Native earthworm communities, soil processes and sustainability of Colombian savannas[1]

Loss of beneficial soil organisms and subsequent depletion of environmental services and ecosystem function

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Agricultural context of Neotropical savannas

Tropical savannas cover 43% of the plains of Latin America, with an area of 243×10^6 ha. They are traditionally used for extensive cattle ranching of low productivity (Rippstein et al. 1996; Vera and Seré 1985). Common agroecosystems range from pure grass or legume/grass-based improved pastures, to high input annual crops (Thomas et al. 1995). The substitution of the native savanna by introduced grasses from Africa has been a widely accepted practice in the Colombian "Llanos" during the last 20 years. As a result agricultural production has increased rapidly but the long-term sustainability of these agroecosystems is limited. Such an evolution has important economical implications, and still scarce knowledge exists about biological processes involved in these land use changes and how these can alter fundamental ecosystem processes and services.

This case study is a brief compilation of some results obtained from a more detailed and comprehensive study undertaken during several years (1993-1999) at the "Centro Nacional de Investigaciones" Carimagua (CIAT-CORPOICA agreement), in the well-drained isohyperthermic savannas of the Eastern Plains of Colombia (4° 37' N and 71° 19' W, 175 metres altitude). The climate is subhumid tropical with a four month dry period from December to March and an average yearly rainfall and temperature of 2280 mm and 26°C, respectively. Vegetation is characterised by open herbaceous savannas with scattered trees and bushes in the uplands ("altos") and gallery forests and palm trees ("morichales") in the low-lying savannas ("bajos"). Soils at the study site are Oxisols (Tropeptic Haplustox Isohyperthermic) in the uplands and Ultisols (Ultic Aeric Plintaquox) in the lowlands (USDA). These soils are characterized by their acidity (pH 4.5, water), a high Al saturation (> 80%) and low concentrations of exchangeable Ca, Mg and K.

Of the innumerable life forms that inhabit soils only a small number of macroinvertebrates (earthworms, termites and ants) are capable to plow soil and produce a large variety of organo-

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[1] Case study prepared by J.J. Jiménez (AGLL consultant) and adapted from different articles published by J.J. Jiménez and T. Decaëns

mineral structures (biogenic structures) with important ecological implications on agricultural systems. These organisms are known as "ecosystem engineers" (Stork and Eggleton 1992; Jones et al. 1994) of the soil and their structures have been described as "biogenic structures" (Anderson 1995; Lavelle 1997). Ecosystem engineers actively regulate the activity of soil microorganisms in the organo-mineral structures that they produce (e.g. earthworm casts, termite mounds or ant nests) and may have important effects on soil aggregation and the regulation of organic matter dynamics.

Diversity of biogenic structures created by soil macroinvertebrates

In the savannas of Carimagua a non-exhaustive list of 14 ecosystem engineers are capable of producing biogenic structures in the soil surface (Decaëns et al. 2001; plate 1).

Plate 1. Diversity of biogenic structures produced by termites in the savannas of Carimagua (Eastern Plains of Colombia). Black and white plates (Pictures 1, 3, 5, and 6 from left to right (top-bottom) from Decaëns; pictures 2 and 4 (colour plates) from Jiménez.

