

Properties of anaerobically digested and composted municipal solid waste assessed by linking soil mesofauna dynamics and nitrogen modelling

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Abstract We have studied the effect of anaerobically digested (ADMSW) and composted municipal solid waste (CMSW) on mineralization and foodweb dynamics to verify the hypothesis that ADMSW would immobilize N right after addition to soil in contrast to addition with CMSW. Another hypothesis was that the mesofauna (enchytraeids and microarthropods) would stimulate N release from the decomposer community. We measured excretion of NH_4^+ -N and urea-N from the mesofauna and hypothesized that enchytraeids would release urea. ADMSW and CMSW were amended to pots with sandy loam and barley. The pots were divided into treatments with or without mesofauna. Mesofauna, plant N and biomass, soil N and ergosterol (fungal biomass) were measured over a 113-day period of four equidistant samplings. Soil respiration, N mineralization and N release by the mesofauna were modelled from concurrent studies. ADMSW- and CMSW-treated soils initially (<20 days) immobilized N. The amendments did not increase plant growth substantially, and this was probably due to N-limitation in the early stages of plant growth. Enchytraeid abundance was about three times higher in ADMSW- than CMSW-

treated soils, indicating that ADMSW contained more labile compounds, bacteria, and microfauna. The mesofauna did not affect N-content, but the cumulated NH_4^+ -N excreted by the mesofauna was estimated to be substantial and about one-fifth of total plant N in ADMSW. An explanation for this discrepancy might be that in the absence of the mesofauna, other members of the detritivore and microbivore community performed the mesofauna's function. Neither enchytraeids nor microarthropods excreted urea.

Keywords Collembola · Enchytraeid · Enchytraeidae · Mites · Acari · Ammonia · Urea · Excretion · Barley · *Folsomia fimetaria* · *Protaphorura armata* · *Mesaphorura macrochaeta* · *Proisotoma minuta* · *Lepidocyrtus cyaneus* · *Sinella curviseta* · *Enchytraeus crypticus* · *Hypoaspis aculeifer* · Microcosm

Introduction

A range of studies have been published on the effects of composted municipal solid household waste (CMSW) on soil fertility and nutrient dynamics (Bernal et al. 1998; Gabrielle et al. 2005; Hartl et al. 2003; Leifeld et al. 2002; Niklasch and Joergensen 2001) but very few on the effects of anaerobically digested municipal solid household waste (ADMSW) (Bruun et al. 2006). The type of treatment and the transformation method applied to organic matter during the biodegradation process influence the quality and availability of nutrients of the final product. For example, N availability in compost is closely related to the maturity reached during composting (Bernal et al. 1998; Gallardo-Lara and Nogales 1987). The availability of nitrogen (N)

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for plant uptake from organic materials depends on (1) the content of N, (2) mineralization and immobilisation rates and (3) the synchronization of N release with plant requirements.

Amendments of organic waste can increase nutrient levels and promote soil health, for example by activation of natural plant pathogen predators (Gallardo-Lara and Nogales 1987; Zhang et al. 1998) and improve soil physical properties such as increasing porosity and pore connectivity, and thereby, improve living conditions for the soil fauna (Gallardo-Lara and Nogales 1987; Giusquiani et al. 1995).

It is well established that grazing by the soil fauna can affect the microbial community, the cycling of N and other plant nutrients. In this study, we focused on the role of the mesofauna comprising of enchytraeids, Collembola and mites because this group plays a functional role for decomposition processes in the soil (Coleman and Crossley 1996). Enchytraeids ingest microbes and labile organic matter and can affect soil structure through their burrowing activity and excrement production (Didden 1993). In contrast, soil dwelling microarthropods have no burrowing activities, and ingestion and assimilation of litter material plays a secondary role for most species (Hopkin 1997; Schneider et al. 2004). Microarthropods instead fulfil primarily two functions in the soil food web: the first, as secondary decomposers that feed predominantly on fungi and in part litter, and the second, as strict carnivores or omnivores feeding on mixed fungal-carnivore diets (Rusek 1998; Schneider et al. 2004). Ingestion of the various food sources releases plant available N. Quantitatively, the release of N by the mesofauna has been found to be modest in comparison to the release of N by microbes and protozoa in particular (de Ruiter et al. 1993). However, little data has so far been collected on the release of N by Collembola (Sjursen and Holmstrup 2004; Verhoef et al. 1988), and to our knowledge, none on enchytraeids and mites. Direct quantitative measurements can improve the understanding of the role and function of these animals for N mineralization. It has been documented that Collembola and earthworms, another member of the Oligochaeta like the enchytraeids, excrete N in NH_4^+ form (Edwards and Lofty 1977; Sjursen and Holmstrup 2004). Excretion of urea has also been documented in earthworms, but to our knowledge, not in enchytraeids or microarthropods. Hadley (1994) suggested that urea at best is a minor excretory product for terrestrial arthropods. Urea and NH_4^+ are both N forms that can readily be accessed by plants and therefore relevant for evaluating the direct contribution of plant available N by the mesofauna.

The aim of this research was to investigate how anaerobically digested waste and compost from municipal sorted waste, ADMSW and CMSW, respectively, affect the detrital food web, plant N uptake and nutrient dynamics.

