004). For example, Bernal et al. (1998) and Eklind & Kirchmann (2000a) concluded that the extent and rate of OM decomposition are reduced as the
proportion of lignin in organic waste increases, because this is the most resistant fraction to microbial degradation.

The results demonstrated clearly that the organic waste formed in tree-seedling production needs to be mixed with nutrient-rich materials in order to achieve effective growth of the microorganisms responsible for OM decomposition and the consequent rise in temperature needed for the eradication of pathogens and weed seeds. Subsequently, horse manure, urea and methylene urea were tested as additives in this thesis (Chapters 2, 3 and 4). The temperature rose over 55 °C only in the small-scale composts, which contained cutter-chip bedded horse manure (HM1) (Chapter 2, Fig. 1) and in the windrow, which contained peat-bedded horse manure and included forced aeration (HA02) (Chapter 4, Fig. 1). The volume reduction was greatest in the HM1 composts (Chapter 2, Fig. 2a) due to intensive microbial decomposition, as reported also by Inbar et al. (1993), although some of the volume reduction was probably due to mechanical compaction (Churchill et al. 1995). In the windrow composting study, the OM decomposition rate was highest in the windrows containing horse manure during the first summer (Chapter 4, Table 2). Thus, the results also indicate that forced aeration can be used to guarantee sufficient O2 for microbial decomposition during the thermophilic phase of composting, as reported also previously (Fernandez & Sartaj 1997).

The studies showed that horse manure was a suitable additive material for forest-nursery waste composting, because it provided nutrients (N, P and K), easily available C compounds, neutralizing compounds and obviously also microbes for the decomposition process (Chapter 4). Microbial activity was unfortunately not assessed in these studies, and therefore the increased microbial activity remains to be validated. However, manure is rich in microorganisms, and thus can be successfully used as a microbial source in the composting process (Raviv 2005). The results are consistent with those of earlier studies, which have demonstrated the positive effect of manure addition on the decomposition of lignocellulosic materials (Bernal et al. 1998, Paré et al. 1998, Eiland et al. 2001).

In contrast, a high decomposition rate and thermophilic phase were not achieved in the composts amended with urea or methylene urea. Artificial fertilizers like urea lack the other beneficial features typical of organic additives, as discussed in the previous paragraph. This result supports the conclusion that N is not the only limiting factor in the composting of organic waste formed in tree-seedling production. Kostov et al. (1996) reported successful composting of lignocellulosic materials with urea, when monosuperphosphate and K2SO4 were also added to the compost and the initial pH was adjusted to 6.8. In addition, the failure of thermophilic composting in the windrow amended with urea was probably partly due to the lack of O2, which was caused by the too high water content (67 mass-%). In general, a lower limit for optimal water content of 50 - 70 mass-% is recommended in static heaps and windrows in order to support microbial activity (Gray et al. 1971, Golouke 1991, Haug 1993).

7.2 Hygienic aspects

As previously reviewed, the compost temperature has to stay above 55 °C for several hours to weeks for the eradication of faecal pathogens (Composting Council of Canada 1999, Carrington 2001, European Commission 2001, European and Mediterranean Plant Production Organization 2006). In the windrow-composting studies (Chapter 4), the desired temperature-time relationship (55 °C for one month) and the eradication of microbial hygiene indicators were achieved when forest-nursery waste was composted with horse manure and forced
aeration (HA02) (Chapter 4). This is sufficient to fulfil the requirements for the treatment process (55 °C, two weeks) set by the European and Mediterranean Plant Production Organization (2006) to ensure phytosanitary safety. However, the temperature in the forest-nursery waste composted with horse manure and passive aeration (H02) did not increase above 50 °C and the microbial hygiene indicators were not completely destroyed in the H02 windrow. These results are consistent with the temperature-time recommendations (see above). On the other hand, since the microbial hygiene indicators were studied only in the windrows piled in 2002, it is impossible to verify with any degree of certainty whether these organisms were destroyed in the other horse manure containing windrow (H01), in which the temperature rose to 50 °C.

The results concerning the survival of uninucleate *Rhizoctonia*, used successfully as a model pathogen in the small-scale composting studies, also indicate that the high temperature is the main reason for the eradication of pathogens during composting (Chapter 3). The temperature was the highest (67 °C) and exceeded 50 °C for a week only in those composts which contained forest-nursery waste and cutter-chip bedded horse manure (Chapter 3, Table 1). As a result, none of the Norway spruce seedlings, which were grown in these composts, showed any symptoms of damping-off, thus indicating complete eradication of uninucleate *Rhizoctonia* (Chapter 3, Table 3). Compared to the studies of Hoitink et al. (1976), Pullman et al. (1981) and Noble et al. (2004), the temperature reached in the forest-nursery waste, horse manure and forced aeration windrow (HA02) would probably have been high enough to eradicate also *Botrytis cinerea*, *Fusarium oxysporum*, *Pythium ultimum* and *Rhizoctonia solani*, which are other plant pathogens possible present in the organic waste formed in tree-seedling production (Lilja et al. 1997) (See General introduction, Tables 1 and 2).

