ARTICLE IN PRESS

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Ecotoxicology and Environmental Safety ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Ecotoxicology and Environmental Safety

www.elsevier.com/locate/ecoenv

The use of earthworms in ecological soil classification and assessment concepts

J. Römbke[a,*], S. Jänsch[a], W. Didden[b]

[a]ECT Ökotoxikologie GmbH, Böttgerstrasse 2-14, D65439 Flörsheim, Germany
[b]Subdepartment of Soil Quality, Wageningen University, P.O. Box 8005, 6700 EC Wageningen, The Netherlands

Received 30 March 2004; received in revised form 15 June 2004; accepted 22 March 2005

Abstract

Without doubt, earthworms are the most important soil invertebrates in most soils worldwide, in terms of both biomass and activity. Several species are even considered to be ecosystem engineers. Earthworms are also known to influence soil structure, soil chemistry, and, in particular, processes like organic matter decomposition. In addition, standardized sampling methods are available and their taxonomy is well known (even the first PC-aided keys have been developed). For these reasons, earthworms were recognized as a part of ecological classification and assessment schemes early on. However, due to the relatively small number at many sites, they have to be part of a battery approach. By use of examples from The Netherlands (biological indicator of soil quality) and Germany (soil biological site classification), the practicability of the use of earthworms is demonstrated in determining the influence of different anthropogenic land use forms. In these cases, the structure of the earthworm community, as well as their abundance and biomass, were used as endpoints.
© 2005 Elsevier Inc. All rights reserved.

Keywords: Soil quality; Biodiversity; Soil biological site classification, BBSK; Biological indicator of soil quality, BISQ; Oligochaeta

1. Introduction

1.1. Aim of this article

In our modern society, soil has to meet several functions European Commission (EC, 2002), e.g., to buffer pesticides, nutrients, and metals, to enable agricultural production, and to support houses, streets, and railroads. In addition to these functions, which are directly useful to humans, soil also has to perform natural functions like being the substrate for natural vegetation and the habitat for soil organisms; i.e., it has to accommodate thriving microbes, animals, and plants (German Federal Soil Protection Act of 17 March 1998 (BBodSchG, 1998)). However, the biological assessment of soil quality is still at a preliminary stage; there is no commonly accepted procedure (see Beck et al., 2005; Breure et al., 2005). From an ecological point of view, assessment of the quality of soil as a habitat for soil organisms (i.e., the biodiversity of soil organisms) must integrate all possible stress factors. In addition, a soil ecological classification and assessment concept must also be able to differentiate between the myriad different ''natural'' soil types and those that have been adversely affected.

Different biological methods representing different approaches are available for the classification and assessment of soils. They often differ according to the anthropogenic stress. For example, for the assessment of the effects of pesticides or heavy metals, standardized laboratory and field tests are regularly used. Contaminated soil, often containing mixtures of chemicals, is investigated in laboratory tests and with field monitoring methods.

*Corresponding author.
E-mail address: j-roembke@ect.de (J. Römbke).

0147-6513/$ - see front matter © 2005 Elsevier Inc. All rights reserved.
doi:10.1016/j.ecoenv.2005.03.027

The latter approach is also used for the assessment of nonchemical stress factors like land use (e.g., agriculture).

In this contribution, ecological classification and assessment approaches using earthworms are described. The main reasons for the inclusion of earthworms are the important role played by these organisms in many soils (well known in the Northern Hemisphere but increasingly also recognized in tropical areas; see Section 1.2, Römbke et al., 2005), their size and mobility by which they integrate soil properties on a larger scale, the availability of standardized sampling methods (Section 2), and the increasingly common expertise with handling them on the community level (Section 3). Furthermore, lumbricids have already been used in various ecological classification and assessment approaches (Section 4). On the basis of this experience, the information available on the use of earthworms in such concepts has been compiled (including the provision of a practical example; see Section 5). However, it is stressed that efficient use of earthworm species is possible only when they are part of a battery approach.

1.2. Background: earthworm as an important group of soil macrofauna

Earthworms are important members of the soil community due to their ability to change their habitat or even create new habitats for other organisms through various activities (Brown, 1995; Maraun et al., 1999) and, thus, are correctly considered "ecosystem engineers" (Fig. 1; Petersen and Luxton, 1982; Jones et al., 1994; Lavelle et al., 1997; Edwards, 1998; Emmerling et al., 2002). They:

- penetrate the soil by building burrows as well as by increasing pore space;
- transport soil and organic matter by casting;
- comminute organic material as a first step in organic matter breakdown (including cattle feces in meadows);
- provide nutrients to plants (e.g., by concentrating them in burrow linings or by increasing the availability of nutrients like phosphorus);
- relocate seeds in the soil profile;
- change the diversity and improve the activity of the microbial community by selective feeding and provide feces rich in nutrients (e.g., 42% of the aerobe nitrogen-fixing, nonsymbiotic soil microbes are located close to worm burrows (= 1% of the soil volume)).

These activities improve soil structure, increase water infiltration (partly through greater water-holding capacity, Syers and Springett, 1983; Urbanek and Dolezal,

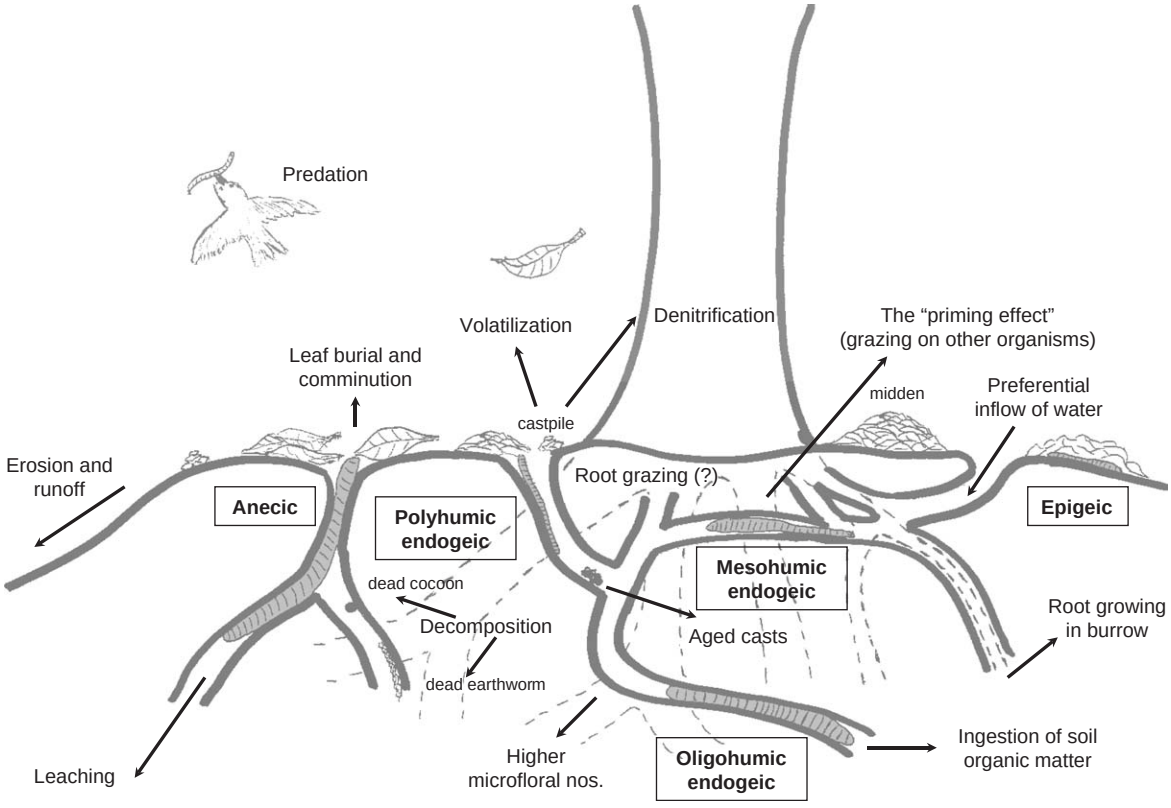


Fig. 1. Schematic representation of the functional relationships between earthworms and their external environment (drawing based on a figure by G.G. Brown (Doube and Brown, 1998, Fig. 1, p. 180).

1992; Edwards and Shipitalo, 1998), often resulting in formation of a humic layer close to the soil surface (mainly in forest ecosystems, Zachariae, 1965; Doube and Brown, 1998), and increase yield in orchards or grassland (e.g., Blakemore, 1997). In addition, it has been shown that earthworm activity (even by the compost worm *Eisenia fetida*) results in the formation of water-stable aggregates, thus decreasing the potential for soil erosion (Ziegler and Zech, 1992; Schrader and Zhang, 1997), in particular at crop sites with a low level of cultivation measures (Henke, 1994).

It must be remembered, however, that earthworms can also have detrimental effects on the soil. For example, earthworms can influence erosion by removing surface litter, which protects soil from the erosive impact of rain droplets (Edwards and Bohlen, 1996). Working in a hilly region of Luxembourg where many fields are located on slopes, Hazelhoff et al. (1981) and van Hoof (1983) reported that farmers complained about the loss of fertile topsoil due to the burrowing activity of *Lumbricus terrestris*.

Any activities described above are performed by various earthworm species to different extents. In temperate regions, most of the earthworms responsible for the activities described above belong to the family Lumbricidae (class Clitellata, phylum Annelida) (Zicsi, 1982). Undoubtedly some species, mainly large, deep-burrowing worms like *L. terrestris*, are involved in several of these activities (especially those involving soil structure and organic matter breakdown) (Swift et al., 1979), while small mineral dwellers like *Murchieona mammalis* have a negligible, or at least difficult-to-measure, effect (Edwards and Bohlen, 1996).

Following Bouché (1977), Lee (1985), and Edwards and Bohlen (1996), earthworms can be divided into three ecological groups (e.g., see Table 1):

- *Epigeics (litter inhibiters)*: These species live above the mineral soil surface, typically in the litter layers of forest soils (partly on tree bark), and do not burrow. They are small, reddish, quick-moving animals with short life cycles, and are under high predation pressure. They survive drought usually in the cocoon stage.
- *Anecics (vertical burrowers)*: These species live in permanent vertical burrows in mineral soil layers (up to 3 m deep). These worms are large and darkly colored on the dorsal side (at least the anterior body), and are able to rapidly withdraw but usually are slow moving. Relatively long-lived species with long life cycles, anecics are under high predation pressure when at the surface but are protected in the burrows. They survive drought usually in a quiescent stage.
- *Endogeics (mineral dwellers)*: These species inhabit mineral soil, making horizontal nonpermanent burrows, mainly in the uppermost 10–15 cm of soil. Endogeics are whitish, slow-moving animals of variable size and intermediate longevity and life cycle length, and are under relatively low predation pressure by surface-dwelling animals. They enter a diapause in response to drought.

