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Aoki's oribatid-based bioindicator systems*

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Abstract

The "MGP analysis" created by Dr. J. Aoki in 1983 and the "100 oribatid species" system proposed by Aoki in 1995, both for using oribatid communities as bioindicators, are described herein and compared to some other bioindicator protocols. By using the term "naturalness", Aoki proposed to explain human impact on a gradient of several environments ranging from urban boulevard trees to intact forests. Although using "naturalness" was a vague concept, the idea might reflect the process of plant succession and changes in oribatid assemblages associated with different seral stages. Therefore, the use of oribatid mites as bioindicators might also be based on succession of the oribatid fauna.

Key words: "100 oribatid species", bioindicators, MGP-analysis.

Introduction

Of the more than 650 named oribatid mite species currently known in Japan, 300 were originally described by Dr. J. Aoki. Although Aoki is generally considered an oribatid taxonomist, he also developed methods for using oribatids as biological indicators. Unfortunately, his proposed bioindicator-methods did not gain much international attention because they were published mostly in Japanese.

Although several systems using oribatids as bioindicators of soil quality have been proposed and elaborated (van Straalen, 1998; Behan-Pelletier, 1999; Ito & Aoki, 1999; Prinzing *et al*., 2002; Maraun, 2000; Maraun *et al*., 2003; Lindo & Visser, 2004; Caruso *et al*., 2007), the systems outlined by Aoki from the 1970s to the 1990s consisted of two unique methods, involving a) taxon scoring ("100 oribatid species") and b) MGP analysis (described below). He used the term "naturalness" to describe the state of health of forests. That term is not a readily definable, but was proposed to explain human impact on a gradient of environments/conditions from highly disturbed urban areas to intact native forests.

Aoki & Kuriki (1980) considered roadside trees to be the poorest environment of that gradient. Despite the poor diversity in such urban settings, Aoki discovered and described new oribatid species (e.g. Aoki, 1974) from trees of busy downtown streets in Tokyo. At the other extreme, the Shinto-shrine forests in Japan represented the undisturbed forests. These "most natural" forests are traced back to ancient animism and modern Shinto religion, which has kept undisturbed forests behind Shinto shrines for hundreds or thousand of years.

Thus, in his research, Aoki collected samples for taxonomic studies of oribatids from environments ranging from urban areas to the natural Shinto-shrine forests all around Japan, using the results of those studies to relate oribatid fauna with human environmental impact. Of course, under ideal circumstances, undisturbed/un-impacted forests should be carefully matched to the geology and climate of the disturbed habitats, but the shrine forests seemed adequate for that purpose. Here I outline Aoki's bioindicator methods and describe how they have been applied and tested.

Literature survey

Data and figures were taken from significant publications of Aoki (e.g. Aoki, 1978, 1979a, b, 1983, 1985; Aoki & Harada, 1985; Harada & Aoki, 1997). Table 1 shows the chronological evolution of the bioindicator methods proposed by Aoki discussed in this paper.

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TABLE 1. Chronological table of proposed bioindicator methods using oribatid mites by Aoki.

Aoki (1979a, b)	Scoring on families or genera
Aoki (1983)	MGP-analysis I and II
Aoki (1989)	Scoring on genera of oribatid mite
Aoki (1995)	Scoring on species of oribatid mite, "100 oribatid species"

Overview of Aoki bioindication methods and discussion

Taxon-based scoring method

Taxon-based scoring methods have been developed for aquatic invertebrates to evaluate river water quality. The Biological Monitoring Working Party (BMWP) of UK attempted a scoring method using ten sensitivity types of families, attributing to each of them grades ranging from one to ten, according to the decreasing [1 = very resistant to pollution, 10 = very susceptible] order of resistance to disturbance and pollution (Chesters, 1980). Total score, named BMWP score, or average score, Average Score Per Taxon (ASPT), are used for evaluation of a given site (Mason, 1991). In nematology, the Maturity Index (MI) (Bongers, 1990) was developed in order to evaluate soil pollution. Families are used in MI and categorized into five levels reflecting occurrence in newly disturbed versus stable soil habitats, from one (= 'colonizer') to five (= 'persister').

Aoki (1979a, b) proposed scoring on families or genera of oribatids (Table 1). He attempted to categorize Japanese oribatid families into five sensitivity types, and reported differences of sensitivity as relative frequency of the types of oribatids in the Japanese vegetation as classified *a priori* into ten grades of 'naturalness' based on degree of human impacts.