For these purposes, microcosms were set up with barley and with or without enchytraeids and microarthropods. A larger amount of CMSW than ADMSW fertilizer was added to obtain similar N net releases in the two treatments over the plant growth period. The N mineralization and respiration dynamics were measured in a concurrent soil incubation study without plants and simulated to the temperature and moisture conditions in the microcosm study (Luxhøi et al. 2007).

We tested the following hypotheses: (1) Plant uptake of N in the CMSW treatment, would be restricted by a slow release of mineral N rather than immobilization by microflora. In contrast, the ADMSW treatment, would initially immobilize N which would be followed by a large release of plant available N as soon as the labile, readily available energy and nutrient sources were exhausted; (2) given that N was immobilized in the ADMSW treatment this would initially depress the plant growth; (3) as ADMSW is likely to contain more easily digestible molecules than CMSW, this would favour the enchytraeids, and their numbers would increase much more rapidly than in the CMSW treatment; (4) in contrast, the large addition of organic matter in the CMSW treatment might favour fungal growth and thus the collembolan food base. The fungal biomarker ergosterol, was used as an indicator for the fungal biomass; (5) as mesofauna release nutrients and is able to stimulate the microbial community by grazing, there would be a higher release of plant nutrients in the treatments with than without mesofauna; (6) we hypothesize that only the enchytraeids, and not the microarthropods, would release urea.

Materials and methods

Soil and amendments

The soil used in the microcosms was collected from the topsoil (0–20 cm) of an arable field at the experimental farm in Taastrup near Copenhagen that is managed by the Royal Veterinary and Agricultural University. The properties of the sandy loam soil (pH 7.0 with 0.01 M CaCl_2) are represented under control in Table 1. ADMSW was made from a mix of bark chips, mesophilic decomposed sewage sludge and kitchen organic waste (1:1:2, w:w) and was produced by Solum, DK in a 2.5-m² container for degassing over a 2-month period. ADMSW contained 62.5% dry matter (24 h at 105°C). CMSW was made by Vejle County Waste Treatment, DK, from 60% municipal solid waste and 40% garden waste (shredded to 10 mm) and composted over a 4-month period. CMSW contained 30.7% dry matter (24 h at 105°C). Soil and amendments were defaunated by three cycles of freezing (72 h at –18°C) and thawing (72 h at

Table 1 Content of total C and N in the amendments and soils (0–24 cm depth) at initiation

| Content | ADMSW ^a | CMSW ^b | Soil control | Soil w/ ADMSW | Soil w/ CMSW |
|------------------------|--------------------|-------------------|--------------|---------------|--------------|
| Total C (%) | 27.4 | 42.3 | 1.48 | 1.57 | 1.68 |
| g C m ⁻² | 262 | 1,630 | 4,300 | 4,570 | 5,970 |
| Total N (%) | 2.6 | 1.6 | 0.148 | 0.154 | 0.164 |
| g N m ⁻² | 24.9 | 61.6 | 431 | 449 | 477 |
| Total C:N ^c | 9.0 | 22.7 | 8.6 | 8.7 | 8.8 |

^a Anaerobically digested municipal solid household waste

^b Composted municipal solid household waste

^c By atoms

22°C). This treatment enabled the microflora, protozoa, and nematodes to recover after defaunation, while mesofauna and earthworms were killed (Bruckner et al. 1995). Soil was homogenized by sieving (≤ 8 mm), and the water content was 12.4%. Soil and fertilizers were stored 3–9 weeks before use at 4°C and -18°C, respectively.

Treatments and sampling

A total of 120 microcosms were initiated corresponding to five treatments, four sampling dates, 29, 57, 85 and 113 days, and six replicates. For practical reasons, microcosms were divided into six series comprising all the treatments at the initiation of the experiment. The series were initiated over a period of 6 weeks. The microcosms were plexiglass cylinders with a height of 35 cm and a volume of 2.43 l, and the lower 24 cm, equal to the soil height, was wrapped with aluminium foil. Defaunated soil was put in the microcosms and there were five treatments; (1) ADMSW with mesofauna, (2) ADMSW without mesofauna, (3) CMSW with mesofauna, (4) CMSW without mesofauna and (5) control with mesofauna. The soil was compacted to 1.25 g cm⁻³ (dry weight equivalent) for the bottom 14 cm and 1.15 g cm⁻³ for the top 10 cm. The water content was raised from 12.4 to 17.0% after compaction, which is equivalent to approximately 43% of the soil water holding capacity. The amendments were mixed homogeneously with the top 5 cm layer soil before addition to the cylinder. The amounts added were either 6.8 g dry weight (DW) ADMSW or 27.3 g DW CMSW (Table 1). Three spring barley seeds (*Hordeum vulgare*) were planted in each container right after soil addition. After 10 days, the most viable plant was retained and the rest were removed.

The fauna treatments consisted of the six collembolan species: *Folsomia fimetaria*, *Protaphorura armata*, *Mesaphorura macrochaeta*, *Proisotoma minuta*, *Lepidocyrtus cyaneus*, *Sinella curviseta* and the enchytraeid, *Enchytraeus crypticus*. They were added to the top of the microcosms. These species constituted the detritivore fauna. Twenty adult individuals of each species were added, except for *S.*

curviseta where only ten individuals were added. All species except *L. cyaneus* came from existing laboratory cultures. *L. cyaneus* was collected from the field by extraction of litter samples under light and transferred to Petri dishes. Twenty individuals of the predatory mite *Hypoaspis aculeifer* (15 females and 5 males) were added 1 week after adding the detritivores. The added numbers were estimated to be the minimum necessary to obtain a viable and reproductive population of each species in the microcosms. The initial densities were 15,850 collembolans m⁻² and 2,880 enchytraeids and mites m⁻², respectively.