They can be classified within four groups owing to their specific physico-chemical properties (Figure 1), biological activity, organic matter and molecular composition (Decaëns et al. 2001). Therefore the amount of the structures produced in a given agroecosystem will have an impact on soil processes, e.g. nutrient dynamics, soil aggregation, water infiltration, etc.
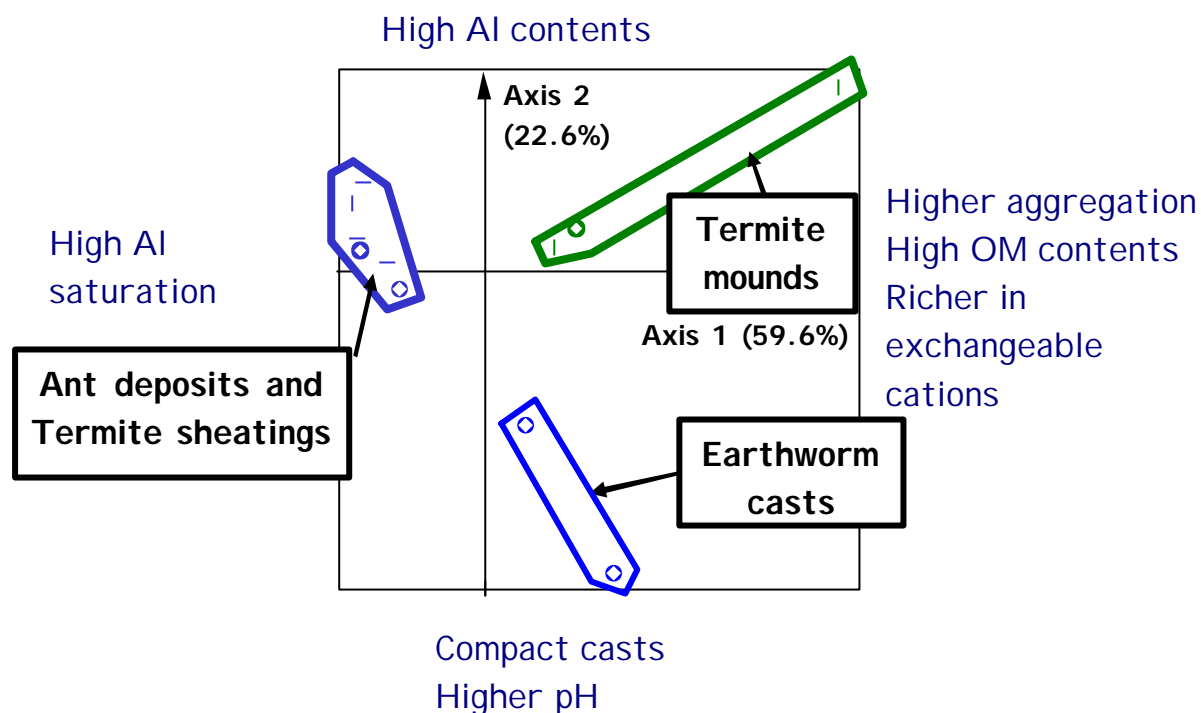
Figure 1. ACP of the physico-chemical properties of the different biogenic structures produced by ecosystem engineers in the savannas of Carimagua (Colombia) (Decaëns et al. 2001).

Soil macrofauna and earthworm communities in natural savannas and introduced pastures

Macroinvertebrate communities of the well drained savannas of Colombia are very sensitive to environmental changes associated with agricultural intensification (Figure 2). Termites (47%) and earthworms (31%) were the major components of biomass. Fire had a spectacular short-term effect on macrofauna. After 6 months, the soil fauna had regenerated: biomass and density were not significantly different from values recorded in the initial savanna and taxonomic richness increased to 20 taxonomic units (TU). Macroinvertebrate communities of improved pastures were characterised by a high biomass and taxonomic richness and a medium population density.

Three types of agroecosystems based on their effects on macrofauna can be distinguished:

(i) *Extensively grazed native pastures*: here the effect of land management is of little significance and re-colonisation of macrofauna after traditional management by burning is rapid. Earthworms are favoured by grazing and fire but their importance decreases with overgrazing. Termites respond in clearly opposite directions and the earthworms/termite ratio may be considered as a sensitive indicator.

(ii) *Introduced pastures*: sowing introduced forage grasses and legumes and increasing animal production on improved pastures has a very important impact on soil macrofauna, especially on earthworm populations that increase significantly their biomass (from 4.8 g/m^2 to up to 51.1 g/m^2). The association of *B. decumbens* + Kudzu seems to be of high value with respect to the maintenance and improvement of soil quality and biodiversity since it also maintains savanna taxonomic richness (an exceptional result when compared to pastures in the Amazon forest, see figures 3 and 4).

