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Oribatid mite biodiversity in agroecosystems: role for bioindication

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Abstract

The general ecology, biology, life history, and available sources for identification of oribatid mites (including Astigmata), the most numerically dominant arachnid group in the organic horizons of most soils, is reviewed. I use this information as the basis to evaluate data on their role for bioindication in agroecosystems, with the following conclusions: (a) oribatid mites with their low metabolic rates, slow development and low fecundity cannot respond rapidly to resource flushes: astigmatic mites with their contrasting life history traits can respond rapidly; (b) because many agroecosystems represent early successional stages, the oribatid species present are those found in heavily disturbed or early successional habitats, wherever these occur; (c) use of oribatid mites for bioindication must incorporate information on life history traits, and habitat and niche profiles for species. ©1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Oribatid mites, the acarine suborder Oribatida or Cryptostigmata, often called ‘moss mites’ or ‘beetle mites’ are associated with organic matter in most terrestrial ecosystems. They are found throughout the soil profile, in surface litter, on grasses, herbs and low-growing shrubs, the bark, twigs and leaves of trees, and in aquatic, semi-aquatic and coastal habitats. Oribatida are one of the most numerically dominant arthropod groups in the organic horizons of most soils, where their densities can reach several hundred thousand individuals per square meter (Norton, 1990). There are about 7000 described species, representing about 1000 genera in more than 150 families (Balogh and Balogh, 1992), but, the fauna of much of the tropics and the southern hemisphere is unknown. Undisturbed soils in agroecosystems can easily yield examples of 20–50 species.

The free-living Astigmata will be treated also in this chapter. Traditionally the Astigmata has been recognized as a distinct acarine suborder. However, the morphological evidence for astigmatic mites being evolved from within a lineage of Oribatida is incontestable (Norton, 1998). Astigmatic life-history traits differ from those of Oribatida (Norton, 1994), and thus they will be discussed independently throughout this chapter. The Astigmata include about 5000 species, representing 800 genera in 70 families. About half of these are obligate parasites of birds or mammals. The remaining taxa include insect and vertebrate associates, and free-living species, and it is the latter, especially those inhabitants of grasslands in the families Acaridae and Histiostomatidae, that will be considered here.

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2. General ecology

Oribatida are actively involved in decomposition of organic matter, in nutrient cycling and in soil formation. All active instars of these mites feed on a wide variety of material, including living and dead plants and fungi, moss, lichens and carrion; many species are intermediate hosts of tapeworms, some species are predaceous, none is parasitic (Krantz, 1978). Oribatid mites are particulate feeders; chelicera and other structures of the mouthparts are used together to cut or tear particles into sizes suitable for intake (Norton, 1990). Species studied in in vitro experiments show fungal preferences, with dermatiaceous microfungi preferred (Klironomos and Kendrick, 1996). Oribatida influence decomposition and soil structure by comminuting organic matter; their fecal pellets provide a large surface area for decomposition, and are in turn an integral component of soil structure in organic horizons. They are the most important group of arachnids from the standpoint of direct and indirect effects on the formation and maintenance of soil structure (Norton, 1986a; Moore et al., 1988). Oribatid mites disperse bacteria and fungi, both externally on their body surface, or by feeding on spores that survive passage through their alimentary tracts. They can enhance endomycorrhizal colonization (Klironomos and Kendrick, 1995). Many species sequester calcium and other minerals in their thickened cuticle (Norton and Behan-Pelletier, 1991). Thus, their bodies may form important 'sinks' for nutrients, especially in nutrient limited environments (Crossley, 1977).

The feeding habits of oribatid mites are traditionally categorized based on analysis of their gut contents (Schuster, 1956; Luxton, 1972). Macrophytophages (including xylophages feeding on woody tissue, and phyllophages feeding on non-vascular tissue) feed on higher plant material. Microphytophages (including mycophages feeding on fungi, phycophages feeding on algae, and bacteriophages feeding on bacteria) feed on the soil microflora. Panphytophages feed on both microbial and higher plant material, either concurrently, or at different stages in the life cycle. Walter (1987) noted that many Oribatida that have been considered mycophagous, also graze on algae and act as predators of nematodes; he defines these species as polyphagous.

Astigmatic mites also facilitate the humification process, fragmenting organic material and providing a greater surface area for subsequent attack by other organisms (Philips, 1990). Astigmata free living in soil feed on plant material, fungi and algae, preferably of high protein content, and also consume the liquified products of decaying organic material (Philips, 1990). Species of *Schwiebia* and *Tyrophagus* are omnivorous, attacking detrital, microbial and animal prey. *Tyrophagus putrescentiae* is an effective predator of the southern corn root worm under no-tillage conditions, and may be a significant over-wintering mortality factor for this pest (Stinner and House, 1990). A species of *Histiostoma* feeds on earthworm eggs (Krantz, 1978), whereas a congener filter feeds on fine organic material and its associated microbes (Walter and Kaplan, 1990). Few soil astigmatic mites are phytophagous, but species of *Tyrophagus* and *Rhizoglyphus* can be significant plant pests, feeding on bulbs and roots (Hughes, 1976).

Recently, oribatid mites, including the astigmatic *Tyrophagus similis* Volgin, have been divided into feeding guilds on the basis of their carbohydrase activity (Siepel and de Ruiter-Dijkman, 1993). Herbivorous grazers show cellulase activity only and can feed on the cell wall and cell content of green plants (both living and dead) and algae. Fungivorous grazers show chitinase and trehalase activity, and can digest both cell walls and cell contents of living and dead fungi. Fungivorous browsers show trehalose activity only and can digest cell contents of living fungi. Herbo-fungivorous grazers are able to digest both green plants and fungi. Opportunistic herbo-fungivores can digest cellulose in litter and cell walls of living green plants, and trehalose in fungi. Omnivores show cellulase and chitinase activity and can feed on components of plants, fungi and arthropods. Species which lack carbohydrase activity entirely probably are predators, or carrion feeders and/or bacteria feeders. Studies on gut content analysis and those on enzyme activity (e.g., Luxton, 1979; Siepel and de Ruiter-Dijkman, 1993; Urbášek and Starŷ, 1994) highlight the range of feeding habits in any oribatid lineage; for example, the Desmonomata includes herbivorous grazers, herbo-fungivorous grazers and opportunistic herbo-fungivores.

Culturing oribatid and astigmatic mites can present a more complete picture of their food requirements and preferences. *Tyrophagus similis*, a fungivorous browser (Siepel and de Ruiter-Dijkman, 1993), developed at similar rates on fungal only or nematode only diets (Walter, 1987). *Pilogalumna tenuiclaves* is a herbo-fungivorous grazer based on carbohydrase activity, but egg clutches of a congener (*P. cozadensis*) were doubled in size when nematodes were added to a diet of fungi and algae (Walter, 1987).

Many digestive enzymes, including cellulase and chitinase, are produced by the diverse and very active gut microflora of oribatid species, which is a subset of the microflora of the surrounding environment rather than a specialized obligate flora (Stefaniak and Seniczak, 1976; Stefaniak, 1981; Norton, 1994). Perhaps, as Norton (1986a) suggests, microorganisms capable of continued enzymic production in the gut are those resistant to digestion. The ability of oribatid mites to adjust to forced changes in diet, and the evidence that gut contents of a given species can vary with site and season (Anderson, 1975; Behan-Pelletier and Hill, 1983) or at different stages in the life cycle (Siepel, 1990a) may reflect changes in this active gut microflora (Norton, 1986a).