Table 1
Ecological groups of relevant Central European earthworm species[a]

Epigeics	Anecics	Endogeics
Lumbricus rubellus	*Lumbricus terrestris*	*Aporrectodea caliginosa*
Lumbricus castaneus	*Aporrectodea longa*	*Aporrectodea rosea*
Lumbricus festivus	*Lumbricus polyphemus*	*Allolobophora chlorotica*
Dendrodrilus rubidus	*Dendrobaena platyura*	*Aporrectodea icterica*
Dendrobaena octaedra		*Proctodrilus oculata*
Dendrobaena illyrica		*Octolasion lacteum*
Dendrobaena attemsi		*Octolasion cyaneum*
Eisenia fetida		*Octolasion tyrtaeum*

[a]Dunger (1983) and see also Ehrmann (1996).

This classification has been viewed as too rough, as it does not consider experience in tropical areas where additional groups have been defined (e.g., Lavelle, 1979, 1984; Hendrix, 1998). It is possible to divide groups like the endogeics into several groups according to their feeding preferences. Also, subgroups within the epigeics like the corticoles, which live below the bark of trees or tree snags, have been identified (Lavelle, 1988). The composition of an earthworm community at a given site according to these ecological categories is a potential measurement endpoint for the biological assessment of soil quality.

The feeding behavior of worms is clearly correlated with their way of life (Lee, 1985):

- Epigeics feed on litter and/or the attached microflora and ingest little or no soil. Some species like *Lumbricus rubellus* and *Lumbricus castaneus* prefer litter, while most *Dendrobaena* species are often found close to rotten wood. A few species, best known among them *E. fetida* and *Eisenia andrei*, are specialists in places with a high organic matter content like compost.
- Endogeics feed on soil more or less enriched with organic matter and are thus often called geophagous. *Aporrectodea rosea* has been shown to actively distinguish between mineral and organic soil particles (like all endogeics?). Some might not differentiate between dead and living plant roots (Stephenson, 1930; Baylis et al., 1986), but probably the most important part of their diet is the attached microflora.
- Anecics feed at the soil surface by dragging leaves, etc., into the soil, some soil is also ingested. They prefer leaves rich in nitrogen and without tannins like lime tree (*Tilia tomentosa*), ash tree (*Fraxinus excelsior*), and sycamore (*Acer pseudo-platanus*).

Satchell (1983) described the behavioral, morphological, and physiological differences between those epigeic species living in the litter layer (e.g., *D. rubidus*, *D. octaedra*, *E. fetida*, *Eiseniella tetraeda*, *L. castaneus*) and the mineral-dwelling endogeics (e.g., *Aporrectodea limicola*, *A. caliginosa*, *A. longa*, *L. terrestris*) as being representative of two evolutionary lineages: r-selection versus K-selection. However, there are also some intermediate species like *A. chlorotica, A. rosea*, and *L. rubellus*.

To summarize the role of earthworms in soils, some species can be considered "keystone species" for this type of ecosystem. In addition, due to their interaction with microorganisms, the earthworm–microbe community has also been called a "keystone association" (Parmelee et al., 1998). In fact, the contribution of earthworms (e.g., with respect to decomposition of organic matter) is most important at sites with low-quality plant residues. Earthworms fragment the crop residues, inoculate them with microbes, and incorporate them into the soil (Hendrix, 1998). Parmelee et al. (1998) reviewed aspects of undesired earthworm activities (increased erosion, riddling of irrigation ditches, increased carbon loss through enhanced microbial respiration). Therefore, it is the net result of the positive and negative effects of earthworms that is important in determining whether or not they are detrimental to soil ecosystems (Hendrix, 1998).

1.3. Reasons for selecting earthworms for soil classification and assessment

To identify those animal groups that would be valuable in soil classification and assessment concepts, certain criteria can be used (e.g., Edwards et al., 1996; Römbke et al., 1996). Earthworms are generally regarded as highly suitable biomonitors because they fulfill these criteria (e.g., Abdul Rida and Bouché, 1995; Cortet et al., 1999; Paoletti, 1999; Stork and Eggleton, 1992). Their main advantages are:

- Nearly all earthworms are true soil inhabitants and many of them are key to ecosystem functioning, notably for decomposition and soil structure maintenance. Several species like *L. terrestris* (Lumbricidae) are considered ecosystem engineers (Lavelle et al., 1997).
- Earthworms are globally distributed, but at one site fewer than 20 species occur; i.e., such species numbers are practical. In Central Europe, usually up to 10 earthworm species are found at one site (Römbke et al., 1997).
- Identification keys are available, mainly for temperate regions. Like many parts of Europe (in particular Central and Northern regions) (e.g., Sims and Gerard, 1985).
- Breeding and handling of some species are easy.
- Standardized guidelines have been developed by OECD and International Organisation for Standardisation (ISO) for several levels of investigation (e.g., ISO, 1999).
- Because of their behavior and morphology, they are in contact with both the aqueous phase and the solid phase of the substrate.
- Most species are not extremely sensitive to low levels of contamination.
- Their reactions to stress are measurable and reproducible at various levels of organization, under both laboratory and field conditions.
- There is a vast and growing body of knowledge on their biology, ecology, and ecotoxicology, and oligochaetes are noncontroversial as test animals.

In addition, they are not highly mobile, with the exception of short periods in summer and winter fairly independent from short-term climatic events, long-living, and more dependent on soil properties than, e.g., predatory species (Bauchhenss, 1998). For these reasons earthworms have been included in all soil ecological classification and assessment concepts published so far (see Section 4). A disadvantage is the often quite small number of species which might complicate the differentiation between different sites or soil qualities. Therefore, and despite their overwhelming ecological importance, soil classification and assessment with earthworms alone is not possible (Muys and Granval, 1997).

Earthworms are sensitive indicators of anthropogenic stress factors (in particular chemicals). For example, they have been successfully used as bio-indicators for (at least): chemicals (e.g., pesticides, biocides, drugs) (Edwards and Bohlen, 1992; Edwards et al., 1996), mixed soil contamination (e.g., heavy metals, PAHs) (Carter et al., 1980; Emmerling et al., 1997; Stephenson et al., 1998; Hund-Rinke and Wiechering, 2001), physical factors (e.g., compaction, hydrology) (Pizl, 1992; Lowe and Butt, 1999), and land use (e.g., agriculture, forestry, orchards) (Lee, 1985). Earthworms are clearly suitable for use in soil classification and assessment approaches.

It should be stressed here that the effect of any stressor on oligochaetes depends on its bioavailability. A number of factors—physical, chemical, biological, temporal, and spatial—make it difficult, if not impossible, to estimate the bioavailability of a chemical from the concentration in soil or sediment (Sijm et al., 2000).

2. Sampling, extraction, and identification of earthworms

The most suitable method for sampling earthworms has been the subject of intense discussion for several decades (e.g., Zicsi, 1958; Raw, 1960; Lee, 1985; Dunger

and Fiedler, 1997; Edwards and Bohlen, 1996; Coleman et al., 1999). Passive (mainly hand sorting) and active (mainly formol extraction) methods for the sampling of earthworms were developed long ago (Bretscher, 1896; Raw, 1959), and because they were never standardized, various versions are known. Consequently, the results of different studies are difficult to compare. Recently, the ISO began to formulate a guideline describing the sampling of earthworms (ISO, 2004). In the following, an overview of existing sampling methods and a detailed description of ISO Proposal 23611-1 are presented.

2.1. The standard approach (ISO, 2004)

Referring to the literature cited above, it is clear that the most suitable standard method is a combination of hand sorting and formalin extraction. However, because this combination has been developed (and is still most often used there) in temperate regions, some modifications like the tropical soil biology and fertility (TSBF) method of this standard are necessary to cover specific situations (in particular the tropics). In addition, at sites without anecic worms, only hand sorting is sufficient, whereas at sites where mainly giant species are found, formalin extraction alone is fine. The aim of the standard method is to guide the sampling of large soil-inhabiting worms (few centimeters to more than 1 m in length) belonging to the order Oligochaeta (class Clitellata, phylum Annelida), e.g., species of the families Lumbricidae (Holarctic), Glossoscolecidae (Latin America), Eudrilidae (Africa), and Megascolecidae (Asia, North America). The standard is not applicable to semiterrestrial soils and might be difficult to be used under extreme climatic or geographic conditions (e.g., high mountains). In any case, the properties of the sampled soil (e.g., texture, pH, C/N ratio, organic matter content) should be determined. Sampling should be done at a time of year suitable for earthworms (e.g., in temperate regions usually spring and autumn, characterized by sufficient moisture and appropriate temperature).

Hand sorting is usually carried out in a sampling hole 50×50 cm ($= 0.25\,m^2$) and 10–20 cm deep. Both dimensions depend on soil properties and worm abundance at the sampling site and thus can vary. In addition, the aim of the study might influence the hole size and depth. For example, at sites with a very low earthworm density, larger holes (e.g., 1×1 m) are appropriate, while the opposite is true for sites with high densities, where holes of $1/8\,m^2$ or even $1/16\,m^2$ are recommended (Rundgren, 1975; Zicsi, 1958). In the first step, the soil is removed with a spade or shovel. Afterward, the removed soil is spread out on a piece of plastic (in the field or in a laboratory). Cautiously, the soil is then searched for earthworms (by hand or with forceps).

Formalin extraction is performed as follows: The same sampling plot used for hand sorting ($= 0.25\,m^2$) is employed. The concentration of formalin, often discussed in the past, is about 0.5%, achieved by diluting 25 mL formalin (37%) in 5 L water. The sampling is done by applying the formalin solution evenly in the sampling hole. This step is repeated until 20 L is added (the amount can be adjusted depending on the soil properties). During the application process and up to 30 min after the last watering, the hole is observed and all worms appearing are collected. The worms should be sampled by hand (using gloves) or with forceps.

After collection the worms are fixed immediately in 70% EtOH (e.g., in 250/500-mL plastic vessels) for at least half an hour but not longer than 24 h. Afterward the worms are kept in 4% formalin for 4 days (better: 1 or 2 weeks). At the end of this period the worms can be stored indefinitely in 70% EtOH. An alternative is immediate fixation of the worms in a mixture of 70% EtOH and 4% formalin (ratio: 98–2%). This liquid is replaced on the day after sampling at the latest. If the worms (or part of their tissue) should be used for genetic studies, ethanol must be avoided. Instead, pure formalin is recommended (Koshiba et al., 1993). In any case, care must be taken when using formalin (in particular, in closed rooms) to avoid danger from inhalation or skin exposure.

2.2. Modification of the standard approach

Like the ISO standard the "modified tropical soil biology and fertility (TSBF) method" (Anderson and Ingram, 1993) is based on a combination of hand sorting and formalin extraction. It is used for the sampling of whole macrofauna and also contains details of the sampling design (e.g., three plots per site with monoliths taken along a transect). It is characterized by the following steps: a separate treatment of the litter layer followed by hand sorting of soil monoliths ($25 \times 25 \times$ 15–30 cm) for macrofauna (body length >2 mm) under the most appropriate conditions (e.g., in the tropics: the end of the rainy season). The monoliths are divided into three layers. All worms (>10 mm) found in a 20-cm trench around the soil monolith are included. Afterwards, formalin (0.2%) is sprayed in the hole (10-min interval), and all collected worms are usually preserved in 4% formaldehyde.