The laboratory incubation of the uninucleate *Rhizoctonia*, which was conducted together with the small-scale composting, indicated that 35 °C is sufficient to kill this pathogen (Chapter 3). Despite this result, the pathogen survived in composts which reached a maximum temperature of 37 - 46 °C (Chapter 3, Table 1). The result indicates that plant pathogens might be able to survive inside the plant material or inside the other large particles often present in composts. This is supported by Garbelotto (2003), who showed that *Phytophthora ramorum* was more resistant to high temperatures inside the leaf parenchyma in compost than on agar growth media in Petri dishes. The clumping of solids may also cause a lack of O₂ within large particles, which then potentially reduce heating at the same site (Haug 1993). In this case heat transport from the surrounding compost would be needed to ensure pathogen destruction within the particles.

The temperature required for hygienization decreases if the duration of exposure increases (Strauch 1991). In addition, the hygienization during composting is also affected by other factors, such as the presence of toxic compounds and microbial antagonisms (Bollen 1984, Noble & Roberts 2004). Thus, the eradication of plant pathogens might also have occurred in the other horse manure containing windrows, in which the temperature stayed above 45 °C for at least one month. Nonetheless, since these parameters were not assessed in the studies, this deduction remains to be validated.

The total eradication of pathogens is difficult in simple composting systems such as bins and windrows, because the temperature will not be uniform throughout the entire composting mass in such systems (Haug 1993). High temperatures are reached in the central part of open compost, whereas cold pockets and a cooler outer zone may allow microorganisms to survive.
Anna-Maria Veijalainen: Sustainable Organic Waste Management in Tree-seedling Production through the composting process (Yuen & Raabe 1984). Therefore, chopping the raw materials and adequate mixing during the thermophilic phase is needed to ensure that the whole composting mass reaches high temperatures (Haug 1993, Noble & Roberts 2004, European and Mediterranean Plant Production Organization 2006).

7.3 Environmental impacts

The windrow composting study showed that the total annual amount of percolation water was small, being less than 1.5 m$^3$ from all the individual windrows ($V = 34 - 50$ m$^3$) (Chapter 4). This result is consistent with an earlier study (Puumala & Sarin 2000), in which the total amount of percolation water was 2.2 - 6.0 m$^3$ from 100m$^3$ cow manure windrows and 0.07 - 0.3 m$^3$ from 30 m$^3$ chicken manure windrows during eight months of composting. Although the amounts of water were negligible, water percolation caused by rain and decreased evaporation (autumn) and melting snow (spring) can still be reduced if the windrows are placed under a roof, as was demonstrated by the windrows piled in 2002 in this study (Chapter 4, Fig. 5). However, the lack of an insulating snow layer under the roof caused freezing up of the surfaces of the windrows. This might have interrupted the air circulation and thereby strongly reduced the decomposition rate. Another solution could be to cover the windrow with waterproof material after the thermophilic phase to reduce water percolation, as recommended by Berner (1989) and Ulén (1993). However, the cover should also allow air circulation, because the windrow-composting study indicated that the decomposition of OM formed in tree-seedling production continues after temperature stabilization (Chapter 4, Table 2).

The small-scale composting studies showed that nutrient concentrations can be relatively high in the leachates if nutrient-rich material is added to the compost (Chapter 2, Fig. 4), as reported earlier (Martins & Dewes 1992, Ulén 1993, Parkinson et al. 2004). In addition, the windrow-composting studies demonstrated that N leaching increased when the functioning of the composting process was inefficient, as was the case in the windrow that contained urea (U00) (Chapter 4, Fig. 5). In contrast, the leaching of P was associated with horse manure addition and the low P absorption of Sphagnum peat (Chapter 2 and 4, Fig. 5) (Rannikko & Hartikainen 1980). Also Juntunen et al. (2002) reported that P is easily leached from the peat used in tree-seedling production. However, the addition of P-rich horse manure promoted the composting process and resulted only in a small total amount of leached P (Chapter 4).