3. Biology and life history

Oribatid and astigmatic mites range in size from about 150 to 1500 mm, but most are in the size range of 300–700 mm. Oribatid mites have six postembryonic instars: an inactive prelarva, and an active larva, protonymph, deutonymph, tritonymph and adult. All active stages feed, and, as noted above, feeding habits may differ between immatures and adults of the same species (Siepel, 1990a). Adults of many oribatid species live a relatively long time, and are iteroparous, spreading oviposition over their adult life rather than ovipositing once (Norton, 1994). Estimates of development time from egg to adult vary from several months to two years in temperate soil (Luxton, 1981), and immatures and adults can overwinter in mixed populations (Cannon and Block, 1988). In cold climates certain oribatid species have life cycles up to seven years (Cannon and Block, 1988). Oribatid mites generally have low metabolic rates, slow development, and low fecundity and exemplify ‘*k*-selected’ organisms (Crossley, 1977). There is no evidence for considering these traits adaptive, rather they reflect evolutionary constraints probably related to the digestive physiology of these mites (Norton, 1994).

Free-living Astigmata have five or six postembryonic instars: an inactive prelarva, an active larva, protonymph, tritonymph and adult, and a heteromorphic deutonymph (hypopus). This latter, facultative in some species, is a nonfeeding instar morphologically and physiologically adapted for phoresy. Other than the hypopus, all active stages feed. Free-living Astigmata in agroecosystems are colonizing mites (‘*r*-selected’), having higher fecundity, faster development and much higher reproductive rates than oribatid mites (Norton, 1994). Many species can complete their life cycle in 8 days to 3 weeks depending on relative humidity and temperature (Hughes, 1976). Under laboratory conditions, females can lay up to 800 eggs in a month and adults have an average longevity of 23–46 days (Philips, 1990, and included references).

Mortality factors for Oribatida and Astigmata are poorly known. Mortality is thought to be concentrated in the immatures, resulting from predation on these soft-bodied instars and the pre-ecdysial resting stages in which mites spend almost a third of their post-hatching development time (Luxton, 1981). Adult Oribatida, however, are subject to predation by a range of animals including ptiliid and scydmaenid beetles (Riha, 1951; Schmid, 1988), newts (Norton and MacNamara, 1976), and odonate larvae (Behan-Pelletier and Bissett, 1993), and they seem to be more vulnerable than immatures to internal parasites (Purrini, 1980; Purrini and Bukva, 1984). Winter mortality may not be an important factor as adult and immature mites in both temperate and cold habitats exhibit extensive supercooling ability (Cannon and Block, 1988).

4. Sampling and preparation

A Tullgren apparatus, based on the Berlese funnel (thus often called Berlese–Tullgren funnel), and its various modifications, is the most commonly used method for separating small arthropods, such as oribatid and astigmatic mites, from soil and litter. Modifications of the Berlese–Tullgren funnel in which the extraction efficiency is improved by enhancing humidity and temperature gradients include the Macfadyen high-gradient funnel (Macfadyen, 1962), the

Kempson apparatus (Kempson et al., 1963), and the Merchant–Crossley extractor (Merchant and Crossley, 1970; Norton, 1986b). For qualitative sampling of large volumes of litter Norton and Kethley (1988) describe a light-weight, collapsible and easily transportable Berlese–Tullgren funnel. Edwards (1991) reviewed most modifications of behavioural extractors and provided details of preferred methods for sampling different soil types.

Behavioral extractors extract only active stages; eggs, prelarva, and quiescent pre-molt stages remain in the sample. In arid soils, deep soils, and for arboreal habitats such as twigs, behavioural extractors are inefficient. Washing of the sample (soil, twigs etc.) with subsequent heptane flotation is recommended for these habitats, it provides complete life-history data for many mites and is the only effective way to assess diversity in deep soils and canopy where mite numbers are low (Walter et al., 1987).

Oribatid and asigmatid mites sorted from mixed extractants using a stereomicroscope, are generally preserved in 75% ethanol. Identification to genus and species requires observation at 200–1000× with a compound microscope, preferably with phase contrast or interference contrast systems. Specimens to be studied are placed temporarily or permanently on microscope slides. Oribatid mites, especially those heavily sclerotized, are often observed using a temporary cavity-slide mount. The depth of field in compound microscopy is minimal, and most adult oribatid specimens must be cleared, and flattened or dissected for optimal resolution (Krantz, 1978).

5. Identification

The use of oribatid mites as indicators of soil conditions and disturbances is not yet widespread, perhaps because the most effective indicators are species, and the taxonomy of the group is incomplete. For most species only the adult stage is described; no monograph on oribatid mites treats the immatures of all species. This is unfortunate because the heteromorphic immatures of brachypyline oribatid mites bear little ressemblance to conspecific adults, unlike the paurometabolous ‘lower’ oribatids.

The number of described genera worldwide has increased from 700 to more than 1000 in the last 20 years (Balogh and Balogh, 1992). Even in Europe new species are described yearly, and in North America about 75% of the fauna is undescribed (Behan-Pelletier and Bissett, 1992). The key to genera of oribatid mites of the world (Balogh and Balogh, 1992) covers all but most recently described genera. It provides superfamily and generic level identifications to adults, but the key is demanding, sometimes even for experts. A more simplified family-level key for adult oribatid mites from soil and litter from North America, north of Mexico, is that of Norton (1990). Monographic works to the superfamily level which are valuable for species identification, are listed in Table 1. Though there are no monographs to the North American fauna, the catalogue of oribatid mites of Canada and continental USA (Marshall et al., 1987), which includes about 1000 species is a remarkably useful comprehensive guide to the literature on each species. No similar catalogue exists for the fauna of other zoogeographic regions, but there are recent checklists of oribatid species for many regions.

The most useful key to species of free-living Astigmata is Hughes (1976). Though this key is to the mites of stored food and houses, many of these species are found in grasslands or cultivated soils. Philips (1990) provides a useful key to the families and genera of free-living terrestrial Astigmata of North America, whereas the Palearctic Astigmata are covered in Ghilyarov and Krivolutsky (1975).

The effective use of a group of organisms as bioindicators requires user-friendly keys. In the future many of these will be image-based, interactive computer identification aids, similar to COMTESA developed for the soil fauna of the Pacific Northwest (Moldenke et al., 1991), or the CD-ROM using DELTA software to identify oribatid species of Australia (Hunt et al., 1998).