Based on the experience gained during an ecological study near Manaus (Amazonas, Brazil), it became clear that the usual procedure was not appropriate due to the occurrence of giant earthworms (Glossoscolecidae longer than 100 cm) (Römbke et al., 1999). This modification is also useful at sites with a low earthworm density. It is characterized by the use of 2×2-m plots (approximate size, depends on local conditions). The litter layer is treated separately (i.e., it is removed and worms are

searched for before application of the formalin solution). The main step is application of the formalin solution (0.5%), up to 80 L per plot. In all other respects, the sampling process is the same as described above (e.g., fixation of worms).

Other methods not mentioned so far are considered not to be appropriate for the routine sampling of earthworms, either because they are not efficient compared with the standard method or because they require more research (Vetter, 1996). This statement is true for electrical sampling (Thielemann, 1986) and the use of other expellants like mustard (Gunn, 1992).

3. The handling of earthworms in soil ecological classification and assessment

3.1. Recommended taxonomic level

For the biological assessment of soils, the optimum taxonomic level would be the species level. Because of the relatively great effort needed to reach this level, in particular when handling large numbers of worms in monitoring programs, the genus level has been proposed as the most appropriate. However, for the following reasons, the species level is still recommended in the case of earthworms:

- The species within one genus are clearly different in terms of behavior, physiology, and ecological group (e.g., the anecic *L. terrestris* and the epigeic *L. castaneus*).
- The dependency of the species on soil properties like pH also varies.
- The small number of species in northern temperate regions, as well as the relatively good knowledge of their taxonomy, allows us to address the species level relatively easily.

Therefore, the proposal of Brauckmann et al. (1997) to determine not the species of the Central European Lumbricidae but only four genus groups is not necessary, at least not for adults. However, differentiation of juveniles is very time-consuming and often difficult to do by external characters, so determination of juveniles to the genus level is acceptable.

For more than a decade, it has been tried to facilitate species determination of earthworms by providing regionally differentiated electronic keys. The first example was made by Paoletti and Gradenigo (1997) for Northern Italy. More recently, Blakemore (2000) developed an elaborated program for the determination of the earthworms of Tasmania. However, up to now no easy-to-use program (e.g., like those of the LINNAEUS initiative as provided by UNESCO) is available today.

3.2. Earthworm (lumbricid) taxonomy and biogeography

It is not the aim of this article to give an exhaustive overview on the determination of earthworms. However, as a starting point, the following references (mainly addressing lumbricid and peregrine species) might help, particularly beginners: Introduction to Earthworm Determination: Ljungstrøm (1979); see also the homepage of the First International Oligochaete Taxonomy Meeting (IOMT), hosted by A. Moreno from the Museum of Madrid, Spain: http://www.ucm.es/info/tropico. Selected keys for some earthworm families can be found in Bouché (1972), Qiu and Bouché (1998b), Blakemore (2002), Csuzdi and Zicsi (2003), Graff (1953), Sims and Gerard (1985), and Støp-Bowitz (1969).

In Central and Northern Europe, about 25 (plus some introduced (= peregrine)) species are known in total (Csuzdi and Zicsi, 2003). For example, in two countries of roughly the same area, the numbers of species are also comparable. In Germany, 23 species are listed as common and another 12 as rare (Graff, 1953), whereas in England, the total number is 23 (Sims and Gerard, 1985). In Southern Europe, the number is much higher, probably because this area escaped the detrimental effects of the Ice Age (in southern France alone, at least 50 species are known, Bouché, 1972; Qiu and Bouché, 1998a). The earthworms had to recolonize these northern areas after the natural soil was destroyed by moving glaciers (Støp-Bowitz, 1969). Most of the species found in soils in northern temperate regions belong to the genera *Aporrectodea*, *Dendrobaena*, *Lumbricus*, and *Octolasion*.

It should be noted that the very large genus *Allolobophora* has been split in recent years into several new genera (sometimes with only one or two species), such as *Proctodrilus* (formerly *Helodrilus*; see Höser, 1997), *Murchieona*, and, most importantly, *Aporrectodea*. This process was continued by Mrsic (1990, 1991), who, partly based on the description of 21 new species from the Balkans, defined various new genera, e.g., by elevating three former subgenera (*Allolobophoriella*, *Panoniona*, *Serbiona*) to genetic rank or by retaining *Microeophila* and *Spermophorodrilus* as genera. It is too early to decide whether these far-reaching changes will fully be accepted by lumbricid taxonomists (for a historical overview, see Reynolds, 1995).

On a global scale the situation is more difficult. Knowledge of the native earthworm fauna of vast areas in the Americas, Africa, and Asia is very limited. The situation is probably best for the Caribbean and parts of South America (e.g., Fragoso et al., 1995; Righi, 1990), but the information is often very scattered and difficult to assess. As mentioned earlier, the only exception is the compilation of peregrine species, covering those earthworm species distributed by humans within the last five centuries (Blakemore, 2002).

3.3. Recommended endpoints

Because of the often very high variability of quantitative parameters like abundance and biomass in soil biology in space and time, the use of qualitative endpoints for the ecological classification and assessment of soils, in particular the species composition of the earthworm community, is recommended. This parameter is relatively independent of climatic or seasonal factors. In addition, it is known that stress factors like chemicals have influenced the dominance spectrum (e.g., Abdul Rida and Bouché, 1995). Despite the problems caused by the interpretation of quantitative parameters, it is appropriate to use the information on abundance or biomass, because usually at least a rough estimate is gained when performing a monitoring program. It is important not only to know whether a species was found at the site to be assessed but also to have an idea whether it is dominant or just occurring with a few individuals. For example, Beylich et al. (1994) and Graefe (1997) combined qualitative information on the occurrence of oligochaete species with data on the abundance of these worms. To make this approach more practicable, the abundance (in individuals/m^2) is classified into four classes. However, it must be noted that these data are difficult to compare with literature values because in a typical monitoring program only very few sampling dates are possible (no annual means are available).

4. Earthworm-based concepts

4.1. First ideas

The idea to use earthworms as indicators of soil quality is old. Ghilarov (1949) was probably the first to formulate such an approach. However, the first author who developed an entire concept of how to use earthworms (among other soil macrofauna) was Volz (1962). With his approach, called the pedozoological site doctrine, various forest sites were characterized, in two different ways. In one method, the biomass of at least six macrofaunal groups was used; in the second method, the earthworm species composition at these sites was used. By doing so, five forest groups could be distinguished: (I) areas with partly semiterrestrial character; (II) moist, darkly colored, humus-rich soils; (III) "fresh" alluvial soils; (IV) soils with a moder-type humus; (V) montanous forest soils. Problems related to this approach are the great effort needed to determine the biomass of the various macrofauna groups, as well as the negligence of the mesofauna. With the exception of Dunger (1968), this proposal was more or less ignored by the scientific community. Probably most important is the fact that in the early sixties there was no (legal, economical, environmental) use of such a concept as soil was not regarded or valued as an environmental compartment of its own.

Later, however, several ecological studies confirmed the close relationship between the occurrence of earthworm species and soil and site properties (e.g., Phillipson et al., 1976), but this information was not incorporated into a wider approach.

4.2. Further examples

In the nineties, independent of each other, comparable approaches using earthworms were developed in several European countries; these are briefly summarized here:

- About 30 years after Volz, a Dutch group defined ecotope/ecological species groups for, inter alia, earthworms in analogy to plant sociology (Sinnige et al., 1992). The main endpoint was the species composition of diplopods, chilopods, ants, collembolans, and oligochaetes. However, this approach was never put into practice.
- Slightly later, Heeb and Vetter (1995) developed a semiquantitative assessment concept, focusing exclusively on earthworm biomass and microorganisms (respiration, enzyme activity, and cellulose degradation). In this approach, many "undisturbed" sites (differentiated according to human use) were studied with respect to these parameters in Switzerland. These "observed values" were then compared with the actual value for the site to be assessed. The assessment is first done separately for earthworms and microbes, but in a second step the two results are integrated into one index. Up to now, this concept has not been used.
- More or less at the same time, a British group tried to work out a terrestrial concept parallel to the already accepted aquatic approach RIVPACS (see Breure et al., 2005), called Soil Invertebrate Prediction Classification Scheme (SOILPACS) (Spurgeon et al., 1996; Weeks et al., 1998). Earthworms (among others) were sampled at selected sites, e.g., to document the influence of heavy metals at a site in Wales. Sampling results were assessed using statistical methods like TwinSpan and discriminative analysis. However, because of the small number of data sets from reference sites in England, this project has not been considered further.
- Finally, a group working mainly in southern Germany focused its activities on earthworms and microorganisms in forests (Friedel et al., 1999; Vollmer et al., 1999). It is not known whether this approach has been used somewhere else.

4.3. Decomposer communities

Graefe (1993a, 1994, 1997) defined biological soil quality as a condition of the soil that emanates from the

interaction between all soil organisms, which is equivalent to the composition and activity of the soil decomposer community (= characteristic composition of litter-decomposing microorganisms and animals). As it is virtually impossible to describe this complex system completely, an indicator consisting of a part of the soil community that exhibits sufficient differentiation should be used (Beylich et al., 1994). For this, they proposed to use the composition of annelid communities, as these comprise both earthworms as key species in ecosystem functioning and smaller annelids (in terrestrial ecosystems mainly enchytraeids) that, by their higher abundance and diversity, allow a more sensitive differentiation between sites. By use of an adaptation of the system of indicator values coming from plant sociology (Braun-Blanquet, 1964; Ellenberg et al., 1992) to annelids, both qualitative and quantitative descriptions of the annelid community as an indicator were possible (e.g., Graefe, 1997, 1998, 1999; Graefe and Belotti, 1999; Graefe et al., 1998). The definitions of indicator values are intentionally diffuse (no concrete numbers are given) to reflect the "continuum in nature" (Graefe and Schmelz, 1999). This method has regularly been used in Germany to assess sites and the anthropogenic impact on soil (e.g., Beylich et al., 1994; Graefe, 1993b), always with earthworms and enchytraeids together. Because of the small number of earthworm species in Germany, lumbricids alone are not sufficient.

Likewise, Irmler (1999) was able to characterize earthworm communities from various habitats based on the abiotic soil parameters moisture, pH, calcium, carbon, and C:N. Such data may be used for the development of an indicator system because they allow, at least in principle, a comparison of the potentially occurring community with the actual one. Yet, because of the inherent complexity in field studies of oligochaete communities with respect to the relations between community composition, soil characteristics, and management practices, it is often problematic, if not impossible, to ascribe changes recorded to any particular factor or factors (e.g., Tarrant et al., 1997).

4.4. Earthworms within BBSK and BISQ

As described more in detail in Breure et al. (2005), the concepts soil biological site classification (BBSK) and biological indicator of soil quality (BISQ) have been developed independently in Germany and The Netherlands (Römbke et al., 1997; Schouten et al., 1997). An example of how to use earthworms within the BBSK concept is given in Section 6. The experience gained with earthworms in a pilot project of BISQ in which 20 grasslands on clay and 17 horticultural farms were sampled as part of the Dutch Soil Quality Network (DSQN), can be summarized as follows (Table 2): Earthworm characteristics, notably abundance and biomass (only 28.6% and 39.7% of the numbers at the ecological farms were found at the sites of the network), contributed considerably to the observed type and management practices, while the percentages of epigeic and endogeic species were less indicative (70% and 60%, respectively) (Schouten et al., 1999).

