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Biodiversity of Compost Mesofauna and its Potential as an Indicator of the Composting Process Status

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ABSTRACT

One of the key issues in compost research is to assess the quality and maturity of the compost. Biological parameters, especially based on mesofauna, have multiple advantages for monitoring a given system. The mesofauna of compost includes Isopoda, Myriapoda, Acari, Collembola, Oligochaeta, Tardigrada, Hexapoda, and Nematoda. This wide spectrum of organisms forms a complex and rapidly changing community. Up to the present, none of the dynamics, in relation to the composting process, of these taxa have been thoroughly investigated. However, from the mesofauna, only nematodes possess the necessary attributes to be potentially useful ecological indicators in compost. They occur in any compost pile that is investigated and in virtually all stages of the compost process. Compost nematodes can be placed into at least three functional or trophic groups. They occupy key positions in the compost food web and have a rapid respond to changes in the microbial activity that is translated in the proportion of functional (feeding) groups within a nematode community. Furthermore, there is a clear relationship between structure and function: the feeding behavior is easily deduced from the structure of the mouth cavity and pharynx. Thus, evaluation and interpretation of the abundance and function of nematode faunal assemblages or community structures offers an in situ assessment of the compost process.

Keywords: Acari, Collembola, Isopoda, maturity, Nematoda, Myriapoda, Oligochaeta, succession

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INTRODUCTION

Composting is an aerobic, heat-producing, and controlled process by which a wide spectrum of organisms converts a mixed organic substrate into water; carbon dioxide (CO_2); inorganic nutrients; and stabilized sanitized organic matter (humus). In contrast to natural rotting or decomposition, the environmental conditions during composting (e.g., moisture, temperature, substrate composition, and oxygenation) remain controllable (Zucconi and de Bertoldi 1987; Sharma *et al.* 1997; Baldwin and Greenfield 2009). Composting is considered important for sustainable agriculture and partly solves the problem of organic waste treatment (Sharma *et al.* 1997; López *et al.* 2008). Multiple benefits of compost addition to the soil's physical and chemical characteristics have been reported extensively in recent literature and include increased soil organic matter content (Termorshuizen *et al.* 2004) and the subsequent improvement of soil aeration, soil porosity, drainage, and water holding capacity (Termorshuizen *et al.* 2004; Kuo *et al.* 2004; Cogger 2005; Baldwin and Greenfield 2009). Furthermore, compost can provide an important source of nutrients for plants by promotion of mineralization of compost nitrogen in the soil (Cogger 2005; Zvomuya *et al.* 2008). Composts are also known for their disease-suppressive activity based on both physicochemical and biological mechanisms (e.g., Akthar and Malik 2000; Gamliel *et al.* 2000; Reuveni *et al.* 2002; Vallad *et al.* 2003; Bailey and Lazarovits 2003; Kuo *et al.* 2004; Renčo *et al.* 2010).

One of the key issues in compost research is to assess compost maturity as the status of the compost determines ultimately the quality of the product and the associated advantages as mentioned above (Tognetti *et al.* 2007; Moral *et al.* 2009). Nevertheless, compost maturity is often loosely defined as the state when compost is dominated by humic substances (Dinel *et al.* 1996) or as the state where the temperature reaches a near-ambient level (Cooperband 2000). For the past decade, researchers have proposed multiple chemical and physical variables (Zmora-Nahum *et al.* 2005; Sellami *et al.* 2008) to assess maturity as well as biological parameters (Gomez *et al.* 2006). At present and to the best of our knowledge, none of the proposed tests reliably, consistently, and unequivocally quantify compost maturity (Rynk 2003). Other important characteristics that need to be considered for evaluation of proposed maturity tests are required expertise, necessary lab equipment, time, and costs.

