SILVA FENNICA

Silva Fennica 41(1) research articles

www.metla.fi/silvafennica · ISSN 0037-5330
The Finnish Society of Forest Science · The Finnish Forest Research Institute

Forest Nursery Waste Composting in Windrows With or Without Horse Manure or Urea – the Composting Process and Nutrient Leaching

Anna-Maria Veijalainen, Marja-Liisa Juntunen, Arja Lilja, Helvi Heinonen-Tanski and Leo Tervo

Veijalainen, A.-M., Juntunen, M.-L., Lilja, A., Heinonen-Tanski, H. & Tervo, L. 2007. Forest nursery waste composting in windrows with or without horse manure or urea – the composting process and nutrient leaching. Silva Fennica 41(1): 13–27.

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

Received 27 March 2006 **Revised** 22 September 2006 **Accepted** 9 January 2007

Available at http://www.metla.fi/silvafennica/full/sf41/sf411013.pdf

1 Introduction

Finnish forest nurseries deliver over 150 million tree seedlings annually for planting (Finnish Forest Research Institute 2004). Almost 90% of the seedlings are produced by 24 enterprise-owned forest nurseries, and the remainder is grown in 60 to 70 small, family-owned forest nurseries. Forest nurseries are usually located in rural areas with long distances to community facilities or landfill sites (Poteri 2003).

According to a survey (Juntunen and Rikala 2001), forest nurseries find the handling of organic waste problematic (unpublished data). The annual amount of organic waste varies, but in the late 1990's the average amount was 50 m^3 per forest nursery (Veijalainen et al. 1999). The Finnish Waste Act (1072/1993) does not allow the heaping up or burning of organic waste in an uncontrolled fashion in forest nurseries. Landfilling is not a solution because the regulations dealing with the use of landfills have been tightened up in order to encourage the composting of organic wastes and the utilization of the produced compost for agricultural purposes or ecological improvement (European Communities 1999). Thus, the most practical solution for forest nurseries would be to compost the organic wastes on-site in the fields and reuse the composted material.

However, Finnish forest nurseries have limited resources to carry out composting. The rationalization of seedling production, and the severe competition in this sector, have led to a need for minimizing production costs including labor costs. As a result, there is less time and personnel available to take care of waste management, even though waste management is important to ensure good nursery hygiene. The composting method should therefore be inexpensive and easy to implement technically, without any negative environmental impacts.

Composting has been studied extensively in the municipalities, as well as in agriculture and horticulture, which produce considerable amounts of easily decomposable material (e.g. Koivula et al. 2000, Bertran et al. 2004). Forest nursery waste, in contrast, consists mainly of woody tree seedlings and their growth media (low humified *Sphagnum* peat), which are difficult to degrade (Gray et al. 1971a, Puustjärvi 1991). However, forest nursery waste also includes easily decomposable material, e.g. weeds, leaves and grass clippings, which may enhance the process and raise the temperature sufficiently to kill pathogens and weed seeds (Haug 1993, Grundy et al. 1998, Noble and Roberts 2004). Although the fundamentals of the composting process are well known, this is, as far as we know, the first study concerning with large-scale composting of organic wastes typical of forest nurseries.

Forest nurseries are usually located on groundwater aquifers and/or near lakes and rivers (Juntunen and Rikala 2001). The relatively high nutrient concentration in the leachates from manure compost and small-scale forest nursery waste composts indicates that nutrient leaching may be a pollution risk to water resources (e.g. Martins and Dewes 1992, Ulén 1993, Parkinson et al. 2004, Veijalainen et al. 2007). Consequently, nutrient leaching from large-scale forest nursery waste windrows containing different nutrient sources needs to be studied.

The quality of the compost product depends on the properties of the raw materials, the composting method used, and the process functionality (Rynk 1992, Haug 1993, Raviv 2005). It is currently recommended that the quality of the compost product should be evaluated by monitoring the process and by using a combination of physical, chemical and biological methods, which are well documented (e.g. Zucconi et al. 1981, Mathur et al. 1993, Bernal et al. 1998, Levanon and Pluda 2002). The methods suitable for forest nurseries should be economically viable and simple to carry out.

The main goal of this study was to find the best management practices for composting forest nursery waste on-site using nursery-scale windrows. The limited resources of the forest nurseries were taken into account by keeping the method as simple as possible, while ensuring that the process functioned properly. More specific aims were to study the microbial hygiene, organic matter decomposition and nutrient leaching in forest nursery waste composting with and without horse manure, urea and forced aeration. Certain properties of the produced composts were also evaluated in more detail.

Table 1. Features of the 2-year experimental windrows piled in Suonenjoki forest nursery during 1999–2002. Windrow codes: N99: nursery waste, U00: nursery waste and urea, N01: nursery waste, H01: nursery waste and horse manure, H02: nursery waste and horse manure, HA02: nursery waste, horse manure and aeration.

Windrow	N99	U00	N01	H01	H02	HA02
Volume, m^3	50	50	50	50	34	34
Forest nursery waste, m^3	47	50	50	38	17	17
Horse manure, m^3	3 [a]	0	0	12 [a]	17 [b]	17 [b]
Urea, kg [c]	0	75	0	0	0	0
Dimensions, m [d]	9×6×1.8	9×6×1.8	9×6×1.8	9×6×1.8	10×4×1.7	10×4×1.7
Composting period	7.7.1999–4.6.2001	20.6.2000–4.6.2002	13.6.2001–10.6.2003	13.6.2001–10.6.2003	9.7.2002–26.5.2004	9.7.2002–26.5.2004
Aeration	5 pipes + turnings	8 pipes + turnings	1 pipe + turnings	1 pipe + turnings	1 pipe + turnings	Duct fan + turnings
Direction of pipes	across [e]	1 along and 7 across [ef]	along	along	along	along

[a] Cutter chip bedded horse manure; [b] Peat bedded horse manure; [c] $CO(NH_2)_2$, (46.3% N) Kemira Corp., Finland;
[d] Length, width and height; [e] The distance between pipes was ca. 1.5 m; [f] Pipes in two layers (30 and 80 cm above the bottom)

2 Materials and Methods

2.1 Construction of the Windrows

Forest nursery waste was composted in six nursery-scale windrows for a 2-year period at the Suonenjoki forest nursery in Central Finland (Table 1). Sufficient waste material was available to build only 1 or 2 windrows per year, depending on the amount of rejected seedlings. Thus, windrows were piled in four consecutive years during 1999–2002.