A limitation of the system for scoring bioindicators based on genera was observed, in that many species proved to be exceptions to their generic 'norms' (Aoki, 1979a, 1989). Thus, the system was later reworked to function at the species level. Aoki (1995) scored (integrals number: from one to five) each of a total of one hundred species, according to the response to environmental changes. They were categorized in five groups, as follows: A (Fig. 1): (5 points), 25 species found mainly in natural and shrine/temple forests (usually a few hundred years old); B (Fig. 2): (4 points), 22 species found mainly in a gradient from natural forests to secondary forests; C (Fig. 3): (3 points), 21 species found mainly in secondary forests; D (Fig. 4): (2 points), 20 species found mainly in various environments; E (Fig. 5): (1 point), 12 species found mainly in artificial city environments (e.g. mosses on building).

The overall "naturalness" of a site was evaluated by a score calculated as follows: (number of species of group A x 5 + number of species of group B x 4 + number of species of group C x 3 + number of species of group D x 2 + number of species of group E x 1) / total number of species (A–E), collected at that site. High score means high grade of "naturalness".

This "100 oribatid species" system was applied to the warm-temperate zone of Japan. Harada & Aoki (1997) evaluated this system across seven vegetation types, namely short grass fields, boulevard trees and agroecosystem, high grass field, plantation of *Cryptomeria* or *Pinus*, bamboo forests, broad-leaved deciduous forests and evergreen broadleaf forests. The average of the scores (Aoki, 1995) and the sum of the points (total score) were calculated for 88 sites in the Kanto District (outskirts of Tokyo), in Central Japan. The results of 15 sites at the Yokohama National University are shown in Fig. 6. Here the total score clearly has a better fit to the hypothesized order of plant succession than does the average score (Fig. 7). This proved true for all cases. It was discussed by Harada & Aoki (1997) that the species of group D (2 points), which were commonly found in several environments, tended to obscure the differences among the average scores for several environments.

Harada & Aoki (1997) discussed Aoki's (1995) emphasis on the identity of oribatid species as opposed to focusing on measures of community structure such as diversity indices. Soil fauna succession

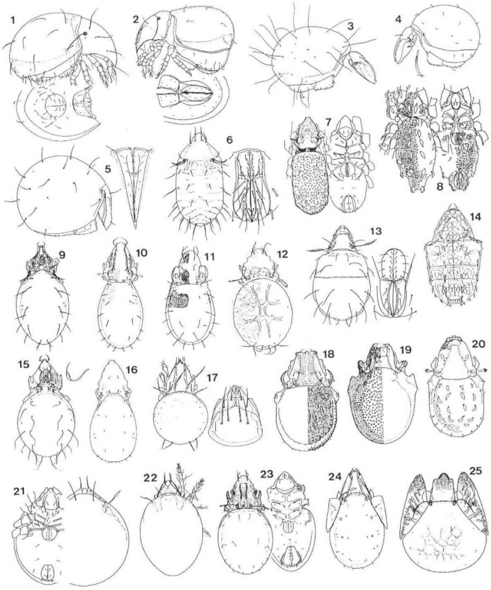

FIGURE 1. Species of "100 oribatid species" system used as biological indicators (Aoki, 1995).
Group A, 5 points: species that are found mainly in natural forest and shrine/temple forest. 1, *Mesoplophora japonica* Aoki (lateral and ventral view); 2, *Archoplophora rostralis* (Willmann) (lateral and ventral view); 3, *Phthiracarus setosus* (Banks); 4, *Phthiracarus clemens* Aoki (lateral view and sensillus); 5, *Indotritia javensis* (Sellnick) (lateral view and genito-anal region); 6, *Mixacarus exilis* Aoki (dorsal view and genito-anal region); 7, *Nippohermannia parallela* (Aoki) (dorsal and ventral view); 8, *Cosmohermannia frondosa* Aoki & Yoshida (dorsal and ventral view); 9, *Allosuctobelba grandis* (Paoli); 10, *Fissicepheus mitis* Aoki; 11, *Tokunocepheus mizusawai* Aoki; 12, *Joshuella transitus* (Aoki); 13, *Hypochthonius rufulus* C. L. Koch (dorsal view and genito-anal region); 14, *Brachychthonius jugatus* (Jacot); 15, *Allosuctobelba tricuspidata* Aoki; 16, *Microppia minus* (Paoli); 17, *Ceratoppia bipilis* (Hermann) (dorsal view, and ventral view of labial jaw and hysterostome); 18, *Carabodes rimosus* Aoki; 19, *Tegeozetes tunicatus breviclava* Aoki; 20, *Yoshiobodes nakatamarii* (Aoki); 21, *Gustavia microcephala* (Nicolet) (ventral and dorsal view); 22, *Liacarus orthogonios* Aoki; 23, *Eremaeus tenuisetiger* Aoki (dorsal and ventral view); 24, *Cultrobates nipponicus* Aoki; 25, *Galumnella nipponica* Suzuki & Aoki.

