Agriculture, Ecosystems and Environment 74 (1999) 1–18

Agriculture Ecosystems & Environment

# Using bioindicators based on biodiversity to assess landscape sustainability

Maurizio G. Paoletti *

*Dipartimento di Biologia Università di Padova, via U. Bassi, 58/b, 35121 Padova, Italy*

**Abstract**

Although not new, the use of bioindicators is an innovative approach for assessing various types of environmental mismanagement, including pollution, high input farming, inappropriate disposal of wastes, contamination, etc. This approach uses biological organisms (including invertebrates, the focus of this volume) and biodiversity as tools to assess ongoing situations in the environment. Although lab work is needed, bioindicator-based studies rely extensively on field assessment of a few or limited number of taxa. Sampling, statistics and species identification form a large part of these studies, and must be supported by knowledge of the basic biological and ecological features of the organisms and landscape under study. Computerized open databases offering images and multiple entering accessions are expected to improve the current identification and analysis methods based on manuals, books and two-dimensional figures.

Bioindicator-based studies have the potential to make a major contribution to optimizing different farming systems, input practices, new crops, rotation, etc., and to influence political policies governing landscape management, urban and industrial areas; landscape reclamation and transformation.

In particular, laws aimed at reducing environmental contamination and at remediating high input farming must take into consideration environmental benefits that can be assessed using bioindicators; evaluations of new genetically engineered crops must consider biodiversity as a value and bioindicators as tools that can help in reaching decisions about their environmental impact. 

*Keywords:* Biodiversity; Bioindicators; Invertebrates; Taxonomy; Environments; Landscapes; Rural environments; Reclamation

## 1. Introduction

The use of biodiversity as a tool to assess landscape structure, transformation and fate is a valid component of policies applied to rural, managed, industrial and urbanized areas to reduce human mismanagement and alleviate pollution (Wilson, 1997). The argument for the importance of biodiversity in directing environmental policy presupposes that animals, plants, microorganisms and their complex interactions respond to human landscape management and impacts in different ways, with some organisms responding more quickly and definitively than others. It has to be assumed that changes in landscape management influence the biota, and that certain transient or permanent signs remain inside the system of biological communities (Richardson, 1987; Jeffrey and Madden, 1991; Paoletti and Pimentel, 1992; Szaro and Johnston, 1996; Pankhurst et al., 1997). This assumption is supported by two recent books summarizing current

* Tel.: +39-(0)49-8276304/5; fax: 0039-(0)49-8276300/8072213; web page: http://www.bio.unipd.it/agroecology/
*E-mail address:* paoletti@civ.bio.unipd.it (M.G. Paoletti)


PII: S0167-8809(99)00027-4

data on insects as indicators of pollution and environmental change (Harrington and Stork, 1995; Manawar et al., 1995). However, much work is needed to directly relate this assumption to the pragmatic problems encountered as attempts are made to improve the living landscape.

Disappearance of species is most readily apparent in the case of birds, butterflies and mammals; the threatened extinction of such conspicuous organisms often raises public concern and garners attention from news media. For the most part, knowledge of small organisms remains conceptual, and common knowledge of the relationships between biota and their environments is approximate at best (Table 1); the importance of small creatures in food chains is poorly understood or ignored (Pimm, 1991; Hammond, 1995).

Although larger, feathered, furry, or colorful animals like birds, mammals and butterflies are easier to see and of greater interest to the public, media, and scientists, the small, inconspicuous invertebrates such as insects, mites and nematodes can offer a database of millions of species (Hammond, 1995; Erwin, 1997), thereby offering a more abundant (and assumed) sophisticated tool to assess the environment (Van Straalen and Krivolutskii, 1996; Paoletti and Bressan, 1996; Paoletti et al., 1996; Van Straalen, 1997). However, most people, and even some scientists, find it difficult to become alarmed about the disappearance of one isopod species or a nematode or a protozoan due to pesticides or tillage operations. Lack of sufficient knowledge or inaccessability of information makes it all the more difficult to recognize the importance of this array of small creatures and their fate. The possibility to take advantage of the vast available memory of computers at a low cost will greatly facilitates identification of small organisms (at least the most common ones) by non experts (Paoletti and Gradenigo, 1996). The current limited availability and content of databases could be corrected by increased use of computer webs.

In most cases, ‘modern’ management of landscapes has supported few plants and animals. The agricultural revolution in the last 13,000 years has in general seen efforts concentrated on a limited number of species. This process of reducing species numbers is common trend in agriculture, with widespread use of systems in an early succession stage and concentration on a few short cycle plants like cereals. Most of citizens living in towns eat a limited variety of plants and animals and are aware of few invertebrates. The situation is quite the oppposite in some Amazon regions dominated by the forest and/or savannas and populated by hunter–gatherers and horticulturalists (Table 1).

Simplification in landscape management in most cases signifies maintaining the first stages of one succession and large numbers of few dominant species (Odum, 1984). Most applied fields of landscape management, including agriculture, tend to deal with only few species: monocultures are the rule both in fields and on our desks. The majority of today’s scientists, engineers and university-educated professionals are trained to solve a narrow range of problems and have a limited ability to deal with complex systems (Funtowicz and Ravetz, 1993). Most successful human endeavors have involved reduction of variables (species), with positive economic results, at least in the short term.

Assessing landscape quality by means of indicators based on biodiversity involves a substantial change in perspective not only by the experts and technicians, but also by the public and society in general. People who expect a productive, clean and harmonious landscape that can be sustained for future generations must learn more about the diversity of life and make efforts to allow cultures that have their base in the plurality of organisms to maintain their territories and way of life.

## 2. Plurality of species and bioindicators

Making identification of biota (biodiversity) easier for non experts is an important goal that must be reached without delay if bioindicators are to be used to read the environment and its quality. Although humans are particularly adept at distinguishing three-dimensional forms (for instance the faces of our friends), the capacity to memorize such information is limited. For example, although the Chinese pictograms account a maximum of around 49,000 forms, experienced sinologists rarely memorize more than 12,000–15,000 of them (Needham, 1954), and it is difficult for the average person to memorize more than 800–3600 different persons’ faces and their names, even if they are linked with their life history or share personal relationships. Likewise, although some highly skilled and dedicated taxonomists can

Table 1
Estimated (maximum) number of species known and consumed as food by western civilized peoples and forest- and savanna-dwelling peoples in Amazonas (Venezuela)

| Population | Plants | Mammals | Fishes | Birds | Insects | Total |
|---|---|---|---|---|---|---|
| Students at Padova University[a] | 48 | 10 | 12 | 5 | 0 | 75 |
| Guajibo Amerindians[b] | 38 | 22 | 18 | 18 | 12 | 108 |
| Curripaco Amerindians[c] | 46 | 18 | 32 | 25 | 4 | 125 |
| Piaroa Amerindians[d] | 68 | 24 | 18 | 38 | 14 | 168 |
| Yanomamo Amerindians[d] | 125 | 52 | 56 | 96 | 61 | 390[e] |

[a] The university students were attending animal ecology courses in their third year at the University of Padova. Interviews were performed by university personnel (1995–1996) using forms filled out in class; oral interviews were carried out in Amerindian villages located near Puerto Ayacucho, Amazonas (1997).
[b] The Guajibo live in the savannas near P. Ayacucho, Amazonas, Venezuela.
[c] The Curripaco are an expert river margin-dwelling group living near P. Ayacucho, Amazona, Venezuela.
[d] The Piaroa and Yanomamo are more strictly forest-living Amerindians in the Alto Orinoco, Amazonas, Venezuela. The Yanomamo maintain strong links with the forest for their survival.
[e] Based on different sources and evaluations, the total number could be around 1400 species.

remember names and forms of 6000–10,000 species, results of direct interviews with experts indicate that this is an exception rather than the rule. How can the quality and availability of knowledge be improved of millions of invertebrate species that historically and psychologically have been ignored, or worse, disliked because of their status as human parasites, crop pests, or carriers of disease rather than as potential sources of food (Paoletti and Bukkens, 1997)? How can people be made aware of the 600–3000 species of invertebrates living in most mixed landscapes in temperate countries or the perhaps 5000–18,000 species in tropical forested landscapes (Paoletti et al., 1992; Hammond, 1992)? As each form has at least several different larval stages and sometimes exhibits sexual dimorphism and variability in color pattern, the information for each species must be multiplied at least 5–6-fold, and multiplied again if varieties of each species are included.

An estimated 1.4–1.8 million species have been identified (Hammond, 1995; Wilson, 1988; Reaka-Kudla, 1997); estimates of actual living species range from 12.5 million to over 100 million, with insects contributing the majority of species (Hammond, 1995; Erwin, 1997; Stork, 1997). The knowledge of this multitude of species, with their diversified and specialized roles in the food webs that are linked with everyday lives, is horrendously deficient. Computers could improve this situation by complementing limited knowledge and memory and ability to discriminate the multitude of living creatures.

Books and book figures and taxonomical identification keys are useful but, with some exceptions, are suited only for experienced researchers. Open identification systems afforded by computer programs greatly facilitate the task of classifying organsims that at first glance are very similar in appearance (see the Lombri CD-ROM developed for earthworm identification; Paoletti and Gradenigo, 1996). This is the new approach to accomplishing the first step of any biodiversity study, i.e., correct identification of the organisms present in a system.

