

Sistemas Agroflorestais

Bases Científicas para o Desenvolvimento Sustentável

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UNIVERSIDADE ESTADUAL DO NORTE FLUMINENSE DARCY RIBEIRO
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Biodiversity and Function of Soil Animals in Brazilian Agroforestry Systems

GEORGE G. BROWN, JÖRG RÖMBKE, HUBERT HÖFER, MANFRED VERHAAGH, KLAUS D. SAUTTER & DALVA LUIZ DE QUEIROZ SANTANA

INTRODUCTION

Agroforestry (AF) systems are generally considered to have positive effects on biodiversity and its conservation when compared with simpler agroecosystems (McNeeley & Schroth, 2006). Both above and belowground biodiversity may be positively affected by the adoption of AF systems, particularly as the structure of the system approaches that of the native vegetation. It is generally assumed that below-ground biodiversity is positively influenced by the diversity of plants growing above ground, but the nature of this relationship is still far from clear, as a large number of interactive processes are involved (Hooper et al., 2000). Consequently, little information is available regarding the role of plant diversity in regulating soil biodiversity at different levels of the landscape (Susilo et al., 2004). In simpler systems and for some groups of soil organisms, positive relationships are apparent, but as the system becomes more complex, the relationships become less clear (van Noordwijk, 1999). Furthermore, the taxonomic level of identification is also important; group diversity of soil animals may have positive relationships to plant diversity (e.g., Luizão et al., 2001; Barros et al., 2006), but at species level, relationships may be lost. Clarification of this relationship is an important and urgent task for soil ecologists, particularly in the light of agricultural expansion and intensification in many tropical countries such as Brazil. Land use cover change, especially for agriculture, has been considered one of the main driving forces of the present "biodiversity crisis" (Wilson, 1985).

The relationship between species richness and functional diversity in soils is also rather loose, and little information is available which shows that soils function better in the presence of greater soil animal biodiversity (Ekschmitt & Griffiths, 1998). The difficulty of showing this relationship is heightened by the apparent functional redundancy of many species of soil animals, as well as the wide range of functions and services that they perform in soils (Bengtsson, 1998). For instance, in an agroecosystem, the local spider, ant or beetle community may be represented by dozens up to hundreds of species, many of them performing similar (and/or multiple) functions. In fact, redundancy and species richness may also be an important component of the ecosystem's stability and resilience to perturbations (Ekschmitt & Griffiths, 1998; Wardle et al., 1999). Therefore, even a large number of apparently redundant species may be desirable. Once again, this may be particularly the case as agriculture expands and intensifies to feed growing populations and human aspirations. It is in these simpler (agricultural) systems that various associated risks from lack of biodiversity both above- and below-ground may increase (Giller et al., 1997). Therefore, the possibility of AF as a sustainable alternative land use system needs further exploration, particularly its role in mitigating species loss

and in enhancing biodiversity (above- and below-ground), ecosystem functions and services at the local and regional scale (McNeeley & Schroth, 2006).

In the present chapter, we review the currently available data on soil animal communities under AF systems in Brazil, focusing particularly on the impact of various Amazonian AF systems on the conservation and maintenance of soil animal populations. We also summarize the diversity and functional roles of animals in soils and review the available data on their potential roles in the functioning of Amazonian AF systems.

SOILS AND GLOBAL BIODIVERSITY

Much beyond being only substrates for growing plants, soils are living entities and the home of numerous organisms whose diversity may even surpass that of the aboveground flora and fauna, especially in agroecosystems. Soils are among the most biologically rich habitats on earth (Brussaard et al., 1997; Wall & Moore, 1999). Nowhere in nature are species so densely packed as they are in soil communities (Hågvar, 1998). For example, a single gram of soil may contain millions of bacteria and several thousand species of microorganisms (Torsvik et al., 1994), while soils of tropical forest habitats (e.g., a few hectares of Amazonian or Atlantic Rainforests) may harbor more than 2200 species of invertebrates (Mathieu, 2004) in a single site. Of these, only a few (less than 20) are likely to be earthworms (Fragoso & Lavelle, 1992) or pseudoscorpions (Franklin & Morais, 2006), while spiders, mites and myriapods might be represented by several dozen species each (Franklin et al., 2004; Adis, 2002). However, the vast majority of the total are likely to be nematodes (Huang & Cares, 2006) and insects (Barros et al., 2006), each representing generally more than 100 species (the latter mostly of beetles and ants).

In fact, over 1 million species of insects may inhabit Brazilian ecosystems (Lewinsohn & Prado, 2005), and a large proportion (up to 25% or more) of these may be associated with soils for an important part of their life cycle (Decaëns et al., 2006). Therefore, as many as 250,000 species of soil insects may live in Brazilian soils. Presently, more than 50,000 species of soil + litter inhabiting animals have been described from Brazil (Table 1), being the beetles, Protozoa, spiders, nematodes, ants, and mites the most diverse, each with > 1,000 classified or estimated species. However, most groups of soil animals remain poorly known, and their species diversity is certainly much larger than the currently known totals. For instance, only 3% and 5% of the world's estimated diversity of nematodes and mites is presently known (Hammond et al., 1995). Furthermore, several groups of animals lack specialists in many tropical countries (including Brazil; Brandão et al., 2006), complicating identification, and many important collections of soil invertebrates are located in foreign museums (mainly in Europe and the USA), making access difficult for taxonomists from developing countries.

This immense diversity, added to the technical difficulties associated with studying the soil ecosystem and the lack of taxonomists to describe it, has resulted in an appallingly poor knowledge of the world's soil biodiversity. Therefore the few currently available taxonomic inventories fall short of an accurate picture of the number of species living in soil systems (Table 1; Lewinsohn et al., 2005; Brandão et al., 2006). Because soil communities are so diverse yet so poorly known and described, they have been called the "other last biotic frontier" (André et al., 1994), or the "poor man's tropical rainforest" (Usher et al., 1979; Giller, 1996). Further efforts are urgently needed to overcome the taxonomic challenges involved in describing the world's soil biota, especially considering the potential negative impacts on global biodiversity of climate and further land use changes worldwide.

Soils are also very complex physically. Crisscrossed by an immense network of micropores, macropores and tunnels, soil pore spaces provide the habitat for a wide range of organisms and their activities. The great spatial and temporal variability in available organic matter (OM), water, and other nutrients promotes a complex niche structure in the soil. The soil structure and its food resources provide conditions for the evolution and maintenance of complex interactions between soil organisms, as well as apparently functionally redundant species or trophic groups. Given this ecological complexity, myriad plant, animal, and microbial communities are able to coexist and provide a range of functions and services. However, this vital and dynamic subterranean soil ecosystem often is unrecognized, little understood, and therefore mismanaged.

Table 1 - Estimates of global and national species diversity of various representatives of soil + litter inhabiting animals (values taken from Adis, 2002; Brandão et al., 2006; Brown & Fragoso, 2006; Culik & Zeppelini Filho, 2003; Lewinsohn & Prado, 2005; 2006; Lewinsohn et al., 2005; Moreira et al., 2006)

Taxonomic/size categories Common (Scientific) names	Nº species ¹	
	Brazil	World
<i>Microfauna</i>		
Protozoans (Protista)	[3,060-4,140]	36,000
Nematodes (Nematoda)	[1,280-2,880]	15,000
Rotifers (Rotifera) ²	457	2,000
Tardigrades (Tardigrada) ²	67	750
<i>Mesofauna</i>		
Diplura	NA	659
Mites (Acari)	1,500	45,000
Potworms (Enchytraeidae)	100	800
Pseudoscorpions (Pseudoscorpionida)	>100 ³	3,235
Springtails (Collembola)	199	7,500
Symphyla	NA	200
<i>Macrofauna</i>		
Ants (Formicidae)	2,750	11,826
Beetles (Coleoptera)	30,000	350,000
Carabidae	1,132	30,000
Cerambycidae	4,000	35,000
Curculionidae	5,041	65,000
Elateridae	590	9,300
Leiodidae	22	4,240
Lucanidae	70	1,200
Pasalidae	72	600
Ptiliidae	9	430
Scarabidae	1,777	25,000
Scydmaenidae	59	200
Staphylinidae	1,571	35,000
Tenebrionidae	1,234	18,000
Earthworms (megadriles)	306	3,800 [8,000]
Glossoscolecidae	202	533
Harvestmen (Opiliones)	951 [1,800]	5,500
Myriapoda	424	15,100
Centipedes (Chilopoda)	150	2,500
Millipedes (Diplopoda)	NA	10,000
Scorpions (Scorpionida)	119	1,259
Snails (Gastropoda)	670 [2,000]	30,000
Spiders (Araneae)	2587 [10,000]	38,884
Termites (Isoptera)	290 [600]	2,800
Velvet worms (Onychophora)	4	90
Woodlice (Isopoda) ²	135	4,250

¹Number shown is of classified species; the numbers in brackets [] is the estimated number; NA = Data not available.

²Includes soil and aquatic species. ³ 75 spp. of pseudoscorpions are known from Brazilian Amazonia.

SOIL FAUNA AND SOIL FUNCTION

Soil animals have a broad range of body sizes, feeding strategies, and life habits, from strictly aquatic to obligatorily terrestrial (Lavelle & Spain, 2001). They range in size from the tiniest one-celled protozoa, to the more complex nematodes and micro-arthropods, to the visible earthworms, insects, small vertebrates. Together with bacteria, fungi, algae, plant roots and litter, this community of organisms makes up the soil food web—including probably the longest food chains found in nature (Coleman et al., 2004), with multiple primary producers (plants, lichens, moss, photosynthetic bacteria and algae) and numerous consumers (primary, secondary, tertiary, and so-on) (Figure 1). The food-chain concept is basic to ecology and represents an ecosystem in a simple way, as a chain of species where one species is preyed upon by the next. The chain also depicts how energy, fixed by plants as primary producers, is transferred over trophic levels to the top consumers.