Table 2
Amount of earthworms in conventional grassland farms on marine clay relative to an ecological farm on the same soil[a]

	Average in network	Ecological farm	%
Abundance (number m^{-2})	318	1113	28.6
Biomass ($g\,m^{-2}$)	70	177	39.7
Endogéeic taxa	2.1	3	70.0
Epigéeic taxa	1.2	2	60.0

[a]Data from Schouten et al. (2000).

The first step in using one of these elaborate classification and assessment concepts is the derivation of expectation values; i.e., it must be known how many and which species may be present at a given site under its specific conditions (in particular, land use and soil properties).

5. The derivation of expectation values

5.1. Introduction

Expectation values for earthworms can be derived by using different methods. Three are now described in detail, based on literature data and experience gained in a German project in which more than 20 sites were sampled (Römbke et al., 2002):

(1) correlation of species occurrence with five soil properties (pH, texture, C/N ratio, C_{org}, and moisture);
(2) identification of typical indicator species (i.e., appearance: yes or no);
(3) comparison of abundance values per site with mean abundance values per site type.

The first option is considered to be the ecologically most relevant. Despite the fact that an enormous amount of literature data linking the occurrence of lumbricids with soil property data is available, this information has not been adequately evaluated, due mainly to the sheer amount of data often difficult to compare.

Other methods, such as comparison of the abundance of lumbricids at individual sites with mean values derived from the literature, the distribution of worms

among the three main ecological groups, or the use of dominance values, are additional options that have to be analyzed in detail in the future (Vollmer et al., 1999). Unfortunately, defining expectation values by means of dominance distribution or by assignment on the basis of reproduction strategy (r/K continuum), followed by computation of an index, as has been done for nematodes and gamasid mites (see Mulder et al., 2005; Ruf and Beck, 2005) is not feasible for earthworms because of the very small number of species usually present at one site.

5.2. Dependency on the five soil properties

In Table 3, first estimates of the expectation values for five soil properties are compiled for the 15 most frequently observed lumbricid species of Central Europe. These values are based on the following references:

Germany: Auerswald et al., 1996; Bauchhenss, 1997; Brauckmann et al., 1996, 1997; Broll and Brauckmann, 1994; Ehrmann and Vollmer, 1997; Keplin et al., 1995; Keplin and Broll, 1997; Kühle, 1986; Nagel, 1996; Philipp, 1990; Römbke et al., 2000; Vollmer et al., 1999.

Belgium: Muys and Granval, 1997.

France: Bono, 1984; Bouché, 1972; Qiu and Bouché, 1998a; Ponge and Delhaye, 1995.

Information provided in analogy to vegetation sociology (i.e., the preference of a species for a relatively defined moisture level or pH range) could not be recalculated in a way that these data could be compared with absolute moisture or pH values (Graefe, 1993a; Muys and Granval, 1997). Data on the same species but from sites outside of Central Europe were not included at this stage (e.g., Briones et al., 1995; Glasstetter, 1991; Pop, 1997; Sanchez et al., 1997).

Despite the availability of data for all five properties, their resilience is different. Clearly, knowledge of pH preferences, based on laboratory as well as field studies, is quite good (e.g., Satchell, 1955; Bouché, 1972; Nordström and Rundgren, 1974). Recently, the occurrence of four common lumbricid species in northern Germany with respect to soil pH was elaborated (Graefe and Beylich, 2003). To a smaller extent, the same is true for the C/N ratio (e.g., Bouché, 1972; Kühle, 1986). On the other hand, the correlation between occurrence of earthworm species and organic matter content is weak. This is partly due to the fact that it is difficult to clarify which layer—which part of the litter layer or of the mineral soil—and, therefore, which value is most relevant for the respective species.

Surely the moisture is the most problematic soil property. In the work cited here (Römbke et al., 2002), an ecologically relevant "moisture factor" (NFKWe (= utilizable field capacity of the root zone) plus precipitation) was calculated. Unfortunately, it is very rarely cited in the literature. Even though it was not possible to get expectation values for this moisture factor from the literature, a first estimation was tried (see Table 3). In addition, data on the moisture preferences of individual species are quite inconsistent: For instance, in laboratory tests *Aporrectodea trapezoides* (= *A. caliginosa*) reacts very different to soil

Table 3
Expectation values for important earthworm species in Central Europe with respect to the five selected soil properties

Species	Soil texture	pH value	Moisture factor	C/N ratio	Organic matter (%)
A. caliginosa	Sand, silt, loam, clay	>4.5–7.5 (?)[a]	Very low to medium	<10 to >20	<2–8
A. chlorotica	?	>4.5	Medium to high	>10 to >20	>4
A. limicola	Loam	>3.5–6.5	High	>10–20	<2–8
A. longa	Silt, loam, clay	>5.0	Low to medium	<10–20	>2
A. rosea	Silt, loam, clay	>4.5	Low to medium	<10–20	>2
D. attemsi	?	>3.5–5.5	Low to medium	?	?
D. octaedra	Sand, silt, loam, clay	<3.5–4.5	Low to medium	<10 to >20	>8
D. rubidus	Sand, silt, loam	<3.5–4.5	Low to medium	<10–20	>4
E. fetida[b]	Compost	>4.5	Low to medium	>10–20	>8
E. tetraeda[b]	?	>4.5	High	>10–20	?
L. castaneus	Silt, loam, clay	>3.5	Low to medium	>10 to >20	>4
L. eiseni[b,c]	?	<3.5–4.5	Low to medium	>10–20	>4
L. rubellus	Sand, silt, loam, clay	<3.5>	Low to high	>10 to >20	>4
L. terrestris	Silt, loam, clay	> 4.0–0.5 (?)	Low to medium	>10 to >20	>4
O. cyaneum	Loam	>3.5–6.5	Medium to high	<10 to >20	<2–8
O. tyrtaeum	Loam, clay	>4.5	Medium to high	<10–20	>2–8

Note: In the original publication in this table class numbers were used. Information from Graefe and Beylich (2003) is also included.
[a]?, no data available.
[b]In specific biotopes: compost, below bark, or shores.
[c]New name: *Allolobophoriella eiseni*.

water depending on the clay content, whereas for the closely related species *A. rosea*, the soil moisture tension of the soil is decisive (Doube and Styan, 1996). However, extrapolation of laboratory data to the field is difficult: At two Canadian sites the occurrence of *A. rosea* is determined primarily by soil water content (Thomson and Davies, 1974).

The dependence of the occurrence of earthworm species on soil texture is difficult to classify, because in the literature it is usually the correlations between texture and abundance or biomass that are studied, not the occurrence itself. For example, at crop sites a positive correlation between abundance of earthworms and clay content (up to 25%) was observed, but the reason may be that moisture and organic matter content are often higher in clay soils (Nagel, 1996). Naturally, there is less dependence on soil texture in epigeic species like *Dendrobaena* sp. than in endogeic or anecic species.

By use of the information provided in Table 3, the earthworm species probably occurring at certain site types in Central Europe can be predicted. In Table 4, those species that should be there and those that may be there are listed, differentiated according to 28 site types (four crop sites, eight meadows, and 16 forests). These site types are defined according to their land use (crop sites, meadows, and forests) and then by the most important soil properties per use group (mainly pH values, moisture, texture).

5.3. Identification of indicator species or groups

It has long been known that typical combinations of earthworm species occur with certain combinations of soil properties. For example, in Central European beech forests, two species groups were identified very early (Bornebusch, 1930; Satchell, 1983):

- a mull group containing the species *L. terrestris*, *A. caliginosa*, and *A. rosea* plus, more rarely, *A. longa* and *O. cyaneum*, i.e., mainly large endogeics and anecics;
- a mor group containing the species *D. rubidus*, *D. octaedra*, and *L. rubellus* plus *Lumbricus* (now

Table 4
Classification of earthworm species by site[a]

Site type	Site type definition	Main species	Possible species
A I	Sand, pH < 5.0	*L. rubellus*	*A. caliginosa*
A II	Sand, pH > 5.0	*A. caliginosa*, *L. rubellus*	*A. chlorotica*
A III	Other texture, pH < 5.0	*L. castaneus*, *L. rubellus*	*A. limicola*, *O. cyaneum*, *O. tyrtaeum*
A IV	Other texture, pH > 5.0	*A. caliginosa*, *A. rosea*, *L. castaneus*, *L. rubellus*, *L. terrestris*	A. chlorotica, *A. limicola*, *A. longa*, *O. cyaneum*, *O. tyrtaeum*
G I	Moist, pH < 5, sand	*L. rubellus*	*E. tetraeda*
G II	Moist, pH > 5, sand	*A. chlorotica*, *L. rubellus*	*A. caliginosa*, *E. tetraeda*
G III	Moist, pH < 5, other texture	*L. rubellus*, *O. cyaneum*, *O. tyrtaeum*	*A. limicola*, *E. tetraeda*
G IV	Moist, pH > 5, other texture	*A. chlorotica*, *A. limicola*, *L. rubellus*, *O. cyaneum*, *O. tyrtaeum*	*A. caliginosa*, *E. tetraeda*
G V	Not moist, pH < 5, sand	*L. rubellus*	*A. caliginosa*
G VI	Not moist, pH > 5, sand	*L. rubellus*	*A. caliginosa*, *A. longa*
G VII	Not moist, pH < 5, other texture	*L. rubellus*, *A. rosea*, *L. castaneus*	
G VIII	Not moist, pH > 5, other texture	*A. caliginosa*, *L. rubellus*, *A. rosea*, *L. castaneus*, *L. terrestris*	*A. caliginosa*, *A. longa*
W I	pH < 4.5, sand, moist	*L. rubellus*, *D. octaedra*, *D. rubidus*	
W II	pH < 4.5, silt, moist	*L. rubellus*, *D. octaedra*, *D. rubidus*	
W III	pH < 4.5, loam, moist	*L. rubellus*, *D. octaedra*, *D. rubidus*	*A. limicola*
W IV	pH < 4.5, clay, moist	*L. rubellus*, *D. octaedra*	
W V	pH < 4.5, sand, dry	*D. octaedra*, *D. rubidus*, *L. rubellus*	
W VI	pH < 4.5, silt, dry	*D. octaedra*, *D. rubidus*, *L. castaneus*, *L. rubellus*	
W VII	pH < 4.5, loam, dry	*D. octaedra*, *D. rubidus*, *L. castaneus*, *L. rubellus*	
W VIII	pH < 4.5, clay, dry	*D. octaedra*, *L. castaneus*, *L. rubellus*	
W IX	pH > 4.5, sand, moist	*L. rubellus*	*A. caliginosa*, *A. chlorotica*
W X	pH > 4.5, silt, moist	*L. rubellus*	*A. caliginosa*, *A. chlorotica*
W XI	pH > 4.5, loam, moist	*A. limicola*, *L. rubellus*, *O. cyaneum*, *O. tyrtaeum*	*A. caliginosa*, *A. chlorotica*
W XII	pH > 4.5, clay, moist	*L. rubellus*, *O. cyaneum*, *O. tyrtaeum*	*A. caliginosa*, *A. clorotica*, *L. terrestris*
W XIII	pH > 4.5, sand, dry	*L. rubellus*, *L. terrestris*	*A. caliginosa*
W XIV	pH > 4.5, silt, dry	*L. castaneus*, *L. rubellus*, *L. terrestris*	*A. caliginosa*, *A. longa*, *A. rosea*
W XV	pH > 4.5, loam, dry	*L. castaneus*, *L. rubellus*	*A. caliginosa*, *A. longa*, *A. rosea*
W XVI	pH > 4.5, clay, dry	*L. castaneus*	*A. caliginosa*, *A. longa*, *A. rosea*

[a](A) Crop site; (G) meadows; (W) forest.