The aim of bioindicator-based studies is to use the living components of the environment under study (especially those with the highest diversity, the invertebrates), as the key to assess the transformations and effects, and, in the case of landscape reclamation, to monitor the remediation process in different parts of the landscape over time. This approach could improve policies aimed at reducing the stress placed on landscapes. For example, bioindicator-based studies could help in the process of amelioration and remediation of the rural landscape as result of implementation of policies such as the set-aside in Europe (Jordan, 1993; Jorg, 1994). Reduction in agricultural pesticide use could be adequately monitored by bioindicators to assess the benefit of a new policy (Pimentel, 1997; Paoletti, 1997). Bioindicators could be used to assess and remediate contaminated or polluted areas to be reclaimed (Van Straalen and Krivolutskii, 1996).

Such applications of bioindicators can be expected to help not only in improving the environment but

Table 2
Total estimated economic benefits of biodiversity in the United States and worldwide (from Pimentel et al., 1997)[a]

| Activity | United States | World |
|---|---|---|
| Waste disposal | 62 | 760 |
| Soil formation | 5 | 25 |
| Nitrogen fixation | 8 | 90 |
| Bioremediation of chemicals | 22.5 | 121 |
| Crop breeding (genetics) | 20 | 115 |
| Livestock breeding (genetics) | 20 | 40 |
| Biotechnology | 2.5 | 6 |
| Biocontrol of pests (crops) | 12 | 100 |
| Biocontrol of pests (forests) | 5 | 60 |
| Host plant resistance (crops) | 8 | 80 |
| Host plant resistance (forests) | 0.8 | 11 |
| Perennial grains (potential) | 17 | 170 |
| Pollination | 40 | 200 |
| Fishing | 29 | 60 |
| Hunting | 12 | 25 |
| Seafood | 2.5 | 82 |
| Other wild foods | 0.5 | 180 |
| Wood products | 8 | 84 |
| Ecotourism | 18 | 500 |
| Pharmaceuticals from plants | 20 | 84 |
| Forests' sequestering of carbon dioxide | 6 | 135 |
| Total | 319 | 2928 |

[a] Data in billions of US dollars.

also in augmenting awareness of the living creatures around so that a better appreciation of the crucial role in sustaining life on the planet is obtained.

## 3. What is biodiversity and how can it be used to assess the landscape?

Without biodiversity, life on earth would be impossible. Based on recent estimates, biodiversity accounts for between 319 billion and 33,000 billion dollars per year in value (Pimentel et al., 1997; Costanza et al., 1997) (Table 2). Biodiversity encompases all of the species, food chains, and biological patterns in an environmental system as small as a microcosm or large as a landscape or a geographic region (Heywood and Watson, 1995; Wilson, 1988, 1997). The concept of biodiversity has grown with the perception of its loss due to increasing human impact and mismanagement of the environment (Wilson, 1988). Whether on a local, regional or global scale, reduced biotic diversity is associated with increased environmental stress and reduced environmental heterogeneity (Erwin, 1996; Van Haaften and Van de Vijver, 1996). The concept of biodiversity implies that any environment is rich in different organisms and can be read as a system in which species circulate and interact. Structure, scale, and features of the landscape also enter into the definition of biodiversity.

Although human activities do not invariably work against biodiversity, they can strongly reduce it: for example, in agriculture, productivity of a crop per unit of time and market opportunity "almost always" make monoculture cropping more profitable and convenient (Odum, 1984; Paoletti et al., 1989; Paoletti and Pimentel, 1992). However, this is not always the case, as demonstrated by the fact that both in temperate and tropical areas, certain practices of polyculture and agroforestry or specialized types of agriculture (organic or integrated farming) can maintain high biodiversity while at the same time producing adequate returns for farmers (see Altieri, 1999; De Jong, 1997; Paoletti et al., 1993). It has also been observed that some urban areas support greater numbers of species (birds) than the surrounding rural landscape dominated by monocultures (Paoletti and Pimentel, 1992).

Careful analysis of apparently 'unmanaged' primary rain forests demonstrate that, in addition to being manipulated by their 'natural' components, they are sometimes strongly influenced by human activities as well. The well-studied case of the relationship between the Kayapo Indians and their environment in the Brazilian Amazon (Posey, 1992) may have many similar, unstudied equivalents, e.g., the Yanomamo, Piaroa, Curripaco and Makiritare Indians (living near Puerto Ayacucho, Amazonas, Venezuela). The author has observed these Indians scattering the forest paths with seeds from edible fruits collected in the forest from wild trees (Annonacean *Duguetia lepidota* disseminated in the case of the Piaroa). The Makiritare (Alto Orinoco, Amazonas, Venezuela) have been observed actively disseminating their favoured edible white benthic earthworms (*motto*) on the beaches of affluents of the Orinoco river (personal observations). Likewise, the hedgerows found in many European landscapes (in some cases originating by the Ancient Roman centuriations; Paoletti, 1988) and the terracing used in Mediterranean agriculture are associated with increased numbers of species and landscape diversity (Paoletti and Pimentel, 1992).

## 4. What are bioindicators and how to use them

The concept of bioindicators is a trivial simplification of what probably happens in nature. It can be defined as a species or assemblage of species that is particulary well matched to specific features of the landscape and/or reacts to impacts and changes (Paoletti and Bressan, 1996; Van Straalen, 1997). Examples of bioindicators are species that cannot normally live outside the forest, species that live only in grasslands or in cultivated land, those that support high levels of pollutants in their body tissues, species that react to a particular soil management practice, and those that support waterlogging. Bioindication is not a new term; instead, it has evolved from geobotany and environmental studies since the last century (Paoletti et al., 1991). It has become an important paradigm in the process of assessing damaged and contaminated areas, monocultures, contaminated orchards, disposal areas, industrial and urban settlements, and areas neighboring power plants.

In empirical terms a bioindicator can be thought of as a label for a particular situation and environmental condition. However, this is a very simplistic statement. Although the identification of a species as a label for a particular environment can be convincing, rapid changes in landscape use, especially in the mosaic situation, can reduce the bioindicative value of a particular singular species. Most species react to environmental changes and can adopt new patterns and behaviour to cope with the change; the many pest species that have evolved from wild, non pest species is an obvious example of this phenomenon. Evolutionary mechanisms involving species are not absent in the managed area. The disappearance of a single species from a landscape can be traced from either a complex combination of events, including the collapse of metapopulations as affected by reduction of connectivity (e.g. margins, lanes, hedgerows, riverbanks) or to a single major event, such as field dimension, tillage, field contamination, etc. (Burel, 1992, 1995).

Instead of focusing on a few indicator species, more reliable information can be gained from studies of a set of species or one or more higher taxon, with measurements made not at the level of presence/absence but as numbers, biomass, and dominance. The use of guilds such as detritivores, predators, pollinators, parasitoids, dung decomposers, carrion scavengers, etc., as bioindicators can reveal interesting differences in the landscape.

Patterns of herbivory in polluted areas, e.g., the abundance of aphids on trees or mining lepidoptera, have been correlated with industrial pollution and in particular with increased levels of available nutrients (free amino acids) in the stressed trees (Holopainen and Oksanen, 1995). A study in Denmark showed that the complex of parasitoid Hymenoptera (up to 164 species) living in cereal field soils can accurately discriminate between fields that have been spread with the currently used pesticides and untreated fields (Jensen, 1997). Also, Reddersen (1995) has shown the importance of fungivores in detecting ceral fields with and without pesticide (fungicide) inputs.

## 5. What is sustainability?

Table 3 shows the potential meaning and current use of the term sustainability, focusing on the aspect of stability over time. In terms of the environment, sustainability signifies maintaining the productivity and potential of an ecosystem used by humans with time. This theoretical situation normally never happens in practice (Conway and Barbier, 1990; Altieri, 1995). As discussed by Carter and Dale (1974), most civilizations in the past have collapsed and disappeared as in ecological successions, because of the destruction of natural resources, especially soil. The few cases in which fertility has been maintained for long periods (more than 800–2000 years) always involved active input, such as the regular replenishment of carbon and nutrients in the Nile valley of Egypt by flooding of the Nile River. By changing the temporal scale, civilizations that have disappeared because of mismanagement of resources can be looked upon as a succession inside the ecosystem (Golley, 1977). Human intervention in the landscape almost always has a strong impact on resources, which become depleted or degraded in their potentialities and are soon substituted with artificial ones that are more energy intensive (e.g., organic compounds in agroecosystems substituted by chemical fertilizers and pesticides). Loss of diversity and species is practically guaranteed in most agricultural systems (Naeem et al., 1994; Tilman et al., 1996). Increasing the cost of crops in terms of energy by adopting modern technologies is a trend that has been