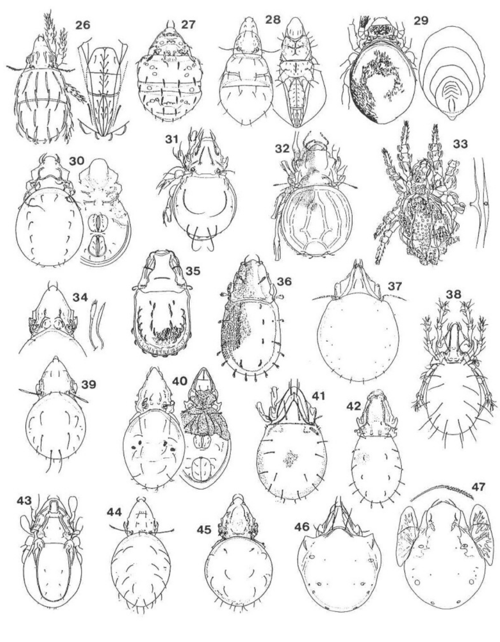

FIGURE 2. Species of "100 oribatid species" system used as biological indicators (Aoki, 1995).
Group . B, 4 points: species that are found mainly in the gradient from natural forests to secondary forests. 26, *Eohypochthonius crassisetiger* Aoki (dorsal view and genito-anal region); 27, *Liochthonius sellnicki* (Thor); 28, *Hypochthoniella minutissima* (Berlese) (dorsal and ventral view); 29, *Neoliodes zimmermanni Sellnick* (dorsal view and exuviae on hysterosoma); 30, *Belba vercosa japonica* Aoki (dorsal and ventral view); 31*, *Defectamerus* sp. = *D. crassisetiger coreanus* Choi & Aoki; 32, *Adrodamaeus striatus* Aoki; 33, *Masthermannia hirsuta* (Hartman) (dorsal view and dorsal seta); 34, *Neotrichoppia zushi* (Aoki) (dorsal view of prodorsum and sensillus); 35, *Gibbicepheus frondosus* (Aoki); 36, *Carabodes peniculatus* Aoki; 37, *Metrioppia tricuspidata* Aoki; 38, *Megalotocepheus japonicus* Aoki; 39, *Goyoppia sagami* (Aoki); 40, *Machuella ventrisetosa* Hammer (dorsal and ventral view); 41, *Xenillus tegeocranus* (Hermann), 42; *Fissicepheus coronaries* Aoki, 43; *Quadroppia quadricarinata* (Michael); 44, *Multioppia bravipectinata* Suzuki; 45, *Cycloppia restata* (Aoki); 46, *Ceratozetella imperatoria* (Aoki); 47, *Pergalumna intermedia* Aoki (dorsal view and sensillus). * In this publication, we replaced unidentifiable name with valid scientific name according to Aoki's personal communication.

was studied in forests of different ages since human disturbance (Aoki & Harada, 1982) and on plantation (Fig. 8; Aoki & Harada, 1985). The concept was further considered by Aoki (1995) is evaluating the succession of oribatid fauna (Harada & Aoki, 1997). They concluded that overall the average values (Aoki, 1995) of each site coincide with vegetation naturalness, but this was not true for all sites.