Despite the fact that the compost fauna is not well known, interest in the ecological effects of composting has been growing and recently soil fauna is proposed as a potential tool to evaluate the ecotoxicology of compost (Kapanen and Itavaara 2001). However, the compost is comprised of fauna that can be used in assessing the maturity and quality of the compost. In general, biological parameters have enormous advantages for monitoring a given system, i.e., they are well correlated with ecosystem functioning, they respond sensitively to management practices and climate, and

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they illustrate the chain of cause and effect (Doran and Zeiss 2000). The surplus value of biological parameters in system monitoring holds true, especially for compost being the direct result of a biological process.

Compost supports a diversity of microbes (e.g., fungi, bacteria, actinomycetes, and algae), micro-fauna (protozoa), and mesofauna (mainly annelids, arthropods, and nematodes) (Cooperband 2000; Young *et al.* 2005). The microbes and micro-fauna are the chemical decomposers responsible for the organic matter decomposition through aerobic respiration, while the larger organisms (mesofauna) are the physical decomposers important for the (initial) mechanical breakdown of organic materials into smaller particles, thereby increasing surface area for microbial action (Cooperband 2000; Young *et al.* 2005) and/or mesofauna and occupying key positions in the compost food chain.

Although microbes execute the lion's share of the primary decomposition, mesofauna have multiple advantages over soil microbes and micro-fauna as an indicator for the quality and status of the compost. In general, mesofauna are more integrated in the food web by being one or two steps higher and their response to changes in the environment are more significant on a stable temporal scale because of their longer generation time, this way making it possible to distinguish between "real" environmental changes and transient nutrient flushes. In addition, some mesofauna groups (e.g., nematodes and mites) occur at more than one level in the energy pyramid and are representative of several levels of consumers.

In this paper, we provide an overview of the mesofauna found in compost and discuss for the potential for each taxon to be an indicator of compost quality and process status. In the second step, the use of effective indicators is further elaborated, based on nematodes as the most promising group.

MESOFAUNA IN COMPOST

Together with bacteria, fungi, and other microbes (e.g., actinomycetes), the mesofauna in compost form a complex food web or energy pyramid with primary, secondary, and tertiary levels of consumers. Obviously, the base of the pyramid or the energy source is made up of organic matter. All the levels above are populated, though not exclusively, by mesofauna. The mesofauna of compost includes Isopoda, Myriapoda, Acari, Collembola, Oligochaeta, Tardigrada, Hexapoda and Nematoda. This wide spectrum of organisms forms a complex and rapidly changing community that is not limited to a specific compost but can be found from vermicompost to mushroom compost and from small- to large-scale controlled or open-air composting processes. However, the available information on mesofauna from compost is limited and mainly only present in "gray" literature or from non-scientific works. Information on their presence relative to the stage of a compost process (thermophilic phase, cooling phase, and maturation phase) is virtually absent. This limited information on compost mesofauna, ranging from structuring or natural compost inhabitants to more accidental taxa, will be listed in the following text. The known compost taxa can hereby be roughly classified according to the following main focuses: 1) their direct and visible influence on the compost process (i.e., mainly Oligochaeta) and 2) merely accidental records from general biodiversity studies.

Within the phylum Annelida, earthworms occur in diverse habitats with a lot of organic material like manure, litter, and compost (Sharma *et al.* 2005). Earthworms are very important physical decomposers in the composting process because they maintain the aerobic condition in the compost by tunneling, and therefore mechanically partitioning the organic material while feeding on this material. As a consequence, they facilitate the transformation of nutrients into available forms and increase microbial activity (Devliegher and Verstraete 1995; Yakushev *et al.* 2009). When earthworms are artificially added to a composting process, the process is called vermicomposting. Many recent studies focus on this inoculation with epigeic earthworms and their potential to recycle organic waste materials into value-added products is well documented (e.g., Suthar and Singh 2008). Inoculation with earthworms accelerated the decomposition process (Manna *et al.* 2003), though the composting potential of different species in diverse compost situations remains to be investigated (Suthar and Singh 2008). In a study on forest litter decomposition by Manna *et al.* (2003), the compost potential of *Eisenia fetida* was clearly superior compared to other species (i.e., *Perionyx excavatus* and *Dicogaster bolaui*). At present, *E. fetida* is the most popular compost earthworm and is known under various common names, including redworms, brandling worms, and tiger worms. Owing to its recognized function in a compost process, *E. fetida* specimens are widely commercially available in temperate regions for use in vermiculture. Domínguez *et al.* (2001) investigated the biology and ecology of the earthworm *Eudrilus eugeniae*, which is indigenous in Africa but bred extensively internationally for the fish bait market. These researchers concluded that this earthworm species might be a good candidate for vermicomposting in tropical climates. Thus, earthworms have a well-known positive effect on compost, but they usually only reach high densities after inoculation and/or within specific controlled circumstances. Furthermore, they are not present in all stages of the composting process.