Table 3
Comparison of social, economic and environmental sustainability (from different sources, especially the work of Goodland and Pimentel, 1998)

| Social sustainability | Economic sustainability | Environmental sustainability |
|---|---|---|
| Cohesion of community, cultural identity, diversity, solidarity, tolerance, humility, compassion, patience, forbearance, fellowship, cooperation, fraternity, love, pluralism, commonly accepted standard of honesty, laws, discipline, etc. constitute the aspects of social capital least subject to rigorous measurement, but essential for social sustainability.<br>This *moral capital* requires maintenance and replenishment by shared values and equal rights, and by community, religious and cultural interactions. Without such care it depreciates as surely as would physical capital.<br>Human and social capital, investment in education, health and nutrition of individuals is now accepted as part of economic development, but the creation and maintenance of social capital as needed for social sustainability is not yet adequately recognized. | Economic capital should be stable. The widely accepted definition of economic sustainability Is *maintenance of capital*, or keeping capital intact. The amount consumed in a period must maintain the capital intact because only the interest rather than capital has to be consumed. Economics have rarely been concerned with natural capital (e.g. intact forests, healthy air, stable soil fertility). To the traditional economic criteria of allocation and efficiency must now be added a third, that of scale. The scale criterion would constrain throughput growth— the flow of material and energy (natural capital) from environmental sources to sinks. Economic values are restricted to money; valuing the natural intergenerational capital like soil, water, air, biodiversity is problematic. | Although ES is needed by humans and originated because of social concerns, ES itself seeks to improve human welfare by protecting the sources of raw materials used for human needs, and ensuring that the sinks for human wastes are not exceeded, in order to prevent harm to humans.<br>Humanity must learn to live within the limitations of the biophysical environment. ES signifies that natural capital must be maintained, both as a provider of inputs of sources and as a sink for wastes. This requires that the scale of the human economic subsystem be held to within the biophysical limits of the overall ecosystem on which it depends. ES needs sustainable consumption by a stable population.<br>On the sink side, this translates into holding waste emissions within the assimilative capacity of the environment without impairing it.<br>On the source side, harvest rates of renewables must be kept within regeneration rates. |

documented in an array of situations worldwide (Pimentel and Pimentel, 1996). Although the trend toward reduced biodiversity in managed environments continues to worsen, systems for sustainable use of natural resources exist and are growing in number. For example, in the tropics, government policies aimed at giving permanent settlement to horticulturists adopting slash and burn practices in the forest tend to result in ‘savannization’. This process occurs because, instead of being allowed to choose fresh plots, the farmers are restricted to reusing forest plots near their villages, which consequently have limited fallow periods between plantings (Lopez Hernandez et al., 1997; Netuzhilin et al., 1997). The savannization process is apparently less severe when the farmers have access to more forest area (Kleinman et al., 1995; De Jong, 1997).

With sustainability, reduction of external inputs and improved management of species improves diversity of the system, while at the same time maintaining a constant level of productivity. This process requires sophisticated knowledge of the resources. For example, some groups of Amerindians living in tropical rain forests are able to manage over 1400 different species of plants and animals (Table 1). Without a strong educational system, the knowledge involved in these practices would be lost from the group and the the forest would no longer be optimally managed. Paradoxically, introduction of formal schools can reduce propagation of this traditional knowledge in the extended family groups, thereby rendering the younger generations unable to live the forest in a sustainable manner.

Sustainability of a given unit (farm, factory, urbanized area, complex landscape) can be assessed only by comparison with other similar units that are under different management. Although it is difficult to assign absolute values of sustainability to a given landscape, comparisons with other landscapes can indicate promising, compatible practices (Paoletti and Bressan, 1996).

Table 4
Farming systems that can augment biodiversity in agroecosystems (from Paoletti et al., 1996, modified)

| Sustained invertebrate biodiversity | References | Decreased biodiversity |
|---|---|---|
| Hedgerows | Paoletti et al., 1989; Favretto et al., 1991; Paoletti et al., 1997a | Wild vegetation removal |
| Dikes with wild herbage | Paoletti et al., 1989; Favretto et al., 1991 | Tubular drainage or dikes removal |
| Polyculture | Altieri et al., 1987; Paoletti, 1988 | Monoculture |
| Agroforestry | Altieri et al., 1987; Paoletti, 1988 | Monoculture |
| Rotation with legumes | Werner and Dindal, 1990 | Monosuccession |
| Dead mulch, living mulch | Stinner and House, 1990; Werner and Dindal, 1990 | Bare soil |
| Herbal strip inside crops | Joenie et al., 1997; Lys and Nentwig, 1992, 1994 | Homogeneous fields |
| Appropriate field margins | Paoletti et al., 1997a | Large fields |
| Small fields surrounded by woodland | Paoletti et al., 1989 | Large fields |
| Hedgerow surrounded fields | Nazzi et al., 1989 | Open fields |
| Ribbon cropping | Unpublished assessments (Paoletti 1987–1990) | Conventional cropping |
| Alley cropping | Unpublished assessments (Paoletti 1987–1990) | Monoculture |
| Living trees sustaining grapes | Unpublished assessments (Paoletti 1987–1990) | Artificial stakes |
| Minimum, no tillage, ridge tillage | Stinner and House, 1990; Exner et al., 1990 | Conventional plowing |
| mosaic landscape structure | Paoletti, 1988; Noss, 1990; Karg, 1989 | Landscape simplification, woodland clearance |
| Organic sustainable farming | Matthey et al., 1990; Werner and Dindal, 1990 | Intensive input farming |
| On farm research | Stinner et al., 1991; Lockeretz, 1987 | Conventional plot research |
| Organic fertilizer | Matthey et al., 1990; Werner and Dindal, 1990 | Chemical fertilizer |
| Biological pest control | Pimentel et al., 1991; Paoletti et al., 1993 | Conventional chemical pest control |
| Plant resistance | Pimentel et al., 1991 | Plant susceptibility |
| Germplasm diversity | Altieri et al., 1987; Lal, 1989 | Standardization |

When developing an assessment program, it is useful to have a substantial number of cases in order to aid in understanding the situation and to make a final judgement regarding the best choice of management practices to be promoted. Environmental sustainability must match economical viability, social acceptance and long term equitability (Conway and Barbier, 1990). In addition to well-thought out general policies to prevent inappropriate environmental stresses (Goodland and Pimentel, 1998; Van Haafte and Van de Vijver, 1996), improved sustainability of landscapes requires education of citizens, farmers and policy makers. In any case, bioindicators, the small organisms of a given habitat, represent the practical tools to assess comparatively the sustainability of a farm, a piece of landscape, or a reclaimed area (Table 4, Paoletti et al., 1997a).

## 6. Which is a landscape and landscape structure?

A landscape is a complex and large-scale system, river basin, region, etc., in which different ecosystems, soils, species, animal and plant guilds, ecological cycles, and human activities are associated with each other. In rural areas different farms can adopt different crops, sometimes changing styles of farming over time and space (Fig. 1) (Aebischer, 1991; Paoletti et al., 1993; Paoletti et al., 1997b). In urban and industrialized areas, cycles of production, management and waste disposal are the key elements that determine the profile of a landscape. In both rural and urban-industrialized landscapes, the strategy of waste disposal is the most important factor affecting the environment.

Species distribution and abundance are affected by the landscape mosaic structure, the presence and fragmentation of margins, and management of different parts of the agroecosystems contained in the landscape.

## 7. Margin effects (hedgerows, shelterbelts, weed strips)

Trees organized in rows, shelter belts, and patches of bushes, vines and herbs are a constant component of traditional farming landscapes in many tropical

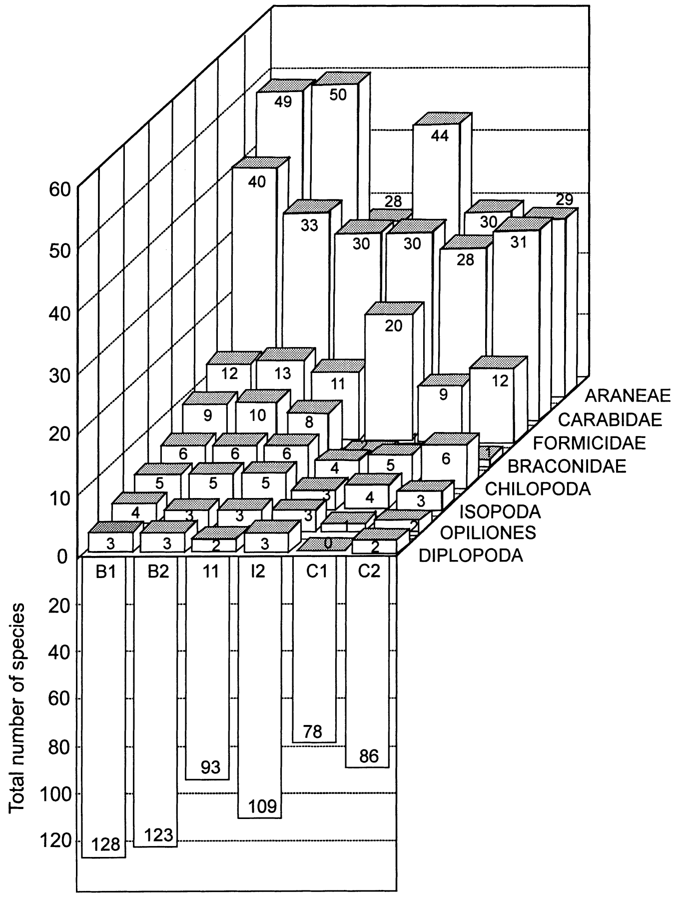
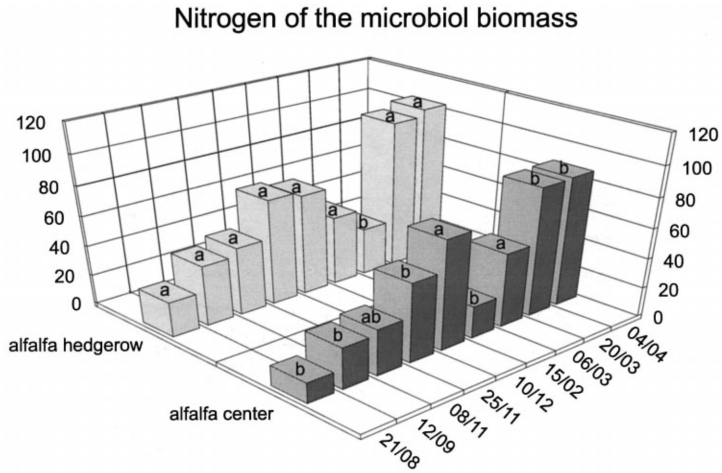