Every year compost material consisted mainly of 1-year-old container silver birch (*Betula pendula* Roth) seedlings, 1- and 2-year-old container and 4-year-old bare-root of Norway spruce (*Picea abies* (L.) Karst.) seedlings and 1-year-old container and 2-year-old bare-root of Scots pine (*Pinus sylvestris* L.) seedlings, and occasionally of some other tree species. The compost material also included the growth media (low humified *Sphagnum* peat) of the container seedlings, weeds, grass clippings and dead leaves. The material was not pre-processed before composting. The roots of the weeds and bare-root seedlings, which were grown in the field, were usually sandy and thus contributed inorganic material to the windrows.

Composting was done with or without horse manure or urea in six 34–50 m^3 windrows (Table 1). N99, U00 and N01 windrows consisted of pure forest nursery waste. Urea fertilizer (75 kg, Kemira Corp., Finland) was added to U00 windrow as a nitrogen source. Cutter chip bedded horse manure (3 m^3) was added to N99 windrow as a microbial source (Raviv 2005). The other three windrows, H01, H02 and HA02, consisted of forest nursery waste and horse manure. H01 windrow consisted of forest nursery waste (3/4 of the total volume) and cutter chip bedded horse manure (1/4 of the total volume). H02 and HA02 windrows consisted of peat bedded horse manure equivalent to half of the total volume, and a layer of wood chips about 25 cm thick at the bottom of the windrow.

Each year the compost material was mixed and piled using a bucket loader into a windrow (with a triangular cross section) located on an asphalted area (Table 1). The percolation water running out from each windrow was collected in separate concrete wells. Each windrow was composted on the asphalted area for 2 years, except for the N01 and H01 windrows, which were moved to the field after one year due to the construction of walls and a roof for the composting area. The lower part of the back and sides of the asphalted area consisted of a wall made of concrete bricks (height 1 m, constructed in June 2002). A roof and wooden lath walls were installed on top of the concrete brick wall in September 2002 and June 2003, respectively.

Aeration of the windrows was provided passively using perforated pipes (∅ = 6 cm) and turnings in all the windrows except HA02, which was aerated forcibly using a circular duct fan (Model K160 M, Systemair Oy, Finland) with 150 m^3 daily air stream for the first 6 months and for one month after 11 months composting (Table 1). The fan was connected to the perforated pipe running longitudinally through the pile. The pipe was located on the wood chip layer beneath the compost material. The windrows were turned using a bucket loader after ca. 3, 12, and 24 months of composting. The N99 and U00 windrows were covered with polyethylene sheeting after 12 months of composting. After piling the other windrows were covered with woven polypropylene fabric to prevent the growth of weeds on the surface of the windrows.

2.2 Monitoring the Composting Process

2.2.1 Temperature

Temperature was measured with thermocouples located at 5–10 points inside the windrows at least 2 times a week during the first month, and subsequently at 1- or 2-week interval during the 2-year composting period. Temperature was also measured at depths of 10 and 30 cm in all the windrows (except N99) from October to June.

2.2.2 Physical and Chemical Properties

Compost material (n = 4–6, volume 4 l) was sampled from each windrow at the start and at the turning time in order to determine the physical and chemical properties of the compost. Organic matter (OM) was determined by loss of mass on ignition of oven-dried samples at 550°C to constant mass. OM decomposition (%) during the 2 years' composting was calculated using the equation (Haug 1993):

$$OM\ decomposition\ \% = \frac{\left(OM_b\,\% - OM_a\,\%\right)100}{OM_b\,\%\left(100 - OM_a\,\%\right)}100$$

where $OM_b\%$ is the organic matter content before composting and $OM_a\%$ is organic matter content after composting. The water content, pH, and the carbon (C), nitrogen (N) and phosphorus (P) concentrations were determined as described in Veijalainen et al. (2005). The potassium (K) concentration was determined in the same way as for the P concentration. Electrical conductivity (EC) (CDM-80, Radiometer, Denmark) was measured on the same suspension (1:5 by volume) as the pH.

The ammonium (NH_4-N) and nitrate + nitrite (NO_3-N + NO_2-N) concentrations were determined, following extraction of the sample with 1 M KCl, by flow injection analysis (FIA) (QuikChem 8000, Lachat Instruments, USA) during 2001–2004. Bulk density (on a dry mass basis) was measured by weighing a 10 litre bucket filled with fresh compost material during 2001–2004. Odour, colour and structure of the compost material were evaluated subjectively at the time the windrows were turned.

2.2.3 Microbial Hygiene

The microbial hygiene of the compost material in the H02 and HA02 windrows was studied after 2 months' composting. Hygiene analyses were made on 2 different bulked samples (n = 3), which were taken at depths of 30 cm and 100 cm. Faecal coliforms, coliphages (hosts *Escherichia coli* ATCC 13705 and 15597), enterococci and faecal clostridia (sulphite-reducing clostridia) were determined as described by Heinonen-Tanski and Savolainen (2003). The detection limit was 10 cfu g^{-1} for coliphages and faecal clostridia, and 100 cfu g^{-1} for faecal coliforms and enterococci.

2.2.4 Wood Decomposition

One litre of barkless 30-year-old Norway spruce shavings (15×20×1 mm) were bagged in nylon mesh bags (mesh size 6 mm) and placed in H02 and HA02 windrows during piling. Six bags were placed together at 3 different locations (at the front, middle and back part) in the windrows. Three bags were removed from each location after 1 and 2 years' composting. The bags were stored frozen (–15°C) until analysis, which was carried out in November 2004. Three uncomposted shaving bags were stored in the same way as the composted shaving bags until analysis.

Only the inner contents of the shaving bags were used in the analyses, because the outer part of the shavings was contaminated with compost material during composting. The oven-dried (+40°C, 2 days) shaving samples were milled. The α-cellulose, total sugars and uronic acids were analyzed as described by Anttonen et al. (2002). The hemicellulose + starch concentration was calculated (% of dry matter) using the formula: total sugars – α-cellulose + uronic acids.

2.3 Water Percolation and Nutrient Leaching

The volume of the percolation water was measured at 2-weeks intervals during the 2-year composting (except for one year in the N01 and H01 windrows). Water samples were collected monthly if any water had percolated out of the windrows. The samples were stored frozen and filtered through Schleicher & Schuell 589/2 filter paper before the nutrient analysis. Total P was analysed by inductively coupled plasma atomic emission spectrophotometry (ICP/AES, ARL 3580, Switzerland). Total soluble N, NH_4–N and (NO_3–N + NO_2–N) were analysed by FIA (flow injection analysis) (Tecator 5012, Foss, Sweden and QuikChem 8000, Lachat Instruments, USA).