6. Role as bioindicators

Oribatid and astigmatic species and species assemblages offer several advantages for assessing the quality of terrestrial ecosystems: their diversity is high, they occur in high numbers, they are easily sampled, they can be sampled in all seasons, adult identification, at least in central Europe is relatively easy, most

Table 1
Useful taxonomic works for Oribatida and Astigmata

Taxonomic level	Geographic scope	References
Oribatida: keys to superfamily and genus	Worldwide	Balogh and Balogh, 1992
Oribatida: key to family	North America	Norton, 1990
Oribatida: keys to family, genus and species	former USSR	Ghilyarov and Krivolutsky, 1975
Oribatida: keys to family, genus and species	Neotropics	Balogh and Balogh, 1988, 1990
Oribatida: keys to genus and species	Central Europe	Sellnick, 1960
Oribatida: keys to family and genus	former Czechoslovakia	Kunst, 1971
Oribatida: keys to family and common species	Poland	Niedbła, 1980
Oribatida: keys to family, genus and species	Japan	Suzuki, 1978
Oribatida: keys to family, genus and species	Australia	Hunt et al., 1998
Oribatida: keys to family, genus and species	New Zealand	Luxton, 1985
Macropylina (lower oribatids): keys to family, genus and species	Palaearctic	Balogh and Mahunka, 1983
Poronotic Oribatida: keys to superfamily, family, genus and species	Iberian Peninsula	Pérez-Iñigo, 1993
Phthiracaroidea: keys to family, genus and species	worldwide	Niedbała, 1992
Ceratozetoidea: keys to family, genus and species	Ukraine	Pavlitshenko, 1994
Astigmata: key to family, genus and species	Europe	Hughes, 1976
Astigmata: key to free-living family, genus and species	former USSR	Ghilyarov and Krivolutsky, 1975
Astigmata: key to free-living genera	North America	Philips, 1990

live in the organic horizons, the site of soil fertility, and they represent a trophically heterogenous group. They include taxa characterized by low fecundity, long immature and adult lifespans and a low capacity for population increase (Oribatida), as well as those with high fecundity and short immature and adult lifespans (Astigmata) (Lebrun and Van Straalen, 1995). Many free-living astigmatic mites have an effective dispersal phase—the non-feeding deutonymph. Few oribatid mites have modifications for dispersal, and those that do disperse as adults (Norton, 1994, and included references). As a result oribatid mites cannot easily escape from stress conditions.

Linden et al. (1994) list the different properties of soil animals which can be potentially used as indicators of soil quality. These include: single organism level characteristics (e.g., behavior, development); community characteristics (e.g., species richness, trophic groups, functional groups); and characteristics of the biological process (e.g., bioaccumulation, soil modification).

Use of single organism characteristics of oribatid or astigmatic mites as indicators of soil quality is still at a preliminary stage. In the last 15 years there have been numerous studies on the ecological and reproductive response of oribatid species to environmental changes (e.g., Hågvar and Abrahamsen, 1980; Hågvar and Kjondal, 1981a, 1981b; Wauthy and Vannier, 1988; Siepel, 1990b; Denneman and Van Straalen, 1991; Lebrun and Van Straalen, 1995; Van Straalen and Verhoef, 1997). Building on these studies and his own research, Siepel (1994, 1995a, 1996a) proposed a method of comparing the effects of management practices across landscapes and between geographic regions based on knowledge of the life-history of the species in any assemblage, and comparing life-history ‘tactics’ of species in assemblages between sites. Siepel (1996b) has shown how effective this approach can be in predicting species loss, and the method will be more precise, useful and widely adopted as knowledge of taxonomy and ecology of species improves, and datasets are assembled on habitat and niche profiles of species.

Use of biological process level characteristics of oribatid or astigmatic mites as indicators of soil quality is still in its infancy, though Rusek (1986, and included references) has studied the structure of oribatid faeces and its contribution to soil structure.

Use of community level characteristics is more advanced (Van Straalen, 1998). However, central to the use of community level characteristics as bioindicators is knowledge of the taxonomy and ecology of species in the community. From this dataset, appropriate indicators can be selected once the stress has been defined (Day, 1990; Linden et al., 1994). In addition, some baseline (benchmark) or reference point must be established against which to compare changes in the indicator (Linden et al., 1994).

Examples of suitable baseline data for assessing the bioindicator potential of oribatid species are few. Weigmann and Kratz (1981) present ecological data on the oribatid species known from Germany, based on the occurence of species in 20 plant associations, the moisture of the habitat, and whether the habitat is edaphic or epiphytic. From these data, Weigmann and Kratz established that numerous species occur predominantly in characteristic habitats or plant associations, and appear suitable as bioindicators. The habitat profile of these species has been further enhanced in subsequent publications (e.g., Weigmann, 1991).

As a first step in the development of bioindicators for stresses on glassland used as pasture for cattle and sheep in Ireland, Curry (1976) studied the species composition and ecology of the microarthropod fauna associated with grass and weed species. This provided the baseline for studies on impact of agronomic practices on these grasslands (e.g., Bolger and Curry, 1980, 1984; Curry, 1986; Curry and Ganley, 1977; Emmanuel et al., 1985).

6.1. General trends in community structure of Oribatida and Astigmata in agroecosystems

Agroecosystems are artifically maintained at an early or intermediate stage of succession (Odum, 1984). In addition to being extremely perturbed by physical and chemical means, conventionally managed agroecosystems contain unnatural plant communities (Crossley et al., 1992). Edwards and Lofty, (1969, Fig. 7) summarized the general changes in microarthropod populations due to agriculture practices. Cultivation, rotations, monoculture, and application of pesticides soon eliminates species susceptible to damage, desiccation and destruction of their microhabitats, especially those with a life cycle longer than one year, such as Oribatida. Practices such as drainage, irrigation and fertilizer use may encourage multiplication of the remaining arthropod groups, such as Prostigmata. These observations have been confirmed by many subsequent studies. For example, Oribatida, although sometimes the most diverse suborder of mites in soils under agriculture, are less species rich than in nearby forests (Mahunka and Paoletti, 1984; Tomlin and Miller, 1987). In a field cultivated with arable crops for about 100 years in Sweden, Oribatida were represented by only *Oppiella nova*, *Oppia* spp., and *Tectocepheus* spp. (Lagerlöf and Andrén, 1988), whereas there were 10 species of Mesostigmata and 8 species of Prostigmata. Similarly, only *Tectocepheus velatus* and *Oppiella nova* were recovered from cultivated soil in Alberta in summerfallow for 7–8 years, though seven species each of Mesostigmata and Prostigmata were collected from the same soil (Berg and Pawluk, 1984). This reflects the generally low metabolic rates, slow development, and low fecundity of oribatid mites which cannot rapidly respond to access resource flushes caused by pulses of primary productivity. Oribatid mites have little capacity to respond numerically to short-term environmental alterations. Their populations decline rapidly when their habitat is damaged, a characteristic which allows detection of environmental degradation (Lebrun and Van Straalen, 1995; Siepel, 1996b).

In contrast, Astigmata are comparatively well represented in arable soils with three species in both the above mentioned cultivated sites (Lagerlöf and Andrén, 1988; Berg and Pawluk, 1984). Astigmata are specialists in exploiting spatially and/or temporally restricted microhabitats (Norton et al., 1993), and can be both diverse and numerous in agroecosystems. Their populations often are significantly increased as a result of human activities, e.g., cultivation (Kines and Sinha, 1973; Philips, 1990), and manure application (Weil and Kroontje, 1979). They were the dominant mite group in urban roadside soil in Japan (Aoki and Kuriki, 1980). These increases in population probably are related to decline of predator populations, the short generation time of astigmatic mites, and the presence of an effective dispersal stage—the hypopus. The general resilience of soil Astigmata to perturbation has been observed after carbofuran application (Broadbent and Tomlin, 1982), after disruption of soil for pipeline construction (Tomlin, 1977), and as pioneer species in reclamation sites (Hudson, 1980).