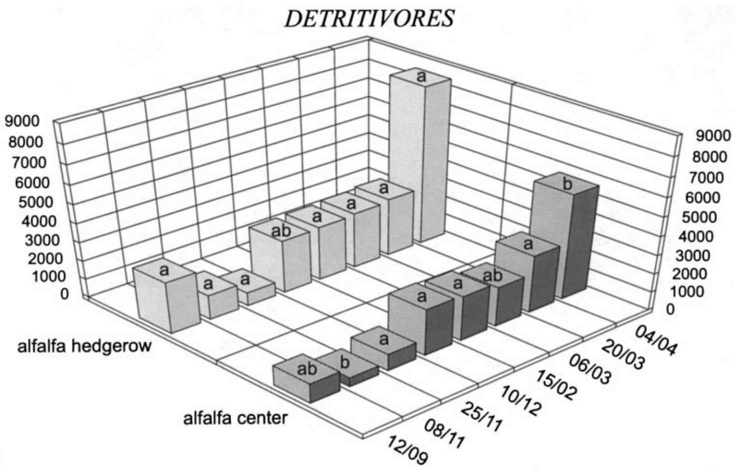

Fig. 1. Number of arthropod species and input strategies in three peach orchard types in Emilia Romagna, Italy. B1 and B2 are biological orchards; IPM1 and IPM2 are integrated orchards; C1 and C2 are conventional high input orchards. A decreased number of invertebrate species was noted in integrated and conventional farms compared to biological (organic) farms (from Paoletti and Sommaggio, 1996). Samplings was performed by pitfall traps and sweeping nets on a monthly basis for two years.

and temperate countries. Weedy margins (sometimes used as paths for machinery), ditches, fences, walls, and enclosures all create margins. These structures, in particular hedgerows and shelterbelts, serve many purposes, including providing a source of wood for burning and building, securing emergence fodder, providing a microclimate, and improving diversity (Joenie et al., 1997). In many cases, these microhabitats represent important refugia for beneficial predators and parasitoids (Nazzi et al., 1989; Paoletti and Lorenzoni, 1989; Sommaggio et al., 1995; Paoletti et al., 1997b). Is not clear whether such wild vegetation patches can also enhance the activities of pests in the rural landscape. The property of margins to host some pests (e.g., aphids and spidermites) is compensated by the fact that they can support polyphagous predators as well, providing overwintering sites which allow them to effectively predate early in the season (Paoletti and Lorenzoni, 1989; Paoletti et al., 1997b).

These less managed areas (hedgerows, strip weed margins) can also support a higher diversity of soil fauna (including more earthworms and carabids; unpublished data), accompanied by increased microorganism activity (microbial nitrogen and phosphorus) (Fig. 2 ).




(a)




(b)

Fig. 2. (a) Nitrogen microbial biomass is in general more abundant in an alfalfa margin near the hedgerow than in the center of the alfalfa field.(b) Detritivores are more abundant near the hedgerows than in the center of the alfalfa field.(c) Predators (microfauna sorted with modified Tullgren) are more abundant near the hedgerows than in the center of the alfalfa field. Survey carried out in Po Valley, province of Venice (from Ottaviani, 1992).

Peculiar ‘beetles banks’ and managed field margins seeded with mixed grasses and leguminous plants have been shown to be important habitats for polyphagous predators like carabids, spiders and other invertebrates over the seasons, and are also good refugia for overwintering. In addition, these strips or margins can help in disseminating beneficial invertebrates into cultivated fields (Paoletti and Lorenzoni, 1989; Lys and Nentwig, 1992, 1994; Lys et al., 1994; Frank and Nentwig, 1995; Carli, 1998; Joenie et al., 1997; Pankhurst et al., 1997).

## 8. Corridors in the landscape

When forested landscape is transformed and managed, the natural vegetation removed and substituted with crops, movements of small organisms become more problematic; this problem can in part be overcome by the presence of elements such as hedgerows, channels, banks, paths, path margins, road margins, etc., which provide a continuum in space (Burel and Baudry, 1990; Joenie et al., 1997). Connectivity is the property that spatially links different parts of a land-

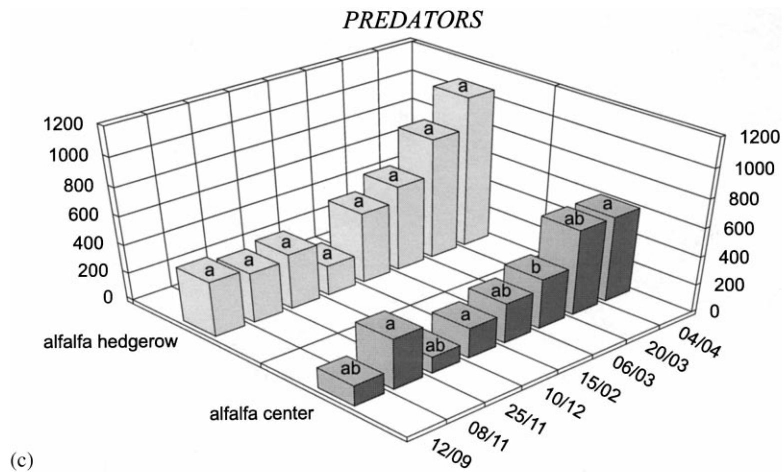



Fig. 2. *Continued*.

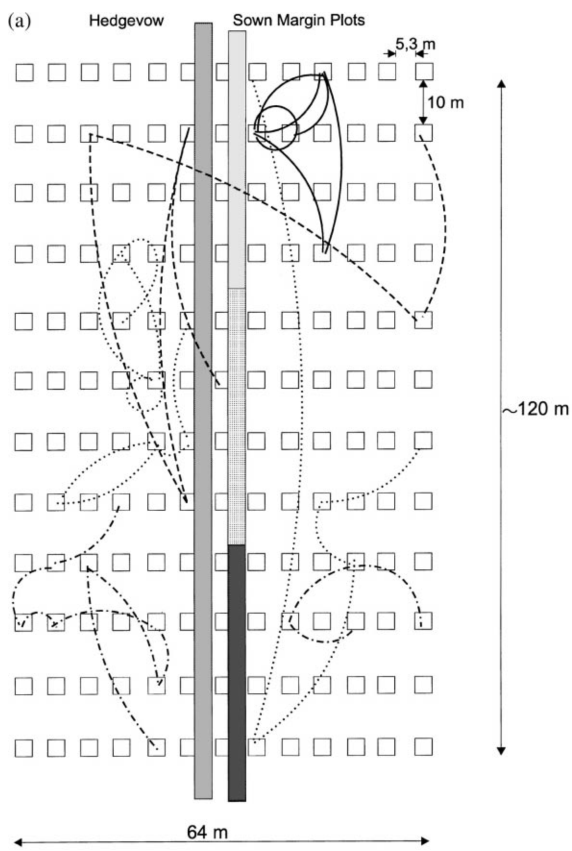



Fig. 3. (a) Pitfall recapturing experiments show that hedgerows can affect the free circulation of the soil-moving polyphagous carabid *Pterostichus melanarius* (England, near Bristol). (b) Hedgerows in summer attract a typical field ground beetle, *Harpalus rufipes* (England, near Bristol). (c) The pendular movement of another ground beetle, *Anchomenus dorsalis*, from the hedgerow to the field and back to the hedgerow, which might serve as an overwintering site (Castello di Brussa, province of Venice, Italy) (from Joenie et al., 1997).