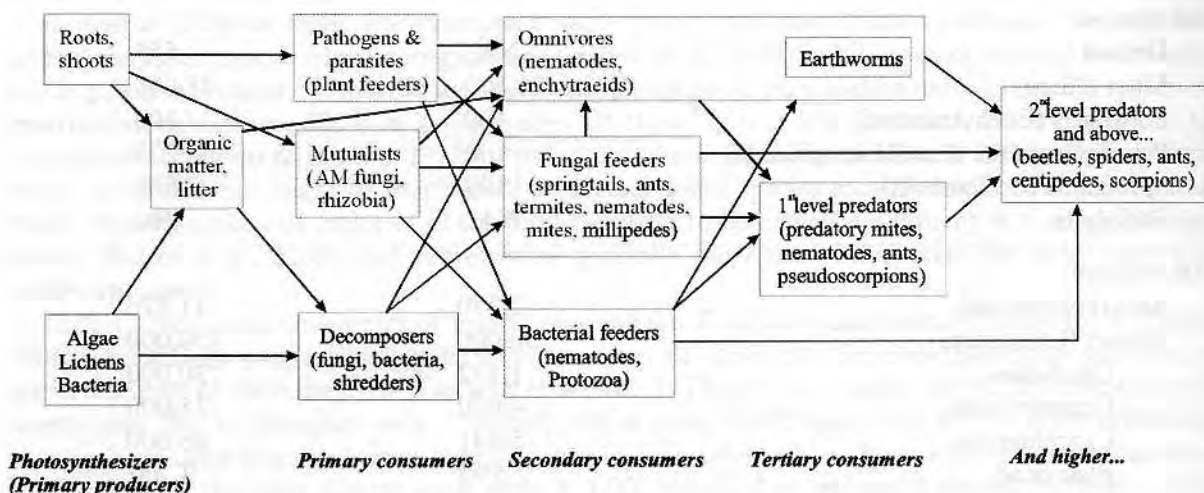


Figure 1 - Example of a complex belowground food web. Note particularly, the disjunct placement of earthworms and omnivores, which occupy several levels of the trophic food chain hierarchy, depending on the predominant food sources (modified after USDA-NRCS, 1998).

Important aspects of the structure, functioning and stability of the belowground part of ecosystems can be captured in a study of the dynamics of the soil food web (Neutel et al., 2002). However like most natural communities, soil communities are not simple chains of species. They are diverse, complex systems, where species often feed on more than one trophic level. With food-web models, ecologists have, over the years, attempted to capture the interconnected dynamics of populations in complex soil communities. These studies have provided insight into processes like overall energy flow and nutrient cycling of the soil system, and also the stability of communities and the environments in which they live (de Ruiter et al., 1994). However, considerable methodological challenges still need to be overcome in the wide scale application of food web models to (adequately) predict soil community interactions and their effects on soil function (Lavelle, 2000).

Soil animals perform various ecosystem services and key functions in both natural and agricultural ecosystems (Table 2). Biocontrol is achieved primarily through predation, although changes in the soil environment may also indirectly affect populations of pests, parasites and disease agents. Decomposition, nutrient cycling and carbon sequestration are influenced mainly by soil animal feeding habits and digestive processes. Soil formation and its physical properties such as porosity and aggregation, that affect aggregate stability, soil erodibility, gaseous exchanges, C sequestration, water runoff, infiltration and storage capacity, are affected primarily by soil animal bioturbation. Some soil animals, particularly snails, earthworms, ants, termites, beetle grubs and caterpillars are also important sources of food for indigenous human societies (Paoletti, 2005). Many insects that often spend a

critical stage of their life cycle within the soil or on its immediate surface are important plant pollinators. The combined physical, chemical and biological effects of soil animals on soil properties and processes and their feeding preferences (e.g., plant residues, decaying roots, living plant parts—both shoots and roots) can also significantly influence plant growth, both positively and/or negatively. Finally, soil animals and their biodiversity have also been widely used as bioindicators of soil and water quality (Paoletti, 1999; Römbke & Moltmann, 1996).

It has been estimated that the value of the ecosystem services provided each year by the soil biota worldwide might exceed 1.5 trillion US dollars (van der Putten, 2004; values estimated from Pimentel et al., 1997 and Costanza et al., 1997). The recycling of organic wastes is estimated to provide some 50% of the total benefits of soil biotic activity worldwide. Were it not for the decomposing/recycling activity of soil organisms, much of the world's land surface would be literally covered with organic debris, including the 38 billion metric tons of organic waste produced annually by humans worldwide (Pimentel et al., 1997).

Table 2 - Ecosystem services and soil functions performed by the different classes of soil animals (modified from Brown et al., 2006)

Ecosystem services/soil functions	Size classes of soil animals involved		
	Microfauna	Mesofauna	Macrofauna
Decomposition of organic matter and nutrient cycling	X	X	X
Gas exchanges and carbon sequestration	X	X	X
Maintenance of soil structure and regulation of soil hydrological processes			X
Plant growth control (positive and negative)	X	X	X
Pollination			X
Soil formation			X
Sources of food and medicines			X
Biological control of pests, parasites and diseases	X	X	X
Symbiotic and asymbiotic relationships with plants and their roots			X (ants)

The function of soil animals and their role in providing ecosystem services is therefore highly variable depending on their body size, feeding habits and where they live (e.g., litter, rhizosphere, soil pores or water films), although the latter (where) is mainly governed by the former two features (size and food sources) (see Table 3).

The ability to transport, ingest, or modify greatly the soil's physical structure is generally positively related to the body size of the organism, so that larger animals (earthworms, termites, and ants) are more able to modify soils than smaller ones. On the other hand, litter decomposition and soil chemical reactions are performed mainly by the smaller biota (mites, springtails, and particularly microorganisms), although some larger animals (the litter shredders) may be particularly important in preparing the materials for and enhancing the roles of the smaller biota. Thus a classification based on body size produces certain correlation between taxonomy and function.

- The *microfauna* are the smallest soil animals (less than 0.1 mm in diameter) and include the extremely abundant, ubiquitous, and diverse nematodes, protozoa, turbellarians, tardigrades, and rotifers, that generally live in soil water films and feed on microorganisms, plant roots, other microfauna, or sometimes larger organisms.
- The *mesofauna* (organisms generally ranging in size from 0.1 to 2.0 mm in diameter) include mainly microarthropods, such as pseudoscorpions, Protura, Diplura, springtails, mites, small myriapods (Paupoda and Symphyla) and potworms (enchytraeids). This group of organisms

has limited burrowing ability, generally lives in soil pores, and feeds on OM (some on plant roots), microbiota, or other invertebrates.

- The *macrofauna* (organisms generally greater than 1 cm in length or 2.0 mm in diameter and visible to the naked eye) include mainly soil invertebrates (e.g., ants, termites, millipedes, centipedes, earthworms, woodlice and other crustaceans, caterpillars, cicadas, ant-lions, beetle larvae and adults, fly larvae, earwigs, swordfishes, silverfishes, snails, spiders, harvestmen, scorpions, crickets, and cockroaches) that live and feed in or on the soil or surface litter and their components. Large insects such as bees and wasps occasionally burrow into the soil, but these are generally not considered soil organisms, even though their influence can sometimes be important.

Table 3 - Size, habitat and food preferences of some of the principal soil animals (modified from Susilo et al., 2004)

Soil animal	Size (length, mm)	Habitat			Food preferences ¹
		Litter	Soil	Rhizo- sphere	
Protozoa	0.002–0.2	X	X	X	Microbes
Nematodes	0.25–5.5	X	X	X	Microbes, fungi, plant and animal tissue (parasites), other nematodes (cannibals)
Mites	0.1–6	X	X		Microbes, detritus, nematodes, other microarthropods, other mites (cannibals)
Springtails	1–10	X	X		Microbes, detritus, fungi
Ants	1–30	X	X		Other arthropods & annelids (carnivores), fungi, plant parts (exudates, pollen), honey dew
Woodlice	5–20	X	Under rocks		Detritus, fungi, excrements, occasionally plants
Termites	0.5–20	X	X		Wood, litter, humus, fungi
Scorpions	12–180	X	Under rocks or logs		Other arthropods, lizards, mice and birds (carnivores); other scorpions (cannibals)
Spiders	0.5–90	X	X		Similar to scorpions
Centipedes	25–280	X	X		Similar to scorpions
Beetles	0.5–200	X	X		Plants, detritus, animal dung, carcasses, other arthropods & annelids (carnivores)
Millipedes	2–250	X	X		Detritus, excrements
Earthworms	20–2000	X	X		Detritus, soil OM, microbes, excrements

¹Microbes = Bacteria, yeasts and algae and protozoa. Fungi and nematodes considered separately.

It is important to note that there may be considerable overlap between some of these categories: for instance, some springtails, mites or enchytraeids may be larger than 2 mm, while some species of ants and beetles might be smaller than 1 cm in length and/or 2 mm in diameter. Therefore, Lavelle et al.'s (2003) definition is more appropriate: the animals are considered macrofauna when > 90% of its specimens are easily visible to the naked eye.

The food preferences of soil animals can be divided into five main classes: a) microbes; b) other animals (living or dead); c) plant residues in various stages of decomposition; d) fresh plant tissues (roots or shoots); and e) soil with its organic fraction (see Table 3).