The containers incubated in a greenhouse with a 15-h light and a 9-h dark cycle with daily average temperature ranging between 14.1 and 18.0°C with a mean of 16.1°C over the entire period. On sunny days, the temperature occasionally reached 35°C for a few hours. The microcosms were watered twice a week to maintain approximately the initial 17% soil water content. After watering, the containers were randomly relocated to obtain average identical ambient climate and light.

Mesofauna was determined in 0–5 cm, 5–10 cm and 10–24 cm soil layers at all four sampling occasions (completely balanced for all factors: treatments, layers, block and sampling occasions). The soil was sampled by pushing the bottom of the soil core through the top of the cylinder with a piston and slicing the core into the three layers. Soil from each layer was divided into different portions (75 g fresh weight for enchytraeids, 200 g fresh weight for microarthropods, 20 g fresh weight for ergosterol (top layer only) and 30 g fresh weight for C and N analysis). Enchytraeids were extracted by wet funnel extraction (O'Connor 1962) and microarthropods in a Macfadyen high gradient extractor (collection fluid: benzoic acid). Soil C and N were determined at 0 and 113 days only. The plant biomass (roots and shoots) was determined on all sampling occasions (completely balanced for all factors: treatments, block and sampling occasions). Roots were thoroughly washed. Plant material was oven-dried at 35°C until constant weight. Shoot N was analysed at days 57 and 113. The measured values were subsequently transformed to units per square meter on the basis of microcosm area.

NH₄⁺ and urea excretion by soil fauna

Excretion of NH₄⁺ and urea was measured on laboratory cultures raised on yeast or oat bran. The animals were transferred to new substrates 2 days before the measurement period to increase activity and oviposition. The following method was adapted from Sjørnsen and Holmstrup (2004). The animals incubated for 6 h at 21°C, and the number of microarthropods per sample ranged from 10–15 to 30–100 specimens (the smaller the species, the more numerous). Fifteen specimens per sample were used in the case of *E. crypticus*. The animals were incubated in containers with 1.0 g sand treated with 270 ml of buffer. After incubation, animals were removed and 4.0 ml water was added to the containers. The containers were subsequently sealed, shaken and frozen without any further treatment. In the case of NH₄⁺ analysis, 2.0 ml of the liquid were analysed with the salicylate–hypochlorite (Bower and Holm-Hansen 1980). Urea was measured on 5 µl samples using the 96-well QuantiChrom™ Urea Assay Kit (DIUR-500) procedure at 520 nm on an enzyme-linked immunosorbent assay (ELISA). There were six replicates per species including controls whose values were subtracted from those measurements with fauna.

Modelling of soil respiration, N-mineralization and soil fauna excretion

In a concurrent study (Luxhøi et al. 2007), respiration and net N mineralization were determined in a soil incubation experiment, conducted under constant temperature (15°C). The soil was not defaunated before incubation, as in the microcosm experiment, and there were no plants or fauna additions. The accumulated respiration derived from the amendments was fitted to an exponential model, and net N mineralization was predicted from the CO₂ respiration and C:N-ratio of the decomposing organic matter, as described by Bruun et al. (2006). To adjust the predicted respiration and net N mineralization to the more variable temperatures in the present microcosm study, the decay rates were modified according to $Q_{10}=2$.

The NH₄⁺-N excretion from fauna in the microcosm experiment was modelled by multiplying the estimated fauna biomass and NH₄⁺-N excretions. The microarthropod estimates in Table 2 are either based on length measurements of this experiment using the transformation values by Petersen (1975) or weight measurements of samples collected after 56 and 84 days in a preliminary microcosm experiment. The enchytraeid weight estimates were based on soil extracted animals sampled after 30 days where the animals had an average length of 4.6 mm. The biomass at each day was estimated by interpolating the numbers between each sampling occasion with linear regression and subsequently multiplying with the conversion values given in Table 2. The rate of *S. curviseta* was used for species not included in the N excretion experiment.

Chemical analyses and statistics

Both C and N were measured on a mass spectrometer (type 20-20) coupled to an ANCA-SL sample preparation module (both Europe Scientific, Crewe, U.K.). Ergosterol was extracted from 2.5 g fresh weight soil samples stored at –18°C and quantified fluorodensitometrically on CAMAG's TLC Scanner 3 according to the procedure described by Larsen et al. (2004).

Statistical analyses were performed using procedures of SAS/STAT (SAS Institute 1999). Before analysis, the data were checked for variance inhomogeneity by SAS/LAB (SAS Institute 1992). The model fitted to the data was a factorial mixed model with the fixed effects: type of fertiliser, animal additions and duration of incubation (months) and the random block effect variable named “series” and their first order interactions.