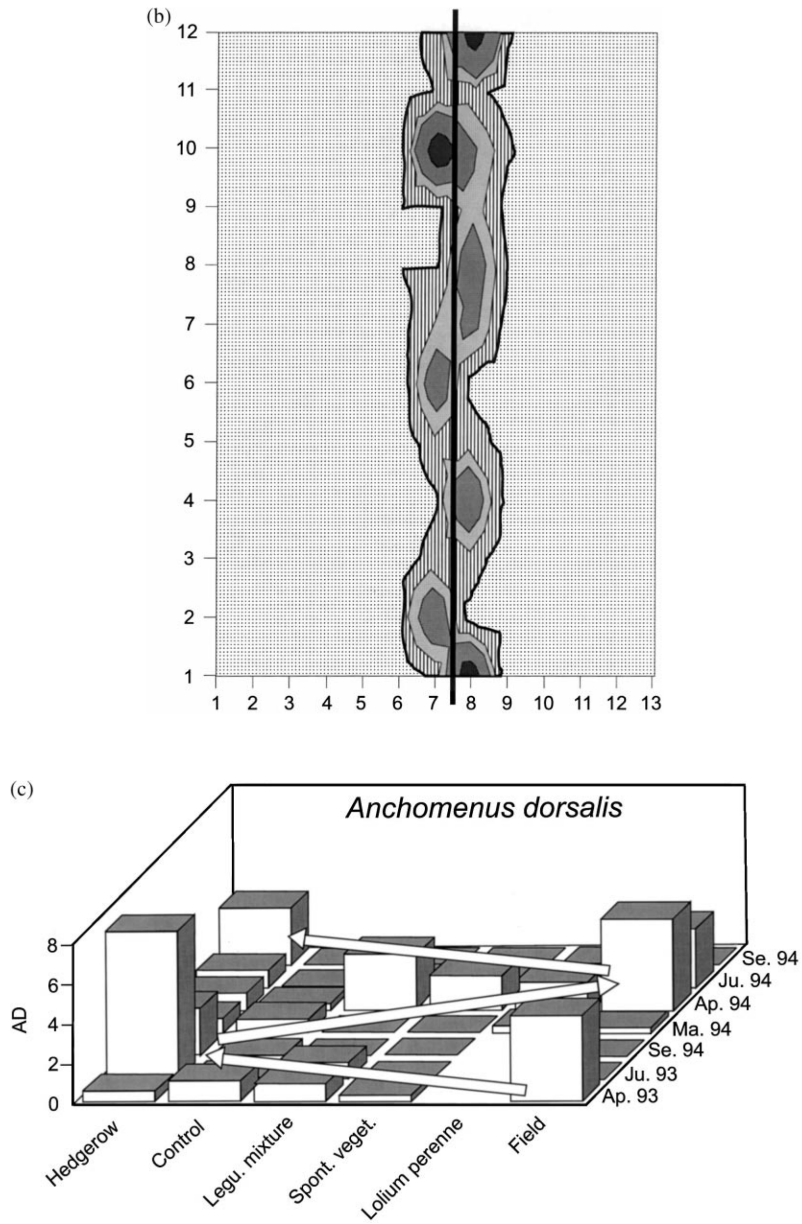



Fig. 3. (*Continued*).

scape. Biota, especially small animals but also plants, can be intensively affected by this feature of the landscape (Yu et al., 1999). In addition, hedgerows, roads, rivers can contain metapopulations. Fig. 3 (a–b), which illustrates a study of recaptured carabids carried out in England and Italy, demonstrates the border effect of hedges.

## 9. Effect of mosaics in the landscape

Incorporation of a plurality of patterns, margins, and different plant-crop units into a landscape confers ‘patchiness’, the mosaic effect that can be measured and be related to animal biota (abundance and distribution). In rural landscapes, the pattern of different soil uses within a farm can confer a peculiar mosaic character to the area. Different farming systems affect the rural landscape and the biota living in the area. Particular styles of farming (adopting rotation instead of monoculture, perennial crops instead of annuals, contour tillage, minimum tillage, etc.) can transform the mosaic character of a given area. Rotation instead of monoculture offers a different level of patchiness to the landscape. River banks, ditch slopes, and grassy margins can represent important elements for colonization in the landscape. The layout of the fields (dimension and shape) can also affect movements and colonization patterns of herbivores and predators (Paoletti and Lorenzoni, 1989; Sommaggio et al., 1995).

## 10. Perennials versus annual crops

In most agricultural systems, perennial crops have been abandoned and replaced with annuals or short term plants for many reasons, including the following: better short-term productivity; rapid crop maturation; limited susceptibility to predators, pathogens and pests; less risk in case of war and invasions, fire, etc. For example, an apple orchard needs at least three years to become productive; in tropical countries of the Far East, a sago palm (*Metroxylon* spp. and other species) requires 9–12 years before its starchy medulla can be harvested.

Monocultures of short-term crops currently dominate in most Western fossil energy-subsidized agricultural systems. Wheat, corn, soybean, and rice are all short-term crops, with 4–7 months needed between their seeding and harvest. These short maturation times in some cases permit planting of two or three crops per year on a single plot (especially in tropical or subtropical countries).

On the other hand, planting of perennial crops causes less severe erosion and limits soil loss, especially in the tropics (Pimentel et al., 1995). Although some perennial crops (e.g., apple, pear, peach, orange, grape, cherry) that require very high quantities of pesticides to control their pests (Pimentel, 1997) are among the highest input crops, other crop trees (e.g., Chinese domesticated: apricot, oriental persimmon, kiwifruit, jujubes) require no or limited application of pesticides (Pimentel, 1997; Paoletti, 1999).

Introduction of a hay crop into a perennial crop reduces erosion, improves soil fertility and helps maintain populations of predators (Giampietro et al., 1997; Yan et al., 1997). The proposal to produce perennial grains has been faced by several agroecologists that expect reduced input like tillage and chemical fertilizers (Wagoner, 1990; Jackson, 1991). However, at the moment, perennial grains are too low in productivity, and much research effort is needed to improve these candidates. In the tropics, staple foods are obtained from several types of trees, including palms (e.g., different sago palms) chestnut trees, bread trees, etc., and bushes (e.g., Cassava— *Manihot esculenta*).

## 11. Impact of pollution

At the landscape level, pollution is rarely a punctiform impact, e.g., the case of a power plant that disseminates undesired by-products into the surroundings (Bressan and Paoletti, 1997) or an intensive farm (e.g., apple orchard) that routinely uses high doses of pesticides. Although few data are available, most intensively cultivated areas (especially orchards) are probably severely polluted by current and past residues of pesticides. For example, arsenium can be present at high levels in soils of most apple orchards worldwide, despite the fact that pesticides containing arsenium have been abandoned since the beginning of this century. The same for residues of DDT and other persistent pesticide residues and their contaminants. Diffuse pollution includes acid deposition, the diffusion of ozone around highly trafficked areas and the diffuse water eutrophication in intensive high input farming areas.

Bioindicators have the potential to discriminate different situations in different environments. In most cases, pollution and landscape mismanagement create a loss of biodiversity (Van Straalen and Krivolutskii, 1996; Giampietro et al., 1997).

## 12. Waste disposal, reclamation and rehabilitation, bioremediation

Various materials are dumped into the landscape, including contaminated muds, industrial byproducts,

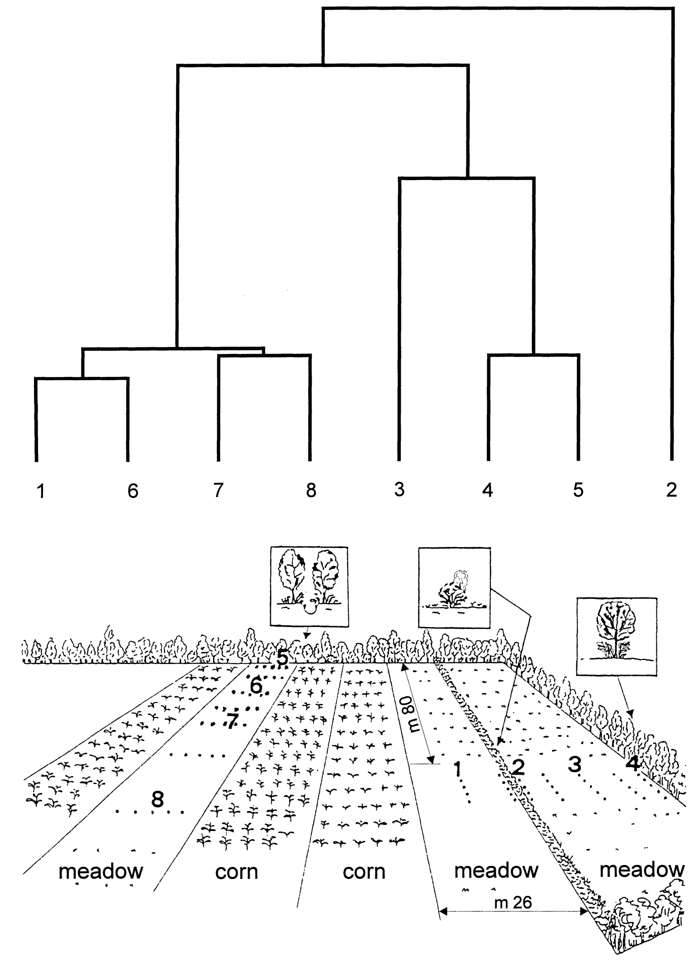



Fig. 4. Ancient Romans established centuriated fields in some previously wooded landscapes of Europe. Hedgerows represented the margins of this 'new' landscape. Some present-day rural landscapes (e.g., Riese Pio Decimo, province of Treviso, Italy) are still organized by the hedgerows and the encircled fields. It was observed that the dimensions of these fields influence the assemblage of invertebrates moving on the soil surface (data from pitfall traps). In addition, several carabids living in association with the hedgerows thrive better in the encircled fields than in the open fields

different liquid manures, sludges, as well as chemical fertilizers that can contain unwanted contaminants such as heavy metals, pesticide residues, etc. Pesticides applied to crops generally escape into the soil, where they can accumulate in a manner similar to some heavy metals.