2.4 Germination Tests

Preliminary germination tests of cress (*Lepidium sativum*) and Norway spruce seeds were carried out with different-aged composted material in summer 2004. Seeds (n = 5 for both species) were sown in 1.0 litre pots (5 replicate pots) filled with composted material from the different windrows. *Sphagnum* peat was used as a control growth medium. Growing was carried out under greenhouse lamps with a 16 h day at 22°C and 18°C during the dark period. Water was sprayed on the sown area regularly to keep the seeds and medium moist. The number of germinating cress seeds was counted 7 days after sowing, and of Norway spruce seeds 7, 14 and 21 days after sowing.

2.5 Statistics

Repeated measures of ANOVA (SPSS 13.0 for Windows) and the Bonferroni pairwise comparison were used to determine the statistically significant differences in the α-cellulose and hemicellulose + starch concentrations before and after 1 or 2 years' composting. One-way ANOVA was used to determine the statistically significant differences in the germination of cress and Norway spruce seeds in compost material from the different windrows. The data were arc sin square root transformed before the statistical analysis in order to fulfil the assumptions of variance analysis. Means were compared for significant differences at $p<0.05$ by Tukey's test.

3 Results

3.1 Composting Process

3.1.1 Temperature

The temperature increased above 40°C (thermophilic phase) 2 days after piling in HA02 and H02, and after 7 and 11 days in H01 and N99, respectively. In U00 and N01, the temperature did not increase over 40°C (Fig. 1).

The highest temperature (61°C) was observed in HA02 after 2 weeks' composting. The temperature stayed over 55°C for one month in HA02. A maximum temperature of 50 and 48°C was reached in H01 and H02 after 3 and 2 weeks' composting, respectively. Without horse manure addition, the maximum temperature was 41, 36 and 32°C in N99, U00 and N01 after ca. 2, 4 and 10 weeks composting, respectively (Fig. 1). The temperature varied (SD 2–8°C) inside the windrows during the thermophilic and cooling phase. The variation was wide in the windrows containing horse manure or urea, obviously because the raw materials had not been mixed very uniformly by the bucket loader.

The longest thermophilic phase occurred (3.5 months) in HA02. In the other windrows the temperature stayed above 40°C for 2, 1.5 and 1 months in H02, H01 and N99, respectively. In the middle of September, the windrows gradually

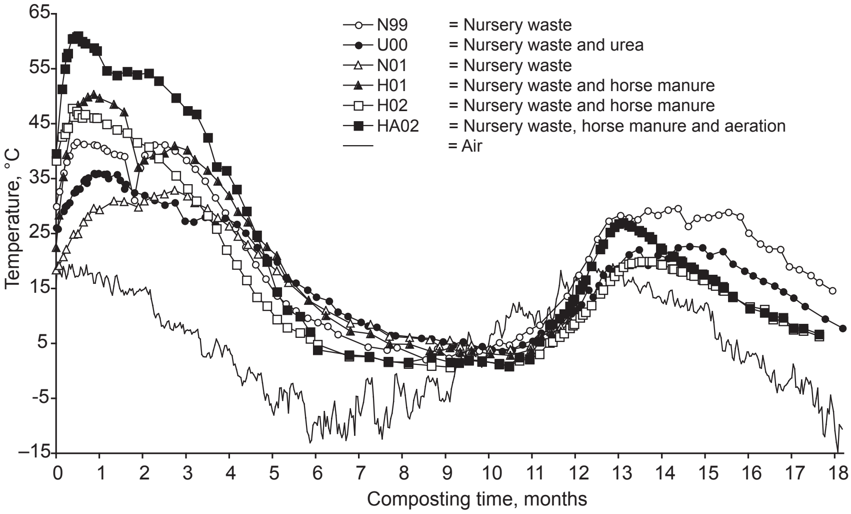

Fig. 1. Windrow temperature (°C) and average air temperature during 18 months' composting. Surface temperatures (at depths of 10 and 30 cm) are not included in the average windrow temperature.

started to cool down along with the decrease in the ambient air temperature. However, the windrows (except the surface layer of the HA02 and H02) did not freeze during the winter. The surface temperature of HA02 and H02 was a few degrees below zero (–5°C at the lowest) for 2 months, because the roof over the windrows prevented the formation of an insulating snow layer on top of the windrows.

After the winter, the temperature increased slowly along with the ambient air temperature and was at its highest in August when the air temperature began to decrease. In H02 and HA02 the temperature decreased along with the air temperature. However, in N99 and U00, the temperature remained relatively constant for 3 and 2 months, respectively, in the autumn (Fig. 1).

3.1.2 Physical and Chemical Properties

The OM content was initially 35–56% in all the windrows (Table 2). The addition of horse manure did not increase the OM content before composting. The OM content decreased in all the windrows during the 2-year composting. OM decomposition was the highest in the windrows containing easily decomposable horse manure

Table 2. Organic matter content (OM, % of DM) before and after two years' composting. Average ± standard deviation. OM decomposition (%) annually during the 1st and 2nd composting year, and after the whole two years' composting. For windrow codes, see Fig. 1.

Windrow	OM, %		OM decomposition, %		
	before	after	1st yr	2nd yr	during 2 yrs
N99	35±10	24±3	–1	–40	–41
U00	47±18	32±1	+8	–56	–48
N01	40± 7	31±2	–38	+4	–34
H01	56±12	35±4	–48	–9	–57
H02	37± 4	29±5	–42	+10	–32
HA02	46± 8	35±2	–30	–7	–37

during the first year. In contrast, OM decomposition was the highest in N01 during the first winter, and in N99 and U00 during the second year.

The initial total N concentration was, on the average, lower in N99, N01 and H02 than in U00, H01 and HA02 (Fig. 2a). The N concentration decreased by 20–30% in the forest nursery waste windrows and in H01 during 2 years' composting. During the same period the N concentration increased in H02 and HA02. Horse manure addition increased the initial P and K concentrations (Fig. 2b and c). The P and K concentrations did

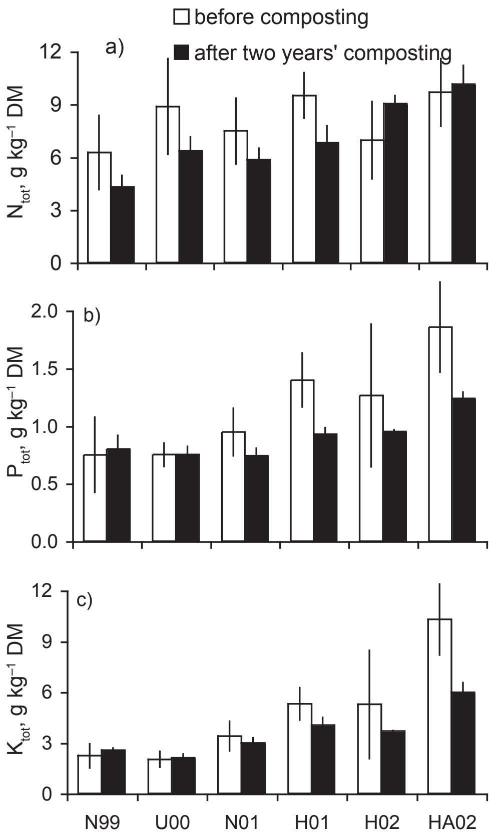

Fig. 2. Total nitrogen (N) (a), phosphorus (P) (b) and potassium (K) (c) concentrations (g kg^{-1} of dry matter) before and after two years' composting. Standard deviations are indicated by bars. The initial N concentration before urea addition in U00 windrow. For windrow codes, see Fig. 1.