Results

Properties of solid waste, respiration and N-mineralization

The N-mineralization modelled from the soil incubation study show that both ADMSW and CMSW amendments

Table 2 Estimated mass of species (µg DW individual⁻¹) of the soil fauna in the microcosm study

| Day | <i>F. fimetaria</i> ^a | <i>H. aculeifer</i> ^a | <i>S. curviseta</i> ^b | <i>M. macrochaeta</i> ^a | <i>Sminthuridae</i> ^b | <i>P. armata</i> ^a | <i>L. cyaneus</i> ^b | <i>P. minuta</i> ^a | <i>E. crypticus</i> ^c |
|------------|----------------------------------|----------------------------------|----------------------------------|------------------------------------|----------------------------------|-------------------------------|--------------------------------|-------------------------------|----------------------------------|
| 0 | 7.50 | 8.95 | 21.7 | 1.69 | NA | 27.9 | 20.0 | 6.78 | 50.0 |
| 29 and 57 | 1.78 | 7.50 | 15.2 | 0.64 | 5.02 | 4.21 | 8.08 | 1.33 | 21.0 |
| 85 and 113 | 1.73 | 7.50 | 15.2 | 0.64 | 5.02 | 6.26 | 8.08 | 1.37 | 21.0 |

All values except those from day 0 are based on estimates.

^a Values transposed from weight measurements in preliminary microcosm studies

^b Converted from length measurements on representative samples using the transformation values by Petersen (1975)

^c Weight of animals with an average length of 4.6 mm

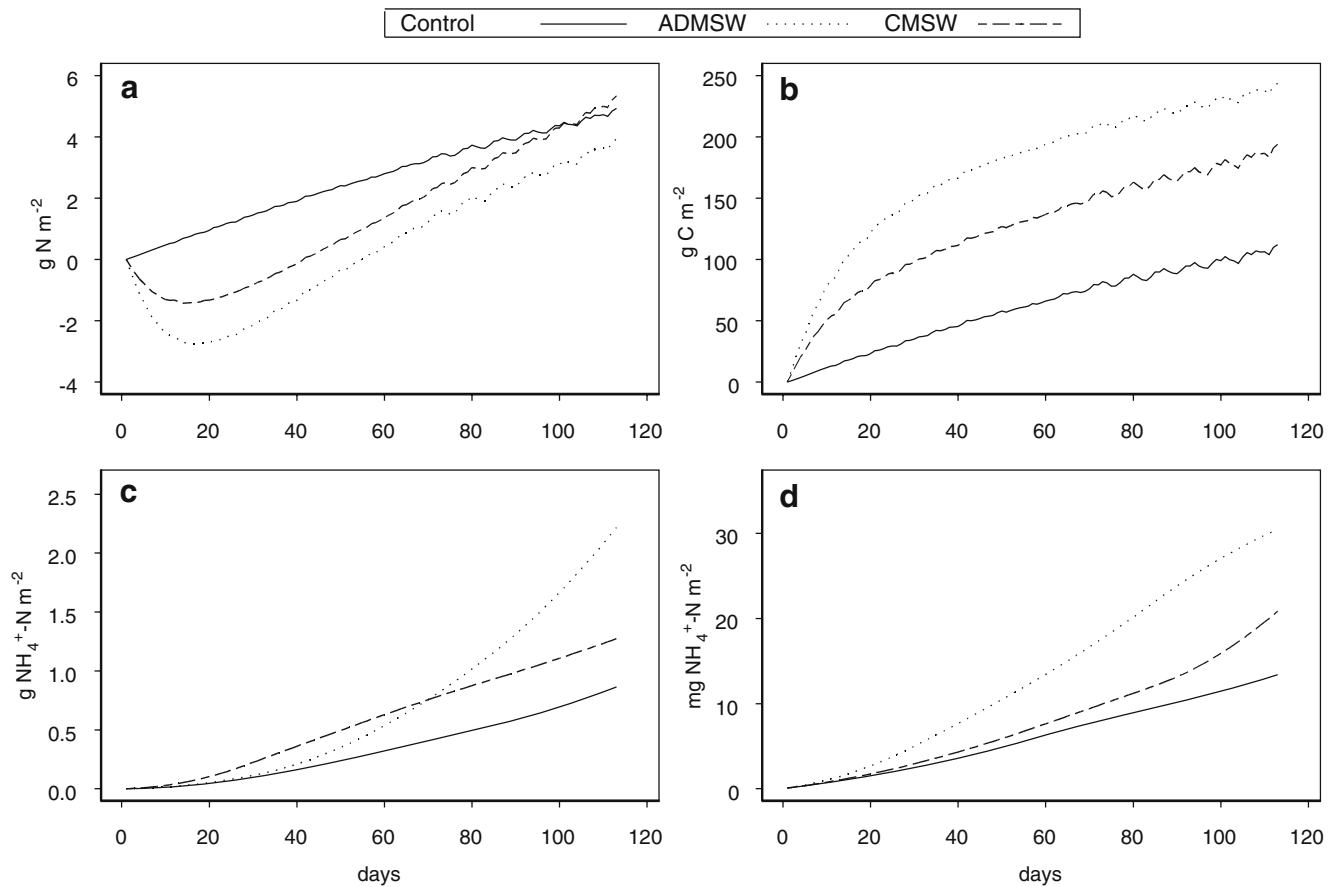


Fig. 1 Modelled cumulative N-mineralization (a), modelled cumulative respiration (b), modelled cumulative excretions by enchytraeids (c) and microarthropods (d) in control (no amendment), anaerobically

digested waste (ADMSW) and compost amended (CMSW) soils. The oscillations in (a) and (b) reflect daily temperature fluctuations

caused an N immobilization, which was largest for ADMSW (Fig. 1a). Both amendments had not mobilized or released more N than the control at the time of the last sampling, which is 113 days. The model for respiration (Fig. 1b) illustrates that ADMSW initially respired more than CMSW, which indicates a larger microbial activity. At 113 days, C losses in the ADMSW and CMSW amended soils accounted for 243 and 194 g C m⁻², which corresponds to 93 and 12% of the organic C initially added, respectively.