Accumulation of different contaminated residues occurs in limited disposal areas. For example, it has been calculated that 400,000–600,000 hazardous waste sites are disseminated in USA alone. Up to 75% of the chemicals that are released into the environment can be degraded by biological organisms (Pimentel et al., 1997; Yount and Williams, 1996). Bioremediation is a promising way to reduce pollution and represents an alternative to chemical and physical methods. These hazardous waste sites could be monitored using appropriate bioindicators (Kuperman, 1996), and transformed and reclaimed over time using different strategies, including bioremediation.

## 13. Soil tillage and soil compaction

Modern agriculture relies heavily on tillage to control weeds and to improve soil texture for seed germination. The mouldboard plought, invented in China several centuries before its adoption in Western countries, is currently used in most agroecosystems to turn over the topsoil; its action also harms soil biota that are abundant in the topsoil, especially when the plough goes deep enough (El Titi and Ipach, 1989). Several options for reducing soil tillage (minimum and no-tillage, ridge-tillage) have been adopted to reduce this effect on biota (Stinner and House, 1990). Equipment used to smooth soil before seeding can also harm soil invertebrate macrofauna (Paoletti, 1988). Soil compaction in fields can be increased by passing heavy machinery, trucks and other heavy equipment. As with deep tillage, compaction can reduce the biomass and diversity of most soil organisms (Stinner and House, 1990; Paoletti and Bressan, 1996). Soil compaction caused by traffic on ski trails and animal trampling can also disturb soil organisms (Paoletti and Bressan, 1996).

## 14. Biotechnology: genetically engineered plants

Introduction of genetically modified crops makes the environment richer in alien genes, which are associated with both opportunities and risks. For example, BT (*Bacillus thuringiensis*) toxins inserted in an array of crops have the potential to produce several environmental problems (Paoletti and Pimentel, 1995, 1996). These BT-modified crops can: (1) promote rapid development of unwanted resistance of the key pests, e.g., lepidoptera, that are targeted for control; (2) deprive integrated and organic farming of a potential selective bioinsecticide (*Bacillus thuringiensis*) if the key pests become resistant; (3) produce side effects in different non target insects, including pollinators, parastoids, and detritivores; (4) release unwanted and possibly harmful residues into the soil food webs (Jepson et al., 1994; Yu et al., 1997); and (5) place pressure on polyphagous herbivores to become new pests.

Although side effects of the new herbicides (e.g., glyphosate) associated with herbicide-resistant engineered crops (HRC) could be used in lower quantities, these herbicides produce side effects in non target organisms, including increased mutagenesis in some cases (e.g., bromoxynil). Biotechnology associated with HRC has also been questioned because of the high risk of gene escape through hybridization of native plants that could become weeds (Mc Cullum et al., 1998).

Evaluation of the impact of these engineered crops with bioindicators is a promising trend that could improve the environmental and sustainable assessment of new crops. Rather than focusing on the few routinely used laboratory species, this type of study requires examining a whole array of invertebrates that normally live in agroecosystems, including detritivores, predators, parasitoids, pollinators, and scavengers. For example, it is not difficult to imagine that the study by Yu et al. (1997) that assessed soybean and cotton engineered with BT endotoxin using only two components of soil microfauna not commonly found in the cultivated fields might have missed important effects on relevant soil biota.

## 15. Practical approaches for field assessment with bioindicators to monitor decreasing impact

Bioindicator-based studies must be simple and easily repeated by different people in different situations, feasible in different environments, and suitable for assessing large areas. Using small invertebrates as a tool to evaluate the extent of environmental damages such as the effects of high input practices in agroecosystems (high pesticide input, tillage, chemical fertilization, sludging, trampling, monoculture) appears to be a good strategy. In the real landscape is not easy to focus on just one or few potential impacts. In most cases, pesticides, tillage and crop rotation are all present in varying levels depending on the style of farming.

Both integrated and conventional farms show a consistent reduction in species (Paoletti and Sommaggio, 1996). Fig. 1 shows results of a two-year bioindicator-based assessment of six peach orchards that were managed using three different input styles (organic, integrated and conventional). The organic and integrated orchards were found to support a higher number of species than the conventional orchards; the highest species number were present in the organic orchards. Such loss of species and in general biomass is the basic story for most intensive agricultural situations; however, this problem is avoided in some agricultural systems (Paoletti, 1988).

Successful taxonomical assessment of groups of organisms including mesoinvertebrates and microinvertebrates depends on the availability of a good team of taxonomists. Fortunately, in some cases, assessment of a selection of high-level taxa or guilds can provide enough detailed information to permit evaluation of the sustainability of a system in comparison with others.

In any case, choosing only one taxonomic group for all environments is not the best way to proceed. Very common groups in humid environments (e.g., earthworms) are completely absent from sandy soils, very acidic soils, and desert soils. Ground beetles are very rare in most tropical rain forest soils. Ants that are abundant in rain forests are almost absent in the Andes over 3500 m in altitude.

The first step in designing a study using bioindicators could be a preliminary rapid assessment using very simple collection systems such as pitfall traps (Kromp, 1999) (some traps might contain meat or bits of excrement), hand sorting, modified Tullgren, yellow traps or sweep netting. This rapid appraisal would allow the investigator to identify the most abundant and promising groups and the most appropriate approach to sample them.

Working with microfauna or microorganisms requires more dedicated sampling methods, for example, those indicated for nematodes by Yates and Bongers (1999), for protozoa by Foissner (1999) and for mites by Koheler (1999); Behan-Pelletier (1999). Although they can be more accurate, sophisticated sampling systems such as emergence traps (Jensen, 1997) or malaise or large window traps are limited to environments that can be protected from large animals and people, who could severely harm the large, expensive equipment. In addition, if left in place for long periods, these systems can collect an incredible number of specimens, which will require an overwhelming effort just to sort.

The second step in a bioindicator study is to plan the plots, repetitions and sites to be compared and to select an appropriate statistical method that will discriminate differences among the plots and sites. The third step is to select, in the area to be investigated, the sites potentially less disturbed by the key factor that are considered as a ‘natural’ reference. For example, planning to assess different rotation practices on a farm, it would be useful to have a stable, ‘less disturbed’ reference site such as a riverbank, meadow, hedgerow, or a plot of woodland.

The simpler the collection system, the better the data obtained, especially if time, people and funding are the limiting factors, as is generally the case. This is the reason why pitfall traps (Fig. 4), sweeping nets, small window traps and yellow plates are used more frequently than other systems. However, many different collection systems have to be organized together in order to attain the most accurate measurements of species numbers and behavior.

## 16. Decreasing environmental impact

Many countries have adopted policies to reduce pesticides and other agricultural and environmental inputs, e.g., The Netherlands, Sweden, Denmark, Indonesia and the province of Ontario, Canada (Pimentel, 1997; Paoletti, 1997). Without an appropriate campaign for monitoring the changing rural landscape, the environmental benefits arising from these policies cannot be appreciated; in this context, bioindicator-based studies are invaluable for assessing changes and evaluating benefits.

Assessing rural and industrial landscapes and contaminated sites along with their process of rehabilitation is the key objective of adopting biodiversity as an index. It is difficult to imagine the benefits gained from laws designed to reduce environmental impact without having a suitable instrument to assess the transformation. Invertebrate bioindicators represent one such instrument.

## 17. Concluding remarks

Studies with bioindicators apply biodiversity as a principal tool to evaluate landscape quality and function and to assess different impacts and remediation processes. Limits to its practicability are linked to the limited knowledge of the most small living creatures that populate all corners of landscapes. The invertebrates described in this volume are only the ones that historically (or sometimes by chance) have been more extensively adopted for these studies. When designing and carrying out bioindicator-based studies, it must be kept in mind that incertitude linked to limited knowledge and variability in the field can lead to disappointment and/or excessive expectations. Prudence is always required in interpreting field data; repetitions and appropriate statistical methods are essential.

Additional limits are imposed by the low reputation that small living creatures paradoxically have among some experts, administrators and farmers who are responsible for making decisions that influence the fate of the environment. Many of us consider insects as pests that must be disinfested; biologists and entomologists have been trained to focus more on pest problems related to invertebrates than their potential usefulness. The focus of applied entomology and plant pathology on the frightening consequences of pest infestations and plagues is perhaps exaggerated.

There is a need to increase knowledge of the undervalued small creatures in order to better appreciate the many benefits that humans derive from their existence. Last but not least, there is a need to strengthen the links between diversity and economic features of agroecosystems. D. Pimentel has calculated the value of biodiversity (Pimentel et al., 1997); Thus the need is to work harder to evaluate the incremental value of biodiversity in restored versus damaged and/or polluted situations, and to bring to light the values and cost of these processes to life in the countryside, towns, agroecosystems, and industrial settlements.