- (a) Microbial grazers include mainly small invertebrates, especially protozoa, nematodes, mites and springtails that feed on microorganisms. They live freely in the soil pore spaces and water films. Predation of microorganisms, particularly by nematodes and Protozoa, plays an important role in regulating the biomass and activity of fungi and bacteria, and can lead to significant nutrient (especially N) release (Clarholm, 1985; Ingham et al., 1985).
- (b) Predatory soil animals such as ants, centipedes, beetles (e.g., carabids), spiders and other arachnids (scorpions, pseudo-scorpions, opilionids, predatory mites) prey mainly on decomposers and microbial grazers, but also on other predators including individuals of the same or closely related species. Their activity tends to be more concentrated in the litter layer than in the soil. When they prey on herbivores or parasites, they may play an important role in bio-control.
- (c) Decomposers, also called litter transformers or shredders are organisms that comminute and stimulate the decomposition of plant residues, and produce purely organic fecal pellets, that are less persistent than those produced by geophagous animals. Often, these animals also graze on the fungal biomass colonizing decomposing plant litter, or on feces produced by other animals (or themselves), once assimilable organic compounds have been released by microbial preconditioning. This group includes micro- and macro-arthropods, woodlice, termites, some species of slugs, snails, earthworms and enchytraeids (epigeic) that feed on and live in the litter layer. Also included in this category are anecic species (termites, earthworms, some species of scarab beetle larvae and leaf-cutter ants) that remove surface litter, burying it in the soil.
- (d) Herbivores, such as some species of beetles, stinkbugs, snails, slugs, nematodes and cicadas (among others) feed on above- and below-ground plant parts, affecting plant growth and primary productivity. Leaf-cutter ants among the Attini (esp. the genera *Atta* and *Acromyrmex*) that cultivate and feed on fungi growing on chewed fresh plant leaves, should also be considered herbivores.
- (e) Geophagous animals include primarily endogeic species (mainly earthworms and termites) that live in the soil and feed on OM and dead roots, ingesting and casting large quantities of mineral materials.

Through their feeding activities, especially geophagous and anecic animals move a considerable amount of topsoil and OM, redistributing it through the soil profile, simultaneously forming galleries and channels that alter soil structure and macroporosity. This bioturbation process also produces stable, resistant structures (mounds, chambers, casts) that may persist for long periods of time (from months to years) and which profoundly affect nutrient cycling and the environment for other organisms, including plants, invertebrates, and microbes (Lavelle et al., 1997; Brown et al., 2000). Therefore, these animals have been termed *ecosystem engineers* (Jones et al., 1994).

Many soil animals contribute to a specific soil process, operating at different scales of magnitude in space and time. Moreover, many animals contribute to several discrete processes. For example, nematodes feeding on bacteria and fungi at the micrometer scale may influence nitrogen mineralization (Ingham et al., 1985), and mites and springtails feeding on nematodes and fungi at the scale of a few millimeters may affect microbial community processes over several centimeters (Anderson, 1995). On the other hand, earthworms create tunnels or burrows several millimeters in diameter and centimeters in length that, in turn, may affect soil structure and hydrological processes over a scale of several meters. Finally, the wide-ranging activities associated with termite and ant colonies may affect soil physical and chemical processes over several hectares (Swift et al., 1996).

DETERMINANTS OF SOIL ANIMAL POPULATIONS IN AGROFORESTRY SYSTEMS

Soil animal populations are controlled by a suite of hierarchically organized determinants, operating at different scales of space and time (Lavelle, 1996) (Figure 2). At the top of the hierarchy, climate determines moisture and temperature regimes. These, in turn, help shape regional vegetation and soil parameters, which determine the nature and abundance of clay minerals and soil nutrient content (also partly determined by the parent bedrock). At this level, the landscape variability, topography and species diversity/pool of the vegetation are also important. Finally, at the plot level, quality and quantity of the organic materials and litter (above- and below-ground) produced, and the number (single or mixtures) and type of different plants present are of great significance in determining soil animal populations and their diversity. Finally, soil foodweb interactions and the community of soil animals, particularly of ecosystem engineers are, in turn, proximate determining factors for the diversity of subordinate animals within the community (Lavelle et al., 1997).

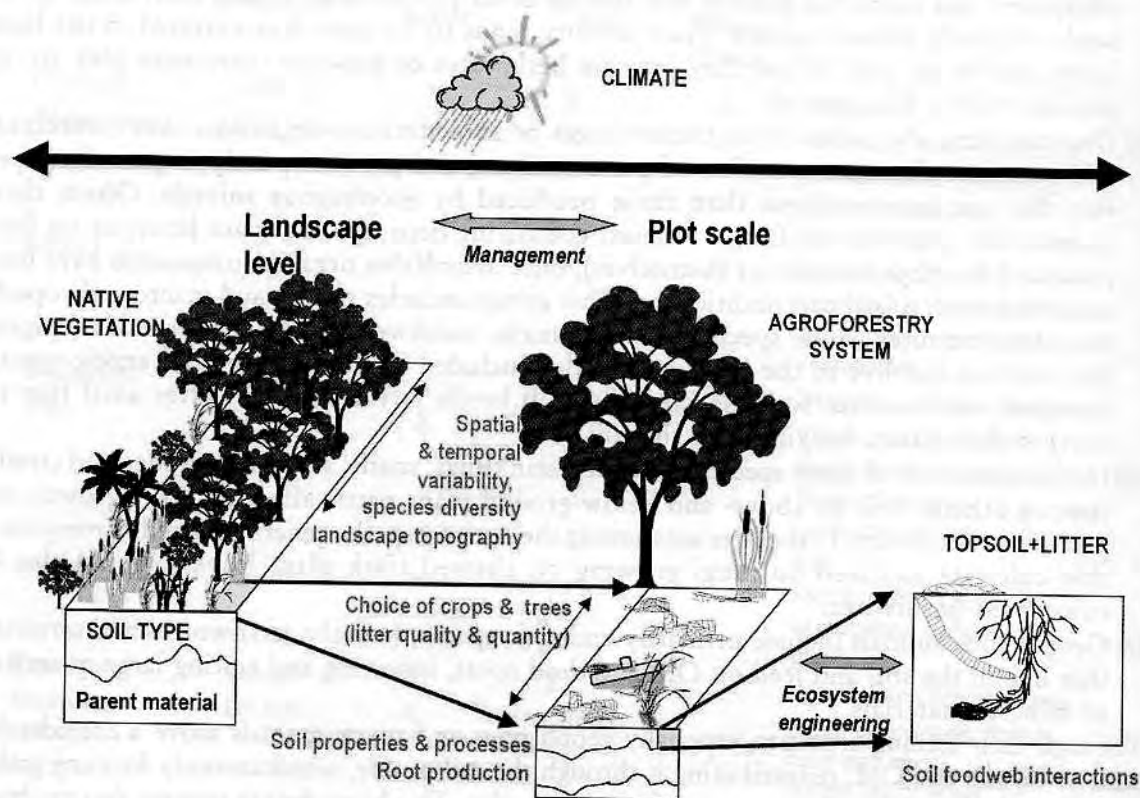


Figure 2 - Hierarchical determinants (sensu Lavelle, 1996) of soil animal communities in agroforestry systems (drawing by G. Brown).

Climatic vagaries such as the El Niño or La Niña oscillations, hurricanes and other natural disasters can cause significant shifts in the populations of some soil animals (particularly epigeic species that respond more to variations in litterfall), although the effects may be partly buffered in more stable ecosystems such as the Amazonian rainforest (Hanagarth et al., 2004). Seasonal variations in the population densities of soil animals are common, and determined by rainfall and temperature regimes; in general, populations reach their maxima in the rainy season, although this depends on the sampling depth. In the rainy season, animals are more concentrated at the soil surface, while in the dry season, they tend to migrate deeper into the soil (Bandeira & Harada, 1998).

Differences in vegetation and soil types within the same region are also important in determining

soil animal communities at a particular site (Barros et al., 2004; Bandeira & Harada, 1998). Ecosystems including soil surface protection and more abundant organic resources tend to have higher soil animal populations (Lavelle et al., 2001). For instance, the presence of trees (e.g., in AF systems) affects soil and litter microclimates, properties and processes and therefore the living conditions for soil animals. In this regard, the amount of shade, rooting patterns, and the quality and quantity of litter produced are main controlling factors (Tian et al., 1995; Vohland & Schroth, 1999; Martius et al., 2004b) (Figure 2). Therefore, the choice of trees and crops is critical in affecting the properties and spatio-temporal dynamics of litter production and quality, soil cover, shade and evapotranspiration in AF systems.

The provision of food, particularly the quality and quantity of the litter system is a key feature in the maintenance of diverse soil animal communities (Lavelle & Spain, 2001). Tree-based systems tend to favor epigeic animals such as detritivorous micro- and macro-arthropods, small litter-dwelling earthworms, predators such as spiders and ants, as well as some anecic invertebrates that live in the soil, but feed on surface litter (e.g., some termite and earthworm species). Vohland & Schroth (1999) and Lavelle et al. (2001; 2003) calculated that an active community of macroinvertebrates would need around 3-6 t ha⁻¹ yr⁻¹ of surface litter and 2 t ha⁻¹ yr⁻¹ of assimilable OM to sustain their activities. However, litter quality, feeding preferences, assimilation efficiencies, are highly variable among different soil animals, so these estimates require much further refining for different AF practices at different sites (Lavelle et al., 2003).

Human management decisions therefore play a crucial role in the determination of several factors important to the maintenance of active and beneficial soil animal community (and in the control of pest species). The absence of tillage in AF systems favors a particular soil animal community, as soil disturbance generally has a negative effect on many soil invertebrates (House & Parmelee, 1985). Other management decisions important at the plot scale in AF systems are the use (or not) of various agrochemical inputs (lime, fertilizers, herbicides, pesticides), organic amendments, cover crops and green manures, rotations, irrigation, fire and heavy machinery. The effect of these practices is variable, and can lead to both positive and/or negative effects on total soil animal populations or the density and diversity of particular species/groups (Figure 3). Anecic and epigeic species are particularly affected by practices that alter the litter system, such as burning, compaction, tillage (negative effects), cover crops, organic amendments and no tillage (positive effects). On the other hand, endogeic species appear to be more resistant and persistent to many agricultural practices.