Incubation, plant growth and N-content

The variability of plant growth was high (Table 3) and about one-third of the plants did not reach stem elongation and inflorescence emergence and remained in a vegetative stage. No significant effect of mesofauna on plant growth and plant N was found ($p < 0.05$), so treatments with and without mesofauna were pooled in the subsequent analyses. The differences in plant biomass between were not significantly different ($p < 0.05$) except at 85 days where the plant yield of the control was significantly lower than that of the ADMSW

treatment (Table 3). Total plant N was similar among the treatments at 57 days. At 113 days, plant N in ADMSW was significantly higher than in the control (Table 3).

Effect of solid waste amendments on fauna and ergosterol

The biomass of the enchytraeids (Fig. 2a) was much higher than that of the microarthropods (Fig. 2b), the former making up between 98.1 and 99.6% of the total faunal biomass in all the treatments at the time of the last sampling, which is 113 days. The ADMSW-treated soil had significantly more enchytraeids than the control soil except at 29 days and had significantly more than the CMSW-treated soil at 85 and 113 days ($p < 0.05$). There were significantly higher numbers of microarthropods in ADMSW-treated soil than in the control soil except at the last sampling ($p < 0.05$, Fig. 3). In the CMSW-treated soil, there was a very large increase in microarthropod numbers between the 85 and 113 days sampling, resulting in significantly more microarthropods than those of ADMSW- and control-treated soils. On the species level, the few significant differences were limited to significantly more *L. cyaneus* and Sminthuridae in

Table 3 Plant dry matter, plant N (roots and shoots), and ergosterol (0–5 cm depth) and C and N (0–24 cm) contents of soil

| Analysis | Units | Day | Control | ADMSW ^a | CMSW ^b |
|------------------|-----------------------|-----|--------------------|---------------------|--------------------|
| Plant dry matter | g DW m ⁻² | 29 | 83.2 ^a | 88.3 ^a | 104 ^a |
| | | 57 | 595 ^a | 557 ^a | 634 ^a |
| | | 85 | 710 ^b | 1,080 ^{ab} | 1,170 ^a |
| | | 113 | 1,080 ^a | 1,390 ^a | 1,240 ^a |
| Plant N | g N m ⁻² | 57 | 5.94 ^a | 7.13 ^a | 7.22 ^a |
| | | 113 | 6.94 ^b | 10.4 ^a | 8.57 ^{ab} |
| | Percent N | 57 | 0.84 | 0.66 | 0.62 |
| | | 113 | 0.62 | 0.75 | 0.69 |
| Ergosterol | μg g ⁻¹ DW | 29 | 1.77 ^b | 5.49 ^a | 5.87 ^a |
| | | 57 | 1.94 ^b | 4.77 ^a | 4.65 ^a |
| | | 85 | 2.10 ^c | 3.73 ^a | 4.69 ^b |
| | | 113 | 1.81 ^b | 3.26 ^a | 4.07 ^a |
| Soil C and N | g C m ⁻² | 113 | 4,260 ^a | 4,510 ^b | 5,910 ^c |
| | g N m ⁻² | 113 | 425 ^a | 443 ^b | 476 ^c |

Treatments with and without fauna were pooled. Different letters apply to rows and signify significant differences between treatments (Tukey's test, $p < 0.05$, $n = 6$ for control, $n = 12$ for treatments with amendments).

^a Soil amended with anaerobically digested municipal solid household waste

^b Soil amended with composted municipal solid household waste

the ADMSW-treated soil than control soil at 29 and 57 days, respectively (Fig. 3, Tukey's test, $p < 5\%$). Sminthuridae were not added to the containers at the initiation, and their presence was probably due to survival after the mild freeze/thaw cycles of the soil. *P. minuta* was the most abundant microarthropod species ($p < 0.05$), and at the last sampling, it accounted for 71%, 68 and 78% of the overall numbers of control, ADMSW- and CMSW-treated soils, respectively (Fig. 3). No correlations were found between fauna abundance and plant growth in the different treatments. Ergosterol, which was measured in the 0–5 cm layers only, was not affected significantly by the soil fauna, and for that reason, the treatments with and without fauna were pooled (Table 3). Ergosterol concentrations were significantly higher in the treatments with amendments than in the control. Both the ADMSW- and CMSW-treated soils showed similar ergosterol contents except that the CMSW-treated soil had significantly more ergosterol than the ADMSW-treated soil at 85 days ($p < 0.05$).