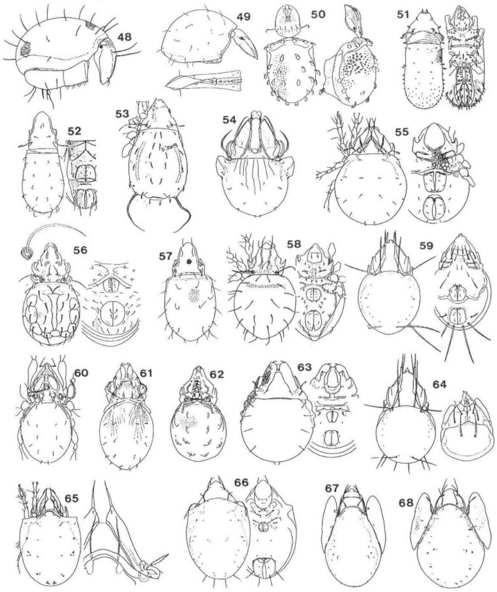

FIGURE 3. Species of "100 oribatid species" system used as biological indicators (Aoki, 1995).
Group . C, 3 points: species that are found mainly in secondary forests. 48, *Plonaphacarus kugohi* (Aoki); 49, *Mesotritia okuyamai* Aoki (lateral view and genito-anal region); 50, *Hoplophorella cucullatus* (Ewing) (dorsal and lateral view); 51, *Papillacarus hirsutus* (Aoki) (dorsal and ventral view); 52, *Epilohmannia palida pacifica* Aoki (dorsal view and genito-anal region); 53, *Nothrus palustris* C. L. Koch; 54, *Microzetes auxiliaris* Grandjean; 55, *Cultroribula lata* Aoki (dorsal and ventral view); 56, *Eremobelba minuta* Aoki & Wen (dorsal view, sensillus and genito-anal region); 57, *Malaconothrus pygmaeus* Aoki; 58, *Eremulus avenifer* Berlese (dorsal and ventral view); 59, *Austroceratoppia japonica* Aoki (dorsal and ventral view); 60, *Flagrosuctobelba naginata* (Aoki); 61, *Striatoppia opuntiseta* Balogh & Mahunka; 62, *Suctobelbila tuberculata* Aoki; 63, *Sadocepheus undulatus* Aoki (dorsal and ventral view); 64, *Ceratoppia quadridentata* (Haller) (dorsal view and ventral view of labial jaw and hysterostome); 65, *Ceratozetes japonicus* Aoki (dorsal view of idiosoma and prodorsum); 66, *Xylobates magnus* (Aoki) (dorsal and ventral view); 67, *Protokalumma parvisetigerum* Aoki; 68, *Neoribates roubali* (Berlese).

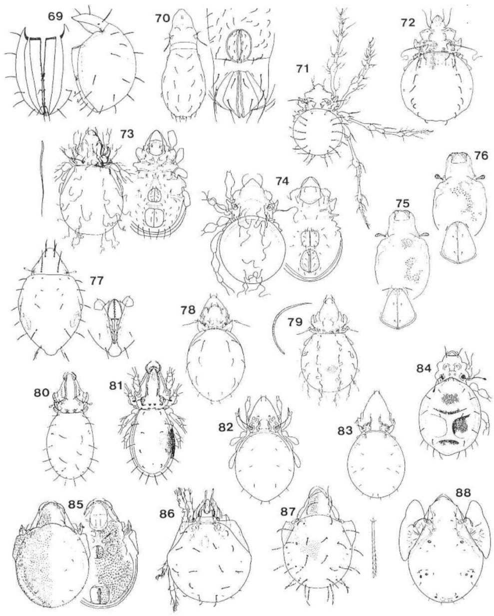

FIGURE 4. Species of "100 oribatid species" system used as biological indicators (Aoki, 1995).
Group D, 2 points: species that are found across a range of environments. 69, *Acrotritia ardua* (C. L. Koch) (lateral view and genito-anal region); 70, *Epilohmannia ovata* Aoki (dorsal view and genito-anal region); 71, *Tectodamaeus armatus* Aoki; 72, *Tectodamaeus striatus* Enami & Aoki; 73, *Eremobelba japonica* Aoki (dorsal and ventral view, and sensillus); 74, *Epidamaeus fragilis* Enami & Fujikawa; 75, *Tectocepheus velatus* (Michael) (dorsal view and anal-adanal region); 76, *Tectocepheus cuspidentatus* Knülle (dorsal view and anal-adanal region); 77, *Trhypochthonius japonicus* Aoki (dorsal view and genito-anal region); 78, *Arcoppia viperea* (Aoki); 79, *Eremobelba okinawa* Aoki (dorsal view and sensillus); 80, *Dolicheremaeus elongatus* Aoki; 81, *Fissicepheus clavatus* (Aoki); 82, *Lauroppia neerlandica* (Oudemans); 83, *Oppiella nova* (Oudemans); 84, *Fosseremus quadripertitus* Grandjean; 85, *Rostrozetes ovulum* (Berlese) (dorsal and ventral view); 86, *Eupelops acromios* (Hermann); 87, *Peloribates barbatus* Aoki (dorsal view and dorsal seta); 88, *Trichogalumna nipponica* (Aoki).