(iii) *Annual crop*: they have a dramatic effect on earthworms and arthropod populations, with a spectacular decrease of biomass, population density and taxonomic richness. The factors responsible for this phenomenon can be found in agricultural practices such as tillage, fertilisation or application of pesticides, in the reduction of root production and the modification of the soil microclimate occurring after clearing the natural vegetation. The loss of abundance and diversity of communities under annual crops may result in a loss of certain important soil functions (Giller et al. 1997; Lavelle 1997).
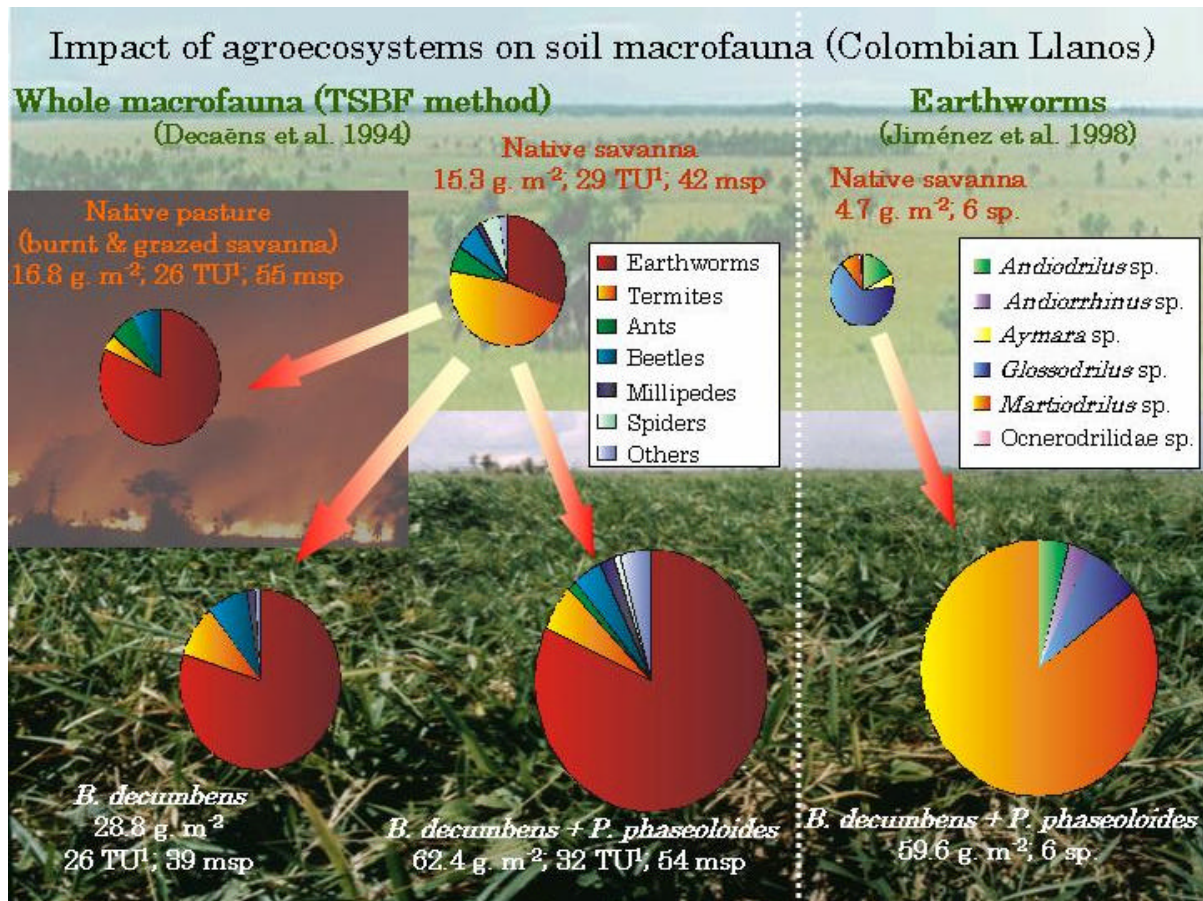

Figure 2. The structure of soil macrofauna communities and earthworms in the savanna and pastures of Carimagua (data from Decaëns et al. 1994, Jiménez et al. 1998b).