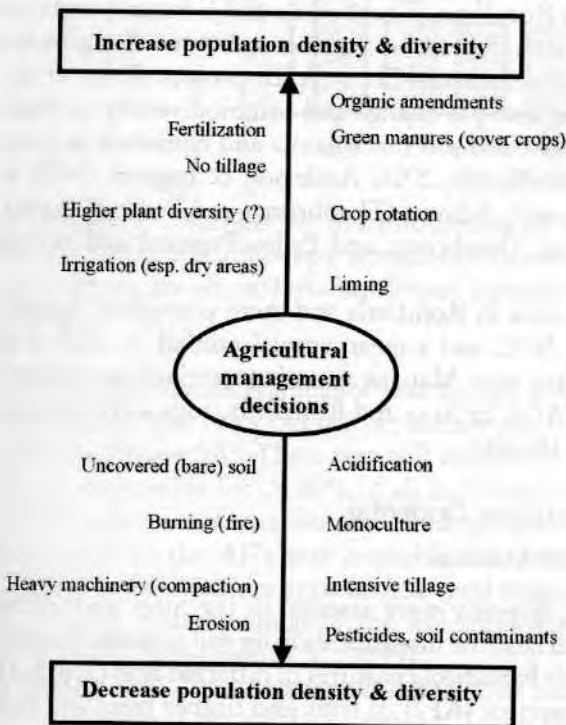


Figure 3 - The effect of different agricultural management practices on soil animal populations (density and diversity) (after Hendrix et al., 1990). The position of the various practices on the y-axis represents their hypothetical relative contribution (importance) to increasing or decreasing soil animal populations.

The currently available data on soil animal populations under AF systems worldwide show that these systems have rather specific fauna communities compared with conventional row-cropping systems (Lavelle et al., 2003; Barros et al., 2006), due to their intrinsic and particular management features (mentioned above). Most of the studies in Brazil have been performed in the Amazonian region, with only one study (to the authors' knowledge) focusing on the Atlantic forest biome in northeastern Brazil (Peneireiro, 1999). In the following section therefore, we discuss three case studies of the impact of AF systems on soil animal communities, taken from the Central and Western Amazonian regions. These studies are the result of several international projects, undertaken by Brazilian and foreign research institutions.

SOIL ANIMALS IN BRAZILIAN AGROFORESTRY SYSTEMS: THREE CASE STUDIES FROM CENTRAL AND WESTERN AMAZONIA

The sites for the first two case studies were located N of Manaus, at two separate Embrapa Amazônia Ocidental Research Stations: the first at the Distrito Agropecuário SUFRAMA, km 54 of the BR-174 (approximately 2°31'S, 60°01'W), and the second near the Agroforestry Research Station at km 29 of the Manaus-Itacoatiara road (approximately 3°08'S, 59°52'W). At the first site, meso- and macrofauna communities were evaluated in pastures of different ages, disturbed natural forest, fallows, agrosilvopastoral (ASP) and AF systems planted on abandoned pastures, as part of several projects involving the Institut de Recherche pour le Développement (IRD), the Instituto Nacional de Pesquisas da Amazônia (INPA) and Embrapa (further details below). At the second site, meso- and macrofauna communities were evaluated in disturbed natural forest, secondary forest, and an abandoned rubber plantation planted with various fruit and timber producing trees (further details below), as part of a collaborative project involving European (ECT, SMNK) and Brazilian (INPA, Embrapa) Institutions (under the SHIFT Program umbrella).

Soil animals at both sites near Manaus were sampled using a variety of methods: mesofauna were extracted from small soil cores and litter samples with Berlese funnels or a Kempson apparatus; macrofauna was extracted from large soil monoliths and large litter samples manually (TSBF; Anderson & Ingram, 1993) or from large cores (21 cm diam.) with Berlese; large anecic earthworms were extracted with 0.5% formalin, and microdriles (e.g., enchytraeids, tubificids) were wet extracted from small soil cores.

The third case study was undertaken at two sites in Rondônia (Theobroma and Ji-Paraná) and two in Acre (Pedro Peixoto and a nearby reforested site; RECA = Reflorestamento Econômico Consorciado Adensado), as part of the Alternatives-to-Slash-and-Burn (ASB) project (Palm et al., 2005), undertaken to investigate relationships between land-use change and soil biodiversity in Indonesia, Cameroon, Brazil and Peru. At the four Brazilian sites, soil macrofauna and nematode populations were evaluated using standard methods (Swift & Bignell, 2001; Anderson & Ingram, 1993) in disturbed forests (Theobroma, RECA and Pedro Peixoto), fallows (Theobroma and Pedro Peixoto), AF systems (Ji-Paraná and RECA), pastures (Ji-Paraná, Theobroma and Pedro Peixoto) and annual cropping systems (Theobroma and Pedro Peixoto).

The climate at both sites near Manaus and at the sites in Rondônia and Acre is tropical, humid, with a mean annual temperature between 24°C and 26°C and a mean annual rainfall > 2000 mm (type Am; Köppen classification). The soil at the sites near Manaus was characterized as a clayey "Latossolo Amarelo" (Brazil), or Xanthic Ferralsol (FAO). In Acre and Rondônia, soils were Xanthic Ferralsols (FAO) or Ultisols (USDA), depending on the site.

Case Study 1. Embrapa Amazônia Ocidental Research Station, 54 km N of Manaus

Soil macrofauna populations and morpho-species diversity were assessed in the litter and soil to evaluate the environmental impacts of deforestation and land-use intensification on soil animals. Samples were taken in the rainy season of 1995 in five *Brachiaria humidicola* pastures of different ages (3, 6, 8, 15 yr), two AF systems including low (AF1) or high-diversity (AF2) of fruit and timber trees and two

ASP systems with different level of external inputs (HI=high input; LI=low input), two fallows of different ages (10, 20 yr) and a slightly disturbed native forest fragment (Barros, 1999; Tapia-Coral et al. 1999; Luizão et al., 2001; Barros et al., 2001; 2003; 2004; 2006). Sampling was repeated again in rainy season of 1997 in the pasture with high density of *Pontoscolex corethrurus* earthworms (Barros et al., 2004), and litter macrofauna was re-sampled the same year in the AF/ASP systems and the 10 yr fallow (Tappia-Coral et al., 1999). The AF/ASP systems were installed over abandoned pastures of *B. humidicola*. AF1 and AF2 were both fruit-tree based systems, but AF1 was palm based and had 3 fruit trees and one forest tree (total 4 spp.), while AF2 had six fruit trees, a trailing vine-fruit (passion-fruit, *Passiflora edulis*), Brazil nut, and two timber trees (total 10 spp.). The HI ASP received mechanical tillage, fertilizers and lime, while the LI system was manually prepared and received only P-fertilizer (Barros et al., 2003). Three tree species were used, and the soil was covered with a grass pasture (*Brachiaria brizantha* in HI and *B. humidicola* in LI) and a fodder legume (*Desmodium ovalifolium*) (Tapia-Coral et al., 1999).

Morphospecies diversity of the sampled land use systems (Figure 4) was highest in the native forest (156 spp.), and lowest in the 20 yr old fallow (29 spp.) and in the pastures, where richness ranged from 26 (site with high density of *P. corethrurus*) to 48 spp. (old, degraded pasture) (Decaëns et al., 2004; Barros et al., 2004; 2006). The pastures also tended to have a higher number of invasive species, non-native to the forest (Barros, 1999). In the ASP systems, morphospecies richness was intermediate (around 60-65 spp.), but still much lower than in the native forest (Barros, 1999).

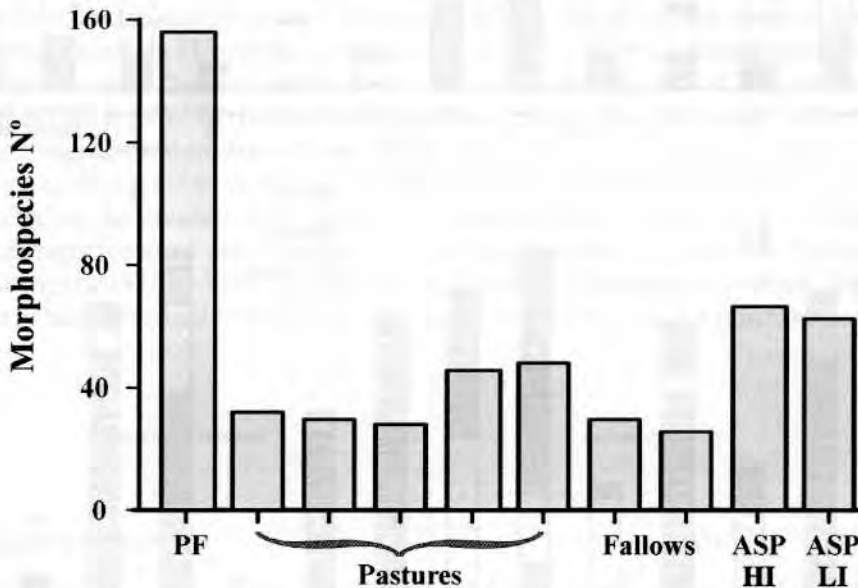


Figure 4 - Number of morphospecies of soil macrofauna in various land use systems at and surrounding the Embrapa Amazônia Ocidental Research Station near Manaus (Barros, 1999). PF=primary forest; ASPHI=high-input agrosilvopastoral system; ASPLI=low-input agrosilvopastoral system.

Soil macrofauna abundance was highest (over 10,000 indiv. m⁻²) in the low- and high-input ASP systems and the 10 yr old fallow, mainly due to the large number of termites and ants found in these systems (Figure 5A). These two soil animals predominated throughout the land use systems sampled, being responsible for > 80% of all individuals collected in all sites except the 15 yr pasture (that had the lowest macrofauna density of all sample sites). The high number of soil animals in the ASP's compared to the AF's was probably due to the faster growth and better soil cover of the forage legume and the pasture grass in ASP (and hence better food supply and soil microclimate conditions). In the AF systems much of the soil surface was bare, as the litter system had still not developed properly (Tapia-Coral et al., 1999).