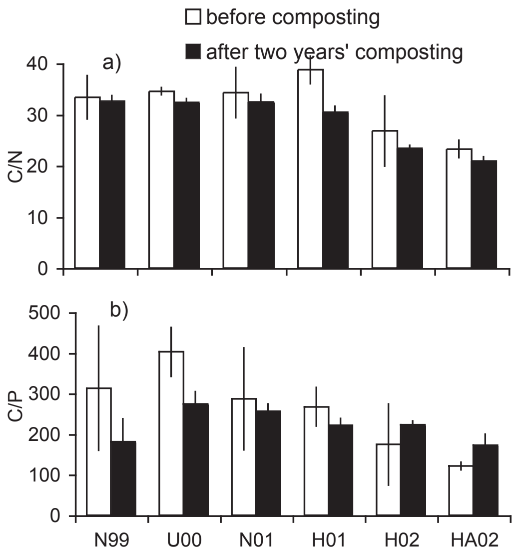

Fig. 3. Carbon to nitrogen ratio (C/N) (a) and carbon to phosphorus ratio (C/P) (b) before and after two years' composting. Standard deviations are indicated by bars. For windrow codes, see Fig. 1.

not change markedly in the forest nursery waste windrows, but they did decrease in the windrows containing horse manure during 2 years' composting.

The C/N ratio was <40:1 in all the windrows before composting (Fig. 3a). In H02 and HA02, which contained the greatest amount of horse manure, the C/N ratio was <30:1. In H01 the C/N ratio was the highest, despite the horse manure addition. The C/N ratio decreased by 20% in H01 during 2 years' composting. The decrease was less in the other windrows. The C/P ratio was high in forest nursery waste windrows and in H01 before composting (Fig. 3b). In HA02 and H02 the C/P ratio was <200, and thus more favourable for microbial growth.

The mean NH_4–N concentration was higher (380–1400 mg kg^{-1} DM) in the horse manure windrows than in the forest nursery waste windrows (220 mg kg^{-1} DM) at the beginning of composting. The NH_4–N concentration decreased as composting proceeded, and was <50 mg kg^{-1} DM in all the windrows after 2 years' composting. The initial NO_3–N concentration was, on the average, <80 mg kg^{-1} DM in all the windrows, except in H02 where it was 200 mg kg^{-1} DM. In contrast to the NH_4–N concentration, the NO_3–N concentration increased in all the windrows during 2 years' composting, and was the highest (>650 mg kg^{-1} DM) in H02 and HA02 after composting. The NH_4/NO_3 ratio was ≤ 0.16 in all the windrows (except N99 and H01) after 2 years' composting (Table 3).

The addition of horse manure increased the initial pH (Table 3). However, the pH remained below 7.0 in all the windrows during the 2 years' composting. In H01 and N01 the pH remained relatively constant during the whole composting period. The pH decreased below 5.0 in U00

Table 3. NH_4/NO_3 ratio, pH and bulk density (kg m^{-3} DM) of the compost material before and after two years' composting. The average water content (by mass, %) and electrical conductivity (EC, mS m^{-1}) of the compost material during 2 years' composting. Average ± standard deviation. For windrow codes, see Fig. 1. nd = not determined.

Windrow	NH_4 / NO_3		pH		Bulk density, kg m^{-3} DM		Water content, %	EC, mS m^{-1}
	before	after	before	after	before	after		
N99	nd	5.60	5.3±0.5	6.0±0.1	nd	nd	58±6	30±10
U00	nd	0.08	5.3±0.4	4.5±0.1	nd	245± 5	67±6	60±30
N01	3.02	0.16	5.4±0.3	5.6±0.2	140±10	290±10	61±6	60±20
H01	6.72	0.27	5.9±0.2	5.8±0.3	180±20	265±65	62±7	80±30
H02	4.00	0.03	6.2±0.6	4.8±0.1	270±50	385±25	52±7	180±70
HA02	18.06	0.05	6.6±0.3	4.9±0.2	300±40	310±20	55±4	220±80

after 1 year's composting, and in H02 and HA02 windrows after 2 years' composting. An increase in pH was observed only in N99 during 2 years' composting.

The initial bulk density was, on the average, higher in the windrows piled in 2002 than in 2001 (Table 3). The bulk density increased during composting. The average water content was 52–67 mass-% in all the windrows during the 2 years' composting (Table 3). The mean water content was the highest in U00 and the lowest in H02 and HA02. The mean EC was lower in the forest nursery waste windrows than in the horse manure windrows (Table 3).

3.1.3 Microbial Hygiene

The hygienic quality of the compost material in the HA02 windrow was found to be good after 2 months' composting. No faecal coliforms, coliphages or enterococci were detected in the material taken from HA02. The number of faecal clostridia was 18 cfu g^{-1} in the material taken from HA02.

The compost material in H02 was not totally hygienized. No coliphages or enterococci were detected in the material taken from H02. However, the number of faecal coliforms was 2790 and 810 cfu g^{-1} in samples taken at depths of 30 and 100 cm, respectively. Similarly, the number of faecal clostridia was 20 and 280 cfu g^{-1} at depths of 30 and 100 cm.