The amounts of leached nutrients were ten times higher in the small-scale composting studies than the amounts leached from the nursery-scale windrows (Chapters 2 and 4, Fig. 5). Thus, the results of small-scale composting experiments cannot be directly generalized to apply to the current composting practices. The results suggest that nutrient leaching associated with the nutrient and microbial sources needed for effective composting might pose a risk to the environment if the compost is placed at the same site for a long time and water percolation is not prevented. However, the use of leachate collection and circulation systems is an easy way to avoid the negative environmental impacts of composting when the amount of percolation is not high, as was the case in these studies. Leachate collection should be done especially if the forest nursery is located on groundwater aquifers and/or near lakes and rivers.

It has been reported that the gaseous N losses cause more harm to the environment than leaching losses during manure composting (Martins & Dewes 1992, Puumala & Sarin 2000). However, NH$_3$ volatilization is not likely to occur during the composting of forest-nursery waste, because the presence of peat and lignocelluloses, together with the acidic conditions,
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retard gaseous N losses (Golouke 1991, Airaksinen et al. 2001, Sánchez-Monedero et al. 2001). Therefore, it can be concluded that other environmental impacts, apart from nutrient leaching, are not likely during the composting of forest-nursery waste.

7.4 Compost quality and utilization in tree-seedling production

A prerequisite for the successful use of compost in growing media is that the compost is hygienized, as well as sufficiently matured (Hoitink & Fahy 1986). According to the Finnish Fertilizer Product Act (539/2006), the NO$_3$-N/NH$_4$-N ratio, microbial respiration (i.e. CO$_2$ production) and phytotoxicity tests (i.e. root length index) are suitable as measures of the maturity of compost which is intended to be sold or delivered free as soil improvers. For example, the assessment criteria for the maturity of soil improving compost are that the root length index is over 80%, the NO$_3$-N/NH$_4$-N ratio over 1, and the CO$_2$ production under 3 mg CO$_2$-C/g VS/day (Ministry of Agriculture and Forestry Decree 12/07). High quality, well-matured compost may stimulate root growth to such an extent that the root growth index is over 100%.

The studies of this thesis indicated that the duration of composting should be at least two years in order to ensure the decomposition of lignocellulosic material (Chapter 4). Nonetheless, composting times longer than 2 – 3 years cannot be recommended for the organic waste formed in tree-seedling production because the final compost, with an even lower OM content, is of poor quality (Puustjärvi 1991, Raviv 2005). After two years’ composting, the microbial respiration is slow (Benito et al. 2003) and phytotoxic substances are completely absent (Zucconi et al. 1981), and therefore the determination of CO$_2$ production and use of phytotoxicity tests are probably not necessary. However, if younger compost is to be used, then these determinations should be performed in accordance with the Fertilizer Product Act (539/2006).

Monitoring changes in NH$_4$-N and NO$_3$-N concentrations is a useful method for evaluating the maturity of the compost during the composting of forest-nursery waste and horse manure (Chapter 4). The decrease in NH$_4$-N and increase in NO$_3$-N concentrations were clear indicators of nitrification and, after two years’ composting, the NH$_4$-N/NO$_3$-N ratio was in most windrows less than 0.16, which is considered to be the limit for mature compost (Bernal et al. 1998, Sánchez-Monedero et al. 2001). However, when forest-nursery waste was composted with insufficient amount of additives, then nitrification was probably limited due to the low N concentration and low pH and, consequently, the NH$_4$-N/NO$_3$-N ratio did not always fall below 0.16 (Chapter 4, Table 3). In the study of Benito et al. (2003), the NH$_4$-N/NO$_3$-N ratio decreased during the composting of pruning wastes, but it was still 1.9 after 190 days and thus above the suggested limit.

The windrow composting studies (Chapter 4) suggest that the temperature, odour and structure of the compost material can be monitored easily, and can be used routinely as indicators of process functioning and maturation during nursery-scale composting, as proposed earlier by Haug (1993) and Rynk (1992). The structure of the compost product was relatively uniform after 2 years’ composting. Only the woody shoots of the 4-year-old bare-rooted spruce seedlings were recognisable in the compost product at that time. These shoots should be removed, e.g. by sieving, before utilization in order to prevent N immobilization, which may have a negative effect on plant growth (Rynk 1992, Mathur et al. 1993).
Neither the colour nor the C/N ratio was suitable for maturity assessment during forest-nursery waste composting. A high proportion of Sphagnum peat gave a characteristic colour to the waste material, which did not markedly change during composting. The decrease in the C/N ratio was in general small due to the high amount of stable C compounds. Moreover, N losses due to leaching increased the C/N ratio, and thus masked the decreasing effect of decomposable C on the C/N ratio. For example, Benito et al. (2003) also concluded that the C/N ratio is not suitable for evaluating the maturity of pruning waste compost, because of the high proportion of woody compounds.