## Acknowledgements

The author thanks D. Pimentel and W. Nentwig for suggestions and comments on the previous version of this manuscript.

## References

Aebischer, N.J., 1991. Twenty years of monitoring invertebrates and weeds in cereal fields in Sussex. In: Firbank, L.G., Carter, N., Darbyshire, J.F., Potts, G.R. (Eds.), The 32nd Symposium of the British Ecological Society and the Association of Applied Biologists, University of Cambridge, Blackwell Scientific Publications, Oxford, pp. 305–331.

Altieri, M.A., 1999. The Ecological Role of Biodiversity in Agroecosystems. Agric. Ecosyst. Environ. 74 (1–3), 19–31.

Altieri, M.A., 1995. Agroecology. The Science of Sustainable Agriculture, Westview Press, Boulder, CO, 433 pp.

Behan-Pelletier, V.M., 1999. Oribatid mite biodiversity in agroecosystems: role for bioindication. Agic. Ecosyst. Environ. 74 (1–3), 411–423.

Bressan, M., Paoletti, M.G., 1997. Leaf litter decomposition and soil microarthropods affected by sulfur dioxide fall out. Land Degradation Dev. 8 (2), 189–199.

Burel, F., Baudry, J., 1990. Hedgerow network patterns and process in France. In: Zonneveld, I.S., Forman, R.T.T. (Eds.), Changing Landscapes: An Ecological Perspective, Springer, New York, pp. 99–120

Burel, F., 1992. Effect of lanscape structure and dynamics on species diversity in hedgerow networks. Landscape Ecol. 6, 161–174.

Burel, F., 1995. Ecological patterns and processes in European Agricultural Landscapes. Landscape and Urban Planning 31 (1–3), 1–412.

Carli, E. 1998. I Margini erbiti come fonte di biodiversità in agroecosistema planiziale veneto. Tesi di laurea, Dipartimento di Biologia, Università di Padova.

Carter, V.G., Dale, T., 1974. Topsoil and Civilization, University of Oklahoma Press, Norman, 291 pp.

Conway, G.R., Barbier, E., 1990. After the Green Revolution: Sustainable Agriculture for Development, Earthscan Publishers, London

Costanza, R. et al., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.

De Jong, W., 1997. Developing swidden agriculture and the threat of biodiversity loss. Agric. Ecosyst. Environ. 62, 187–197.

El Titi, X., Ipach, U., 1989. Soil fauna in sustainable agriculture: results of an integrated farming system at Lautenbach, F.R.G. Agric. Ecosyst. Environ. 27, 561–572.

Erwin, D., 1996. The geologic history of diversity. In: Szaro, R.C., Johnston, D.W. (Eds.), Biodiversity in Managed Landscapes, Oxford University Press, Oxford, pp. 3–14.

Erwin, T., 1997. Biodiversity at its utmost: tropical forest beetles. In: Reaka-Kudla, M.L., Wilson, D.E., Wilson, E.O. (Eds.), Biodiversity II, J. Henry Press, Washington, D.C., pp. 27–40.

Foissner, W., 1999. Soil protozoa as bioindicators: pros and cons, methods, diversity, representative examples. Agric. Ecosyst. Environ. 74 (1-3), 95–112.

Frank, T., Nentwig, W., 1995. Ground dwelling spiders (Araneae) in sown weed strips and adjacent fields. Acta Oecologica 16, 179–193.

Funtowicz, S.O., Ravetz, J.R., 1993. Science for the post-normal age. Futures 25 (7), 739–754.

Giampietro, M., Paoletti, M.G., Bukkens, S.G.F., Hand Chunru, H., 1997. Preface. Biodiversity in agriculture for a sustainable future. Agric. Ecosyst. Environ. 62 (2,3), 77–79.

Golley, F.B., 1977. Ecological Succession. Dowden, Hutchinson and Ross, Stroudburg, PA, 373 pp.

Goodland, R., Pimentel, D., 1998. Environmental sustainability and integrity in the agriculture sector. In: Noss, R.F., Westra, L. (Eds.), Ecological Integrity.

Hammond, P.M., 1995. Described and estimated species numbers: an objective assessment of current knowledge. In: Allsopp, D., Hawksworth D.L., Colwell, R.R. (Eds.), Microbial Diversity and Ecosystem Function, CAB International, pp. 29–71.

Hammond, P.M., 1992. Species inventory. In: Groombridge, B. (Ed.), Global Biodiversity, Status of Earth Living Resources. Chapman & Hall, London, pp. 17–39.

Harrington, R., Stork, N.E., 1995 (Eds.) Insects in a Changing Environment, Academic Press, London, 535 pp.

Heywood, V.H., Watson, R.T., 1995. Global Biodiversity Assessment. Unep, Cambridge University Press New York, 1140 pp

Holopainen, J.K., Oksanen, J., 1995. Arboreal insects as indicators of air pollution effects on woody plants. In: Manawar, M., Hanninen, O., Roy, S., Munawar, N., Karelampi, L., Brown, D. (Eds.), Bioindicators of Environmental Health, SPC Academic Publishing, Amsterdam, pp. 83–96

Jackson, W., 1991. Development of perennial grains. The eighteenth international conf. on the unity of sciences, Seoul, Korea, Aug. 23–26, 1991.

Jensen, P.B., 1997. The influence of unspraying on diversity of soil-related hymenopteran parasitoids in cereal fields. J. Appl. Ent. 121, 417–424.

Jeffrey, D.W., Madden, B., 1991. Bioindicators and Environmental Management. Academic Press, London, 458 pp.

Jepson, P.C., Croft, B.A., Pratt, G.E., 1994. Test systems to determine the ecological risks posed by toxin release from *Bacillus thuringiensis* genes in croplands. Molec. Ecol. 3, 81–89.

Joenie, W., Burel, F., Gerowitt, B., Paoletti, M.G., Thomas, C.F.G., Moonem, C., Baudry, J., Le Coeur, D., Kleijn, D., Schippers, P., Kopp, A., Thenail, C., Marshall, E.J.P., 1997. Field boundary habitat for wildlife, crop and environmental protection, Long Ashton Research Station, Bristol, UK, 313 pp.

Jorg, E., 1994. Field margin-strip programmes. Landeranstalt fur Pflanzenbau und Pflanzenschutz, Mainz, Germany, 182 pp.

Jordan, V.W.L.(Ed.), 1993. Expert Presentations of Future Demands and Perspectives for Good Agricultural Practice, Commission of the European Communities, Agriculture, Bruxelles, pp.

Kleinman, P.J.A., Pimentel, D., Bryant, R.B., 1995. The ecological sustainability of slash-and-burn agriculture . Agric. Ecosyst. Environ. 1995, 235–249.

Koheler, H.H., 1999. Predatory mites (Gamasina, Mesostigmata). Agric. Ecosyst. and Environ. 74 (1–3), 395–410.

Kromp, B., 1999. Carabid beetles in sustainable agriculture: a review on pest control efficacy, cultivation impacts and enhancement. Agric. Ecosyst. Environ. 74 (1-3), 187–228.

Kuperman, R.G., 1996. A hierarchical approach to ecological assessment of contaminated soils at aberdeen proving ground, USA. In: Van Straalen, N.M., Krivolutskii, D. (Eds.), Bioindicator Systems for Soil Pollution, NATO ASI Series, vol. 16, Kluwer Academic Publishers, pp. 197–212.

Lopez Hernandez, D., Garcia-Guadilla, M.P., Torres, F., Chacon, P., Paoletti, M.G., 1997. Identification, characterization, and preliminary evaluation of Venezuelan Amazon production systems in Puerto Ayacucho Savanna- forest ecotone. Interciencia 22 (6), 307–314.

Lys, J.A., Nentwig, W., 1992. Augmentation of beneficial arthropods by strip-management 4. Surface activity, movements, movements and activity density of abundant carabid beetles in a cereal field. Oecologia 92, 373–382.

Lys, J.A., Nentwig, A., 1994. Improvement of the overwintering sites for Carabidae, Staphylinidae, Staphylinidae and Araneidae by strip-management in cereal field. Pedobiologia 38, 238–242.

Lys, J.A., Zimmermann, M., Nentwig, W., 1994. Increase in activity density and species number of carabid beetles in cereals as result of strip-management. Entomologia Experimentalis et Applicata 73, 1–9.

Mc Cullum, C., Pimentel, D., Paoletti, M.G., 1998. Genetic engineering in agriculture and the environment: risks and benefits. In: Thomas, J.A. (Ed.), Biotechnology and Safety Assessment, in press.

Manawar, M., Hanninen, O., Roy, S., Munawar, N., Karelampi, L., Brown, D. (Eds.), 1995. Bioindicators of Environmental health, SPC Academic Publishing, Amsterdam.

Naeem, S., Thompson, L.J., Lwler, S.P., Lawton, J.H., and Woodfin, R.M., 1994. Declining biodiversity can alter the performance of ecosystems. Nature 368, 734–736.

Nazzi, F., Paoletti, M.G., Lorenzoni, G.G., 1989. Invertebrate dynamics of soybean agroecosystems encircled or not by hedgerows in Friuli, Italy. First Data. Agriculture Ecosystems and Environment 27 (1–4).