MGP-analysis

One of Aoki's original publications showed that many kinds of plant debris constitute specific microhabitats in forest floor inhabited by different oribatid species (Aoki, 1967). Based on this understanding he established and tested the "gleaning" sampling method (Aoki, 1978). By the gleaning method, not only surface layers of soil, but also mosses and all the kinds of plant detritus, such as

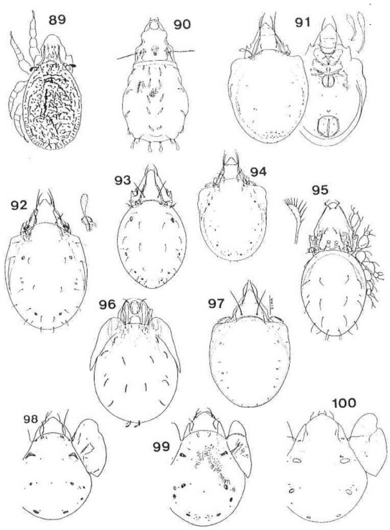

FIGURE 5. Species of "100 oribatid species" system used as biological indicators (Aoki, 1995).
Group E, 1 point: species that are found mainly in artificial city area (e.g. mosses on building). 89*, *Scutovertex* sp.= *S. japonicus* Aoki; 90, *Nothrus biciliatus* C. L. Koch; 91, *Scheloribates latipes* (C. L. Koch) (dorsal and ventral view, and sensillus); 92, *Transoribates agricola* (Nakamura & Aoki) (dorsal ventral view and sensillus); 93, *Oribatula sakamorii* Aoki; 94*, *Scheloribates* sp. A = *Scheloribates decarinatus* Aoki; 95, *Ramusella sengbuschi tokyoensis* (Aoki); 96, *Peloptulus americanus* (Ewing); 97, *Scheloribates laevigatus* (C. L. Koch); 98, *Galumna cuneata* Aoki; 99, *Pergalumna altera* (Oudemans); 100, *Pergalumna magnipora capillaris* Aoki. * In this publication, I have replaced the previous unidentified name with the valid scientific name according to Aoki's personal communication.

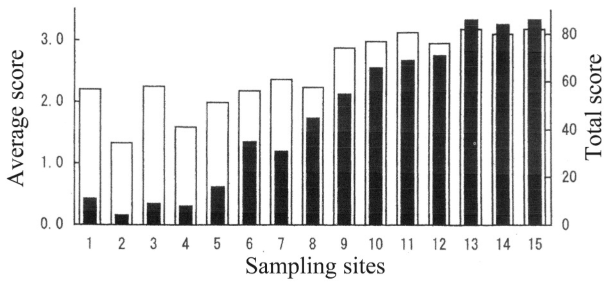

FIGURE 6. Evaluation by the "100 oribatid species" system (Aoki, 1995) of several environments in the Yokohama National University (after Harada & Aoki, 1997). The open bar means average scores (calculation method in text), filled bar means total scores. The numbers 1–15 mean sample sites: 1, grass field dominated by *Ambrosia*; 2, grass field dominated by *Equisetum*; 3, grass field dominated by *Zoysia*; 4, grass field dominated by *Trifolium*; 5, grass field dominated by *Artemisia* and *Oenothera*; 6, grass field dominated by *Solidago* and *Miscanthus*; 7, grass field dominated by *Arundinella* and *Miscanthus*; 8, *Pinus thunbergii* forest; 9, *Chamaecyparis* forest; 10, *Cryptomeria* artificial forest; 11, Mixed forest dominated by *Styrax* and *Swida*; 12, *Castanopsis* forest; 13, *Cinnamomum* artificial plantation; 14, *Pinus taeda* artificial forest; 15, *Quercus* forest.

fallen twigs of larger sizes, fallen cones and bark, rotten wood and stumps were sampled by hand in an area of 3 x 3 m to make ca. 1.5 L of total volume of collected material. The gleaning method was found to be more appropriate for thorough surveys of soil mites than "coring" sampling, consisting of 5 cm x 4 cm and 5 cm deep core samples, much more commonly used in qualitative studies. Aoki (1978) suggested that the faunal analysis based only on material for quantitative study using core samples might be faulty, overlooking many important species inhabiting the investigated area.