Oribatid genera found in cultivated soil are those also found in heavily disturbed or early successional habitats, wherever these occur, or whether the disturbance is natural, e.g., frost-boils in the high arctic, or anthropogenic, e.g., cultivated sites, demolition sites, mine tailings. Species in the families Brachychthoniidae, Tectocepheidae and Oppiidae generally are common to all these disturbed habitats. For example, primary colonizers in agricultural soils are species of *Brachychthonius*, *Tectocepheus*, *Oppia* and *Suctobelba* (Karg, 1978). Similarly in roto-tilled and oily-waste treated soils in northeastern North America the Brachychthoniidae, and the genera *Tectocepheus*, *Oppiella*, *Scheloribates* and *Punctoribates* were well represented (Norton and Sillman, 1985). In urban ruderal biotopes a species of each of *Oppiella*, *Suctobelbella*, and *Oribatula* were the first oribatid mites recorded from an isolated plot approximately 1 km from other vegetated areas (Weigmann, 1982). In urban roadside soil in Japan *Oppia, Quadroppia, Tectocepheus, Oribatula*, and *Eremulus* were recorded (Aoki and Kuriki, 1980). Species of *Oppiella, Tectocepheus,Trhypochthonius*, *Scutovertex*, *Scheloribates*, *Trichoribates*, and *Punctoribates* were common on metallurgic dumps in Poland (Skubała, 1995). Many species in these genera are pioneers and are either drought-tolerant ubiquitous species or drought-loving species. Species in the families Brachychthoniidae, Trhypochthoniidae, Tectocepheidae and Oppiidae are mostly thelytokous, a reflection of the 'general purpose genotypes' of these species (Norton, 1994).

Oribatid species assemblages are considered to respond to agricultural practices such as crop selection, tillage practice, pesticide treatments, and fertilizers in a predictable manner, and as such can be used to detect whether soil quality is being aggraded or degraded. They can be used either by themselves or in concert with chemical and physical measures as both diagnostic and confirmatory tools of soil quality. However, as the same genera and often the same species form the oribatid species assemblage in all disturbed landscapes, the question is whether there are differences in population structure that can be used as indicators of the type of disturbance. Hågvar (1994) proposes change in dominance structure of a community of soil microarthropods as an 'early warning' indicator of stress. He documents how characteristic changes occur in the log-normal dominance structure of stable communities under various types of stress: an initial flattening of the curve as species sensitive to stress become less dominant, and a strongly skewed dominance curve as sensitive species become very rare. Steiner (1995) noted similar changes in the dominance curve of oribatid communities subject to increasing levels of air pollution. Siepel (1996b) found lower genetic diversity of *Oppiella nova* on a high-input grassland site, in comparison with a low-input grassland site and a forested site.

To date, however, most studies on population structure and change in agroecosystems have focussed on the impact of specific management practices on soil fauna, including Oribatida and Astigmata (see Table 2 for examples). These include studies on the impact of low-input, minimum till, fertilizer application, grazing, and ecological agricultural practices on the soil fauna, including Oribatida (e.g., Moore et al., 1984; Mueller et al., 1990; House and Parmelee, 1985; Stinner et al., 1988). Marshall (1977) reviewed the literature on effects of manures and fertilizers on soil fauna, including Oribatida, up to mid-1973. Many studies in North America have identified no further than suborder or family level, which precludes use of the results in establishing bioindicators for particular environmental stresses. European studies have analyzed the impact of specific management practices on the species assemblage (e.g., Persson and Lohm, 1977; Lagerlöf and Andrén, 1988), but whether changes in population structure following stress are predictive, as Hågvar (1994) proposes, requires further study.

A confounding factor to the perdictability of changes in oribatid populations following cultivation practices is the poorly researched impact of windbreaks, hedges, uncultivated ditches and grassy margins on this fauna. These uncultivated areas can have a different community structure than that of cultivated fields and population levels can also differ significantly. Uncultivated areas can function as refugia or corridors of diversity in the agricultural landscape, functioning as a source of colonizing species (Paoletti, 1988; Miko, 1993; Sgardelis and Usher, 1994).

6.2. Restoration management

While Astigmata, Mesostigmata and Prostigmata colonize newly reclaimed land within a few months, oribatid mites require considerable longer time (Beckmann, 1988; Skubała, 1995). Long-term studies documenting succession in oribatid community structure in agroecosystems following initial disturbance are rare. Karg (1978) estimated a period of 4–7 years for recolonization of grassland. An 8 year study of changes in the oribatid assemblage following ploughing of virgin grassland in the former USSR documented a 'transi-

Table 2
Examples of impact of various agricultural practices on Oribatida

Taxonomic level	Habitat	Stress	Impact	Reference
Oribatida	sorghum/rye (USA)	conventional tillage (CT) versus no-tillage (NT) for 17 years	populations: NT 36809; CT 14990	House and Parmelee, 1985
Oribatida	sorghum/clover (USA)	conventional tillage versus no-tillage for 17 years	populations: NT 33272; CT 5097	House and Parmelee, 1985
Oribatida	grass (USA)	No-tillage versus no-tillage with Atrazine	populations: negatively affected by Atrazine; returned to control levels at end of season	Moore et al., 1984
Oribatida	grassland (Ireland)	Pig slurry: normal rate of application; 2× field rate; 5× field rate	species abundances frequencies and diversity strongly affected by greater than field rate application	Bolger and Curry, 1984
Oribatida	arable: maize, conventional tillage (USA)	Poultry manure	population: increase at 54 and 85 t ha^{-1}; decrease at 27 and 110 t ha^{-1}	Weil and Kroontje, 1979
Oribatida	grassland 300 years old (England)	ploughed and disked	populations: reduced to 40% of that in undisturbed grassland	Edwards and Lofty, 1969
Oribatida	turf, 10 years pesticide free USA)	Margosan-O (neem seed-kernel extract with 3 g l^{-1} azadirachtin) versus chlorpyrifos	populations: reduced by 1.5× with Margosan-O; populations: higher with chlorpyrifos treatment.	Stark, 1992
Oribatida	continuous corn under conventional tillage (Canada)	carbofuran application	populations show wide short-term fluctuations; no long-term effects	Broadbent and Tomlin, 1982
Brachychthonius jugatus	pasture (Canada)	malathion, carbaryl (recommended application rate)	population: greater than control	Smith et al., 1980
Tectocepheus velatus *Oppia minus*	pasture (Canada)	organophosphate or chlorinated hydrocarbon	populations: greater than control	Smith et al., 1980
Scheloribates pallidulus	pasture (Canada)	carbaryl, mexacarbate (recommended application rate)	population: greater than control	Smith et al., 1980
Oppiella nova	pasture (Canada)	diazinon, malathion, methoxychlor (recommended application rate)	population: less than control	Smith et al., 1980
Rhysotritia ardua ardua	cotton fields (Egypt)	profenofos, chlorofluazuron, fenvalerate	population: positively effected	Al-Assiuty and Khalil, 1995
Zygoribatula exarata *Xylobates capucinus*	cotton fields (Egypt)	profenofos, chlorofluazuron, fenvalerate	populations: negatively effected	Al-Assiuty and Khalil, 1995
Oppiella spp.	corn production versus grassland control (USA)	moldboard plowing versus moldboard + Atrazine in corn	populations: grassland and moldboard + atrazine start and finish the same following seasonal fluctuations	Mallow et al., 1985

tional' fauna dominated by species rare in both control virgin grassland and an adjacent 30-year-old wheat monoculture (Gadzhiyev, 1991). The Horseshoe Bend (see Crossley et al., 1992 and included references) study which has tracked changes in conventional and no-till 'old-field' sites since 1978, recovered most of the original oribatid genera 10 years following cultivation. As normal rotation practices vary from 3 to 7 years, this implies that the oribatid assemblage in cultivated soils never has a chance to stabilize or return to predisturbance levels.