Allolobophoriella) *eiseni*, i.e., mainly small reddish epigeics.

Based on investigation of 116 meadow and crop sites in Bavaria, Bauchhenss (1997) defined two typical species groups, which both resemble the mull group described above:

Crop sites: *L. terrestris*, *A. rosea*, and, often, also *A. caliginosa* und *O. tyrtaeum*.
Meadows: *L. terrestris*, *L. rubellus*, *A. caliginosa*, *A. rosea*, *O. tyrtaeum*, *L. castaneus*.

In addition, some species are considered to be indicators of specific site conditions:

E. fetida, E. andrei: Collections of organic material like compost heaps.
A. chlorotica, *E. tetraeda*: Very high moisture and limnic conditions like shore areas.
L. eiseni: Tree stubs or barks (often more than 1 m above the soil surface).
L. terrestris: Slightly acid to neutral deep soils with low sand content, i.e., the "classic" indicator of mull soils.

In contrast to other soil organism groups like enchytraeids, there are no lumbricid species that can be considered as indicators of anthropogenic stress.

5.4. Comparison of abundance per site with mean per site type

It is not clear which factors determine the abundance of lumbricid earthworms at a certain site. For example, Keplin (1995) argues that at the meadow sites she investigated, the food (amount and quality) is mainly responsible. Philipp (1990) identified soil properties, particularly texture and moisture, as decisive for the size of lumbricid populations at fallow sites (see also Auerswald et al., 1996). Despite the high variability of earthworm numbers within a year and the wide range of data between years, comparison of the abundance at one site with the mean numbers for certain site types taken from the literature can be attempted. A conspicuous difference is evident if the sampled number (as individuals/m^2) is outside the known range (minima/maxima or certain percentile?). However, it must be stated that right now, abundance values cover only use classes (e.g., Römbke et al., 1997), not individual site types as, e.g., shown in Table 4. The use of abundance classes as proposed by Graefe (1993a) is not supported due to the fact that the size of such classes has not been justified so far.

6. Example

In a project sponsored by the German Environmental Protection Agency, 23 sites (crop sites, meadows, and forests) located all over Germany were sampled with the same methods (hand sorting followed by formalin extraction). The results were evaluated in different ways. In addition to some simple comparisons described in Section 5, two statistical methods were used that are discussed in detail in Sections 6.1 and 6.2.

6.1. Correspondence analysis

Correspondence analysis (CANOCO) was used to assess the dominance values of all earthworm species occurring at the 23 sampled sites (in a few cases the sampling was done twice) in two ways: In the first method, the sites were arranged with respect to species composition of earthworms. As can be seen in Fig. 2, two very large groups of sites were distinguished:

- Forest sites with acid soil: BBK, BEK, LUB, NIB, SBB, SCF, TAM. Sites with similar earthworm communities, like BBK and BEK, are sometimes far from each other, which is difficult to understand. The same is true of the results of two samplings at the same site: In the case of SCF, there is virtually no difference, whereas other sites, like SBB and TAM, are different in the 2 years. It is remarkable that site SBB belongs to the acid forest group in both years (1998 and 2000), a result that is not supported by the soil properties. In addition, the overlap of two acid

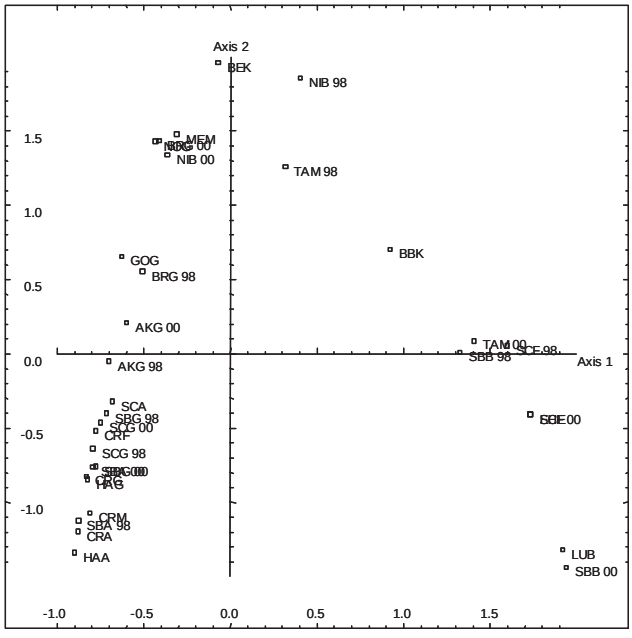


Fig. 2. Correspondence analysis (CANOCO) of 23 sites and earthworms.

forest sites (MEM, NIB 2000) with meadow sites (BRG 2000, NOG) is conspicuous. This probably indicates a problem at the latter two sites.

- Within the large group of meadow and crop sites, four sites, all located in northern Germany (BRG, NOG, GOG, and, less clearly, AKG) can be distinguished from the rest. The remaining sites are relatively homogeneous, but it is conspicuous that in the center of this group the coniferous forest site CRF is located. However, this site has soil properties very similar to those of two adjacent crop and meadow sites (CRA, CRG).

It seems that this method of assessment does not provide a lot of new information except for revealing some conspicuities that might have otherwise been overlooked.

With respect to the classification of individual species, a very distinctive scheme can be observed (Fig. 3). All species of the genus *Dendrobaena* are characteristic of acid forest soils, whereas species of the genus *Aporrectodea* (including *Helodrilus* (now *Proctodrilus*)), as well as both *Octolasion* species, are typical of meadows and crop sites. Somehow undifferentiated are *A. chlorotica* and all species of the genus *Lumbricus*. Such a similarity between taxonomic and ecological classifications is rarely observed. One explanation might be that only very few species are included in this assessment. Summarizing the CANOCO experience, it seems that the use of earthworm data alone does not increase considerably the amount of information already available when looking at the raw data.

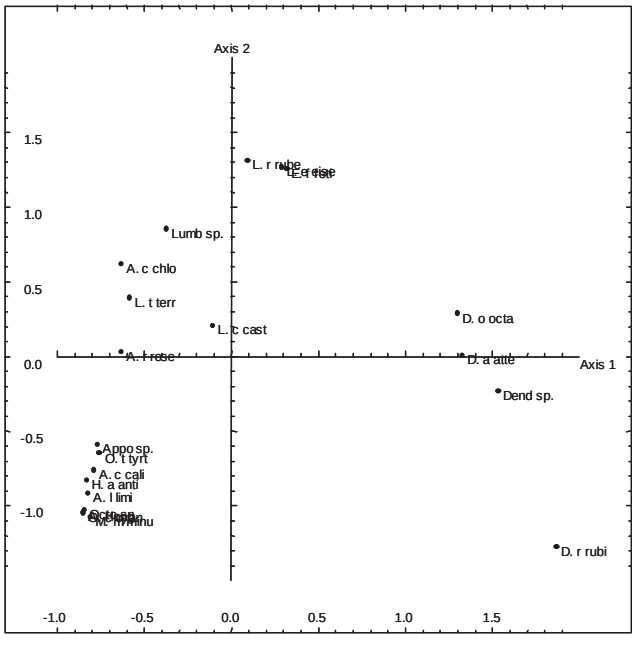


Fig. 3. Correspondence analysis (CANOCO) with all earthworm species at all sites.

6.2. Site classification using TwinSpan

TwinSpan analysis was carried out using the dominance spectrum data of those 13 sites at which the entire battery of animal groups was investigated (i.e., earthworms, enchytraeids, oribatids, gamasids, nematodes, isopods, diplopods, and chilopods). On Level 1, only two forest sites included in this analysis were identified (Table 5). These two sites remain together on Levels 2 and 3, which is strange as they do not have similar soil properties. This observation might be considered proof of the conspicuity of site SBB (see Section 6.1). At Level 2, the four north German meadows are separated from the other meadows and crop sites, while at Level 3, a biogeographic division is visible: On the one side are the sites from Bavaria and North Rhine–Westphalia and on the other side are the sites from Hesse and Baden-Wuerttemberg. However, this division cannot be explained on the basis of the soil property data available. The only conspicuity is then the beech forest site SBB.

By use of all 23 sites investigated (including the repeated samplings at some sites) a much more detailed TwinSpan analysis is possible (Table 6). At the first three levels, separation according to the use of the sites is observed. Only two forest sites with a mull humus and a high pH (CRF, CRM) remain among the group of meadow and crop sites. Again, the conspicuity of forest SBB is confirmed, as either it belongs to the acid forest group or, starting at Level 3, it forms a group of its own. On Level 4 the isolated position of forest TAM in the year 1998 and its adjustment to the other acid forest as based on the sampling in the year 2000 become apparent. This difference can be explained by the occurrence of the compost species *E. fetida* in the

Table 5
Qualitative comparison of the species composition at the sites where all animal groups were sampled using TwinSpan (13 sites)

Level 1	AKG BRG GOG NOG SBA SCA SBG SCG CRA HAA HAG			SBB SCF
Level 2	AKG BRG GOG NOG	SBA SCA SBG SCG CRA HAA HAG		SBB SCF
Level 3	AKG BRG GOG NOG	SBA SCA SBG SCG	CRA HAA HAG	SBB SCF

Table 6
Qualitative comparison of the species composition at 23 sites (all animal groups except nematodes) using TwinSpan

Level 1	CRM CRA HAG HAA SBA98 SCG98 CRF SCG00 SBA00 SBG00 SBG98 BRG98 AKG98 CRG SCA GOG AKG00 BRG00 NOG BEK MEM NIB00							TAM98 NIB98 SCF98 BBK TAM00 SBB98 LUB EHE SCF00 SBB00				
Level 2	CRM CRA HAG HAA SBA98 SCG98 CRF SCG00 SBA00 SBG00 SBG98 BRG98 AKG98 CRG CRA GOG					AKG00 BRG00 NOG BEK MEM NIB00		TAM98 NIB98 SCF98 BBK TAM00 SBB98			LUB EHE SCF00 SBB00	
Level 3	CRM CRA HAG HAA SBA98 SCG98 CRF SCG00 SBA00 SBG00			SBG98 BRG98 AKG98 CRG SCA GOG		AKG00 BRG00 NOG	BEK MEM NIB00	TAM98 NIB98 SCF98 BBK TAM00		SBB98	LUB EHE SCF00 SBB00	
Level 4	CRM CRA HAG HAA	SBA98 SCG98 CRF SCG00 SBA00 SBG00		SBG98 BRG98 AKG98 CRG SCA	GOG	AKG00 BRG00 NOG	BEK MEM NIB00	TAM98	NIB98 SCF98 BBK TAM00	SBB98	LUB EHE SCF00 SBB00	
Level 5	CRM CRA HAG HAA	SBA98 SCG98 CRF SCG00 SBA00	SB G00	SBG98 BRG98 AKG98 CRG SCA	GOG	AKG00 BRG00 NOG	BEK MEM NIB00	TAM98	NIB98 SCF99 BBK TAM00	SBB98	LUB EHE SCF00 SBB00	