The "MGP analysis" was specifically proposed for use of oribatid communities as bioindicators (Aoki, 1983). The name refers to what once were three major taxonomic groups of Oribatida: **M** (Macropylina), **G** (Gymnonota), and **P** (Poronota) [since 1983, oribatid taxonomy has undergone

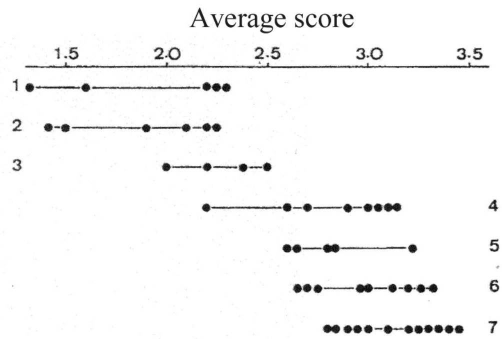

FIGURE 7. From Harada & Aoki (1997), ranges of the average scores evaluated by the "100 oribatid species" system (Aoki, 1995) of several vegetation types in the 88 sites of the Kanto District of Central Japan (after Harada & Aoki, 1997). The numbers 1–7 mean vegetation types: 1, short grass field; 2, boulevard trees and planting; 3, high grass field; 4, plantation (*Cryptomeria* or *Pinus*); 5, bamboo forest; 6, broad-leaved deciduous forest; 7, evergreen broadleaf forest.

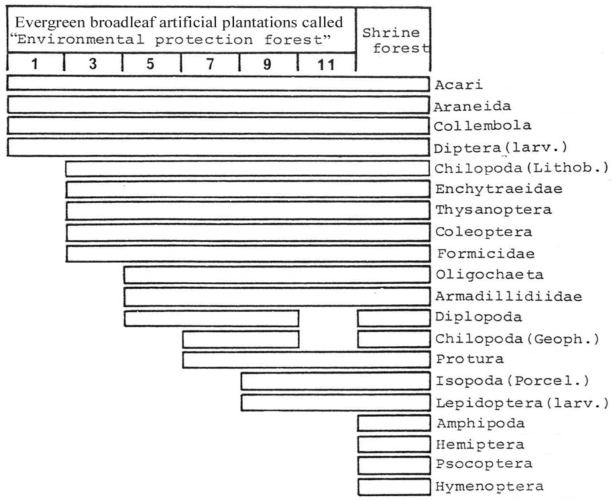

FIGURE 8. Establishment of soil fauna in the soil of evergreen broadleaf artificial plantations called "the environmental protection forest" of different ages (1 to 11 years). Fauna of shrine forest is also shown for comparison (after Aoki & Harada, 1985).

many changes, and none of these taxa is recognized as a natural group in Krantz & Walter, 2009)]. Differing from "100 oribatid species" scoring system, this system is based on species diversity or community structure, so that differences between species of the same genus do not have an important bearing on the analysis. Thus, it is considered adequate for general, worldwide use.

Aoki compared oribatid communities in two ways (Fig. 9), by the dominance of species (MGP-analysis I) or of specimens (MGP-analysis II) for each of the three groups. MGP-analysis I was based on the "gleaning" sampling method (Aoki, 1978) and MGP-analysis II, which needs stricter measures of abundance, was based on the usual "coring" sampling. Aoki recognized seven patterns as shown in Fig. 9: M-type: group M comprising over 50%, G-type: group G comprising over 50%, P-type: group P comprising over 50%, O-type: each of the three groups comprising 20 to 50%, MG-type: groups M and G comprising 20 to 50% and group P comprising less than 20%, GP-type: groups G and P comprising 20 to 50% and group M less than 20%, GP-type: groups M and P comprising 20 to 50 and group G less than 20%.

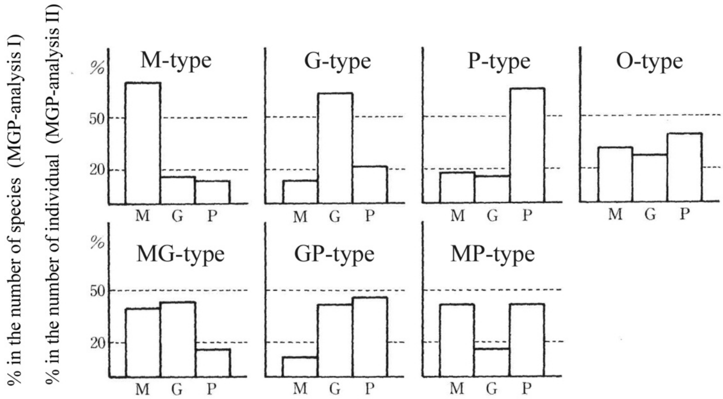

FIGURE 9. The seven types of oribatid communities according to MGP-analyses I and II (after Aoki, 1983).