Use of oribatid mites to assess the 'inertia' (the relative resistance of community structure to perturbation) and 'elasticity' (time to return to the undisturbed state) of agroecosystems must take into account the low fecundity of oribatid mites and their poor dispersal abilities which ensures slow establishment of populations, even if immigration is successful. Other restraints imposed by their feeding habits and generally low metabolism preclude rapid reestablishment of populations.

6.3. *Impact of pesticides*

As with other invertebrate groups, oribatid mites are selectively effected by pesticides. They have been found to be insensitive to some insecticides, e.g., chlorpyrifos (Stark, 1992), positively effected by pesticides (Broadbent and Tomlin, 1979), and negatively effected by pesticides, e.g., azadirachtin (Stark, 1992) and low levels of copper, 2,4,6-trinitrotoluene and *p*-nitrophenol (Parmelee et al., 1993). It is clear that, as with other environmental perturbations, individual oribatid species respond selectively to pesticides (Smith et al., 1980; Streit, 1984; Al-Assiuty and Khalil, 1995; Table 2). However, the paucity of information on pesticide toxicity to Oribatida and other soil fauna, especially in field situations, is striking (Van Straalen and van Rijin, 1998).

6.4. *Urban environments*

Studies of bioindicators of urbanization primarily in Europe show oribatid mites to be sensitive indicators of changing air quality (André, 1976; Kehl and Weigmann, 1992; Porzner and Weigmann, 1992; Weigmann and Jung, 1992). Steiner (1995) demonstrated that air pollution, particularly increased concentrations of NO_2, decreases oribatid species richness and causes more uniform communities. Steiner noted that many species are more strongly influenced by microhabitat characteristics than levels of pollutants, and changes in population structure resulting from pollutants have to be clearly segregated from those due to microhabitat variability before bioindicators can be characterized. He considers *Zygoribatula exilis* and possibly *Eremaeus oblongus* as promising indicators of air pollution in Europe, and confirms the high tolerance of *Camisia segnis* to pollutants. *Humerobates rostrolamellatus* (Grandjean) is highly sensitive to air pollution and has been tested in the laboratory and in the field as an air pollution bioassay monitor (André and Lebrun, 1984).

Population structure, species richness and reproduction of oribatid mites also are negatively effected by the higher dose of heavy metals in urban environments (Denneman and Van Straalen, 1991; Van Straalen et al., 1989; Stamou and Argyropoulou, 1995). Siepel (1995b) noted that fungivorous grazers such as *Platynothrus peltifer, Nothrus silvestris*, feeding on both fungal cell walls and cell contents are more exposed to, and negatively effected by, heavy metals, such as lead, in contrast to fungivorous browsers (e.g., *Tyrophagus similis*) that feed only on fungal cell content. The potential of oribatid mites as selective bioindicators of air and heavy metal pollutants are important where agroecosystems closely abut urban zones.

7. Conclusions

Stork and Eggleton's (Stork and Eggleton, 1992) criteria for using invertebrates as indicators of soil quality can be modified for use as a framework to assess oribatid and astigmatic mites potential as indicators in agroecosystems. Initially, assessment of the taxonomic diversity and species richness of the community, especially of several dominant taxa, will provide a simple indication of the ecological complexity of the soil community. To date, specific keystone species have not been identified for oribatid or astigmatic mites in agroecosystems. Dominance of an assemblage by species of Brachychthoniidae, Tectocepheidae and Oppiidae indicates recent disturbance, although not the specific nature of the disturbance.

When ecological and biological data are available for species in the community, assessment of the species assemblage can provide precise data on soil quality, and potentially identify the nature of the perturbation (Siepel, 1995a). Integration of ecological and biological data on species assemblages with geographical information system (GIS) data on soil physical and chemical parameters, other biotic components, climate and vegetation, could potentially provide assessments of habitat complexity and change under stress at larger spatial scales, and allow comparison between habitats.

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References

Al-Assiuty, A.I.M., Khalil, M.A., 1995. The influence of insecticide-pheromone substitution on the abundance and distributional pattern of soil oribatid mites. Exp. Appl. Acarol. 19, 399–410.

Anderson, J., 1975. Succession, diversity, diversity and trophic relationships of some soil animals in decomposing leaf litter. J. Anim. Ecol. 44, 475−495.

André, H.M., 1976. Introduction a l'étude écologique des communautés de microarthropodes corticoles soumises a la pollution atmosphèrique I. Les microhabitats corticoles. Bull. Ecol. 7, 431−444.

André, H.M., Lebrun, Ph., 1984. On the use of *Humerobates rostrolamellatus* (Acari) as an air pollution bioassay monitor. the incidence of SO_2–NO_2 synergism and of winter temperature. Sci. Total Environ. 39, 177–187.

Aoki, J.-I., Kuriki, G., 1980. Soil mite communities in the poorest environment under the roadside trees. In: Dindal, D.L. (Ed.), Soil Biology as Related to Land Use Practices. Office of Pesticide and Toxic Substances, EPA, Washington, DC, pp. 226–232.

Balogh, J., P. Balogh, 1988. Oribatid mites of the Neotropical Region I. Akadémiai Kiadó, Budapest,. 335 pp.

Balogh, J., Balogh, P., 1990. Oribatid mites of the Neotropical Region II. Akadémiai Kiadó, Budapest, 333 pp.

Balogh, J., Balogh, P., 1992. The oribatid mites genera of the world. Hungarian Natural History Museum, Budapest. vol. I: 263pp, vol. II: 375pp.

Balogh, J., Mahunka, S., 1983. Primitive oribatids of the Palaearctic region. Elsevier, Amsterdam, 372 pp.

Beckmann, M., 1988. Die entwicklung der Bodenmesofauna eines Ruderal-Ökosystems und ihre Beeinflussung durch Rekultivierung: 1, Oribatiden (Acari: Oribatei). Pedobiologia 31, 391–408.

Behan-Pelletier, V.M., Bissett, B., 1992. Biodiversity of Nearctic soil arthropods. Can. Biodivers. 2, 5–14.

Behan-Pelletier, V.M., Bissett, B., 1993. Oribatida of Canadian peatlands. Mem. Ent. Soc. Can. 169, 73–88.

Behan-Pelletier, V.M., Hill, S.B., 1983. Feeding habits of sixteen species of Oribatei (Acari) from an acid peat bog, Glenamoy, Ireland. Rev. Écol. Biol. Sol 20, 221–267.

Berg, N.W., Pawluk, S., 1984. Soil mesofaunal studies under different vegetative regimes in north central Alberta. Can. J. Soil Sci. 64, 209–223.

Bolger, T., Curry, J.P., 1980. Effects of cattle slurry on soil arthropods in grassland. Pedobiologia 20, 246–253.

Bolger, T., Curry, J.P., 1984. Influences of pig slurry on soil microarthropods in grassland. Rev. Écol. Biol. Sol 21, 269–281.