Table 7
Classification of the sites investigated and their assessment using different methods[a]

Site type	Site	Abundance	Species number	Species spectrum		CANOCO	TwinSpan	Total
A III	HAA	+[a]	+	60%	±	+	+	+
A IV	CRA	+	+	25%	+	+	+	+
A IV	SBA	+	+	43%	+	+	+	+
A IV	SCA	+	+	33%	+	+	+	+
G III	BRG	–	–	67%	–	?	+	–
G IV	AKG	–	±	78%	–	+	+	–
G IV	GOG	–	–	75%	–	+	+	–
G IV	NOG	–	–	75%	–	?	+	–
G VII	SCG	+	±	43%	+	+	+	+
G VIII	CRG	+	+	33%	+	+	+	+
G VIII	HAG	+	+	38%	+	+	+	+
G VIII	SBG	+	+	17%	+	+	+	+
W I	EHE	+	+	50%	+	+	+	+
W I	LUB	+	+	50%	+	+	+	+
W I	MEM	+	+	33%	+	+	+	+
W II	NIB	+	+	60%	±	+	+	+
W II	TAM	+	–	40%	+	+	+	+
W III	SCF	+	+	60%	±	+	+	+
W V	BBK	+	+	20%	+	+	+	+
W V	BEK	+	+	50%	+	+	+	+
W XI	CRF	+	+	54%	+	+	+	+
W XI	CRM	+	+	54%	+	+	+	+
W XI	SBB	–	–	100%	–	–	–	–

[a]Conspicuity: –, yes; +, no; ±, not clear.

samples from 1998 but not in those from 2000. Why site NIB was classified into two groups following the two samplings in 1998 and 2000 cannot be explained. Among the nonforested sites, the picture is more complex. No clear distinction between crop sites and meadows is visible. On the other hand, the four northern German meadows are still separated, mainly in the year 2000. Again, it is not possible to verify the site types as defined in this study (four crop sites, eight meadows, and 16 forests) by the occurrence data of the earthworm fauna alone.

6.3. Summary and assessment of the investigated sites

In Table 7, the results of the various methods used to assess earthworm data collected at the 23 sites are compiled. A plus sign indicates no conspicuity for the site, whereas a minus sign indicates a problem. In some

cases, a clear decision was not possible (i.e., a "±" was used). In short, the sum of the individual results is decisive; i.e., the methods are treated similarly. According to this compilation, in 18 of 23 cases (= sites), there were no clear differences between the earthworm community expected and that observed. On the other hand, the habitat function of the soil at the four northern German meadows and the beech forest SBB is considered to be limited. This result is partly explainable: Two of the meadow sites are known to be contaminated by heavy metals and the forest SBB had recently been limed.

7. Summary and outlook

The significant ecological relevance of earthworms and the amount of information compiled about their biology, taxonomy, and ecotoxicology, as well as the availability of standardized sampling methods, support their inclusion in any battery of soil organism groups used for ecological classification and assessment of soils. This does not mean that earthworms have to be sampled at any site in all circumstances. For example, at very acid forest sites, the number of earthworm species is so low that mesofaunal groups would be more useful. On the other hand, it must be noted that adequate differentiation of sites on the basis of oligochaete fauna alone is hardly possible. Ruf et al. (2000) achieved the best differentiation of sites by including all taxa investigated (Chilopoda, Diplopoda, Enchytraeidae, Gamasina, Isopoda, Lumbricidae, Oribatei). By their communities the individual taxa offer different information regarding site parameters and habitats. Thus, earthworms can only be one of several soil-dwelling taxa to be used in a soil ecological classification and assessment system. However, there are still problems to be solved to facilitate the use of earthworms. Most notably, the identification of earthworms has to be simplified further, maybe using an expert system including computer support. In addition, the question of how to handle biogeographic differences remains.

Acknowledgments

We thank Kerstin Hund-Rinke and Andrea Ruf for performing the CANOCO and TwinSpan calculations used in Chapter 6.

References

Abdul Rida, A.M.M., Bouché, M.B., 1995. The eradication of an earthworm genus by heavy metals in southern France. Appl. Soil Ecol. 2, 45–52.

Anderson, J.M., Ingram, J.S., 1993. Tropical Soil Biology and Fertility (TSBF): a Handbook of Methods. CAB International, Wallingford.

Auerswald, K., Weigand, S., Kainz, M., Philipp, C., 1996. Influence of soil properties on the population and activity of geophagous earthworms after five years of bare fallow. Biol. Fertil. Soils 23, 382–387.

Bauchhenss, J., 1997. Bodenzoologie. Boden-Dauerbeobachtungsflächen (BDF). Bericht nach zehnjähriger Laufzeit 1985–1995. Teil III. Boden: Gefüge, Organische Substanz, Bodenorganismen, Vegetation. Bodenkultur und Pflanzenbau. Schriftenreihe Bayrischen Landesanstalt Bodenkultur Pflanzenbau 6/97, 219–234.

Bauchhenss, J., 1998. Methodik und Relevanz von Regenwurmuntersuchungen auf Boden-Dauerbeobachtungsflächen (BDF). Mittl. Deut. Bodenkundl. Ges. 87, 347–350.

Baylis, J.P., Cherrett, J.M., Ford, J.B., 1986. A survey of the invertebrates feeding on living clover roots (*Trifolium repens* L.) using ^{32}P as a radiotracer. Pedobiologia 29, 201–208.

BBodSchG, 1998. Gesetz zum Schutz vor schädlichen Bodenveränderungen und zur Sanierung von Altlasten (Bundes-Bodenschutzgesetz). Bundesgesetzblatt I, 502 vom 17. März 1998.

Beck, L., Römbke, J., Breure, A.M., Mulder, Ch., 2005. Considerations for the use of soil ecological classification and assessment concepts in soil protection. Ecotoxicol. Environ. Saf.

Beylich, A., Fründ, H.C., Graefe, U., 1994. Ökosystemare Umweltbeobachtung und Bioindikation mit Zersetzergesellschaften. ECOINFORMA '94, 389–401.

Blakemore, R., 2000. DELTA—Tasmanian Earthworms. Private CD Publication.

Blakemore, R., 2002. Cosmopolitan Earthworms: An Eco-taxonomic Guide to the Peregrine Species of the World. VermEcology, P.O. Box 414, Kippax, ACT 2615, Australia.

Blakemore, R.J., 1997. Agronomic potential of earthworms in brigalow soils of south-east Queensland. Soil Biol. Biochem. 29, 603–608.

Bono, R., 1984. Regenwurmgesellschaften im Sundgau (Elsass, Frankreich): Aspekte ihrer Struktur und Verbreitung. Verh. Ges. Ökol. 12, 545–552.

Bornebusch, C.H., 1930. The fauna of forest soil. Forstl. Forsoegsvaes. Dan. 11, 1–225.

Bouché, M., 1972. Lombriciens de France. Ecologie et Systématique. INRA Publ. 72-2, Inst. Nat. de Recherches Agriculturelles, Paris.

Bouché, M., 1977. Strategies lombriciennes. Ecol. Bull. 25, 122–132.

Brauckmann, H.-J., Fahrendorf, K., Broll, G., 1996. Regenwurmzönosen extensiv gepflegten Grünlandes unter dem Einfluß des Kontrollierten Brennens. In: Broll, G., Bernhardt, K.-G. (Eds.), Aspekte der Angewandten Landschaftsökologie. Karl-Friedrich Schreiber zum 70. Geburtstag, vol. 2. Arbeiten Inst. Landschaftsökol, Münster, pp. 317–330.

Brauckmann, H-J., Hemker, M., Kaiser, M., Schöning, O., Broll, G., Schreiber, K-F., 1997. Faunistische Untersuchungen auf Bracheversuchsflächen in Baden-Württemberg. Berichte Umweltforsch. Baden-Württemberg 27, 1–158.

Braun-Blanquet, J., 1964. Pflanzensoziologie. Springer, Vienna, New York.

Bretscher, K., 1896. Die Oligochaeten von Zürich. Rev. Suisse Zool. 3, 499–532.

Breure, A.M., Mulder, Ch., Römbke, J., Ruf, A., 2005. Ecological classification and assessment concepts in soil protection. Ecotoxicol. Environ. Saf.

Briones, M.J.I., Mascato, R., Mato, S., 1995. Autecological study of some earthworm species (Oligochaeta) by means of ecological profiles. Pedobiologia 39, 97–106.

Broll, G., Brauckmann, H.-J., 1994. Humusformen und Regenwurmfauna zweier Grünlandbrachen in Südwestdeutschland. Mittl. Deut. Bodenkundl. Ges. 74, 49–52.

Brown, G.G., 1995. How do earthworms affect microfloral and faunal community diversity? Plant Soil 170, 209–231.

Carter, A., Hayes, E.A., Laukulich, L.M., 1980. Earthworms as biological monitors of changes in heavy metal levels in an agricultural soil in British Columbia. In: Dindal, D.L. (Ed.), Soil Biology as Related to Land Use Practices, pp. 344–357.

Coleman, D.C., Blair, J.M., Elliott, E.T., Wall, D.H., 1999. Soil Invertebrates. In: Robertson, G.P., Coleman, D.C., Bledsoe, C.S., Sollins, P. (Eds.), Standard Soil Methods for Long-Term Ecological Research, LTER Network Series. Oxford University Press, New York.

Cortet, J., Gomot-De Vauflery, A., Poinsot-Balaguer, N., Gomot, L., Texier, C., Cluzeau, D., 1999. The use of invertebrate soil fauna in monitoring pollutant effects. Eur. J. Soil Biol. 35, 115–134.

Csuzdi, C., Zicsi, A., 2003. Earthworms of Hungary, Pedozoologica Hungarica No. 1. Hungarian Natural History Museum, Budapest.

Doube, B.M., Brown, G.C., 1998. Life in a complex community: functional interactions between earthworms, organic matter, microorganisms and plants. In: Edwards, C.A. (Ed.), Earthworm Ecology. CRC Press, Boca Raton, FL, pp. 179–212.

Doube, B.M., Styan, C., 1996. The response of *Aporrectodea rosea* and *Aporrectodea trapezoides* to moisture gradients in three soil types in the laboratory. Biol. Fertil. Soils 23, 166–172.

Dunger, W., 1968. Die Entwicklung der Bodenfauna auf rekultivierten Kippen und halden des Braunkohlentagebaus. Ein Beitrag zur pedozoologischen Standortsdiagnose. Abh. Ber. Naturkundemuseums Görlitz 43, 1–256.

Dunger, W., 1983. Tiere im Boden. A. Ziemsen-Verlag, Wittenberg.

Dunger, W., Fiedler, H.J., 1997. Methoden der Bodenbiologie. Fischer–Verlag, Stuttgart.

Edwards, C.A., 1998. Earthworm Ecology. CRC Press, Boca Raton, FL.

Edwards, C.A., Bohlen, P.J., 1992. The effects of toxic chemicals on earthworms. Rev. Environ. Contam. Toxicol. 125, 23–99.