Hence, soil litter arthropod populations sampled in 1997 (Tappia-Coral et al., 1999) were significantly higher in the AF (AF1 and AF2) than the ASP systems or the fallow. Abundance ranged from

20 indiv. m⁻² the fallow to around 29 indiv. m⁻² in the ASP's and 57-95 indiv. m⁻² in AF1 and AF2, respectively. Woodlice predominated, representing > 80% of the abundance and biomass in all sites, except the fallow (70% of total density). The higher numbers in the AF systems compared to the ASP in the present case may have been due to the negative effect of cattle grazing (and trampling) in ASP just before sampling as well as the lower quality and diversity of the litter produced in this system (Tapia-Coral et al., 1999).

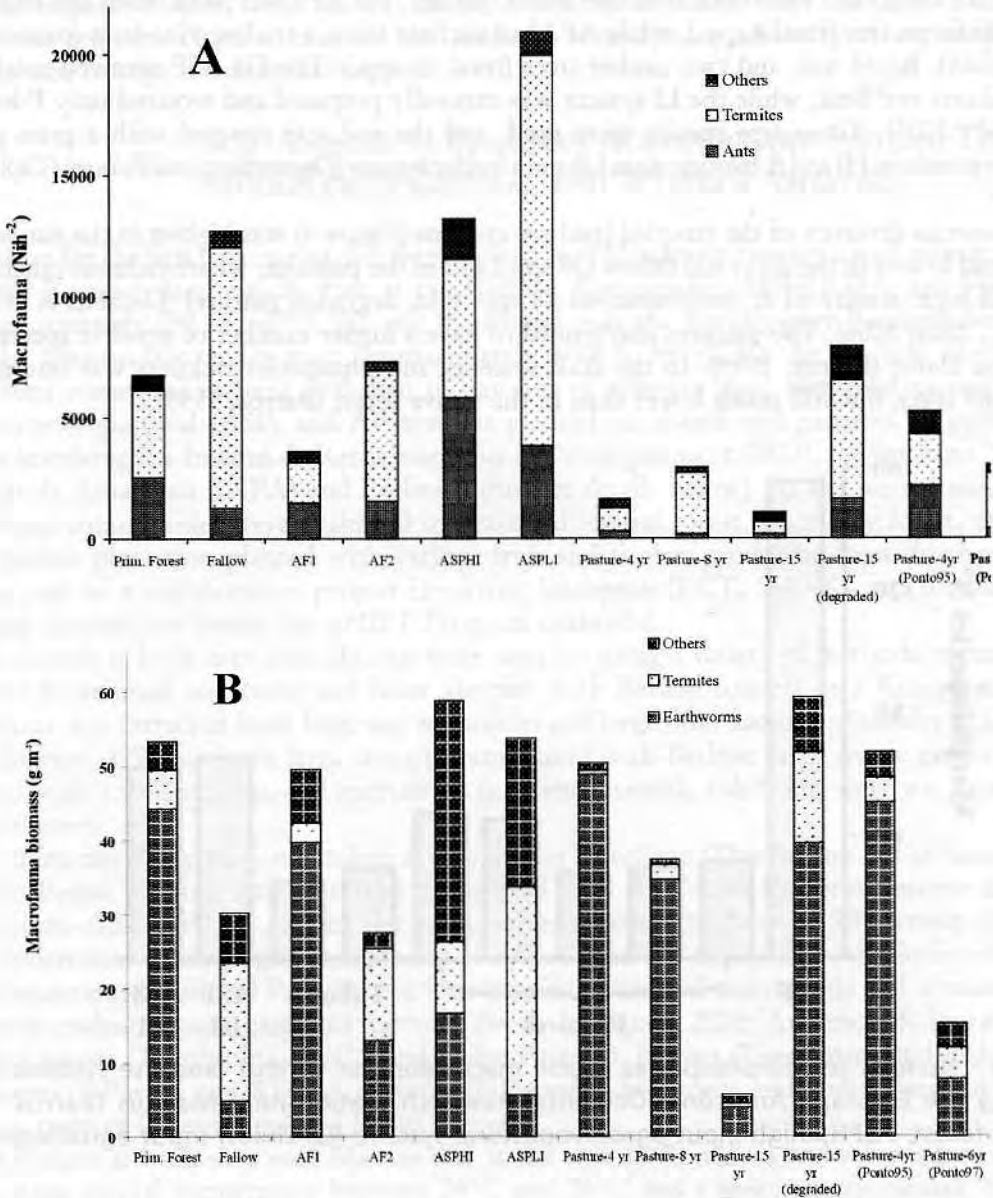


Figure 5 - Abundance of ants, termites and other soil+litter macrofauna (A) and biomass of earthworms, termites and other soil+litter macrofauna (B) in various land use systems at and surrounding the Embrapa Amazônia Ocidental Research Station near Manaus (Barros et al., 2003; 2004; 2006; Decaëns et al., 2004). AF1=low diversity and AF2=high-diversity agroforestry systems; ASPHI and ASPLI = high- and low-input agrosilvopastoral systems; Ponto95=pasture with abundant *P. corethrurus* sampled in 1995; Ponto97=the same pasture sampled in 1997. For further information see text.

On both sample dates, the low-diversity AF1 had fewer soil (Barros et al., 2003) and litter-dwelling (Tapia-Coral et al., 1999) animals than the high-diversity AF2 (Figure 5A), illustrating well the importance of diverse litter input for soil animal communities. Nevertheless, macrofauna biomass in AF1 was higher than in AF2, primarily because of the larger earthworm abundance (Figure 6) and biomass (Figure 5B). In AF1 earthworms were primarily poly-humic endogeics (i.e., geophages feed-

ing on soil rich in OM), living close to the soil surface (0-10 cm), while in AF2 they were oligo-humic species (i.e., geophages ingesting soil without particle selection), living deeper in the soil (> 10 cm). The earthworms may have benefited from the heart-of-palm (“palmito”) harvest in AF1, which left high-quality residues on the soil surface (Barros et al., 2003).

In the AF and ASP systems, significant effects of the presence of trees were observed on the soil and litter macrofauna. Tapia-Coral et al. (1999) found significantly higher macrofauna populations in cupuaçu (> 80 indiv. m⁻²) and peach palm litter (> 60 indiv. m⁻²) in AF1 and AF2 than in the litter of *D. ovalifolium* and *Brachiaria* spp. in ASP1 and ASP2 or the fallow (all < 20 indiv. m⁻²). In the ASP systems, Barros et al. (2003) observed a trend for higher soil animal abundance (density and biomass) under the trees compared with the *D. ovalifolium* and *Brachiaria* spp. pasture in between the tree rows. In AF1, the soil under peach palm (3107 indiv. m⁻²) had a significantly higher total fauna density than under cupuaçu (524 m⁻²), although total biomass in both systems was similar (25.6 and 24 g m⁻², respectively) (Barros et al., 2003; 2006). The difference was mainly in the number of termites under peach palm, and may be related to the faster root and shoot development and soil cover provided by these plants. In AF2, on the other hand, fauna biomass tended to be higher under cupuaçu (10 g m⁻²), than Brazil nut (7 g m⁻²), mahogany (5 g m⁻²) and passion fruit (4 g m⁻²) (Barros et al., 2003).

Comparing the different systems sampled in 1995, macrofauna biomass was highest (> 50 g m⁻²) in the native forest, both ASP systems (HI and LI), AF1, in the 4 yr pastures (with and without *P. corethrorurus*) and the 15 yr degraded pasture (Figure 5B). However, dominance of the various groups in each land use system was different; in the ASP systems, beetles, myriapods (especially millipedes) and isopods contributed significantly to total biomass, while in the remaining systems (except the fallow), earthworms predominated. However, in the native forest and the 4 yr pasture where *P. corethrorurus* had not yet invaded, the high biomass (44 and 49 g m⁻², respectively) was of large native anecic species, probably *Rhinodrilus priollii*. In the remaining pastures, most (if not all) of the earthworms found were *P. corethrorurus*, ranging in abundance from 136 to 403 indiv. m⁻² (Figure 6) and biomass of 3.9 (not-degraded, 15 yr) to 45.1 g m⁻² (4 yr with *P. corethrorurus*). Pasture degradation in the region appears to be intricately linked to the invasion of *P. corethrorurus* (and vice-versa), although the relationship of cause-effect is not straightforward and involves various mechanisms that require further study. For instance, comparing the 1995 and 1997 samples of the degraded *B. humidicola* pasture, density and biomass of *P. corethrorurus* had decreased from 390 to 136 indiv. m⁻² and 45.1 to 7.8 g m⁻², respectively.

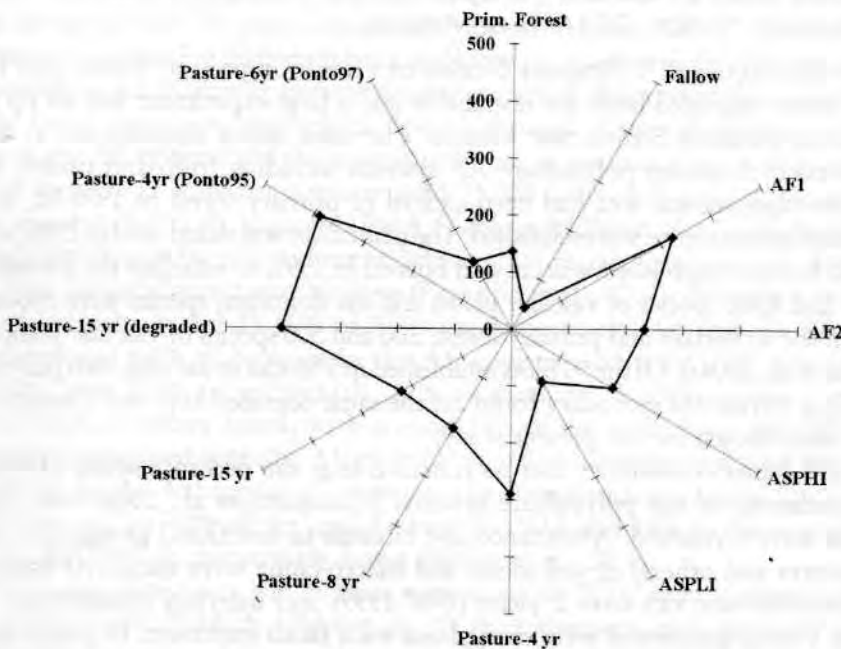


Figure 6 - Earthworm density (N° indiv. m⁻²) in various land use systems at and surrounding the Embrapa Amazônia Ocidental Research Station near Manaus (Barros et al., 2003; 2004; 2006; Decaëns et al., 2004). For meanings of abbreviations see Figure 5 legend.