Broadbent, A.B., Tomlin, A.D., 1979. Species list of Acari recovered from soil of a Guelph cornfield and a London pasture. Proc. Entomol. Soc. Ont. 110, 101–103.

Broadbent, A.B., Tomlin, A.D., 1982. Comparison of two methods for assessing the effects of carbofuran on soil animal decomposers in cornfields. Environ. Entomol. 11, 1036–1042.

Cannon, R.S.C., Block, W., 1988. Cold tolerance of microarthropods. Biol. Rev. 63, 23−77.

Crossley, D.A., 1977. The roles of terrestrial saprophagous arthropods in forest soils: current status of concepts. In: Mattson, W.J. (Ed.), The Role of Arthropods in Forest Ecosystems, Springer, Berlin/Heidelberg/New York, pp. 226–232

Crossley Jr., D.A., Mueller, B.R., Perdue, J.C., 1992. Biodiversity of microarthropods in agricultural soils: relations to processes. Agric. Ecosyst. Environ. 40, 37–46.

Curry, J.P., 1976. The arthropod fauna of some common grass and weed species of pasture, *Proc. Roy. Irish Acad.* 76, Section B, 1-35.

Curry, J.P., 1986. Effects of management on soil decomposers and decomposition processes in grasslands and croplands. In: Mitchell, M.J., Nakas, J.P. (Eds.), Microfloral and Faunal Interactions in Natural and Agro-Ecosystems. Nijhoff/Junk, Dordrecht, pp. 349–398.

Curry, J.P., Ganley, J., 1977. The arthropods associated with the roots of some common grass and weed species of pasture. Ecol. Bull. 25, 330–339.

Day, K., 1990. Rapporteur's report of work group: indicators at the species and biochemical level. Environ. Monit. Assess. 15, 277–290.

Denneman, C.A.J., Van Straalen, N.M., 1991. The toxicity of lead and copper in reproduction tests using the oribatid mites *Platynothrus peltifer*. Pedobiologia 35, 305–311.

Edwards, C.A., 1991. The assessment of populations of soil-inhabiting invertebrates. Agric. Ecosyst. Environ. 34, 145–176.

Edwards, C.A., Lofty, J.R., 1969. The influence of agricultural practice on soil micro-arthropod populations. In: Sheals, J.G. (Ed.), The Soil Ecosystem. Systematics Association Publication No. 8, pp. 237–247

Emmanuel, N., Curry, J.P., Evans, G.O., 1985. The soil Acari of barley plots with different cultural treatments. Expt. Appl. Acarol. 1, 101–113.

Gadzhiyev, I.M., 1991. Succession of oribatid communities under various conditions of utilization of virgin steppeland after ploughing. In: Gadzhiyev I.M. (Ed.), Soil Formation and Anthropogensis: Structural–Functional Aspects. Nauka Publishers, Novosibirs, pp. 73–91.

Ghilyarov, M.S., Krivolutsky, D., 1975. A key to soil-inhabiting mites. Sarcoptiformes, Akad. Nauk SSSR (Leningrad), 719 pp (in Russian).

Hågvar, S., 1994. Log-normal distribution of dominance as an indicator of stressed soil microarthropod communities?. Acta Zool. Fennica 195, 71–80.

Hågvar, S., Abrahamsen, G., 1980. Colonization by Enchytraeidae, Collembola, Collembola and Acari in sterile soil samples with adjusted pH levels. Oikos 34, 245–258.

Hågvar, S., Kjondal, B.R., 1981a. Succession, diversity, diversity and feeding habits of microarthropods in decomposing birch leaves. Pedobiologia 22, 385–408.

Hågvar, S., Kjondal, B.R., 1981b. Effects of artificial acid rain on the microarthropod fauna in decomposing birch leaves. Pedobiologia 22, 409–422.

House, G.J., Parmelee, R.W., 1985. Comparison of soil arthropods and earthworms from conventional and no-tillage agroecosystems. Soil Tillage Res. 5, 351–360.

Hughes, A.M., 1976. The mites of stored food and houses. Ministry of Agriculture, Fisheries and Food, Technical Bulletin 9, Her Majesty's Stationary Office, London, 400 pp.

Hudson, B.R., 1980. Colonization of industrial reclamation sites by Acari, Collembola, Collembola and other invertebrates. J. Appl. Ecol. 17, 255–275.

Hunt, G. S., Norton, R.A., Kelly, J.P.H., Colloff, M.J., Lindsay, S.M., 1998. Oribatid mites. An interactive key to the oribatid mites of Australia. CSIRO Publications, East Melbourne (CD-ROM + booklet).

Karg, W., 1978. Milben als indikatoren zur optimierung von pflanzenschutzmassnahmen in apfelintensivanlagen. Pedobiologia 18, 415–425.

Kehl, C., Weigmann, G., 1992. Die hornmilbenzonosen (Acari, Oribatida) an apfelbaumen im stadgebiet von Berlin als bioindikatoren fur die luftqualitat. Zool. Beitr. 34, 261–271.

Kempson, D., Lloyd, M., Ghelardi, R., 1963. A new extractor for woodland litter. Pedobiologia 3, 1–21.

Kines, K.A., Sinha, R.N., 1973. A laboratory study of fauna and flora in an agriculture soil in Manitoba. Manitoba Entomol. 7, 59–66.

Klironomos, J.N., Kendrick, W.B., 1995. Stimulative effects of arthropods on endomycorrhizas of sugar maple in the presence of decaying litter. Functional Ecol. 9, 528–536.

Klironomos, J.N., Kendrick, W.B., 1996. Palatability of microfungi to soil arthropods in relation to the functioning of arbuscular mycorrhizae. Biol. Fertil. Soils 21, 43–52.

Krantz, G.W., 1978. A manual of acarology. 2nd ed., Oregon State University Book Stores Inc., Corvallis, 509 pp.

Kunst, M., 1971. Oribatei, In: Daniel, R.M. Cerny, V. (Eds.), Klic zvireny CSSR Dil IV. Ceskoslovenska Alkademie Ved. Academia Praha, pp. 551–580.

Lagerlöf, J., Andrén, O., 1988. Abundance and activity of soil mites (Acari) under four arable crops. Pedobiologia 32, 129–145.

Lebrun, Ph., Van Straalen, N.M., 1995. Oribatid mites: prospects for their use in ecotoxicology, Expt. Appl. Acarol. 19, 361–380.

Linden, D. R., Hendrix, P.F., Coleman, D.C., van Vliet, P. C. J., 1994. In: Doran, J. W., Coleman, D.C., Bezdicek, D. F., Stewart, B.A. (Eds.), Defining Soil Quality for a Sustainable Environment. SSSA Special Publication No. 35, pp. 91–106.

Luxton, M., 1972. Studies on the oribatid mites of a Danish beechwood soil. 1. Nutritional biology. Pedobiologia 12, 434–463.

Luxton, M., 1979. Food and energy processing by oribatid mites. Rev. Écol. Biol. Sol 16, 103–111.

Luxton, M., 1981. Studies on the Oribatid mites of a Danish Beech wood soil IV. Developmental biology. Pedobiologia 21, 312–340.

Luxton, M., 1985. Cryptostigmata (Arachnida: Acari)—a concise review. Fauna of New Zealand 7, 106.

Macfadyen, W.A., 1962. Soil arthropod sampling. Adv. Ecol. Res. 1, 1–34.