Mites (Acari) are commonly found in compost (Ødegaard and Tømmerås 2000). Smith *et al.* (1998) and Skoracka *et al.* (2002) provided an overview of the species found in the investigated composts (respectively in Canada and in Central Europe). Clift and Terras (1995) associated bio-indicator value with mites based on a reported range of mite fauna in most of their investigated mushroom composts. This study reported the presence of either red pepper mites (*Siteroptes mesembrinae*) and/or bacterial feeding mites (*Histiostoma feroniarum*) and associated these mites with the reduced mushroom yield. Clift and Terras (1995) believe these species can serve as an indicator species for poor pasteurization or conditioning in mushroom compost processes. Other encounters with mites (i.e., *Pygmephorus* sp., *Histiostoma* sp., and *Parasitus bituberosus*) in mushroom compost were reported by Al-Amidi (1995). Although the contributions of mites in the compost food web are not known, mites cover multiple levels of the food web, ranging from scavenging on organic debris to fungal feeding, bacterial feeding, and predators, and most likely can have a certain structuring effect on the compost process, but this is not yet studied.

Within the arthropods, beetles (Coleoptera) are the most diverse animal group and they can be found in almost all habitats, including compost (Ødegaard and Tømmerås 2000). Beetles might act as decomposers, fungivores, or as predators on other insects present in the compost (Ødegaard and Tømmerås 2000). Compost heaps can be very rich in beetle species: 273 species were found in compost from Lulea in northeastern Sweden (Lundberg and Persson 1973), >260 species in different composts from Uppsala in central Sweden (Palm 1979), and 225 species in seed-composts from Skane in southern Sweden (Baranowski 1978). A number of exotic beetle species (34) have been established in compost heaps in the Nordic countries during the 20th century. Ødegaard and Tømmerås (2000) hypothesized that the successful establishment of exotic species in compost habitats results from the increased frequency of introductions and warm, thermal stability in large compost heaps during the Nordic winter.

Woodlice (Isopoda) are saprophages that generally live in moist soil, but some species such as *Porcellionides pruinosus* and *P. sexfasciatus* live aggregated in compost and manure heaps (Achouri *et al.* 2008). Terrestrial isopods are principally consumers of organic debris in an ecosystem. However, according to Messelink and Bloemhard (2007), extreme populations of woodlice may cause serious damage to vegetables. But whereas populations of woodlice increased strongly in fresh compost, in mature compost they barely survived. Therefore, Messelink and Bloemhard (2007) stressed the importance of a complete compost process in order to manage woodlice populations at an acceptable level.

Centipedes (Chilopoda) and millipedes (Myriapoda) are another group of more accidental compost mesofauna. Centipedes are mainly carnivores (Wallwork 1976; Lewis 1981), while millipedes (Diplopoda) feed on plant materials and fragments of decaying organic material, though both groups are found in similar habitats. In urban areas, their common microhabitat is often extended by building stacks of materials like compost and garbage piles (Riedel *et al.* 2009). The distribution of *Oxidus gracilis* (millepedes) is connected with greenhouses and gardens with compost heaps in higher altitudes (Bergersen *et al.* 2006). Identified centipedes collected from compost heaps include *Geophilus proximus* and *Haplophilus subterraneus* (Rosenberg and Seifert 1977; Bergersen *et al.* 2006).