The role of *P. corethrurus* and a diverse assemblage of soil organisms (other earthworm species, termites, millipedes, isopods, ants, etc.) in destroying and re-creating soil structure was evaluated in a 15 yr old degraded *B. humidicola* pasture and the native forest (Barros et al., 2004). Soil monoliths (25 x 25 cm square x 30 cm deep) were removed from the pasture, where a large and active population of *P. corethrurus* had been found previously, and placed in the native forest. Similar blocks were taken from the forest and placed in the pasture. After one year, the structure of the compacted pasture soil was completely restored to levels of those typical in native forest soils by the action of the diverse community of forest soil animals. Meanwhile the macroaggregate structure of the forest soil was completely destroyed by *P. corethrurus*, reaching compaction and porosity levels similar to those of the degraded pasture.

The research performed in the above studies highlights:

- The importance of a diverse assemblage of plants, including trees and cover crops, in enhancing soil animal populations;
- The major role of a diverse assemblage of macro-invertebrates in the maintenance of soil structure (especially in these kaolinitic soils);
- The role of exotic, invasive species on ecosystem properties and processes;
- The problems associated with management practices that are not well adapted to the environment (i.e., extensive pastures on problem soils after deforestation).

Further work on these topics is necessary, in particular to assess the functional integrity over time, of the community of soil animals in AF and ASP systems, and how they can be managed for maximum benefits and to prevent “biodiversity accidents” such as those described above (Lavelle, 2000). In this regard, connectivity in the landscape for more rapid re-colonization of animals (and plants) in soils recovering from various agricultural (or other) uses, is particularly important. At the study sites near Manaus, lack of continuity (and distance) of the fallows to the native forest led to a low morphospecies richness, even after 20 yr. Apparently, a large proportion of the animals in species-rich soil communities, such as those found in Brazilian Amazonia, are very sensitive to disturbance, particularly deforestation and land use intensification. Many forest species are rare and endemic, and disappear together with the forest. With time, invasive and/or exotic species may replace the native species almost irreversibly, leading to considerable shifts in the potential contribution of the soil animal community to soil function and ecosystem sustainability.

Case Study 2. The SHIFT Program at the Embrapa Amazônia Ocidental Research Station, 30 km N of Manaus

As part of the German-Brazilian SHIFT Program (Studies of Human Impact on Forests and Floodplains in the Tropics), to restore degraded lands for sustainable use, a large experiment was set up at the Embrapa Amazônia Ocidental Research Station near Manaus. The main aim of this trial was to test the ecological viability and impact of various polyculture AF systems including fruit- and timber wood-producing tree species. The experimental area had been cleared of primary forest in 1979-80, when a rubber tree (*Hevea brasiliensis*) monoculture was established. The plantation was abandoned in 1984, and the secondary growth that had become established was cut and burned in 1992, to establish the present trial. The polyculture AF plots had 30-60 species of vascular plants and the dominant species were rubber and three timber tree species; in the secondary and primary forest, 200 and 500 species of vascular plants were found, respectively (Martius et al., 2004a). Of the 90 plots established in 5 blocks in the trial, two polyculture AF plots (POA and POC), a 13-year-old secondary forest on the same degraded land and a nearby little-disturbed primary forest, were chosen for the present study.

The structure of the soil fauna community and its function (e.g. the decomposition of OM), in relation to the abiotic conditions of the polyculture systems (Hanagarth et al., 2004) were studied when the two AF systems were 5-year-old. Abundance and biomass of functional groups (i.e., predators, decomposers, herbivores and others) of soil meso- and macro-fauna were measured using standard methods at three-monthly-intervals over 2 years (1997-1999) and litterbag experiments (filled with a “standard litter” of *Vismia guianensis*) were carried out with fauna exclusion. In most cases the fauna was sorted to higher taxa representing functional groups. Only few taxa were classified to genera, morphospecies or species.

Soil animal diversity tended to be lower in the AF systems compared to the primary forest; this

was the case for ants (Garcia et al., 2000; 2002; Verhaagh, 2005), termites (Martius et al., 2000) and beetles (Hanagarth & Brändle, 2001) (Table 4). Some taxa common in the forest were never found in the AF plots, like Palpigradi and scorpions (Arachnida), most mygalomorph spider species and some ant and termite genera. Nine earthworm species of the family Glossoscolecidae were found (Römbke et al., 1999), and no differences occurred between treatments (the same was true also for enchytraeids). The most conspicuous worms (up to > 1 m long) were *R. priollii* and *R. contortus*, both endemic to the Manaus area. *P. corethrurus* was found in all plots except in the primary forest. The same pattern was observed for five non-autochthonous millipede species, originating from Asia, (*Trigoniulus corallinus*, *Rhinotus purpureus*, *Asiomorpha coarctata*), or introduced by humans from other neotropical regions (*Epitrigoniulus cruentatus*, *Xenobolus carnifex*). Strong shifts in species composition and dominance were also found for beetles and woodlice. In the primary forest plot Philosciidae dominated, whereas the genus *Circoniscus* (Scleropactidae) was rare. This scleropactid woodlouse strongly dominated in the AF plots and is abundant in many other disturbed habitats, probably being one of the most important decomposer species in anthropogenic landscapes.

Table 4 - Biodiversity of selected groups of soil invertebrates in the AF plots (POA & POC), secondary and primary forest at the Embrapa Amazônia Ocidental Research Station near Manaus (results from the SHIFT project) (Garcia et al., 2000; Martius et al., 2000; Römbke, 2000; Römbke & Garcia, 2000; Hanagarth & Brändle, 2001; Höfer et al., 2001). The taxonomic level is indicated for each animal.

Soil animals	AF plot POA	AF plot POC	Secondary forest	Primary forest
Beetles (Families)	24	26	28	36
Ants (Genera)	28	28	35	43
Termites (Genera)	8	8	9	13
Millipedes (Families)	13	13	13	12
Earthworms (Species)	5	8	8	7
Enchytraeids (Species)	19	18	17	18

The macrofauna community at the research sites showed, therefore, a substitution of taxa and functional groups in the AF plots, compared to primary forest. Here, social insects (mainly termites) and earthworms occurred in high abundance and biomass, whereas in the AF system other decomposer groups like woodlice and millipedes became dominant. Strong shifts were also observed within the groups, e.g. on the family, genus or species level. Species richness of several predator and decomposer groups was lower in the AF systems and the secondary forest, as compared to the primary forest.

Soil mesofauna abundance was around 25,000 indiv. m⁻² and dry biomass around 650 mg m⁻² in three sites but distinctly higher in POA (Table 5; Höfer et al., 2001). In all sites the mesofauna was strongly dominated by oribatid mites, which accounted for, on average, 42-59% of all individuals and 58-71% of the total mesofauna biomass (Franklin et al., 2001). Predatory mites were also abundant (7-22% of individuals and 13-16% of biomass, respectively). Springtails accounted for around 5% of abundance and 5-8% of biomass in the AF systems, and their total contribution was greater in the primary forest (13% of individuals, 11% of biomass). Enchytraeidae were more abundant in the primary and secondary forest, with around 24% of the individuals and 12% of total biomass in these sites, when compared with the AF plots (around 16% of individuals and 7% of biomass, respectively). In relation to the arthropod macrofauna, the mesofauna accounted for 83-90% of the total faunal abundance and for 40% of the total biomass in POA and 33% in the secondary forest, but only 22% in POC and 18% in the primary forest (Höfer et al., 2001).

Macrofauna abundance and biomass were lower in POA and the secondary forest than in POC and the primary forest (Table 5; Höfer et al., 2001). Arthropods were generally more abundant in samples taken at the beginning of the rainy season and less abundant in June, at the beginning of the dry season. Predatory arthropods accounted for 46-53% of the whole arthropod macrofauna while decomposers ranged from 35-43% of the total. The most abundant predators in all sites were pseudoscorpions, Diplura, ants and spiders. Ants were most abundant in primary forest (16%), but much less represented in the AF

plots (3-6%). In the AF system millipedes dominated the decomposer guild (around 8% of all arthropods), whereas termites were the most abundant decomposers in the primary forest (24%).

Decomposer biomass differed strongly between the AF plots and the primary forest. In the AF systems, termites had a much lower biomass (Table 5), accounting for only for 8-13% of the total, while in both the primary and secondary forest, their contribution was over 20%. By contrast, millipedes and woodlice dominated strongly in the AF plots (millipedes, 12-18%; woodlice, 17-43 %), but not in the forest (millipedes, 8%; woodlice 11%). The biomass of woodlice was especially high in POC (Table 5), due to the high abundance of large individuals of *Circoniscus* sp., while their biomass was very low in the secondary forest. Earthworms showed rather low and highly variable abundance. The occurrence of very large earthworms led to high biomass values in the primary forest and very high variance in the AF plots, where these large earthworms occurred only occasionally (Table 5). Median biomass of earthworms reached 50% of the biomass of all decomposers in the primary forest, 28% in the secondary forest and 22% in POC, but only 3% in POA (Höfer et al., 2001).

Table 5 - Abundance (indiv. m⁻²) and dry biomass (mg m⁻²) of meso- and macrofauna (including the most important decomposer groups) in the AF plots (POA & POC), secondary and primary forest at the Embrapa Amazônia Ocidental Research Station near Manaus (results from the SHIFT project) (Höfer et al., 2001). Shown are means over 8 sampling events and standard deviations (sd) in % of the mean.