Mahunka, S., Paoletti, M.G., 1984. Oribatid mites and other mites (Tarsonemidae, Anoetidae, Acaridae) from woods and farms monocultivated with corn in the low laying plain (Veneto and Friuli, N-E Italy). Redia 67, 93–128.

Mallow, D., Snider, R.J., Robertson, L.S., 1985. Effects of different management practices on Collembola and Acarina in corn production systems II. The effects of moldboard plowing and atrazine. Pedobiologia 28, 115–131.

Marshall, V.G., 1977. Effects of manures and fertilizers on soil fauna: a review. Commonwealth Bureau of Soils, Special Publication No. 3, 79 pp.

Marshall, V.G., Reeves, R.M., Norton, R.A., 1987. Catalogue of the Oribatida (Acari) of Continental United States and Canada. Mem. Ent. Soc. Can. 139, 418.

Merchant, V.A., Crossley Jr., D.A., 1970. An inexpensive, high-efficiency Tullgren extractor for soil microarthropods. J. Georgia Entomol. Soc. 5, 83–87.

Miko, L., 1993. Effects of poplar windbreaks on soil arthropod communities in heavy soil agroecosystems of east Slovakia. Ekológia Bratislava 12, 163–178.

Moldenke, A., Shaw, C., Boyle, J.R., 1991. Computer-driven image-based soil fauna taxonomy. Agric. Ecosyst. Environ. 34, 177–185.

Moore, J.C., Snider, R.J., Robertson, L.S., 1984. Effects of different management practices on Collembola and Acarina in corn production systems. 1. The effects of no-tillage and Atrazine. Pedobiologia 26, 143–152.

Moore, J.C., Walter, D.E., Hunt, H.W., 1988. Arthropod regulation of micro- and mesobiota in below-ground detrital food webs. Annu. Rev. Ent. 33, 419–439.

Mueller, B.R., Beare, M.H., Crossley Jr., D.A., 1990. Soil mites in detrital food webs of conventional and no-tillage agroecosystems. Pedobiologia 34, 389–401.

Niedbała, W., 1980. Moss mites - mites of terrestrial ecosystems. Panst. Wydawn. Nauk., Warsaw, 255 pp. (in Polish).

Niedbała, W., 1992. *Phthirac aroidea* (Acari, Oribatida) systematic studies. Elsevier, Amsterdam, 612 pp.

Norton, R.A., 1986a. A spects of the biology and systematics of soil arachnids particularly saprophagous and mycophagous mites. Quaest. Ent. 21, 523–541.

Norton, R.A., 1986b. A variation of the Merchant–Crossley soil microarthropod extractor. Quaest. Ent. 21, 669–671.

Norton, R.A., 1990. Acarina: Oribatida. In: Dindal, D.L. (Ed.), Soil Biology Guide. Wiley, New York, pp. 779–803.

Norton, R.A., 1994. Evolutionary aspects of oribatid mites life histories and consequences for the origin of the Astigmata. In: M.A. Houck (Ed.), Mites: Ecological and Evolutionary Analyses of Life-History Patterns, Chapman & Hall, New York, pp. 99–135.

Norton, R.A., 1998. Morphological evidence for the evolutionary origin of Astigmata (Acari: Acariformes). Exp. Appl. Acar. 22, 559–594.

Norton, R.A., Behan-Pelletier, V.M., 1991. Calcium carbonate and calcium oxalate as cuticular hardening agents in oribatid mites (Acari: Oribatida). Can. J. Zool. 69 (6), 1504−1511.

Norton, R.A., Kethley, J., 1988. A collapsible full-sized Berlese-funnel system. Ent. News 99, 41–47.

Norton, R.A., MacNamara, M.C., 1976. The common newt (*Notophthalmus viridescens*) as a predator of soil mites in New York. J. Ga. Entomol. Soc. 11, 89–93.

Norton, R.A., Sillman, D.Y., 1985. Impact of oily waste application on the mite community of an arable soil. Exp. Appl. Acar 1, 287–306.

Norton, R.A., Kethley, J.B. Johnston, D.E., OConnor, B.M. 1993. Phylogenetic perspectives on genetic systems and reproductive modes of mites. In: Wrensch, D., Ebbert, M.A. (Eds.), Evolution and Diversity of Sex Ratio in Insects and Mites, Chapman & Hall, New York, pp. 8–99.

Odum, E.P., 1984. Properties of agroecosystems. In: Lowrance, R., Stinner, B.R. (eds.), Agricultural Ecosystems: Unifying concepts.Wiley, pp. 5–11.

Paoletti, M.G., 1988. Soil invertebrates in cultivated and uncultivated soils in northeastern Italy. Redia 71, 501–563.

Parmelee, R.W., Wentsel, R.S., Phillips, C.T., Simini, M., Checkai, R.T., 1993. Soil microcosm for testing the effects of chemical pollutants on soil fauna communities and trophic structure. Environ. Toxicol. Chem. 12, 1477–1486.

Pavlitshenko, P.G., 1994. A guide to the ceratozetoid mites (Oribatei, Ceratozetoidea) of Ukraine. Kiev, Ukraine, 143 pp.

Pérez-Iñigo, C, 1993. Fauna Iberica, vol. 3, Acari, Oribatei, Poronota. Museo Nacional de Ciencias Naturales, CSIC, Madrid, 320 pp.

Persson, T., Lohm, U., 1977. Energetical significance of the annilids and arthropods in a Swedish grassland soil. Ecol. Bull. 23, 211.

Philips, J.R., 1990. Acarina: Astigmata (Acaridida). In: Dindal, D.L. (Ed.), Soil Biology Guide. Wiley, New York, pp. 757–778.

Porzner, A., Weigmann, G., 1992. Die hornmilbenfauna (Acari, Oribatida) an eichenstammen in einem Gradienten von autoabgas-immissionen. Zool. Beitr. 34, 249–260.

Purrini, K., 1980. On the incidence and distribution of parasites of soil fauna of mixed coniferous forests, mixed leaf forests, and pure beech forests of Lower Saxony, West Germany. In: Dindal, D.L. (Ed.), Soil Biology as Related to Land Use Practices. Proc. 7th Int. Soil Coll. Washington, DC, pp. 561-582

Purrini, K., V. Bukva, 1984. Pathenogenetic agents of oribatid mites (Oribatei, Acarina): a gap in the research on population dynamics, In: Griffiths, D.A., Bowman, C.E. (Eds.), Acarology VI. Horwood, Chichester, vol. 2, pp. 826–837.

Riha, G., 1951. Zur Ökologie der Oribatiden in Kalksteinböden. Zool. Jahrb. Syst. 80, 408–450.

Rusek, J., 1986. Soil microstructures—contributions on (sic) specific soil organisms. Quaest. Ent. 21, 497–514.

Schmid, R., 1988. Morphologische Anpassungen in einem Räuber-Beute-System: Ameisenkäfer (Scydmaenidae, Staphylinoidea) und gepanzerte Milben (Acari). Zool. Jahrb. Abt. Syst. 115, 207–228.

Schuster, R., 1956. Der Anteil der Oribatiden an den Zersetzungsvorgängen im boden. Zeits. Morph. Ökol. Tiere 45, 1–33.

Sellnick, M., 1960. Hornmilben. Oribatei. Tierwelt Mitteleur. 3, 45–134.