Pastures of associations of African grasses and forage legumes, had greatest earthworm biomass (22.9 to 51.1 g. m^{-2}) i.e., 4 to 10 times greater than that of the native savanna. Earthworm populations under pastures were composed of native species, with a large macrofaunal diversity (26 to 32 taxonomic units represented). Annual high input cropping systems (rice and cassava) had the lowest biomass 3.2-4.3 g. m^{-2} and density 429-592 individuals. m^{-2} and a low taxonomic richness. In the savanna endogeic species build up 83.2% of the total biomass, ca. 3.26 g f.w. m^{-2}. On the contrary, in the pasture, endogeic species only represents 12% of the total earthworm biomass, 57.1 g.f.w. m^{-2}, and the anecic species accounts for 88% of total biomass.

For example, pasture establishment in Manaus resulted in important modifications of soil macrofaunal communities. This response of soil organisms is likely to be the result of changes in the soil after the slashing and burning of the forest vegetation (Fragoso et al. 1999). Native earthworms, mainly anecic and epigeic species are eliminated and the vacant niches are rapidly occupied by populations of exotic colonists with high population growth rate that definitively prevent the recuperation of native communities (e.g. *Pontosocolex corethrurus*). In some pastures

at the same study site, 68% of the soil macrofaunal taxa from the original forest are lost and exotic earthworms thus represent up to 90% of the total biomass (Chauvel et al. 1999). This is a common pattern that have been described in other tropical rain forests from South and Central America, where exotic earthworm represent from 60 to 70% of the total earthworm biomass on average (Fragoso et al. 1999).

In the Brazilian Amazon, 95% of the deforested area is converted into pastures, and of these, about 50% can be considered degraded due to mismanagement, phyto-sanitary problems, poor soil fertility and soil structural modification (linked to faunal activity). The kaolinitic soils that predominate in the Amazonian region have a favorable micro-aggregate structure yet it is very fragile, due to low oxy-hydroxide metal contents. When the forest is converted to pasture, the machines and later the cattle trampling the soil lead to severe soil compaction, particularly in the 5-10 cm layer.