Aoki (1978) noted that groups M, G and P tend to predominate (more than 50%) in moors, forests and urban plantations, respectively, while none of the groups predominates in grasslands. Forests generally have a G-type oribatid community (based on both MGP I and II analysis), grasslands O-type (I) and P-type (II), alpine zones O-, MG-, or GP-type (I), and urban plantations GP-type (I). Aoki (1978) did not discuss the likely biological reasons for these patterns. Using MGP-analysis, Aoki & Harada (1985) evaluated the development of oribatid communities of a plantation across its initial growth stages, up to the first thinning. They noted that the P-type oribatid community, present initially (1–5 years), changed to G-type after seven years. A plantation at a nearby shrine forest (G-type) was studied for comparison (Fig. 10) by Aoki & Harada (1985). In the first five years, the dominant species of soil mites were species of *Scheloribates*, whereas after 7–11 years, the dominant species were *Suctobelbella* spp., *Oppia neerlandica* (Oudemans) and *Trichogalumna nipponica* (Aoki).

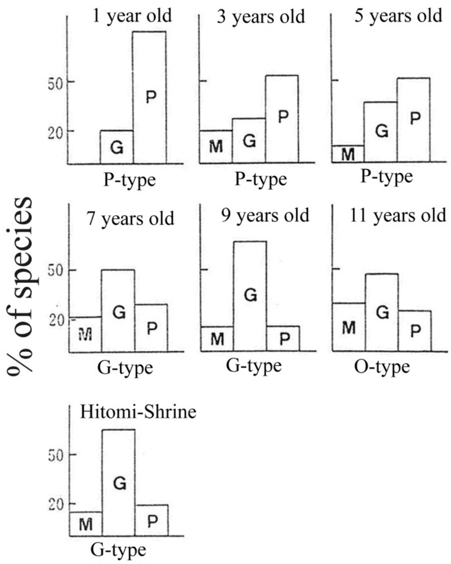

FIGURE 10. The result of MGP-analysis I of the oribatid communities of evergreen forest plantations of different ages (after Aoki & Harada, 1985). Thinning was made when the forest was 11 years old.

Maraun (2000) proposed eight groups (Enarthronota, Suctobelbidae, Phthiracaridae, *Tectocepheus*, Poronota, Oppidae, Desmonomata and 'others'), distinguished according to their feeding habits, life history strategy and distribution patterns, to explain oribatid community patterns. He described a change in dominance of distinct groups that was correlated with changes in the density of six of these groups, noting that Poronota dominates at low total oribatid density, which had also been previously observed by Aoki & Harada (1985). The latter authors observed that with increasing total oribatid density along planting age (Fig. 11), the dominance of Poronota decreased (Fig. 12). The dominance of *Oppia neerlandica* (Oppiidae) declined in the sites 7–11 years after planting (Aoki & Harada, 1985). This phenomenon agrees with Maraun's (2000) observations that the dominance of Oppiidae tends to decline in mature moder soils with thick litter layers.

In many studies of environmental changes and/or comparison across several environments published in Japanese journals of restricted circulation (e.g. Hirauchi, 2003), MGP-analysis (I and/or II) was applied and the results support the hypothesis that human disturbance is one of the main factors driving oribatid assemblage structure.