NH₄⁺ and urea excretion by soil fauna

No urea excretion was recovered from enchytraeids, Collembola or mites. Ammonium excretion ranged from 0.44 μg NH₄⁺-N d⁻¹ mg DW⁻¹ for *H. aculeifer* to 5.57 μg NH₄⁺-N d⁻¹ mg DW⁻¹ for *M. macrochaeta* (Table 4). These species also represented the extremes of the microarthropod mass, but there was a weak correlation ($r^2 = 0.495$, $df = 33$, $p < 0.001$) between microarthropod mass and NH₄⁺-N

excretion. The NH₄⁺-N excretion by *S. curviseta*, for example, was significantly higher ($p < 0.05$) than that by *P. armata* in spite of the same weight of the two species. The values for NH₄⁺-N excretion were multiplied by the mean of biomass measured in the microcosm experiment and divided by the number of days (113) of the incubation period (Fig. 1c and d). Based on these estimates, the average excretion rates of NH₄⁺-N by the mesofauna were 7.8, 19.9 and 11.4 mg N m⁻² day⁻¹ for the control, ADMSW- and CMSW-treated soils, respectively. The modelled contribution of the enchytraeids was 60- to 70-fold larger than that by the microarthropods in all treatments. The amount of excreted NH₄⁺-N relative to the average N uptake by plants at 113 days was 12.6, 21.7 and 15.1% for the control, ADMSW- and CMSW-treated soils, respectively.

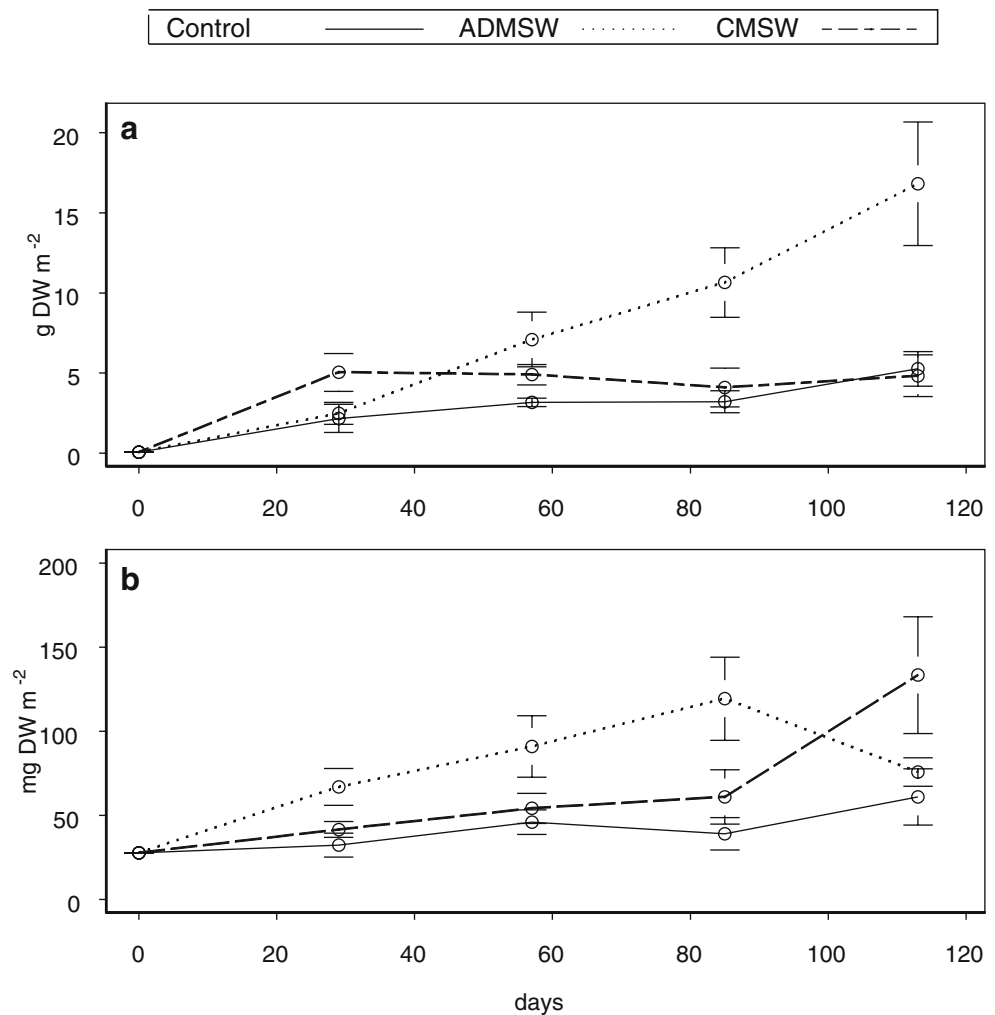
Discussion

Carbon and nitrogen mineralization and plant growth

Both types of solid waste immobilized N in the initial stage of decomposition, thus not supporting our first hypothesis that the compost, CMSW, was mature and would not immobilize N. The N-immobilization in the CMSW treatment indicates that it was not matured and still was metabolically active. The rate of mineral N release after the initial immobilization were similar between ADMSW and CMSW. The N-effects of fertilizers were similar to findings by Amlinger et al. (2003) who reported an N release ranging between 5 and 15% in the first year for compost amendments. The overall N mineralization between 3.1 and 5.2 g N m⁻² (Fig. 1a) is close to what were reported by de Ruiter et al. (1993), who found values ranging from 3.6 to 9.3 g N m⁻² after 113 days. Approximately 93% of the added C in ADMSW was respired in the ADMSW-treated soil, while it was only 12% of the C added in the CMSW-treated soil. Consequently, the gain in the organic C content in soil by the ADMSW amendment was small compared to CMSW amendments. The ADMSW contained a large fraction of easily degradable organic compounds that mineralized quickly following the first order kinetics in the early stages, after which there was no or little respiration.