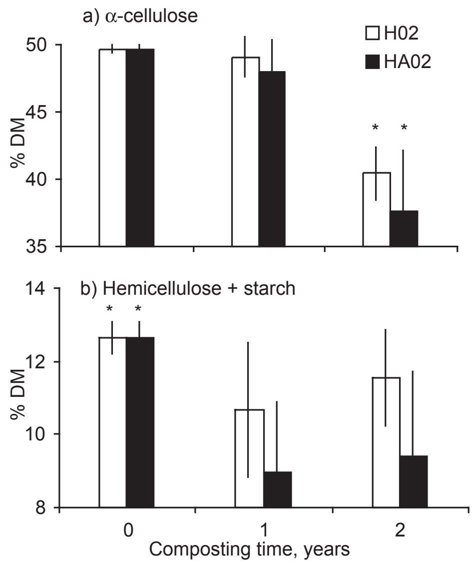

Fig. 4. α-cellulose (a) and hemicellulose + starch (b) concentration (% of dry matter) of wood shavings in H02 and HA02 windrow before and after one and two years' composting. Standard deviations are indicated by bars and significant differences in concentrations between years in both H02 and HA02 windrow by asterisks ($p<0.05$). For windrow codes, see Fig. 1.

3.1.4 Wood Decomposition

The concentration of α-cellulose in the wood shavings placed in H02 and HA02 decreased significantly during the second composting year (Fig. 4a). The hemicellulose + starch concentration of the wood shavings decreased significantly during the first composting year (Fig. 4b).

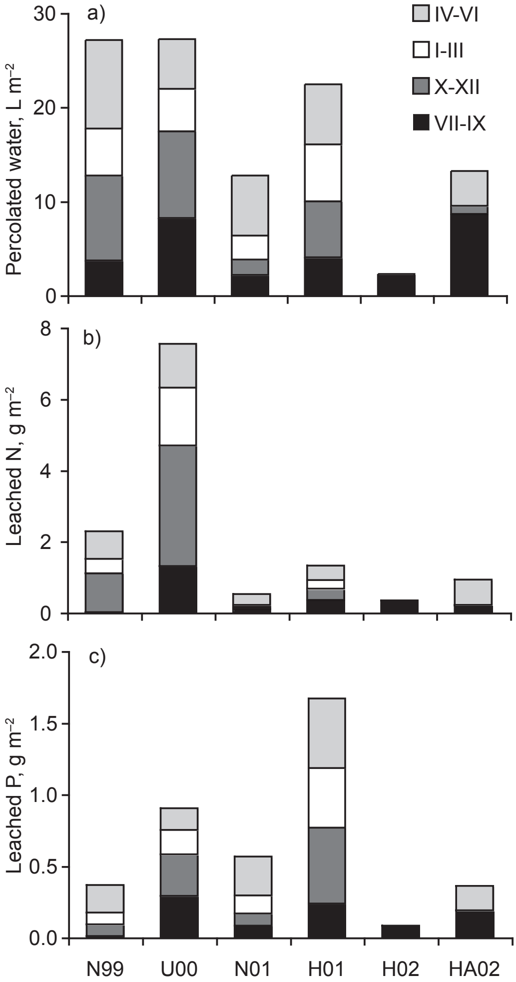

Fig. 5. The amount of percolation water (L m^{-2}) (a), leached nitrogen (N, g m^{-2}) (b) and phosphorus (P, g m^{-2}) (c) during the first summer (VII–IX), autumn (X–XII), winter (I–III) and spring (IV–VI). For windrow codes, see Fig. 1.

3.2 Water Percolation and Nutrient Leaching

3.2.1 Water Percolation

Water percolation was generally small; the annual amount of percolation water was less than 1.5 m^3 from all the windrows. Larger amounts of water (22–27 L m^{-2}) percolated through N99, U00 and H01 than through N01, H02 and HA02 (2–13 L m^{-2}) during the first composting year (Fig. 5a). However, theoretically calculated the annual amount of percolation water was less than 7% of annual precipitation in all the windrows. Percolation was relatively regular throughout the year, although the amount of water increased slightly in U00 and HA02 during the summer (VII–IX), in N99 and U00 during the autumn (X–XII), and in N99 and N01 during the spring (IV–VI). In the case of HA02 and H02, 65 and 100% of the water percolated during the first summer, respectively.

Approximately the same amount of water percolated through N99 during the first and the second composting year. One half less water percolated through U00 during the second composting year. In HA02 and H02, there was no water percolation during the second composting year. Water percolation through N01 and H01 was monitored only during the first year.

3.2.2 Nutrient Leaching

The annual amount of leached N was highest in U00 during the first composting year (Fig. 5b). In the other windrows, the annual amount of leached N was one third or less than that from U00. However, the absolute amount of leached N was negligible (12–407 g a^{-1}) from all the windrows. Almost 50% of the annual amount of N leached out during autumn (X–XII) from N99 and U00. The amount of N leached from N01 and HA02 was the highest (60 and 77%, respectively) during the spring (IV–VI). The leaching of N from H01 was relatively constant during the first composting year.

Most of the leached N was in the form of NO_3–N in all the windrows, except in H01 where 67% of the leached N was organic N. In N01, the leached N consisted of equal amounts of NO_3–N and organic N. The proportion of NH_4–N was $<10\%$ of the total amount of N leached from all the windrows, except for H02 in which 21% of the leached N was NH_4–N.

The addition of horse manure increased the leaching of P only from H01 (Fig. 5c). The annual amount of P leached from the other windrows was 46–95% less. However, the absolute amount of leached P was insignificant (3–90 g a^{-1}) from all the windrows.

The annual amount of leached N was 70 and 80% less from N99 and U00, respectively, during the second year. Also the annual amount of leached P was 75% less from U00. However, the annual amount of leached P was 25% higher from N99 during the second year.

3.3 Compost Product Quality

3.3.1 Odour, Colour and Structure

The compost materials in all the windrows (except U00) had an earthy smell after each turning. In U00, the material had a slightly putrid odour when the windrow was turned for the first time after 3 months' composting. The compost materials in all the windrows had a dark brown colour after each turning. However, seedling shoots and root plugs were clearly visible after 3 months' composting. After 2 years' composting, the visual structure of the compost material was relatively uniform. Only the shoots of the 4-year-old spruce seedlings were still recognisable at that time.

3.3.2 Germination Tests

All the cress seeds germinated in the control peat and in the composted material from HA02. The germination of cress seeds was 96, 88, 80, 80 and 76% in the composted material from H02, U00, N99, H01 and N01, respectively. The germination of cress seeds was significantly lower in N01 than in HA02 and the control peat. The visual appearance of the seedlings was faultless.

All the Norway spruce seeds germinated in the composted material from HA02 and H02. The germination of spruce seeds after 21 days was 96% in peat and 92, 92, 88 and 84% in the composted materials from N01, N99, U00 and H01, respectively. However, the differences were not statistically significant. The visual appearance of the seedlings was faultless.