Needham, J. 1954. Science and Civilization in China. Cambridge University Press, UK

Netuzhilin, I., Paoletti, M.G., Cerda, H., Chacon, P., Lopez Hernandez, D., 1997. Biodiversity tools to evaluate sustainability in Savanna-forest ecotone in the Amazonas (Venezuela). In: Reddy, M.V. (Ed.), Management of Tropical Agroecosystems and Beneficial Soil Biota, Oxford & IBH Publishers, New Delhi, in press.

Odum, E., 1984. Properties of agroecosystems. In: Lawrance, R., Stinner, B.R., House, A. (Eds.), Agricultural Ecosystems, pp. 5–11

Ottaviani, S., 1992. Indicatori biologici del suolo: Azoto della biomassa microbica ed attivita' della pedofauna. tesi di laurea, Dipartimento di Biologia, Università di Padova.

Pankhurst, C., Doube, B.M., Gupta, V.V.S.R., 1997. Biological Indicators of Soil Health, CAB International, London, pp.

Paoletti, M.G., 1997. Are there alternatives to wheat and cows in order to improve landscape quality and biodiversity? In: Napier, T., Camboni, S., Tvrdon, J. (Eds.), Soil and Water Conservation Polices: Successes and Failures, Water and Soil Conservation Society Press, in press.

Paoletti, M.G., 1999. Some unorthodox thoughts: what Western agriculture should learn from Chinese agriculture. Critical review in Plant Sciences 18 (3), 475–487.

Paoletti, M.G., Boscolo, P., Sommaggio, D., 1997a. Predators-parasitoids and beneficial insects in fields sorrounded by hedgerows in North Eastern Italy. Biol. Agric. Hortic. 15 (1-4), 311–373.

Paoletti, M.G., Sommaggio, D., Favretto, M.R., Petruzzelli, G., Pezzarossa, B., Barbafieri, M., 1997b. Earthworms as useful bioindicators of agroecosystem sustainability in different inpur orchards, Appl. Soil Ecol., in press.

Paoletti, M.G., Bukkens, S.G.F., 1997. Minilivestock: sustainable use of biodiversity for human food. Ecol. Food and Nutrition 36 (2–4), 90–341.

Paoletti, M.G., Bressan, M., 1996. Soil invertebrates as bioindicators of human disturbance. Crit. Rev. Plant Sci. 15 (1), 21–62.

Paoletti, M.G., Gradenigo, C., 1996. Lombri CD-ROM. Lapis, Padova.

Paoletti, M.G., Pimentel, D., 1996. Genetic engineeing in agriculture and the environment. Bioscience 46 (9), 665–673.

Paoletti, M.G, Sommaggio, D., 1996. Biodiversity indicators for sustainability. Assessment of rural landscapes. In: Van Straalen, N.M., Krivolutskii, D., (Eds.), Bioindicator Systems for Soil Pollution, NATO ASI Series, vol. 16, Kluwer Academic Publishers, pp. 123–140.

Paoletti, M.G., Sommaggio, D., Bressan, M., Celano, E., 1996. Can sustainable agriculture practices affect biodiversity in agricultural landscapes? A case study concerning orchards in Italy. Acta Jutlandica 71 (2), 241–254.

Paoletti, M.G., Pimentel, D., 1995. The environmental and economic costs of herbicide resistance and host-plant resistance and host-plant resistance to plant pathogens and insects. Technological Forecasting and Social Change 50, 9–23.

Paoletti, M.G., Favretto, M.R., Marchiorato, A., Bressan, M., Babetto, M.M., 1993. Biodiversità in pescheti forlivesi. In: Paoletti M.G. et al. (Eds.), Biodiversità negli Agroecosistemi. Osservatorio Agroambientale, Centrale Ortofrutticola, Forlì, pp. 20–56.

Paoletti, M.G., Pimentel, D. (Eds.), 1992. Biodiversity in Agroecosystems, Elsevier, 356 pp.

Paoletti, M.G., Pimentel, D., Stinner, B.R., Stinner, D., 1992. Agroecosystem biodiversity: matching production and conservation biology. Agric. Ecosyst. Environ. 40, 3–26.

Paoletti, M.G., Favretto, M.R., Stinner, B.R., Purrington, F.F., Bater, J.E., 1991. Invertebrates as bioindicators of soil use. Agric. Ecosyst. Environ. 34, 341–362.

Paoletti, M.G., Lorenzoni, G.G., 1989. Agroecology patterns in Northeastern Italy. Agric. Ecosyst. Environ. 27 (1–4), 139–154.

Paoletti, M.G., Stinner, B.R., Lorenzoni, G.G. (Eds.), 1989. Agricultural Ecology and Environment, Elsevier, 636 pp.

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

Pimentel, D. (Ed.), 1997. Techniques for Reducing Pesticide Use: Economic and Environmental Benefits, Wiley, New York.

Pimentel, D., Wilson, C., McCullum, C., Huang, R., Dwen, P., Flack, J., Tran, Q., Saltman, T., Cliff, B., 1997. Economic and environmental benefit of biodiversity. Bioscience 47 (11), 747–757.

Pimentel, D., Pimentel, M., 1996. Food, Energy and Society, University Press of Colorado, Niwot, CO.

Pimentel, D. et al., 1995. Environmental and economic costs of soil erosion and conservation benefits. Science 267, 1117–1123.

Pimm, S.L., 1991. The Balance of Nature?, The University of Chicago Press, Chicago, 434 pp.

Posey, D.A., 1992. Peoples of the fallow: a historical ecology on foraging in lowland South America. In: Redford, K.H., Padoch, C. (Eds.), Conservation of Neotropical Forests. Working from Traditional Resource Use, Colombia University Press, New York, pp. 21–34.

Reddersen, J., 1995. Feeding biology of fungivorous insects from Danish cerel fields. Pedobiologia 39, 370–384.

Reaka-Kudla, M.L., 1997. The global biodiversity of coral reefs: a comparison with rain forests. In: Reaka-Kudla, M.L., Wilson, D.E., Wilson, E.O. (Eds.), Biodiversity II, J. Henry Press, Washington, D.C., p. 83.

Richardson, D.H.S. (Ed.), 1987. Biological indicators of pollution, Royal Irish Academy, Dublin, 242 pp.

Sommaggio, D., Paoletti, M.G., Ragusa, S., 1995. Nutrients and predators on the abundance of herbivores on stinging nettles *Urtica dioica*, L. Effects of microhabitat conditions. Acta Oecologica 16 (6), 671–686.

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

Stork, N. E., 1997. Measuring global biodiversity and its deadline. In: Reaka-Kudla, M.L., Wilson, D.E., Wilson, E.O. (Eds.), Biodiversity II, J. Henry Press, Washington, D.C., pp. 41–68.

Szaro, R.C., Johnston, D.W., 1996. Biodiversity in Managed Landscapes. Theory and Practice, Oxford University Press, 778 pp.

Tilman, D., Wedin, D., Knops, J., 1996. Productivity and sustainability influenced by biodiversity in grassland ecosystems. Nature 379, 411–429.

Van Haaften, E.H., Van de Vijver, F.J.R., 1996. Psychological consequences of environmental degradation. J. Health Psychol. 1 (4), 411–429.

Van Straalen, N.M., 1997. Community structure of soil arthropods as bioindicators of soil health. In: Pankhurst, C., Doube, B.M., Gupta, V.V.S.R. (Eds.), Biological Indicators of Soil Health, CAB International, London, pp. 235–263.

Van Straalen, N.M., Krivolutskii, D. (Eds.), 1996. Bioindicator Systems for Soil Pollution. NATO ASI Series, Kluwer Academic Publishers, p. 16.

Wagoner, P.A., 1990. Perennial grain development: past effort and potential for future. CRC Crit. Rev. Plant Sci. 9, 381–408.

Wilson, E.O., 1997. Introduction. In: Reaka-Kudla, M.L., Wilson, D.E., Wilson, E.O. (Eds.), Biodiversity II, J. Henry Press, Washington, D.C., pp. 1–3.

Wilson, E.O., 1988. Biodiversity, National Academic Press, Washington DC, 658 pp.

Yan, Y., Yu, Y., Du, X., Zhao, B., 1997. Conservation and augmentation of natural enemies in pest management of Chinese apple orchards. Agric. Ecosyst. Environ. 62, 253–260.

Yates, G.W., Bongers, T., 1999. Nematode diversity in agroecosystems, Agric. Ecosyst. Environ., this volume.

Yount, K.R., Williams, R.H., 1996. Reclamation, redevelopment, redevelopment and reuse of potentially polluted land: comparing apporoaches in the United States and the European Union. Sustain 1, 30–36.

Yu, L., Berry, R.E., Croft, B.A., 1997. Effects of Bacillus thuringiensis toxins in transgenic cotton and potato on Folsomia candida (Collembola: Isotomidae) and Oppia nitens (Acari: Oribatidae). J. Econom. Entomol. 90 (11), 113–118.

Yu, Z., Baudry, J., Zhao, B., Zhang, H., Li, S., 1999. Vegetation components of a subtropical rural landscape in China. Crit. Rev. Plant Sci., in press.