Sgardelis, S.P., Usher, M.B., 1994. Responses of soil Cryptostigmata across the boundary between a farm woodland and an arable field. Pedobiologia 38, 36–49.

Skubała, P., 1995. Moss mites (Acarina: Oribatida) on industrial dumps of different ages. Pedobiologia 39, 170–184.

Siepel, H., 1990a. Niche relationships between two panphytophagous soil mites, *Nothrus silvestris* Nicolet (Acari, Oribatida, Nothridae), and *Platynothrus peltifer* (Koch) (Acari, Oribatida, Camisiidae). Biol. Fertil. Soils 9, 139–144.

Siepel, H., 1990b. Decomposition of leaves of *Avenella flexuosa* and microarthropod succession in grazed and ungrazed grasslands 1. Succession of microarthropods. Pedobiologia 34, 19–30.

Siepel, H., 1994. Life-history tactics of soil microarthropods. Biol. Fertil. Soils 18, 263–278.

Siepel, H., 1995a. Applications of microarthropod life-history tactics in nature management and ecotoxicology. Biol. Fertil. Soils 19, 75–83.

Siepel, H., 1995b. Are some mites more ecologically exposed to pollution with lead than others?. Exp. Appl. Acarol. 19, 391–398.

Siepel, H., 1996a. The importance of unpredictable and short-term environmental extremes for biodiversity in oribatid mites. Biodivers. Lett. 3, 26–34.

Siepel, H., 1996b. Biodiversity of soil microarthropods: the filtering of species. Biodivers. Conserv. 5, 251–260.

Siepel, H., de Ruiter-Dijkman, 1993. Feeding guilds of oribatid mites based on their carbohydrase activities, Soil Biol. Biochem. 25, 1491–1497.

Smith, T.D., McE. Kevan, D.K., Hill, S.B., 1980. Effects of six biocides on non-target soil mesoarthropods from pasture on Ste. Rosalie clay loam St. Clet, Quebec. In: Dindal, D.L. (Ed.), Soil Biology as Related to Land Use Practices. Office of Pesticide and Toxic Substances, EPA, Washington, DC, pp. 56–70

Stamou, G.P., Argyropoulou, M.D., 1995. A preliminary study on the effect of Cu, Pb, Pb and Zn contamination of soils on community structure and certain life-history traits of oribatids from urban areas. Exp. Appl. Acarol. 19, 381–390.

Stark, J.D., 1992. Comparison of the impact of a neem seed-kernel extract formulation ‘Margosan-O’ and chlorpyrifos on non-target invertebrates inhabiting turf grass. Pestic. Sci. 36, 293–299.

Stefaniak, O., Seniczak, S., 1976. The microflora of the alimentary canal of *Achipteria coleoptrata* (Acarina, Oribatei). Pedobiologia 16, 185–194.

Stefaniak, O., 1981. The effect of fungal diet on the development of *Oppia nitens* (Acari, Oribatei), and on the microflora of its alimentary canal. Pedobiologia 21, 202–210.

Steiner, W.A., 1995. Influence of air pollution on moss-dwelling animals 3. Terrestrial fauna, with emphasis on Oribatida, with emphasis on Oribatida and Collembola. Acarologia 36, 149–173.

Stinner, B.R., McCarthy, D.A., Van Doren Jr., D.M., 1988. Soil and foliage arthropod communities in conventional, reduced and no-till corn (Maize, *Zea mays*, L.) systems: a comparison after 20 years of continuous cropping. Soil Till. Res. 11, 147–158.

Stinner, B.R., House, G.J., 1990. Arthropods and other invertebrates in conservation-tillage agriculture. Annu. Rev. Ent. 35, 299–318.

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

Streit, B., 1984. Effects of high copper concentrations on soil invertebrates (earthworms and oribatid mites). Oecologia 64, 381–388.

Suzuki, K., 1978. Key to Japanese oribatid mites (Acarida: Oribatida). Mem. Educ. Inst. Priv. Schools Jap. 56, 121–175.

Tomlin, A.D., 1977. Pipeline construction-impact on soil, micro-, micro- and mesofauna (Arthropoda and Annelida) in Ontario. Proc. Ent. Soc. Ont. 108, 13–17.

Tomlin, A.D., Miller, J.J., 1987. Composition of the soil fauna in forested and grassy plots at Delhi, Ontario. Can. J. Zool. 65, 3048–3055.

Urbášek, F., Starŷ, J., 1994. The activity of some enzymes in the guts of five oribatid species (Acari, Oribatida). Pedobiologia 38, 250–253.

Van Straalen, N.M., 1998. Evaluation of bioindicator systems derived from soil arthropod communities. Appl. Soil Ecol. 9, 429–437.

Van Straalen, N.M., Verhoef, H.A., 1997. The development of a bioindicator system for soil acidity based on arthropod pH preferences. J. Appl. Ecol. 34, 217–232.

Van Straalen, N.M., van Rijin, J.P., 1998. Ecotoxicological risk assessment of soil fauna recovery from pesticide application. Rev. Environ. Contam. Toxicol. 154, 83–141.

Van Straalen, N.M., Schobben, J.H.M., de Goede, R.G.M., 1989. Population consequences of cadmium toxicity in soil microarthropods. Ecotoxicol. Environ. Safety 17, 190–204.

Walter, D.E., 1987. Trophic behaviour of 'mycophagous' microarthropods. Ecology 68, 226–229.

Walter, D.E., Kethley, J., Moore, J.C., 1987. A heptane flotation method for recovering microarthropods from semiarid soils, with comparison to the Merchant–Crossley high-gradient extraction method, with comparison to the Merchant–Crossley high-gradient extraction method and estimates of microarthropod biomass. Pedobiologia 30, 221–232.

Walter, D., Kaplan, D.T., 1990. Feeding observations on two astigmatic mites, *Schwiebia rocketti* (Acaridae), *Schwiebia rocketti* (Acaridae) and *Histiostoma bakeri* (Histiostomatidae) associated with citrus feeder roots. Pedobiologia 34, 281–286.

Wauthy, G., Vannier, G., 1988. Application of an analytical model measuring tolerance of an oribatid community (Acari) to continuously increasing drought. Exp. Appl. Acarol. 5, 137–150.

Weigmann, G, 1982. The colonization of ruderal biotopes in the city of Berlin by arthropods. In: Bornkamm, R., Lee, J.A., Seaward, M.R.D. (Eds.) Urban Ecology, Blackwell Scientific Publications, Oxford, pp. 75–82.

Weigmann, G, 1991. Oribatid communities in transects from bogs to forests in Berlin indicating the biotope qualities. In: Dusbabek, F. Bukva, V. (Eds.), Modern Acarology. Academia, Prague and SPB Academic Publishing, The Hague, vol. 1, pp. 359–364

Weigmann, G., Jung, E., 1992. Die hornmilben (Acari Oribatida) an strassenbaumen in stadtzonen unterschiedlicher luftbelastung in Berlin. Zool. Beitr. 34, 273–287.

Weigmann, G., Kratz, W., 1981. Die deutschen hornmilbenarten und ihre okologische charakteristik. Zool. Beitr. 27, 459–489.

Weil, R.R., Kroontje, W., 1979. Effects of manuring on the arthropod community in an arable soil. Soil Biol. Biochem. 11, 669–679.