4 Discussion

4.1 Composting Process

4.1.1 Hygienization

Horse manure is a source of N, P, K, easily available C compounds, microbes and neutralizing compounds that enable effective growth of the microbes responsible for OM decomposition and consequent rise in temperature (Gray et al. 1971a, Haug 1993, Raviv 2005, Veijalainen et al. 2005). According to many authors, it is necessary to keep the temperature above 55°C for 3–14 days for the hygienization of waste material, in other words to eradicate plant and human pathogens and weed seeds (Fernandez and Sartaj 1997, Grundy et al. 1998, Ryckeboer 2001, Maa- ja metsätalousministeriö and Kasvintuotannon tarkastuskeskus 2004, Noble and Roberts 2004). In our study, the desired temperature-time relationship and the absence of microbial hygiene indicators was achieved only if forest nursery waste was composted with horse manure and forced aeration (HA02). However, if time of exposure increases, the temperature required for total eradification of pathogens decreases (Ryckeboer 2001). Moreover the eradification during composting is also affected by other factors such as toxic compounds and microbial antagonism (Bollen 1984, Ryckeboer 2001, Noble and Roberts 2004). Thus, in our study, the eradification of plant pathogens might have also happened in other horse manure containing windrows, in which the temperature stayed above 45°C at least for a month.

Fernandez and Sartaj (1997) noticed in their studies that, the passive aeration may cause the lack of oxygen, and thus retard microbial activity in windrow composting. This might have happened in passively aerated H02, in which the temperature did not increase over 50°C and the microbial hygiene indicators were not completely destroyed. In H01, the loose cutter chips used as a bedding material and lower bulk density facilitated passive aeration and resulted in higher temperature (Veijalainen et al. 2005). The other reason for the lower temperature in H02 was the lower initial amount of nutrients. Unfortunately, the quality of the horse manure was not uniform, probably due to nutrient losses during storage before piling (Martins and Dewes 1992, Airaksinen et al. 2001).

The temperature profile in the U00 windrow implies that N is not the only limiting factor in the composting of forest nursery waste. Artificial fertilizers like urea lack the other beneficial features typical of organic additives, e.g. horse manure, as discussed earlier. The second reason for the lack of a thermophilic process in U00 may have been the lack of oxygen due to the high water content. In general, a lower limit for the optimal water content (50–70 w/w%) is recommended in static heaps and windrows in order to support microbial activity (Gray et al. 1971b, Golouke 1991, Haug 1993). The third reason was the low pH, which probably had a negative effect on microbial activity also in N99 and N01. Thus, pH adjustment e.g. with lime would be desirable when the material is both acidic and has a low N content, e.g. forest nursery waste (Haug 1993).

4.1.2 Organic Matter Decomposition

In most composting studies, the waste material such as agricultural and food waste has a high amount of organic material, > 75%, which is mainly easily decomposable (Bernal et al. 1998, Koivula et al. 2000). In our study, the waste material had low initial OM content, 35–56%. The high amount of mineral material was caused by the presence of coarse sand, which was used to cover the growth media in the containers, as well as the sand, which was stuck on the roots of the bare-root seedlings and weeds removed from the sandy fields. This, together with the low initial nutrient content and the presence of slowly decomposable and stabile C compounds in tree seedlings and peat explain the slow OM decomposition and low temperatures in forest nursery waste windrows without additives (Puustjärvi 1991, Bernal et al. 1998). Eriksson et al. (1990) and Haug (1993) have also reported that cellulose is relative resistant to biodegradation in wood when it is associated with hemicellulose and lignin as lignocellulose, and requires a relatively long composting time. Accordingly, in our study, the degradation of cellulose in wood shavings, placed in the windrows piled in 2002, happened during the second year.

The OM decomposition rate was the highest in windrows containing horse manure, and consequently easily available C compounds, during the first summer. The decrease in the concentration of hemicellulose + starch in the wood shavings was clearly due to the degradation of more easily degradable starch during the first year (Haug 1993). The degradation of hemicellulose was negligible in this study, although it is considered to be more easily degradable than cellulose due to the lower degree of polymerization (Eriksson et al. 1990). However, the lignocellulosic compounds are often degraded simultaneously, although the relative degradation rate may vary depending upon the microbes and conditions (Eriksson et al. 1990). According to our study, composting time should be long enough to ensure the decomposition of woody seedlings. Nonetheless, the composting time longer than 2–3 years cannot be recommended for forest nursery waste, because the final compost with even lower OM content is of poor quality (Puustjärvi 1991, Raviv 2005).

4.2 Water Percolation and Nutrient Leaching

Puumala and Sarin (2000) have studied the water percolation through cow and chicken manure windrows in Finland i.e. in similar climatic conditions as our study was conducted. In their study, the amount of percolation water was 2.2–6.0 m^3 from 100 m^3 cow manure windrows and 0.07–0.3 m^3 from 30 m^3 chicken manure windrows during eight months composting. In our study, the annual amount of percolation water was same magnitude, being less than 1.5 m^3 from all the windrows. Although the amounts were negligible, water percolation caused by rain and decreased evaporation (autumn) or melting snow (spring) can be reduced if the windrows are placed under a roof, as was done in this study after 2002. Other solution could be covering, e.g. Berner (1989) and Ulén (1993) have recommended covering a windrow with waterproof material after the thermophilic phase to reduce water percolation. However, waterproof material such as plastic prevents the air circulation in windrow (Rynk 1992). In our study, the decomposition continued after the temperature had stabilized, and thus air circulation should be ensured also during curing.

In addition to the amount of water, the depth of the water table and soil characteristics also influence the risk of groundwater contamination (Mälkki et al. 1988), and thus should be taken into account when selecting the site for windrows. The use of water collection and circulation systems is an easy way to avoid the negative environmental impacts of composting when the amount of percolation water is not high (Martins and Dewes 1992), as was the case in our study.

Nutrient leaching can be minimized by optimizing the composting process parameters and conditions in order to ensure that the composting process functions effectively (Berner 1989). In our study, the effect of poorly functioning process on N leaching was apparent in U00 windrow, from which the annual amount of leached N was the highest, 0.4 kg. The leaching of N, specifically NO_3, can result in the contamination of groundwater and poses a threat to drinking water quality (European Communities 1998). Leached NH_4 and organic N are also potential groundwater pollutants, because they can later be transformed into NO_3 in the soil (Killham 1994). Leaching of P was a consequence of horse manure addition and the low P absorption of in the forest nursery waste. According to Rannikko and Hartikainen (1980) *Sphagnum* peat has a low P absorption. Also Juntunen et al. (2002) reported that P is easily leached from the peat medium used in forest seedling production. The leaching of P can cause eutrophication, which is one of the most serious threats to Finnish surface waters (Niemi et al. 2001). However, in our study, the addition of P-rich horse manure promoted the composting process and resulted in small amounts of leached P, 3–90 grams.