Size class	AF plot POA		AF plot POC		Secondary forest		Primary forest	
Animal								
Abundance	mean	sd	mean	sd	mean	sd	mean	sd
Mesofauna	32.890	62%	25.033	28%	24.703	40%	24.450	21%
Macrofauna	3.745	37%	4.266	41%	3.769	31%	4.866	31%
Biomass								
Mesofauna	937	69%	655	29%	679	41%	609	21%
Macrofauna	1.368	28%	2.332	48%	1.391	62%	2.713	38%
Termites	109	111%	304	133%	305	44%	654	24%
Millipedes	247	69%	276	59%	107	72%	220	85%
Woodlice	227	77%	994	81%	34	67%	287	66%
Earthworms	397	205%	963	123%	259	80%	1.541	68%

Decomposition rates measured in each of the land use systems were strongly determined by the macrofauna (rates were much lower in litterbags when macrofauna were excluded). Their role appeared to be particularly important in the primary forest where large earthworms, termites and ants dominated the soil fauna. In the AF plots, where litter originated predominantly from non-planted, adventitious vegetation, an abundant decomposer fauna was also found, but dominated by other groups or species. Decomposition rates in the AF plots were about 60% lower, and soil biological variables like OM, nitrogen-content and water holding capacity were slightly lower than in the primary forest (Martius et al., 2004a) (Figure 7). However, no accumulation of litter was observed.

Furthermore, macrofauna biomass (i.e., arthropods and earthworms) in the plots was positively correlated with decomposition rates and negatively with litter stocks. Conversely, mesofauna biomass was not correlated with decomposition rates and litter stocks, and exclusion of mesofauna in litterbags did not result in further decrease of decomposition rates (Franklin et al., 2004). These functional groups seem to play another role in decomposition than the macro-decomposers (Franklin & Morais, 2006). The latter accelerate physical and chemical decay by fragmenting large organic particles like leaves and wood, while the importance of the mesofauna is mostly due to their grazing effect, exerting control on microbial populations.

Soil- and litter-inhabiting animals depend on the quality and quantity of litter, and on microclimatic conditions in their specific habitats. On the other hand, the feeding and casting activities of decomposer fauna and ecosystem engineers also influences litter quantity and quality and the turn-

over of soil OM. Thus, some of the differences in the soil animal communities and decomposition rates between primary forest and AF sites were explainable by the different abiotic conditions of these habitats (Martius et al., 2004b). The reflection of these parameters was particularly evident in POA, probably due to more extreme microclimatic conditions (i.e., surface temperatures) in this plot. Höfer et al. (2001) also hypothesized that the impoverished macrofauna populations in the secondary forest plot was likely responsible for the observed litter accumulation. These results highlight the importance of soil cover and shade for soil animals and decomposition processes and corroborate the hypothesis that tolerance of secondary vegetation in plantations, although creating competition with the culture plants, has positive effects on microclimate and the litter layer and, consequently, on soil fauna, soil structure and nutrient recycling. These effects seem especially important for low input systems on the extremely poor soils in Amazonia.

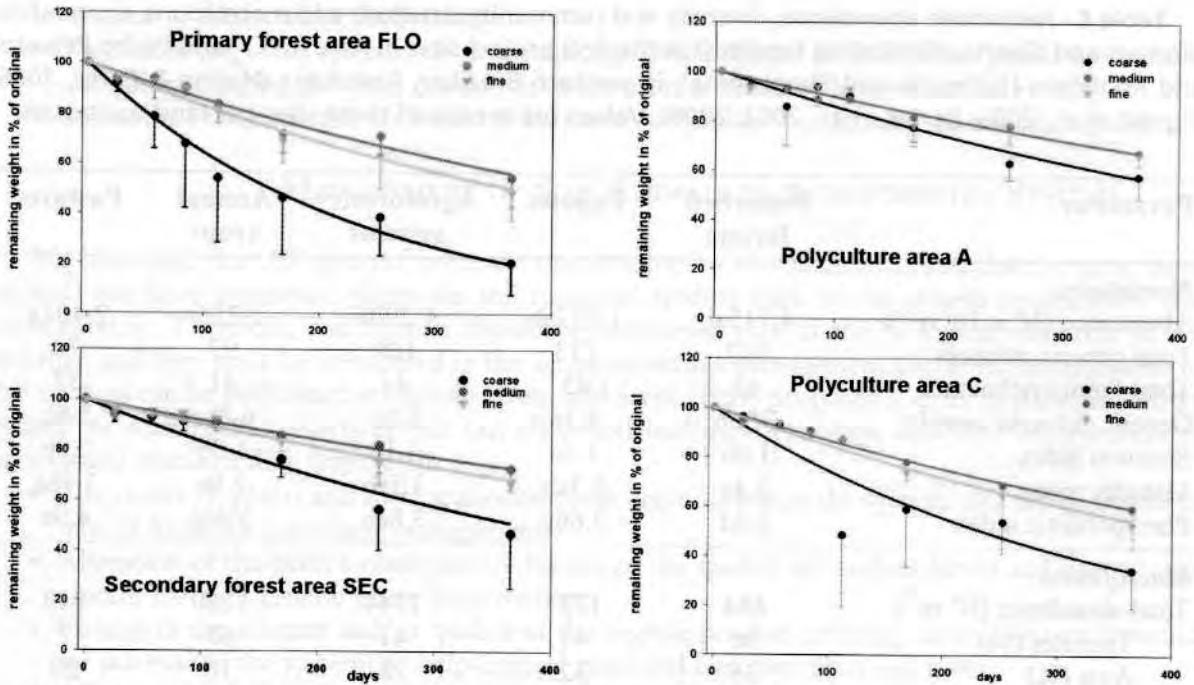


Figure 7 - Decomposition (mass loss) in the AF plots (Polyculture area A and C), secondary and primary forest at the Embrapa Amazônia Ocidental Research Station near Manaus (results from the SHIFT project) (Adapted from Höfer & Luizão, 2000).

In summary, the present experiments found that:

- In terms of species number, the soil fauna in the AF systems often resembles the fauna of the nearby primary forest, but the species composition and dominance spectra are different;
- Nearly no differences in abundance but differences in biomass occurred when primary rain forest was converted to the AF plantations;
- Despite structural differences (i.e., species and dominance spectra), functional efficiency (i.e., concerning litter decomposition) of the soil fauna was similar in all sites, although decomposition rates were lower in the AF plots than in the native forest.

Case Study 3. The Alternatives to Slash and Burn Project Sites (Rondônia and Acre)

The nematodes, recovered from the five land use systems sampled in Rondônia and Acre, were distributed in 159 genera and 59 families (Bignell et al., 2005; Huang & Cares, 2006). At the

genus level, richness was lowest in the pastures (79 gen.), intermediate in the annual crops (97 gen.) and highest in the forests, fallows and AF systems (102, 113 and 108 gen., respectively) (Table 6). Shannon index was also higher in fallows and AF than the other systems (including the forest).

Nematode abundance was significantly greater in the pasture than the cropping and AF systems. Plant parasites were the dominant trophic group, representing 30-75% of the total abundance (depending on the system), followed by the bacterivores (11-24% of total). In the AF systems, forests and pastures, there was a high abundance of plant parasites and low density of bacterivores, while in the fallow plots, the opposite occurred (Huang & Cares, 2006). Plant parasitic index was highest in pastures, followed by the AF systems, intermediate in the fallows and lowest in the annual crops and forests (Table 6).

Table 6 - Nematode abundance, diversity and community structure and macrofauna abundance, biomass and diversity (including termites) at the ASB project sites in Acre (RECA and Pedro Peixoto) and Rondônia (Ji-Paraná and Theobroma), in western Brazilian Amazonia (Huang & Cares, 2006; Bignell et al., 2005; Barros et al., 2002; 2006). Values are means of three sites per land use system

Parameter	Disturbed forests	Fallows	Agroforestry systems	Annual crops	Pastures
<i>Nematodes</i>					
Abundance (N° x 10 ³ m ⁻³)	1,715ab	1,597ab	1,290b	1,226b	2,401a
Total generic richness	102	113	108	97	79
Total family richness	42	45	44	41	37
Generic richness sample ⁻¹	7.3ab	8.1a	8.2a	6.8bc	5.8c
Shannon index	1.0b	1.2a	1.1a	1.0b	0.9b
Maturity index	3.4a	3.3ab	3.3ab	2.9c	3.1bc
Plant parasitic index	3.2d	3.6bc	3.8ab	3.4cd	4.0a
<i>Macrofauna</i>					
Total abundance (N° m ⁻²)	884	1737	1744	1760	840
Termites (%)	30	41	41	68	7
Ants (%)	36	32	38	10	20
Coleoptera (%)	13	5	4	7	29
Earthworms (%)	5	5	5	6	32
Total biomass (g m ⁻²)	10.2	9.2	9.5	9.3	56.2
Earthworms (%)	35	14	56	33	63
Myriapoda (%)	15	42	17	18	5
Coleoptera (%)	27	13	7	8	26
Termites (%)	4	13	6	24	<1
Group richness	13	15	12	14	10
Shannon index	2.2	2.1	1.9	1.6	1.7
Termite genera (N°)	10	7	9	4	2

The Maturity Index showed distinct values in tree-based systems (fallow, AF, forest) than the annual crops and pastures. This index measures the balance between colonizer nematodes (species with and high reproduction rates and tolerance to disturbance) and persistent species (with long life-cycles and low reproduction rates). Therefore, the presence of trees, such as in AF systems, appears to favor a more persistent nematode fauna, typical of more protected, stable environments, while cropping systems and pastures favor more rapid nematode community turnover, with dominance of species more tolerant to disturbance.