Gutiérrez and Mazo (2004) reported springtails (Collembola) from compost processed at the Corporación Universitaria Lasallista. More specific recordings were done by Fjelberg (1998) and Gisin (1960), who found *Hypogastrura manubrialis* and *H. purpurascens* in compost. Nowadays, springtail reproductions in compost products are often used to develop ecotoxicological tests (e.g., *Folsomia candida* (Crouau *et al.* 2002)) or to investigate the survival of potential biocontrol species after the addition in composts (e.g., *Protaphorura armata* (Sabatini *et al.* 2006)).

There also have been more isolated recordings of other Arthropoda taxa in compost. Gutiérez and Vera (2004) found five different families of ants in the compost of the Corporación Univeristaria Lasallista and Buddle (2010) reported compost heaps as typical habitats for pseudoscorpions. Goulson *et al.* (1999) found very large calyptrate fly populations associated with composting sites in the United Kingdom, probably caused by the abundance of warm decaying organic matter. Flies are, however, not involved in the decomposition process itself but use the compost heap as a breeding site.

Finally, tardigrades or water bears, exhibit a high tolerance to extreme environmental conditions such as temperature, making them a likely group to appear in compost. However, published recordings of Tardigrada in compost are scarce. Vargha (1995) described *Hexapodibius reginae* from compost and Hatamoto *et al.* (2008) recorded tardigrades in rice straw compost using DGGE analysis. Our own observations indicate the accidental presence of tardigrades in compost (observations in the framework of studies by Steel *et al.* 2010).

All the above mesofauna groups can be found in compost, but none of these groups is always found in all compost types. None of these groups can be found throughout all successive compost stages. Considering the population dynamics in relation to the composting process, none of the above taxa have been thoroughly investigated. According to the limited current knowledge, only nematodes (phylum Nematoda) occur in any compost pile that has been investigated and they are active in virtually all stages of the composting process (Steel *et al.* 2010). Recordings of nematodes in isolated compost samples were made by several authors, including Andrassy (1983), Anderson (1983), Gagarin (2000), Nadler *et al.* (2003), and Manso (2004). These primarily bacterivorous nematodes were recorded in general biodiversity studies, but their function within the compost process was not discussed. The structure and succession of the nematode community during the composting process was investigated for the first time by Steel *et al.* (2010).

Major shifts in species composition occur during the composting process (**Fig. 1**). At the beginning of the process (thermophilic phase), immediately after the heat peak, the nematode population is primarily built by bacterial-feeding enrichment opportunists (cp-1) (Rhabditidae, Panagrolaimidae, Diplogasteridae), followed by the bacterial-feeding general opportunists (cp-2) (Cephalobidae) and the fungal-feeding general opportunists (Aphelenchoididae). Thereafter, during the cooling and maturation stages, the bacterial-feeding predator opportunistic nematodes (e.g., *Mononchoides composticola*; Steel *et al.* 2011) became dominant. Finally, at the most mature stages, the fungal-feeding Anguinidae (mainly *Ditylenchus filimus*) were most prominent. Hence, nematodes are omnipresent during the composting process and the succession of nematodes is associated with major shifts in life strategies and feeding behavior.