4.3 Compost Product Quality

The odour and colour of the compost material can be monitored easily and should be used routinely as an indicator of process functioning and maturation, respectively (Haug 1993). The putrid odour in the U00 windrow here was an indication of anaerobic conditions, which means that it should have been turned earlier in order to re-establish the pile structure required to support air circulation. In general, the compost should be turned during the thermophilic phase in order to ensure that all the waste material is exposed to the high temperatures required to kill pathogens and weeds (Haug 1993). The high proportion of peat gave characteristic colour to our compost, and thus the colour can not be used as an indication of the maturity. The non-decomposed woody twigs found in compost product should be removed by sieving before utilization, because non-degraded woody material can cause the immobilization of N and have a negative effect on plant growth when it is applied to the soil (Rynk 1992, Mathur et al. 1993).

The decrease in the C/N ratio and NH_4–N concentration and an increase in the NO_3–N concentration have been proposed to be used as an indicator of maturation for many types of compost (Bernal et al. 1998, Sánchez-Monedero et al. 2001, Parkinson et al. 2004). However, the decrease in C/N ratio is usually small in composts with high amount of stabile C compounds, which are hardy broken down by the microbes (Golouke 1991). Moreover, the N loss due to leaching or volatilization may increase the C/N ratio of the compost material (Bertran et al. 2004). In our study, the decrease in C/N ratio was insignificant in all other windrows, except H01, because of the stabile C compounds and N leaching. However, a loss through the volatilization of ammonia is not likely, because the presence of peat and lignocellulosic compounds, together with the acidic conditions, retard the formation and escape of gaseous ammonia (Golouke 1991, Airaksinen et al. 2001, Sánchez-Monedero et al. 2001). Thus, the decrease in C/N ratio cannot be used as an indication of maturity in forest nursery waste composting. Nonetheless, the changes in NH_4–N and NO_3–N were clear indicators of nitrification and after 2 years' composting the NH_4/NO_3 ratio was in most cases less than 0.16, which is considered as the limit for mature composts (Bernal et al. 1998, Sánchez-Monedero et al. 2001).

Phytotoxic substances are produced only in certain stages of decomposition and tend to be rapidly inactivated, and thus they are not likely to exist in 2-year or older composts as here (Zucconi et al. 1981). Therefore, these preliminary germination tests provided useful information about the compost utilization rather than the phytotoxicity of the compost.

5 Conclusions

Forest nursery waste was found to be a slowly decomposable and acidic material with a low initial content of organic material, nutrients and easily available C. Horse manure was suitable additive material for the hygienization of the forest nursery waste. Horse manure was easy to handle, and it provided nutrients, microbes and easily available C compounds to the process, and created, together with the forced aeration, a suitable neutral and aerobic environment guaranteeing the heating process. Woody tree seedlings evidently decomposed at a later stage in the process. Thus, the composting process should be long enough to enable the decomposition of slowly degradable OM. However, extended composting may have a negative effect on compost quality. For this reason, chopping raw material and turning could be used to accelerate the process and to guarantee a uniform quality of the compost product.

Nutrient leaching can pose an environmental contamination risk if the waste material is piled at the same site for a number of years without a water 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 water collection and circulation systems and covering the compost are recommended to avoid an extra nutrient load on the environment.

Forest nursery waste composting in windrows without additives is a feasible way of organic waste management in accordance with the regulations. It is worth noticing, however, that there is a risk that the compost product will not be totally hygienized. Therefore, it is recommended that the compost will be used e.g. on lawns, in parks or for landscaping. The best management practice for forest nursery waste composting is to use horse manure, or other additive materials with similar positive features, and forced aeration to ensure the rise in temperature high enough to kill weed seeds, plant and human pathogens. In consequence, the compost product can probably be used as a part of the growth medium for high-value plants. However, further research is needed before it can be used for horticultural applications.

Acknowledgements

We thank the staff of the Suonenjoki Research Unit and Nursery for their help, Central Laboratory of the FFRI for chemical analyses and the Department of Environmental Sciences in the University of Kuopio for microbial analyses. Special thanks to A. Heikkilä, M.Sc., K. Heikkinen, M.Sc., Ms. M-L. Jalkanen, Ms. S. Kolehmainen, Mr. J. Laitinen, Mr. E. Mölkänen, H. Ruhanen, M.Sc. and Mr. M. Udd for technical assistance. We also thank Dr. J. Heiskanen from FFRI for comments on the manuscript and J. Derome who revised the English. Financial support from the Foundation for Research of Natural Resources in Finland and Metsämiesten Säätiö Foundation is gratefully acknowledged.

References

Anttonen, S., Manninen, A.-M., Saranpää, P., Kainulainen, P., Linder, S. & Vapaavuori, E. 2002. Effects of long-term nutrient optimisation on stem wood chemistry in Picea abies. Trees 16: 386–394.

Airaksinen, S., Heinonen-Tanski, H. & Heiskanen, M.-L. 2001. Quality of different bedding materials and their influence on the compostability of horse manure. Journal of Equine Veterinary Science 21(3): 125–130.

Bernal, M.P., Paredes, C., Sánchez-Monedero, M.A. & Cegarra, J. 1998. Maturity and stability parameters of composts prepared with a wide range of organic wastes. Bioresource Technology 63: 91–99.

Berner, A. 1989. Composting – environmental effect of leachates. In: Djigma, A., Nikiema, E., Lairon, D. & Ott, P. (eds.). IFOAM conference, Ouagadougou 1989. p. 307–316.

Bertran, E., Sort, X., Soliva, M. & Trillas, I. 2004. Composting winery waste: sludges and grape stalks. Bioresource Technology 95: 203–208.

Bollen, G.J. 1984. The fate of plant pathogens during composting of crop residues. In J.K.R. Gasser (Ed.), Composting of agricultural and other wastes. Essex, Elsevier. p. 282–290.

Eriksson, K.-E.L., Blanchette, R.A. & Ander, P. 1990. Microbial and entzymatic degradation of wood and wood components. Springer-Verlag, Berlin. 407 p.

European Communities. 1998. Council Directive 98/83/EC on the quality of water intended for human consumption. Office Journal of the European Communities L330, p. 32–54. [Online Journal]. Available at: http://europa.eu.int/eur-lex/. [Cited 10 Jan 2006].

— 1999. Council Directive 1999/31/EC on the landfill of waste. Office Journal of the European Communities L182, p. 1–19. [Online Journal]. Available at: http://europa.eu.int/eur-lex/. [Cited 10 Jan 2006].