The native soil macro-faunal communities are radically altered, most of the native taxa disappearing (151 vs. 48 morphospecies). These are replaced by an opportunistic invading earthworm (*Pontoscolex corethrurus*), which occupies the empty niches, increasing its biomass up to >450 kg ha^{-1}, and representing nearly 90% of the total soil faunal biomass (Decaëns et al. 2004; Figure 3). This species produces more than 100 Tons ha^{-1} of castings, dramatically decreasing soil macroporosity down to a level equivalent to that produced by the action of heavy machinery on the soil (2.7 cm^3 100g^{-1}).
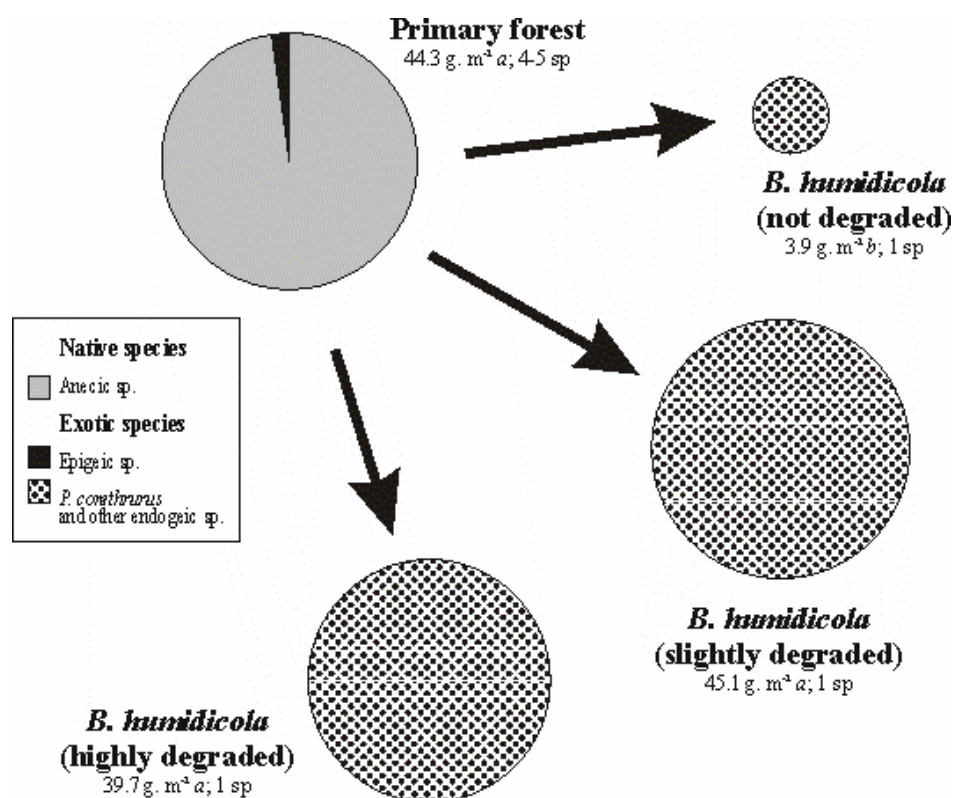

Figure 3. Mean biomass (g fresh mass m^{-2}) and specific richness of earthworm communities in primary forest and intensive pastures in Manaus (Brazil). Different letters indicate significant differences at $P < 0.05$; the diameter of the circles is proportional to the fresh mass m^2 (Decaëns et al. 2004).

The production of large quantities of casts by this species leads to the formation of a 5-cm-thick compact layer at the soil surface that prevents gas exchange between the soil and the atmosphere

and favour anaerobic environment and methane production. The replacement of diverse native communities by monospecific populations of the endogeic *P. corethrurus* has been recognised to have profound and lasting effects on the porosity of pasture soils in Manaus (Barros et al. 2004; Chauvel et al. 1999, Figure 4).
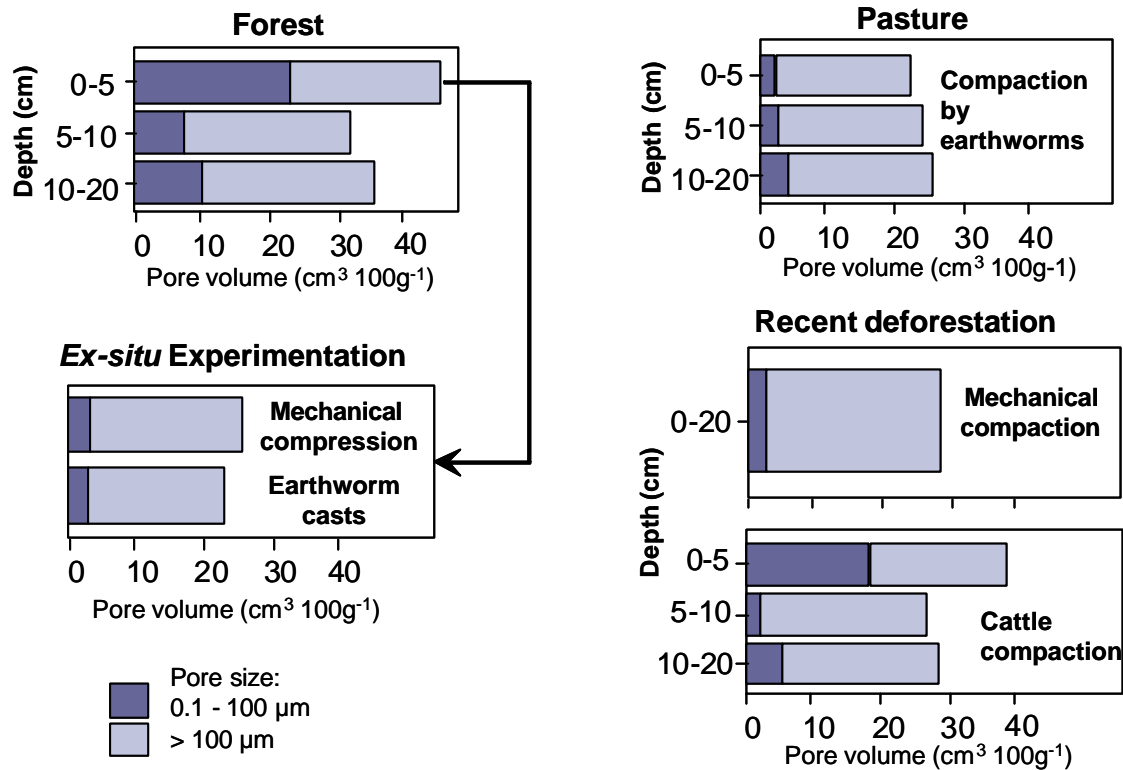