Edwards, C.A., Bohlen, P.J., 1996. Biology of Earthworms, third ed. Chapman & Hall, London.

Edwards, C.A., Subler, S., Chen, S.K., Bogomolov, D.M., Van Straalen, N.M., Krivolutsky, D.A., 1996. Essential criteria for selecting bioindicator species, processes, or systems to assess the environmental impact of chemicals on soil ecosystems. In: Van Straalen, N.M., Kriovolutsky, D.A. (Eds.), Bioindicator Systems for Soil Pollution. Kluwer Academic Publishers, Dordrecht, pp. 67–84.

Edwards, W.M., Shipitalo, M.J., 1998. Consequences of earthworms in agricultural soils: aggregation and porosity. In: Edwards, C.A. (Ed.), Earthworm Ecology. CRC Press, Boca Raton, FL, pp. 147–161.

Ehrmann, O., 1996. Regenwürmer in einigen südwestdeutschen Agrarlandschaften: Vorkommen, Entwicklung bei Nutzungsänderungen und Auswirkungen auf das Bodengefüge. Hohenheimer Bodenkundliche Hefte 35, 1–135.

Ehrmann, O., Vollmer, T., 1997. Regenwürmer im Hegau—Vorkommen und Wirkungen auf das Bodengefüge. Mittl. Deut. Bodenkundl. Ges. 85 (II), 489–492.

Ellenberg, H., Weber, H.E., Düll, R., Wirth, V., Werner, W., Paulißen, D., 1992. Zeigerwerte von Pflanzen in Mitteleuropa. Verlag Erich Goltze, Göttingen.

Emmerling, C., Krause, K., Schöder, D., 1997. Regenwürmer als Bioindikatoren für Schwermetallbelastungen von Böden unter Freilandbedingungen. Z. Pflanzenern. Bodenkd. 160, 33–39.

Emmerling, C., Schloter, M., Hartmann, A., Kandeler, E., 2002. Functional diversity of soil organisms: a review of recent research activities in Germany. J. Plant Nutr. Soil Sci. 165, 408–420.

European Commission (EC), 2002. Communication from the Commission to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions: Towards a Thematic Strategy for Soil Protection. COM(2002)179.

Fragoso, C., James, S., Borges, S., 1995. Native earthworms of the north neotropical region: current status and controversies. In: Hendrix, P. (Ed.), Earthworm Ecology and Biogeography in North America. Lewis, Boca Raton, FL, pp. 67–115.

Friedel, J.K., Sommer, M., Ehrmann, O., 1999. Bewertung von Böden nach ihrer Eignung als Lebenssraum für Organismen am Beispiel von Mikroorganismen und Regenwürmern. Mittl. Deut. Bodenkundl. Ges. 89, 233–236.

Ghilarov, M.S., 1949. Die Besonderheiten des Bodens als Lebensraum und seine Bedeutung für die Evolution der Insekten. Moskau, Leningrad (in Russian).

Glasstetter, M., 1991. Die Bodenfauna und ihre Beziehungen zum Nährstoffhaushalt in Geosystemen des Tafel- und Faltenjura (Nordwestschweiz). Physiogeographica 15, 1–224.

Graefe, U., 1993a. Die Gliederung von Zersetzergesellschaften für die standortsökologische Ansprache. Mittl. Dtsch. Bodenkundl. Ges. 69, 95–98.

Graefe, U., 1993b. Veränderungen der Zersetzergesellschaften im Immissionsbereich eines Zementwerks. Mittl. Dtsch. Bodenkundl. Ges. 72, 531–534.

Graefe, U., 1994. Gibt es bodentyp-spezifische Tiergesellschaften? Mittl. Dtsch. Bodenkundl. Ges. 75, 11–14.

Graefe, U., 1997. Bodenorganismen als Indikatoren des biologischen Bodenzustandes. Mittl. Dtsch. Bodenkundl. Ges. 85, 687–690.

Graefe, U., 1998. Annelidenzönosen nasser Böden und ihre Einordnung in Zersetzergesellschaften. Mittl. Dtsch. Bodenkundl. Ges. 88, 109–112.

Graefe, U., 1999. Die Empfindlichkeit von Bodenbiozönosen gegenüber Änderungen der Bodennutzung. Mittl. Dtsch. Bodenkundl. Ges. 91, 609–612.

Graefe, U., Belotti, E., 1999. Strukturmerkmale der Bodenbiozönose als Grundlage für ein natürliches System der Humusformen. Mittl. Dtsch. Bodenkundl. Ges. 89, 181–184.

Graefe, U., Beylich, A., 2003. Critical values of soil acidification for annelid species and the decomposer community. Proc. 5th Int. Coll. Enchytraeidae. Newslett. Enchytraeidae 8, 51–55.

Graefe, U., Schmelz, R., 1999. Indicator values, strategy types and life forms of terrestrial Enchytraeidae and other microannelids. Newslett. Enchytraeidae 6, 59–68.

Graefe, U., Elsner, D.-C., Necker, U., 1998. Monitoring auf Boden-Dauerbeobachtungsflächen: Bodenzoologische Parameter zur Kennzeichnung des biologischen Bodenzustandes. Mittl. Dtsch. Bodenkundl. Ges. 87, 343–346.

Graff, O., 1953. Die Regenwürmer Deutschlands. Schriftenreihe Forschungsinstitut Landwirtschaft 7, 1–70.

Gunn, A., 1992. The use of mustard to estimate earthworm populations. Pedobiologia 36, 65–67.

Hazelhoff, L., van Hoof, P., Imeson, A.C., Kwaad, F.J.P.M., 1981. The exposure of forest soil to erosion by earthworms. Earth Surf. Processes Landforms 6, 235–250.

Heeb, J., Vetter, F., 1995. Ansatz für eine integrative Auswertung bodenbiologischer Messergebnisse. Umweltmaterialien. BUWAL (Hrsg.), Schattweid.

Hendrix, P.F., 1998. Earthworms in agroecosystems: a summary of current research. In: Edwards, C.A. (Ed.), Earthworm Ecology. CRC Press, Boca Raton, FL, pp. 259–269.

Henke, W., 1994. Einfluß der Bodenbearbeitung auf die Lumbricidenpopulation und deren Aktivität in verschiedenen Ackerböden. Mitt. Hamb. Zool. Mus. Inst. 89, 89–100.

Höser, N., 1997. Standörtliche Bindung als Kriterium der Artentrennung bei der Regenwurm-Gattung *Proctodrilus*. Abh. Ber. Naturkundemuseums Görlitz 69, 151–156.

Hund-Rinke, K., Wiechering, H., 2001. Earthworm avoidance test for soil assessments: an alternative for acute and reproduction tests. J. Soils Sediments 1, 15–20.

Irmler, U., 1999. Die standörtlichen Bedingungen der Regenwürmer (Lumbricidae) in Schleswig-Holstein. Faun.-Ökol. Mitt. 7, 509–518.

International Organisation for Standardisation (ISO), 1999. Soil Quality: Effects of Pollutants on Earthworms. Part 3: Guidance on the Determination of Effects in Field Situations. ISO 11268-3. ISO, Geneva.

International Organisation for Standardisation (ISO), 2004. Soil quality: Sampling of Soil Invertebrates. Part 1: Hand-Sorting and Formalin Extraction of Earthworms. ISO 23611-1. ISO, Geneva.

Jones, C.G., Lawton, J.H., Shachak, M., 1994. Organisms as ecosystem engineers. Oikos 69, 373–386.

Keplin, B., 1995. Untersuchungen zur Bodenfauna städtischer Grünflächen unter dem Einfluss verschiedener Pflegemassnahmen. Mittl. Landschaftsökol. Forschungsstelle Bremen 16, 1–138.

Keplin, B., Broll, G., 1997. Lumbricidenzönosen ausgewählter Stadtbiotope nach Nutzungsänderung Naturschutz. Landschaftsplanung 29, 310–313.

Keplin, B., Hoffmann, U., Broll, G., 1995. Extensivierung einer Pufferzone zum Schutz eines Hochmoorrestes—Auswirkungen der Wiedervernässung auf die Lumbricidenzönose. Mittl. Dtsch. Bodenkundl. Ges. 76 (II), 819–822.

Koshiba, M., Ogawa, K., Hamazaki, S., Sugiyama, T., Ogawa, O., Kitajima, T., 1993. The effect of formalin fixation on DNA and the extraction of high-molecular weight DNA from fixed and embedded tissues. Pathol. Res. Pract. 189, 66–72.

Kühle, J.C., 1986. Modelluntersuchungen zur strukturellen und ökotoxikologischen Belastung von Regenwürmern in Weinbergen Mitteleuropas (Oligochaeta: Lumbricidae). Rheinische Friedrich-Wilhelms-Universität, Bonn.

Lavelle, P., 1979. Relations entre types ecologiques et profils demographiques chez les vers de terre de la Savane de Lamto (Cote d'Ivoire). Rev. Ecol. Biol. Sol. 16, 85–101.

Lavelle, P., 1984. The soil system in the humid tropics. Biol. Int. 9, 2–17.

Lavelle, P., 1988. Earthworms and the soil system. Biol. Fertil. Soils 6, 237–251.

Lavelle, P., Bignell, D., Lepage, M., 1997. Soil function in a changing world: the role of invertebrate ecosystem engineers. Eur. J. Soil Biol. 33, 159–193.

Lee, K.E., 1985. Earthworms: Their Ecology and Relationships with Soils and Land Use. Academic Press, Sydney.

Ljungstrøm, P.-O., 1979. Introduction to the study of earthworm taxonomy. Pedobiologia 10, 265–285.

Lowe, C.N., Butt, K.R., 1999. Interspecific interactions between earthworms: a laboratory-based investigation. Pedobiologia 43, 808–817.

Maraun, M., Alphei, J., Bonkowski, M., Buryn, R., Migge, S., Peters, M., Schaefer, M., Scheu, S., 1999. Middens of the earthworm *Lumbricus terrrestris* (Lumbricidae): microhabitats for micro- and mesofauna in forest soil. Pedobiologia 43, 276–287.

Mrsic, N., 1990. Description of a new subgenus, three new species and taxonomic problems of the genus *Allolobophora* sensu Mrsic and Sapkarev 1988 (Lumbricidae, Oligochaeta). Biol. Vestn. 38, 49–68.

Mrsic, N., 1991. Monograph on Earthworms (Lumbricidae) of the Balkans. Slovenska Akademija Znanosti Umetnosti, Ljubljana, Slovenia (757pp).

Mulder, Ch., Schouten, A.J., Hund-Rinke, K., Breure, A.M., 2005. The use of nematodes in ecological soil classification and assessment concepts. Ecotoxicol. Environ. Saf.

Muys, B., Granval, P., 1997. Earthworms as bioindicators of forest site quality. Soil Biol. Biochem. 29, 323–328.

Nagel, R.F., 1996. Die Bedeutung von Regenwürmern für den C- und N-Umsatz in einer heterogenen Agrarlandschaft. Dissertation, Universität München.

Nordström, S., Rundgren, S., 1974. Environmental factors and lumbricid associations in southern Sweden. Pedobiologia 13, 301–326.