Roughly one-third of plants did not reach the stage of stem elongation and inflorescence, which indicates that a factor independent of treatment hampered plant growth. Watering was done regularly, maintaining stable soil water content. The leaves did not bear any specific traits of micronutrient deficiency. Thus, our second hypothesis that an initial N-immobilization would depress plant growth was not verified, as growth was inhibited in all the treatments. The low plant N content ranging between 0.6 and 0.8% indicates that all treatments were N-limited (Malhi et al. 2006). Plant uptake

Fig. 2 Biomass means with standard error bars of enchytraeids (a) and microarthropods (b) in control (no amendments), anaerobically digested waste (ADMSW) and compost amended (CMSW) soils (control, $n=6$; ADMSW and CMSW, $n=12$)



of N greatly exceeded the estimated N-mineralization, which also supports that the systems were N deficient.

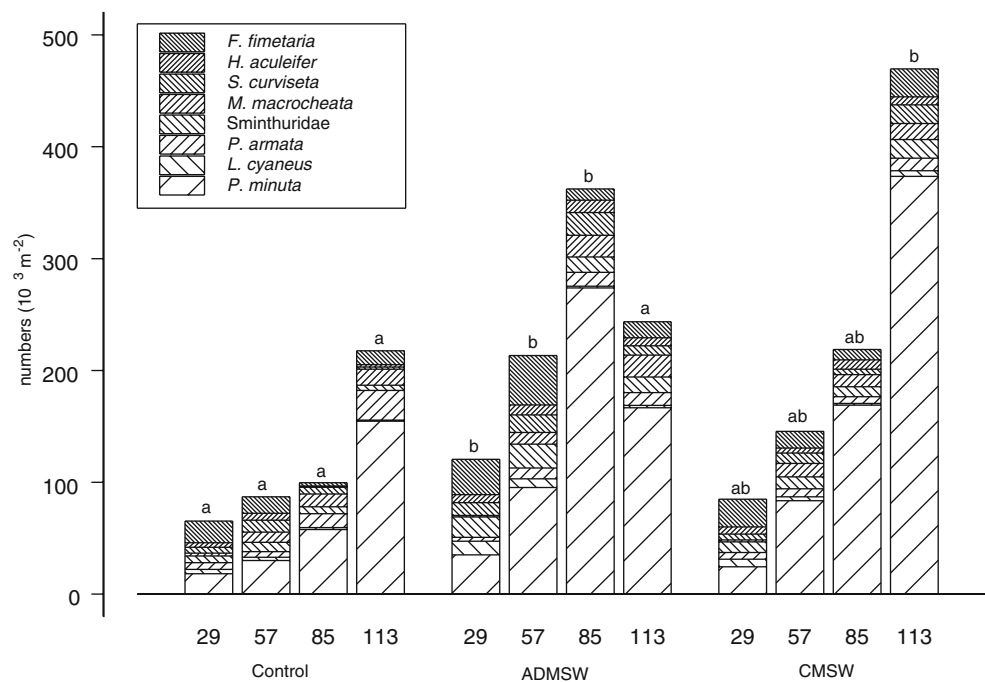
Mesofauna abundance and ergosterol

Our third hypothesis was that there would be a faster increase in enchytraeid numbers in ADMSW than CMSW from the assumption that the ADMSW treatment would contain considerably more easily digestible molecules than the CMSW treatment. However, the modelling of respiration did not support this hypothesis and the enchytraeid numbers were similar in the ADMSW- and CMSW-treated soils at the first two samplings. However, the population of enchytraeids in ADMSW-treated soil increased, and probably, this was a late effect caused by the initial high microbial activity (i.e., respiration) in the ADMSW-treated soils. Dead microbes might have been an important food source and/or that the microbial processing of the organic material increased the dietary value. The contribution of fungi, an essential food source for enchytraeids (Didden 1993), can be excluded as

the content of ergosterol was equal or significantly lower in ADMSW- than CMSW-treated soils.

No significant differences in microarthropod numbers were detected between the ADMSW- and CMSW-treated soils until 113 days when the numbers in the CMSW-treated soils exceeded that of the ADMSW-treated soils ($p < 0.05$). Fungal biomass, an important food base for Collembola (Hopkin 1997), could not explain the higher number of microarthropod in the CMSW-treated soil than in the ADMSW-treated soil at the last sampling at 113 days. Therefore, our fourth hypothesis that the treatment with the highest fungal biomass would support the highest microarthropod abundance was not supported. The late increase in microarthropod abundance in the CMSW-treated soil suggests that decomposition processes probably made organic materials more palatable (Berg et al. 2004) and increased nutrient accessibility due to textural effects (Giusquiani et al. 1995). It is also possible that Collembola fed on the smaller fauna such as nematodes (Chamberlain et al. 2006) increased by the CMSW treatment. In the

Fig. 3 Number of microarthropods of each species (control, $n=6$; ADMSW and CMSW, $n=12$). Different letters denote significant differences in total microarthropod numbers for the given sampling day (Tukey's, $p<0.05$)



ADMSW-treated soils, the decline in Collembola numbers after 85 days could be due to competition of enchytraeids feeding on the same food sources.