Similar to the nematodes, termite genera richness and Shannon index were higher in the tree-based systems (7-10 gen.) than the cropping and pasture systems (4 and 2 gen., respectively) (Table 6). At the

level of macrofauna orders, however, this distinction was not maintained. Macrofauna abundance was similar in fallows, AF and crop systems (around 1750 indiv. m⁻²) and higher than in forests and pastures (840-880 indiv. m⁻²). Total biomass was higher in the pastures (56 g m⁻²) than the remaining land use systems (9.2-10.2 g m⁻²). Lowest and highest macrofauna abundance observed over all the sample sites was 195 indiv. m⁻² (forest, Pedro Peixoto) and 2899 indiv. m⁻² (annual crop, Theobroma), respectively. Lowest and highest overall biomass was 2.8 g m⁻² (fallow, Pedro Peixoto) to 151 g m⁻² (pasture, Ji-Paraná), respectively.

As observed in the Manaus area, ants and termites dominated the abundance of most sites, together representing 63-79% of the total, except in the pastures (27% of total), where earthworms and mainly rhizophagous (pest) beetles predominated (32% and 29% of total, respectively) (Table 6). In terms of biomass, earthworms predominated (especially in the pastures), except in the fallows (where millipedes predominated), as had also been observed previously in Manaus.

In summary, these results show that:

- Tree-based (e.g., AF) systems can maintain higher soil animal diversity than pastures or annual cropping systems, and their communities are more similar to those of native forests;
- Soil animal communities are sensitive indicators of land-use system change and management.

MANAGEMENT OF SOIL ANIMALS IN AGROFORESTRY SYSTEMS

We have seen that AF systems influence the community of soil animals and that, in turn, these animals can have important effects on soil function, feeding back to the system productivity and sustainability. Therefore, soil animals should be considered part of the biological resources of AF systems, and they must be considered in the agroecosystem's management decisions. Management of AF systems can be performed at various levels, and Swift (1999) proposed a series of potential "entry points" or management practices that can affect soil biological processes and their contribution to agricultural sustainability (Figure 8):

- The choice of plants and their spatio-temporal organization in the system, and the inclusion or not of livestock (and their management);
- Alteration of the plant's resistance to disease, or the quality of residues (roots and shoots) produced, through genetic plant improvement;
- Change in the amount and/or quality of the organic residues entering the soil system (external or internal to the system) to help control pests and feed beneficial soil biota;
- Minimum soil disturbance and use of pesticides, irrigation, and fertilizers (when and if necessary);
- Use of biological control (pests and diseases) practices;
- Inoculation of beneficial soil organisms (disease antagonists, microsymbionts, rhizobacteria, and earthworms) for disease control and soil fertility improvement.

These entry points can influence positively and/or negatively soil animal populations directly and/or indirectly. Greatest benefits to soil animal populations (activity and diversity), particularly over the long term, are likely to come from the proper choice of crops and trees and their distribution in space and time in the AF system, the enhancement of natural pest and disease resistance of the chosen plants, improvement in the quality of residues produced, and management of OM and other external inputs (e.g., fertilizers) into the system. Minimum tillage and maintenance of crop residue cover on the soil surface also benefit belowground food webs and processes compared with conventionally cultivated soils (House & Parmelee, 1985; Brown et al., 2002b). The adoption of all these practices should help increase food quality and quality for the soil community and create a more suitable environment for their activities. However, further research is needed, particularly to optimize the supply of organic resources (and in particular, their quality, including mixtures of different litter types) in different AF practices under various soil and climate conditions.

The direct management of soil animal communities, for example the inoculation of earthworms (see below) or the use of biocontrol practices to control diseases and pests (as an alternative to synthetic pesticide use), is generally costly and difficult. Biocontrol techniques are already used widely by farmers and land managers in some countries and for some crops. Nevertheless, they continue to

be underutilized in many less developed countries, particularly by resource-poor farmers, when there is considerable cost involved or when the biocontrol agent is not readily available. Furthermore, biocontrol has not been developed for all major crops and trees of economic significance to developing world farmers. The potential benefits of the use of this technique can be high, and the relevant institutions and governments responsible for agricultural development should promote both research and mainstreaming of available biocontrol agents and practices.

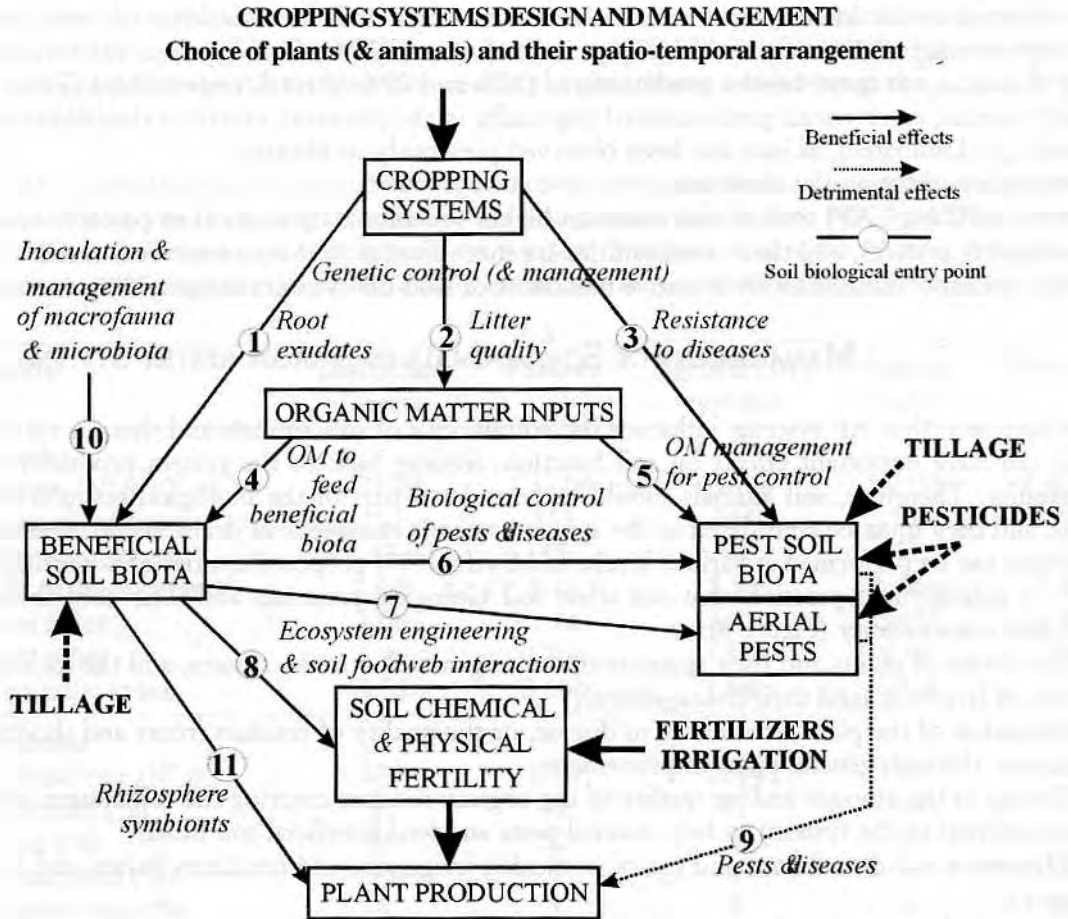


Figure 8 - The potential entry points for biological management of beneficial and pest soil organisms, cropping systems, OM inputs and soil fertility, affecting plant production (Adapted from Swift, 1999; modified from Susilo et al., 2004). OM=organic matter.

Inoculation of beneficial soil animals such as earthworms has been successful under some circumstances (Senapati et al., 1999), but for the meantime still depends on the availability of abundant and cheap human labor (to produce and disseminate the earthworms in the field). A major future challenge to overcome is the development of automated reproduction systems and inoculating machinery. Furthermore, research must show that the inoculated species is strictly beneficial and does not cause any externalities. Native species should be given preference, as exotics have been known to cause problems to soils, plants and other animal species in various parts of the world (Hendrix et al., 2006).

CONCLUSIONS AND FUTURE RESEARCH PRIORITIES

AF systems are a promising alternative to the intensive monoculture-based systems that have been promoted and adopted throughout the world since the green revolution. These systems optimize the ecological interactions and synergies between biological components of the ecosystem and the bio-

logical efficiency of soil processes in order to maintain soil fertility, productivity and crop protection (Swift, 1999).

Diversification, and especially the incorporation of trees (of several species) into agricultural production systems, appears to be a major driving force in determining soil animal communities and soil processes, and can also play an important role in ensuring production in the face of various climatic and other disturbances (e.g., pest and/or disease outbreaks). However, further research is necessary to properly assess these phenomena for a variety of agroecosystems, including AF systems.

Most of the research on soil animal communities in Brazilian AF systems has been done only in Amazonia. Efforts should be made to widen the present knowledge base on soil animals and soil processes in AF and other agroecosystems throughout Brazil, over a wide range of climate, soil and vegetation types. These will help reveal the particular conditions that promote soil biodiversity, ecosystem function and sustainability. Measurements should preferably integrate the spatial structure of the AF production systems at scales from the landscape to the farming system and plot, so that all aspects of the system are included and so that the practical aspects of the results can be scaled-up or down, as needed.

Brazil is host to a large part of the world's biodiversity (Lewinsohn & Prado, 2005). However, many species of the soil biota must still be discovered and described, and this is limited by the few specialists working in Brazil. Mainstreaming and facilitation of taxonomy, as well as training and research on the biology and life history of many groups and species of soil fauna must be prioritized if we are to reach an adequate understanding of soil biodiversity and its role in natural and agricultural ecosystems of Brazil.

Finally, soil animals are part of the biological resources that need to be managed in AF systems. They can be used as indicators of the health of the system and they play an important part in maintaining its fertility and productivity. A diverse community of soil animals may help reduce pest outbreaks (Lavelle et al., 2004), and their activity creates and maintains soil structure (Barros et al., 2004), regulates decomposition and mineralization processes and can influence the long-term turnover and protection of OM (Lavelle et al., 2003). Proper management practices, in particular those that preserve and enhance the litter layer (quantity and quality), protect the soil's physical integrity, minimize the use of external synthetic inputs (especially pesticides), and enhance soil organic resources will be the most interesting to promote soil animal activities and their beneficial role in AF soils.

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