Paoletti, M., Gradenigo, C., 1997. Lombri CD-ROM. Dip. Biologia, Università Padova lapis S.r.l., Padova.

Paoletti, M.G., 1999. The role of earthworms for assessment of sustainability and as bioindicators. Agric. Ecosyst. Environ. 74, 137–155.

Parmelee, R.W., Bohlen, P.J., Blair, J.M., 1998. Earthworms and nutrient cycling processes: integrating across the ecological hierarchy. In: Edwards, C.A. (Ed.), Earthworm Ecology. St. Lucie Press, Boca Raton, FL, pp. 123–146.

Petersen, H., Luxton, M., 1982. A comparative analysis of soil fauna populations and their role in decomposition processes. Oikos 39, 287–388.

Philipp, C., 1990. Einfluss von Bodeneigenschaften auf die Regenwurmabundanz in 32 verschiedenen Böden Bayerns. Seminararbeit TU München/Weihenstephan.

Phillipson, J., Abel, R., Steel, J., Woodell, S.R.J., 1976. Earthworms and the factors governing their distribution on an English beechwood. Pedobiologia 16, 258–285.

Pizl, V., 1992. Effect of soil compaction on earthworms (Lumbricidae) in apple orchard soil. Soil Biol. Biochem. 24, 1573–1576.

Ponge, J.F., Delhaye, L., 1995. The heterogeneity of humus profiles and earthworm communities in a virgin beech forest. Biol. Fertil. Soils 20, 24–32.

Pop, V.V., 1997. Earthworm–vegetation–soil relationships in the Romanian Carpathians. Soil Biol. Biochem. 29, 223–229.

Qiu, J-P., Bouché, M.B., 1998a. Classified list of earthworms (Oligochaeta: Lumbricoidea) after the study of three fifth of them. Doc. Pedozool. Integr. 4, 181–200.

Qiu, J-P., Bouché, M.B., 1998b. Revision of Lumbricoidea supraspecific taxa. Doc. Pedozool. Integr. 3, 179–216.

Raw, F., 1959. Estimating earthworm populations by using formalin. Nature 184, 1661–1662.

Raw, F., 1960. Earthworm population studies: a comparison of sampling methods. Nature 187, 257.

Reynolds, J.A., 1995. Status of exotic earthworm systematics and biogeography in North America. In: Hendrix, P.F. (Ed.), Earthworm Ecology and Biogeography in North America. Lewis, Boca Raton, FL, pp. 1–28.

Righi, G., 1990. Minhocas de Mato Grosso e de Rondonia. CNPq, AED, Polonoroeste, Brasilia.

Römbke, J., Bauer, C., Marschner, A., 1996. Hazard assessment of chemicals in soil: proposed ecotoxicological test strategy. Environ. Sci. Pollut. Res. 3, 78–82.

Römbke, J., Beck, L., Förster, B., Fründ, H.C., Horak, F., Ruf, A., Rosciczewski, K., Scheurig, M., Woas, S., 1997. Boden als Lebensraum für Bodenorganismen und die bodenbiologische Standortklassifikation: Eine Literaturstudie. Texte und Berichte zum Bodenschutz 4/97. Landesanstalt für Umweltschutz Baden-Württemberg, Karlsruhe.

Römbke, J., Meller, M., Garcia, M., 1999. Earthworm densities in central Amazonian primary and secondary forests and a polyculture forestry plantation. Pedobiologia 43, 518–522.

Römbke, J., Dreher, P., Beck, L., Hammel, W., Hund, K., Knoche, H., Kördel, W., Kratz, W., Moser, T., Pieper, S., Ruf, A., Spelda, J., Woas, S., 2000. Bodenbiologische Bodengüte-Klassen, UBA-Texte 6/00.

Römbke, J., Beck, L., Dreher, P., Hund-Rinke, K., Jänsch, S., Kratz, W., Pieper, S., Ruf, A., Spelda, J., Woas, S., 2002. Entwicklung von bodenbiologischen Bodengüteklassen für Acker- und Grünlandstandorte, UBA-Texte 20/02.

Römbke, J., Jänsch, S., Garcia, M., 2005. Earthworms as bioindicators (in particular for the influence of land use). In: Proceedings of the ELAETAO Workshop, Embrapa, Londrina, in press.

Ruf, A., Beck, L., 2005. The use of predatory soil mites in ecological soil classification and assessment concepts, with perspectives for Oribatid mites. Ecotoxicol. Environ. Saf.

Ruf, A., Beck, L., Römbke, J., Spelda, J., 2000. Standortspezifische Erwartungswerte für die Gemeinschaftsstruktur ausgewählter Taxa der Bodenfauna als Bodenqualitätskriterium. Ber. Nat.-Med. Verein Innsbruck 87, 365–379.

Rundgren, S., 1975. Vertical distribution of lumbricids in southern Sweden. Oikos 26, 299–306.

Sanchez, E.G., Munoz, B., Garvin, M.H., Jesus, J.B., Diaz Cosin, D.J., 1997. Ecological preferences of some earthworm species in southwest Spain. Soil Biol. Biochem. 29, 313–316.

Satchell, J.E., 1955. Some aspects of earthworm ecology. In: Mc.E. Kevan, D.K. (Ed.), Soil Zoology. Butterworths, London, pp. 180–201.

Satchell, J.E. (Ed.), 1983. Earthworm Ecology: From Darwin to Vermiculture. Chapman & Hall, London.

Schouten, A.J., Brussaard, L., de Ruiter, P.C., Siepel, H., van Straalen, N.M., 1997. An Indicator System for Life Support Functions of the Soil in Relation to Biodiversity, RIVM Report 712910005. National Institute of Public Health and the Environment, Bilthoven (in Dutch with English summary).

Schouten, A.J., Breure, A.M., Bloem, J., Didden, W., de Ruiter, P.C., Siepel, H., 1999. Life Support Functions of the Soil: Operationalization for the Policy, RIVM Report 607601003. National Institute of Public Health and the Environment, Bilthoven (in Dutch with English summary).

Schouten, A.J., Bloem, J., Breure, A.M., Didden, W.A.M., Van Esbroek, M., de Ruiter, P.C., Rutgers, M., Siepel, H., Velvis, H., 2000. Pilotproject Bodembiologische Indicator voor Life support functies van de bodem, RIVM Report 607604001. National Institute of Public Health and the Environment, Bilthoven (in Dutch with English summary).

Schrader, S., Zhang, H., 1997. Earthworm casting: stabilisation or destabilisation of soil structure. Soil Biol. Biochem. 29, 469–475.

Sijm, D., Kraaij, R., Belfroid, A., 2000. Bioavailability in soil or sediment: exposure of different organisms and approaches to study it. Environ. Pollut. 108, 113–119.

Sims, R.W., Gerard, B.M., 1985. Earthworms. In: Kermack, D.M., Barnes, R.S.K. (Eds.), Synopses of the British Fauna (New Series), No. 31. E.J. Brill/Dr. W. Backhuys, London.

Sinnige, N., Tamis, W., Klijn, F., 1992. Indeling van Bodemfauna in ecologische Soortgroepen. Centrum voor Milieukunde, Rijksuniversiteit Leiden Report No. 80.

Spurgeon, D.J., Sandifer, R.D., Hopkin, S.P., 1996. The use of macroinvertebrates for population and community monitoring of metal contamination: indicator taxa, effect parameters and the need for a soil invertebrate prediction and classification scheme (SIVPACS). In: Van Straalen, N.M., Krivolutsky, D.A. (Eds.), Bioindicator Systems for Soil Pollution. Kluwer Academic Publishers, Dordrecht, pp. 95–109.

Stephenson, J., 1930. The Oligochaeta. Clarendon Press, Oxford.

Stephenson, G.L., Kaushik, A., Kaushik, N.K., Solomon, K.R., Steele, T., Scroggins, R., 1998. Use of an avoidance—response test to assess the toxicity of contaminated soils to earthworms. In: Sheppard, S.C., Bembridge, J.D., Holmstrup, M., Posthuma, L. (Eds.), Advances in Earthworm Ecotoxicology. SETAC Press, Boca Raton, FL, pp. 67–81.

Støp-Bowitz, C., 1969. A contribution to our knowledge of the systematics and zoogeography of Norwegian earthworms. Nytt Mag. Zool. 17, 169–280.

Stork, N.E., Eggleton, P., 1992. Invertebrates as determinants and indicators of soil quality. Am. J. Altern. Agric. 7, 38–47.

Swift, M.J., Heal, O.W., Anderson, J.M., 1979. Decomposition in Terrestrial Ecosystems. Studies in Ecology, vol. 5. Blackwell, London.

Syers, J.K., Springett, J.A., 1983. Earthworm ecology in grassland soils. In: Satchell, J.E. (Ed.), Earthworm Ecology: From Darwin to Vermiculture. Chapman & Hall, London, pp. 67–83.

Tarrant, K.A., Field, S.A., Langton, S.D., Hart, A.D.M., 1997. Effects on earthworm populations of reducing pesticide use in arable crop rotations. Soil Biol. Biochem. 29, 657–661.

Thielemann, U., 1986. Elektrischer Regenwurmfang mit der Oktett-Methode. Pedobiologia 29, 296–302.

Thomson, A.J., Davies, D.M., 1974. Mapping methods for studying soil factors and earthworm distribution. Oikos 25, 199–203.

Urbanek, J., Dolezal, F., 1992. Review of some case studies on the abundance and on the hydraulic efficiency of earthworm channels in Czechoslovak soils, with reference to the subsurface pipe drainage. Soil Biol. Biochem. 24, 1563–1572.

van Hoof, P., 1983. Earthworm activity as a cause of splash erosion in a Luxembourg forest. Geoderma 31, 195–204.

Vetter, F., 1996. Methoden zur Regenwurm-Extraktion. Vergleich der Formalin-, Senf- und Elektromethode. Umweltmaterialien Nr. 62. BUWAL, Bern.

Vollmer, T., Sommer, M., Ehrmann, O., 1999. Die Regenwürmer südwestdeutscher Wälder—Vorkommen und Abhängigkeit von Standortfaktoren. Mittl. Deut. Bodenkundl. Ges. 89, 289–292.

Volz, H, 1962. Beiträge zu einer pedozoologischen Standortslehre. Pedobiologia 1, 242–290.

Weeks, J.M., Hopkin, S.P., Wright, J.F., Black, H., Eversham, B.C., Roy, D., Svendsen, C., 1998. A Demonstration of the Feasibility of SOILPACS, Final Report MIP/CPR2/41/1/247.

Zachariae, G., 1965. Spuren tierischer Tätigkeit im Boden des Buchenwalds. Forstwiss. Forsch. 20, 1–68.

Zicsi, A., 1958. Determination of number and size of sampling unit for estimating lumbricid populations of arable soils. In: Murphy, P.W. (Ed.), Progress in Soil Zoology. Butterworths, London, pp. 68–71.

Zicsi, A., 1982. Verzeichnis der bis 1971 beschriebenen und revidierten Taxa der Familie Lumbricidae. Acta Zool. Acad. Sci. Budapest 28, 421–454.

Ziegler, F., Zech, W., 1992. Formation of water-stable aggregates through the action of earthworms: implications from laboratory experiments. Pedobiologia 36, 91–96.