P. minuta outnumbered *F. fimetaria* and was by far the most abundant species. Cortet et al. (2003) and Filser and Krogh (2002) reported that *F. fimetaria* was the most abundant species in the absence of *P. minuta*. This variation of species dominance stresses the importance of using multispecies assemblages with different life strategies (Cortet et al. 2003).

Abundance for both enchytraeid and microarthropod abundance was higher than those of arable lands (Filser 1995; Petersen 2000) and comparable to that of sludge lumps

on arable land (Brandt et al. 2000). As such, the habitat in the current microcosm study can be considered as a “hot-spot” and cannot be compared to field habitat conditions.

Mesofaunal effects and N excretion

Our fifth hypothesis was that the inclusion of mesofauna would increase nutrient release and thus increase plant N and growth. This was not supported by the results, and we found no significant differences between the treatments with and without mesofauna. This result does not agree with what reported by Cole et al. (2000) and Petersen (2000) on increased N mineralization by microarthropods and enchytraeids but confirms what reported by Anderson et al. (1983) and Cole et al. (2000) who found that enchytraeids had no effects on the release of inorganic N from decomposing oak litter and organic upland soil. Similar patterns have also been observed for microarthropods (Andrén and Schnürer 1985; Ek et al. 1994; Mebes and Filser 1998). Mebes and Filser (1998) speculated that their results were due to the restricted incubation conditions where no migration occurred which could change mesofauna foraging from specialized to generalized. Another explanation can be found in that small microbivores such as nematodes and protozoa, to some extent, performed the function of the mesofauna (Brussaard et al. 1997).

In spite of the lack of mesofauna effects, the enchytraeids might have contributed to release mineral N. We estimated that the cumulated amount of excreted N was about one-fifth of the total plant biomass N in the

Table 4 Ammonium excretion and mean mass of mesofauna from the N-excretion study

| Species | $\mu\text{g NH}_4^+\text{-N d}^{-1}$ mg DW^{-1} | $\mu\text{g DW individual}^{-1}$ ($\pm\text{SD}$) |
|-----------------------|---|--|
| <i>F. fimetaria</i> | 3.68 ^b | 5.0 (1.4) |
| <i>H. aculeifer</i> | 0.44 ^c | 37.0 (6.0) |
| <i>S. curviseta</i> | 3.95 ^b | 10.0 (1.8) |
| <i>M. macrochaeta</i> | 5.52 ^b | 1.9 (NA) |
| <i>P. armata</i> | 1.10 ^{ac} | 10.0 (2.1) |
| <i>P. minuta</i> | 3.40 ^b | 4.1 (0.5) |
| <i>E. crypticus</i> | 2.73 ^a | 45.7 (8.1) |

Different letters indicate significant differences apply to column (Tukey's test, $p<0.05$, $n=6$)

ADMSW-treated soil. This calculation does not take into account that excreted NH_4^+ -N immobilized to organic N by soil microbes (Hodge et al. 2000). The estimated contribution of soil mesofauna to the mineral pool ($7.8 \text{ mg N m}^{-2} \text{ d}^{-1}$ in the control soil to $19.9 \text{ mg N m}^{-2} \text{ d}^{-1}$ in the ADMSW-treated soils) was above the estimates by de Ruiter et al. (1993) in an arable field with winter wheat. The total micro- and mesofauna contributions was estimated to be about $25 \text{ mg N m}^{-2} \text{ d}^{-1}$ in the 0- to 25-cm layer during the most active period, but the enchytraeids and microarthropods only contributed with less than $1.5 \text{ mg N m}^{-2} \text{ d}^{-1}$. However, the enchytraeid numbers were higher in our study than in the De Ruiter et al. (1993) study.

Our hypothesis that only the enchytraeids would release urea was not confirmed, as no urea was recovered from any species. An explanation for this might be that urea is excreted predominantly during starvation or in certain temperature ranges (Edwards and Lofty 1977). In contrast to urea, NH_4^+ was released at significantly different rates between the species. Probably, the species had different metabolic activities or N was excreted in other forms than NH_4^+ . Insects living in dry conditions excrete N as uric acid or degradation products of uric acid, allantoin and allantoic acid (Hadley 1994).

In conclusion, the modelling of N-dynamics enabled us to link several components and mechanisms in the soil system. Both anaerobically digested waste, ADMSW, and compost, CMSW, initially immobilized N indicating that little N was available for barley uptake. Probably as a result of N limitations, barley growth and N content were low in all treatments. However, both amendments greatly increased fungal biomass and mesofauna abundance compared to the control without amendments. The enchytraeids' abundance was highest in the ADMSW-treated soil. In spite of the high mesofauna abundance, plant growth or plant N content were similar between treatments with and without mesofauna. Nevertheless, NH_4^+ -N released by the mesofauna was estimated to be substantial and was about 20% relative to the amount of N taken up by barley in the ADMSW-treated soil. An explanation for the discrepancy between the apparently high release of NH_4^+ -N by the mesofauna and the lack of effects on plant parameters might be due to the fact that other members of the detritivore and microbivore community carried out the functions of the mesofauna in the treatments without mesofauna.

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