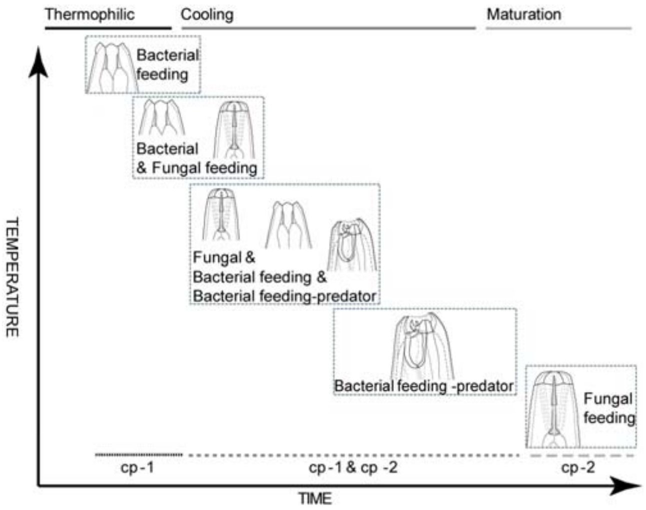

Fig. 1 Succession of nematodes during composting. Cp-1 are enrichment opportunists and cp-2 are general opportunists. Nematode feeding types are schematically presented by nematode heads of *Panagrolaimus* sp. (bacterial feeders), *Ditylenchus* sp. (fungal feeding), *and Mononchoides composticola* (bacterial feeding-predator).

POTENTIAL OF MESOFAUNA AS ECOLOGICAL INDICATOR IN COMPOST

Several authors have used microbial communities (bacteria and fungi) to evaluate compost maturity. For example, Eiland *et al.* (2001) analyzed phospholipid fatty acid (PLFA) profiles of compost microbial communities but concluded that there was no correlation with compost maturity. Conversely, Steger *et al.* (2003, 2005, 2007) and Ryckeboer *et al.* (2003) found typical changes in the microbial community but stressed the need for more studies on different composts. However, mesofauna has multiple advantages over microbial communities as indicators for the quality and status of compost. Firstly, it is very difficult and time-consuming to identify all bacteria, fungi, and protozoa in a sample and databases of biochemical profiles are either incomplete or inadequate, especially for free-living taxa. Secondly, by being one or two steps higher in the food chain, mesofauna serve as integrators of physical, chemical, and biological properties related to their food resources. Third, their generation time (days to years) is longer than metabolically active microbes (hours to days), making them more stable temporally and not simply fluctuating with ephemeral nutrient flushes (Neher 2001).

A successful indicator must be able to reflect a past ecological process or predict a future ecological process (Neher and Darby 2009). Therefore, an indicator should have as many as possible of the following qualities. For soil condition and according to Neher *et al.* (2005) and Doran and Zeiss *et al.* (2000), the indicator should 1) reflect the structure and/or function of ecological processes in the soil no matter what geographical location is sampled, 2) respond to changes in soil condition, 3) have available methodologies, 4) be comprehensible, and 5) be inexpensive to measure. Obviously, a thorough knowledge of the fauna used as an indicator is necessary; however, from the overview, it is clear that the knowledge of compost fauna is only fragmen-

Table 1 Overview of the mesofauna groups used as bio-indicator and their qualities.

	Mites	Collembola	Earthworms	Nematodes
Occurrence				
- Ubiquitous				X
- Large population size			X*	X
- Present on more than 1 level in food web	X	X		X
Function and Services in Ecosystem				
- Important role in N-mineralization				X
- Potential to regulate even suppress magnitude of resources	X		X	X
- Variable sensitivity to stress factors, from extremely sensitive to extremely tolerant			X	X
Practical Applicability				
- Easily extracted and cultured				X
- Easy observation				X
- Identification up to species level not needed	X			X
- Inexpensive techniques and methodologies	X	X	X	X

* When artificially added to the process.

tary. Nevertheless, some mesofaunal taxa present in compost, such as Collembola, mites, earthworms and nematodes, have already proven their potential as bio-indicators (**Table 1**).

Collembola and mites have been widely used to assess the impact of agricultural management practices and disturbances. For example, Barbercheck *et al.* (2009) reported differences in richness, evenness, and abundances of mites and proportions of collembolans among agricultural sites. Other examples for mites as a bio-indicator include Koehler (1999), Gulvik (2007), and Bedano and Ruf (2010) and for Collembola include Fiera (2009), Chagnon *et al*. (2000) and Baretta *et al.* (2008). Despite their potential as bio-indicators, the evaluation of their community assemblages is often limited (O'Neill *et al.* 2010), due to the high proportion of undescribed species (Coleman and Whitman 2005) and insufficient information on general biology, distribution, and functional roles (Bolger 2001; Greenslade 2007). Geissen and Kampichler (2004) also questioned the suitability of collembolan communities as indicators to determine the influence of amelioration measures on soil ecosystems in European forests because they could not find a relationship after five years of study. This limited literature review shows that there is no univocal consensus about the use of mites and Collembola as bio-indicators in terrestrial ecosystems. Hence, an extrapolation to compost is not evident.