Fernandez, L. & Sartaj, M. 1997. Comparative study of static pile composting using natural, forced and passive aeration methods. Compost Science & Utilization 5(4): 65–77.

Finnish Forest Research Institute. 2004. Finnish Statistical Yearbook of Forestry. STV Agriculture, forestry and fishery 2004:45. [Online Publication]. Available at: http://www.metla.fi/julkaisut/index-en.htm. [Cited 10 Jan 2006].

Golouke, C.G. 1991. Principles of composting – understanding the process. In: The staff of Biocycle journal of waste recycling (eds.). The Art and Science of Composting. The JG Press, Inc. Emmaus, Pennsylvania. p. 14–27.

Gray, K.R., Sherman, K. & Biddlestone, A.J. 1971a. A Review of composting – Part 1. Process Biochemistry (June): 32–36.

— , Sherman, K. & Biddlestone, A.J. 1971b. Review of composting – Part 2. The practical process. Process Biochemistry (October): 22–28.

Grundy, A.C., Green, J.M. & Lennartsson, M. 1998. The effect of temperature on the viability of weed seeds in compost. Compost Science & Utilization 6(3): 26–33.

Haug, R.T. 1993. The practical handbook of compost engineering. Lewis Publishers, Boca Raton. 717 p.

Heinonen-Tanski, H. & Savolainen, R. 2003. Disinfection of septic tank and cesspool wastewater with peracetic acid. Ambio 32(5): 358–361.

Juntunen, M.-L. & Rikala, R. 2001. Fertilization practice in Finnish forest nurseries from the standpoint of environmental impact. New Forests 21: 141–158.

— , Hammar, T. & Rikala, R. 2002. Leaching of nitrogen and phosphorus during production of forest seedlings in containers. Journal of Environmental Quality 31(6): 1868–1874.

Killham, K. 1994. The Nitrogen cycle. In: Soil Ecology. Cambridge University Press. p. 108–141.

Koivula, N., Hänninen, K. & Tolvanen, O. 2000. Windrow composting of source separated kitchen biowastes in Finland. Waste Management & Research 18: 160–173.

Levanon, D. & Pluda, D. 2002. Chemical, physical and biological criteria for maturity in composts for organic farming. Compost Science & Utilization 10(4): 339–346.

Martins, O. & Dewes, T. 1992. Loss of nitrogenous compounds during composting of animal wastes. Bioresource Technology 42: 103–111.

Mathur, S.P., Owen, G., Dinel, H. & Schnitzer, M. 1993. Determination of compost biomaturity. I. Literature review. Biological Agriculture and Horticulture 10(2): 65–85.

Maa- ja metsätalousministeriö & Kasvintuotannon tarkastuskeskus. 2004. Soveltamisopas V. Kompostointi- ja biokaasulaitokset sekä lantaa teknisesti käsittelevät laitokset. [Online publication]. Available at: http://www.mmm.fi/el/julk/pdf/biokaasukompostilaitokset.pdf. [Cited 2 Dec 2005]. (In Finnish).

Mälkki, E., Sihvonen, K. & Suokko, T. 1988. The influence of human activity on groundwater. II Forest nurseries. National Board of Waters and Environment. Mimeograph 50. 37 p. (In Finnish with English summary).

Niemi, J., Heinonen, P., Mitikka, S., Vuoristo, H., Pietiläinen, O.-P., Puupponen, M. & Rönkä, E. (eds.). 2001. The Finnish Eurowaternet with information of Finnish water resources and monitoring strategies. The Finnish Environment 445. Finnish Environment Institute, Helsinki. 62 p.

Noble, R. & Roberts, S.J. 2004. Eradication of plant pathogens and nematodes during composting: a review. Plant Pathology 53: 548–568.

Parkinson, R., Gibbs, P., Burchett, S. & Misselbrook, T. 2004. Effect of turning regime and seasonal weather conditions on nitrogen and phosphorus losses during aerobic composting of cattle manure. Bioresource Technology 91: 171–178.

Poteri, M. 2003. Forest nurseries in Finland. In: Riley, L.E., Dumroese, R.K. & Landis, T.D. (eds.). National Proceedings: Forest and Conservation Nursery Associations – 2002. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT. p. 59–63.

Puumala, M. & Sarin, H. 2000. Lannan aumavarastointi. VAKOLAn tiedote 80/2000. Maatalouden tutkimuskeskus, Vihti. 25 p. (In Finnish).

Puustjärvi, V. 1991. Kasvu ja kasvun hallinta kasvihuoneviljelyssä. Kauppapuutarhaliitto ry, Mestari-Offset Oy, Vantaa. 287 p. (In Finnish).

Rannikko, M. & Hartikainen, H. 1980. Retention of applied phosphorus in sphagnum peat. Proceedings of the 6th international peat congress, Duluth, Minnesota, August 17.–23.1980. p. 666–669.

Raviv, M. 2005. Production of high-quality composts for horticultural purposes: a mini-review. Hort Technology 15(1): 52–57.

Ryckeboer, J. 2001. Biowaste and yard waste composts: microbiological and hygienic aspects – suppressiveness to plant diseases. Leuven, Belgium: Katholieke Universiteit Leuven, PhD thesis. 278 p.

Rynk, R. (ed.). 1992. On-farm composting handbook. Northeast Regional Agricultural Engineering Service -54, Cooperative Extension, Ithaca, NY. 186 p.

Sánchez-Monedero, M.A., Roig, A., Paredes, C. & Bernal, M.P. 2001. Nitrogen transformation during organic waste composting by the Rutgers system and its effects on pH, EC and maturity of the composting mixtures. Bioresource Technology 78: 301–308.

Ulén, B. 1993. Losses of nutrients through leaching and surface runoff from manure-containing composts. Biological Agriculture and Horticulture 10: 29–37.

Veijalainen, A.-M., Lilja, A. & Juntunen, M.-L. 2005. Survival of uninucleate Rhizoctonia species during composting of forest nursery waste. Scandinavian Journal of Forest Research 20: 206–212.

— , Juntunen, M.-L., Vänttinen, K. & Heinonen-Tanski, H. 1999. Metsätaimitarhojen jätehuolto – Ohjeita jätehuoltojärjestelyjen kehittämiseksi. Metsäntutkimuslaitoksen tiedonantoja 738. 59 p. (In Finnish).

— , Juntunen, M.-L., Lilja, A. & Tervo, L. 2007. Composting of forest nursery waste and nutrient leaching. Submitted.

Zucconi, F., Forte, M., Monaco, A. & de Bertoldi, M. 1981. Biological evaluation of compost maturity. Biocycle 22: 27–29.

Total of 42 references