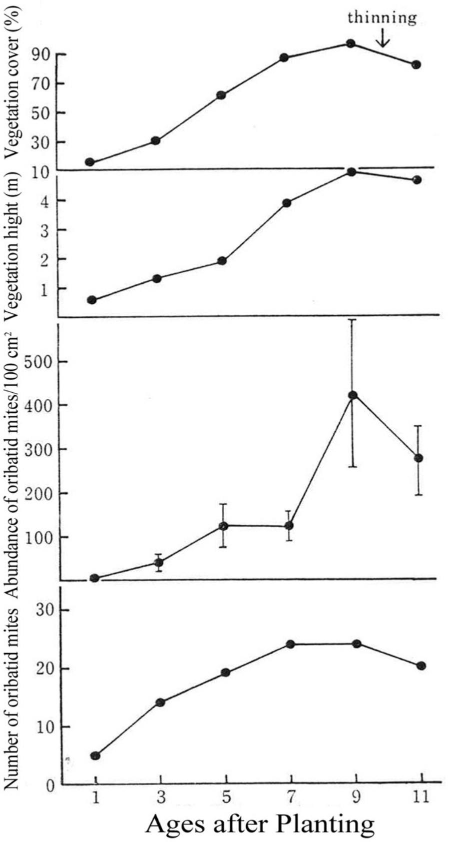

FIGURE 11. Vegetation cover, vegetation height, density of oribatid mites and number of oribatid species at different years after planting (after Aoki & Harada, 1985).

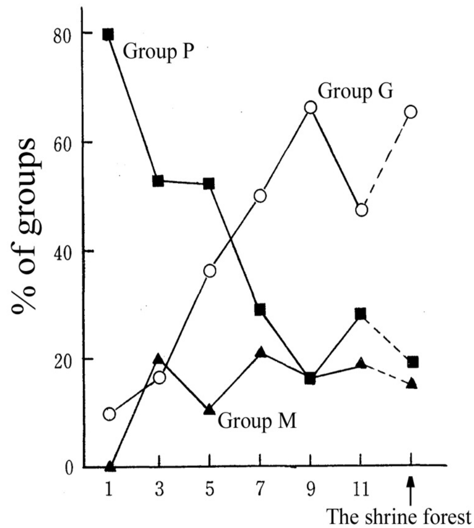

FIGURE 12. Changes in dominance of species of groups M, G, and P inhabiting the forests of different ages and the shrine forest (natural forest for hundreds years) for comparison (after Aoki & Harada, 1985).

Oribatids in urban moss cushions

As an additional bioindicator method, Weigmann & Kratz (1987) showed the effect of air pollution (SO_2) on moss-inhabiting oribatids in 13 sites of the urban district of West Berlin, discussing the use of moss- and bark-dwelling mites as bioindicators of air pollution. Aoki (2000) studied oribatids in moss cushions growing on city constructions as the ultimate human-disturbed environment. A total of 292 samples were obtained from 24 large cities in Japan. Sixty-eight percent of the samples contained oribatids with a total number of 20 species. In this work, Aoki (2000) recognized five categories of non-oribatid animals found in urban areas in Japan: 1) species able to withstand poor environmental conditions (e.g. the diaspidid *Lopholeucaspis japonica*); 2) subtropical species (e.g. the cockroach *Blattella germanica*); 3) species depending on waste food (e.g. the rat: *Rattus norvegicus*); 4) naturalized species from foreign countries (e.g. the Taiwan squirrel: *Callosciurus erythraeus thaiwanensis*) and 5) species from rocky (e.g. rock pigeon: *Columba livia*). Next he gave examples of oribatid species in these categories: 1) the generalist species *Tectocepheus velatus* (Michael) inhabiting several environments, *Trhypochthonius japonicus* Aoki inhabiting urban area and *Oribatula sakamorii* Aoki inhabiting poorest environments; 2) *Allonothrus russeolus* Wallwork described from Ghana and recorded from Tahiti and Fiji, recorded only from moss cushions of urban buildings; 3) although not classically considered an oribatid species (but phylogentically within Oribatida), *Tyrophagus putrescentiae* (Schrank) (Astigmata) depending on waste food; 4) likely from outside of Japan, e.g. *Mochlozetes penetrabilis* Grandjean, *Peloribates grandis* (Wilmann), *Scheloribates decarinatus* Aoki and *Hemileius clavatus* Aoki found on imported *Vanda* plants kept in protected environments (Aoki, 1992), but not in open environments and 5) *Suctovertex japonicus* Aoki usually found only in moss cushions on concrete, possibly originally from rocky limestone substrate. Aoki (2000) also considered that the original habitat of *O. sakamorii*, a typical urban oribatid species, could be the rocky area of wind beaten scrub forest along beaches.

As a result of the resolution of the Convention on Biological Diversity (CBD), an important Work Program has been internationally installed for the Communication, Education and Public Awareness (CEPA) concerning the need to conserve world biodiversity (Hesselink *et al*., 2008). The contribution of Aoki in Japan is considered important within the scope of CEPA. The methods discussed in this paper could represent a significant contribution for the determination of the levels of environmental degradation in different parts of the world, to subsidize actions to be taken to prevent degradation and establish plans of environmental recovery.

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