Conversely, the potential of earthworms as indicators of environmental changes are more generally accepted. Their possibilities as bio-indicators are based on community changes (Tondoh *et al.* 2007) or on a quantifiable bioaccumulation of metals in their tissues (Suthar *et al.* 2008). However, earthworms do not occur in every composting stage and process and the accumulation of contaminations is not the main or only focus in assessing the compost status.

Unlike earthworms, Collembola, or mites, nematodes are ubiquitous, even in disturbed or polluted areas (Neher *et al.* 2005). Nematodes live beside the most diverse and abundant soil organisms and are the most important secondary consumers within soil mesofauna (Mulder *et al.* 2005). They have been extensively used as indicators of soil biodiversity and functioning (Neher 2001; Mulder *et al.* 2005) and as indicators of environmental disturbances in soil (Bongers and Ferris 1999; Ferris *et al.* 2001; Yeates 2003; Čerevková and Renčo 2009). Regarding compost nematodes, they can be placed into at least three functional or trophic groups (**Fig. 1**). They occupy key positions in the compost food web because they interact with the species providing their food (e.g., bacteria, fungi, etc.) and other organisms using the same food resources. They are also involved in predator-prey interactions (e.g., protozoa, fungi, and mites as well as nematodes) (Yeates *et al.* 2009). In these ways, changes in the food web are mirrored in shifts among nematode feeding groups (Yeates *et al.* 2009). Most importantly, nematodes show a rapid response, translated into proportions of functional (feeding) groups, to changes in the microbial decomposition pathway and the availability of food sources (Yeates *et al.* 1999; Brimecombe *et al.* 2001; Zelenev *et al.* 2004; Sánchez-Moreno *et al.* 2008), due to their relatively short generation time (Bongers 1990). In addition, the transparent nature of nematodes allows easy observation of the clear relationship between structure and function: their feeding behavior is easily deduced from the structure of the mouth cavity and pharynx (Bongers and Ferris 1999; Steel *et al.* 2010). Furthermore, the relative abundance and small size of nematodes makes sampling and extraction easier and less costly than for other soil fauna. Neher *et al.* (2005) and Sánchez-Moreno *et al.* (2009) validated the hypotheses that nematode-based soil food web indices are useful indicators of other soil organisms such as mites. Hence, nematode faunal assemblages theoretically have all of the properties needed to enable an optimal *in situ* assessment of the compost process, based on evaluation and interpretation of their abundance and function.

Steel *et al.* (2010) demonstrated that nematodes are effectively omnipresent during the compost process and the succession of nematodes is associated with major shifts in life-strategies and feeding behavior. Based on this remarkable succession of nematodes, nematode-based indices were calculated and followed during the composting process. Both the Maturity Index (MI; an index related to the proportion between K and r life-strategists) (Bongers and Bongers 1998) and the F/B ratio (fungivorous/bacterivorous ratio) (Ferris *et al.* 2001) increase as the compost becomes more mature. Based on these results, these indices were submitted as potential suitable tools to design an index to assess compost maturity (Steel *et al.* 2010).

However, in the future, the generality of these first promising results must be assessed by analyzing disparate composting processes with different feedstock materials. Importantly, the nematode characteristics must also be analyzed along with the microbial and abiotic data (temperature, pH, moisture content and C/N ratio) in order to provide a more profound insight into the precise relation/correlation of nematode community and the composting process. Finally, threshold values of the nematode-based ecological indices must be determined in order to obtain useful and reliable indicators indices of the maturity and quality of the compost.

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