Figure 4. Soil degradation in Amazonian pasture after establishment of pastures and disappearance of native soil macrofauna communities (adapted from Barros et al. 1998; Chauvel et al. 1999; see text for explanation).

It seems that the patterns and trends are largely conditioned by phytogeographic constraints as by the nature and environmental tolerance of native communities. Forest taxa mostly live in the thick litter layer. They are adapted to a shady and humid environment, and hence will not tolerate a shift to a dryer grassland microclimate. Conversely, savanna communities do not suffer from the very slight environmental changes that follow the conversion of the native vegetation into pastures with similar vegetation structure. While vacant niches are occupied by peregrine species in the forest area, native species remain in the pastures derived from the savanna and may prevent the colonisation by exotic species through mechanisms of competitive exclusion.
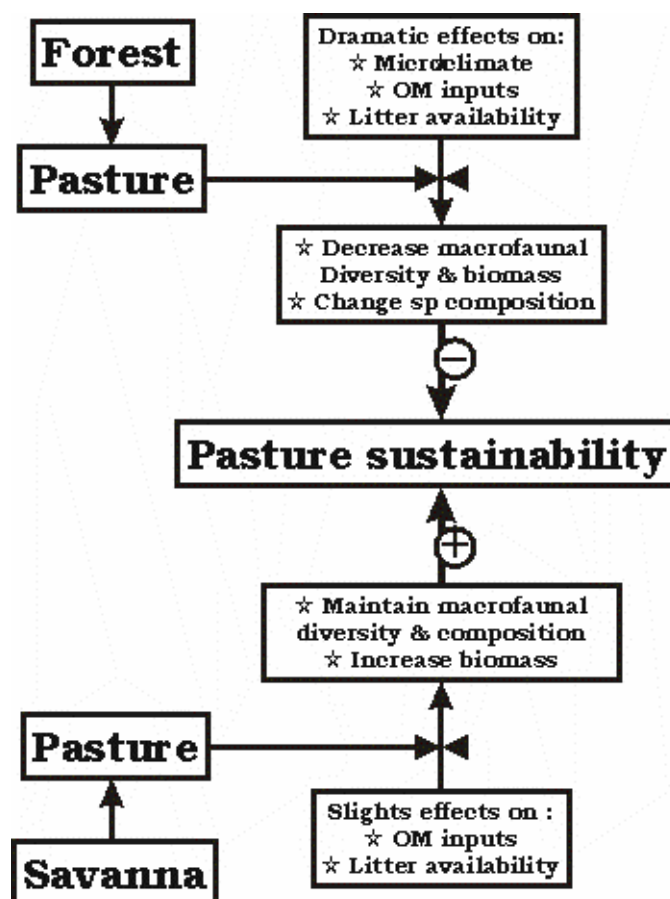
Figure 5. Tentative model of the response of macroinvertebrate communities to pasture establishment and the potential effects on agroecosystem sustainability (Decaëns et al. 2004)