Usability of the compost in tree-seedling production
The utilization study (Chapters 5 and 6) demonstrated that light Sphagnum peat is a better growing medium for Norway spruce container seedlings than the compost produced from the organic waste formed in tree-seedling production. However, three years after out-planting, seedling survival or final height and stem diameter were not significantly different between the seedlings grown in pure peat and in the peat mixture that contained 25 volume-% of compost (Chapter 6, Table 5). Moreover, the amount of compost in the original growing media did not affect the seedling survival after out-planting (Chapter 6). Therefore, the results of this experiment suggest that viable Norway spruce seedlings for forest planting can be produced in containers filled with 75% peat and 25% of the compost mixture under the cultivation practices used in this thesis.

If the containerized growing medium contains more than 25% compost by volume, then it is unfavourable for seedling growth due to its fine texture, increased bulk density (Chapter 5, Fig. 1) and the subsequent problems associated with aeration, wettability and water availability under the nursery-cultivation practices used here (Chapter 5, Fig. 2). The results indicate that the irrigation regime currently in use is unsuitable for a growing medium based on compost. Visual observations indicated that most of the irrigation water was retained in the upper part of the compost medium, which caused dryness and possible water repellence, and consequently restricted root growth in the lowest part of the root plug. Conversely, a high water content and subsequent low air-filled porosity in the upper part of the root plug caused, probably at least, localized oxygen deficiency, which resulted in decreasing germination (Chapter 5, Fig. 4.), seedling survival (Chapter 6) and root growth (Chapter 6, Table 2) with an increasing amount of compost in the growing medium. As a result, the poorly developed root system was not able to supply the shoot system with sufficient water and mineral nutrients, although the amount of plant available nutrients in the compost medium was high (Chapter 6, Table 4). The results show that more research is needed in order to elucidate whether the physical conditions in the compost media can be improved by mixing a coarse-textured constituent, for example vermiculite or other materials, into these container media.

The nursery cultivation techniques for different tree species are not uniform in all countries. In addition, the quality of the compost product varies according to the origin of the organic waste (Raviv 2005). To be more precise, the chemical and physical properties of the compost depend on the composition of the organic waste and have a notable effect on seedling growth, as was found in this thesis. Therefore, direct extrapolation of these growth results to different cultivation systems or production areas must be made with care.
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7.5 Conclusions

This thesis showed that the organic waste formed in tree-seedling production is a slowly decomposable and acidic material with a low initial content of OM, nutrients and easily available C compounds. Horse manure proved to be an advantageous additive material for the hygienization of the organic waste formed in forest nurseries. Horse manure is easy to handle, and it provides nutrients, microbes and easily available C compounds to the composting process, thereby creating, together with forced aeration, a suitable neutral and aerobic environment guaranteeing attainment of the thermophilic composting phase. As woody tree seedlings evidently decompose in a later phase of composting, the composting process should be long enough to enable the decomposition of OM that is highly resistant to microbial degradation. However, extended the composting period may reduce the quality of the compost product. For this reason, chopping and mixing the material are recommended to accelerate the process and to guarantee a uniform compost quality.

The compost used as a medium supplement in container tree-seedling production should be consistently of high quality, as well as mature and free of weed seeds and pathogens, in order to ensure reliable seedling growth. The selected model pathogen, uninucleate *Rhizoctonia* sp., showed potential for use as a test organism in validating the efficacy of the composting process during the composting of organic waste formed in tree-seedling production. A suitable management procedure for forest nursery waste composting is the use of horse manure, or other additive materials with similar positive features, and forced aeration to ensure a sufficiently high rise in temperature for hygienization of the material. On the other hand, although forest-nursery waste composting in windrows without additives is a feasible way of organic waste management in accordance with the legislation, there is a risk that the compost product will not be totally hygienized. Therefore, it is recommended that the compost be used e.g. on lawns, in parks or for landscaping.

Nutrient leaching can pose an environmental contamination risk if the waste material is piled at the same site for many years without a water-tight floor and leachate collection system. Nutrient addition, together with an unsuccessful composting process, may increase the leaching of nutrients in the climatic conditions prevailing in the Nordic countries. Therefore, optimization of the process, the use of leachate collection and circulation systems and covering the compost, are proposed as means of avoiding an extra nutrient load on the environment.

This work showed that mature compost, which is produced from organic waste formed in tree-seedling production, can be mixed into peat at approx. 25 volume-% to produce viable Norway spruce container seedlings for forest planting. If the growing medium contains more compost, however, it will be unfavourable for seedling growth due to its fine texture and increased bulk density and the possible problems associated with aeration, wettability and water availability under the nursery-cultivation practices used in this thesis. On the whole, the quality of the compost products may be variable, and therefore caution should be used when extrapolating these results to other cultivation systems.
References


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