Agricultural intensification

Agricultural intensification can be defined as a set of patterns of land use change of increasing intensity that aim at increasing agricultural production (Giller et al., 1997). It is generally associated with a specialisation in crop or livestock species utilised, an increased mechanisation of management practices, and a generalised use of inputs and pesticides. Ordering agroecosystems along an intensification gradient can be done empirically by classifying land use practices subjectively from the "less" (e.g. burning and grazing of the vegetation) to the "more" (e.g. tilling of the soil, use of chemicals, etc) intensive ones.

In Carimagua, the values obtained with the index of agricultural intensification (AI) reveals the existence of three distinct levels of intensification: (1) semi-natural systems (AI index < 0.2) were represented by the native savanna plots; (2) pastures and fallow were considered as medium-intensification systems (AI index ranging from 0.2 to 0.4); (3) monocrops and crop rotations were identified as high-intensification systems (AI > 0.4).

Two main types of agroecosystems can be identified on the basis of their AI index and their impacts on soil communities: (i) pastures are moderately intensified and, in average, led to a spectacular increase of earthworm biomass and a slight decrease of specific richness; (ii) annual crops and crop rotations are highly intensive systems, with detrimental effects on both the biomass and the specific richness.

Obviously, the patterns of response to agricultural intensification are not the same for all earthworm species, with significant differences in the shape of the density variations along the gradient. These divergent results may be interpreted in the light of the ecological attributes of individual species (Jiménez et al. 1998b), which drives to a certain extent their ability to reconstitute their population densities after perturbations.

The disappearance of some species in cultivated systems was mostly attributed to the lack of recovery of populations after major perturbations like e.g. tillage. The more resistant species were those presenting high surface mobility (i.e. high colonisation capacity) or high population growth potential (i.e. high ability of population recovering after perturbation). Sensitive species disappeared after pastures establishment but richness was recovered in a period of about 3 years. On the other hand, annual crops had deep detrimental impacts that were more accentuated in the rotations (i.e. systems that were tilled twice a year) and were still present in a 2 year-old fallow.

Hence, two management options should be developed according to the results obtained. First, the spatial arrangement of contrasting agroecosystems should facilitate the recolonisation of cropped soils through surface displacements of earthworm populations from "source" plots such as savanna or pastures to "sink" ones.

Role of native earthworms on soil function at different scales. Nutrient dynamics in casts

Martiodrilus n. sp. is an endemic anecic earthworm from Carimagua (Jiménez et al., 1998a). It is a large size, dorsally dark-grey pigmented and surface-casting species. The biogenic structure produced is a tower-like cast with a fresh pasty structure in the top and dry material at its base that is easily recognisable from other soil surface biogenic structures. Casts of *Martiodrilus* sp. are large and ranged from 3 to 6 cm Ø and from 2 to 10 cm height, with an average dry weight of 25 g (Plate 2).

Plate 2. Tower-like cast (turricule) of *Martiodrilus* n. sp. in the natural savanna from Carimagua (scale: length of picture = 20 cm) (Photo: T. Decaëns)

A high N mineralisation occurs in fresh casts. NH_4^+ levels are 5 and 15 times higher on average in 1-day-old casts than in the bulk soil in the savanna and the pasture, respectively. Afterwards, concentration decreased to a very low and constant value similar to the one observed in the surrounding soil. It is important to notice that three significant and transient peaks of NO_3^- were successively observed in the casts, the underlying and the adjacent soil.
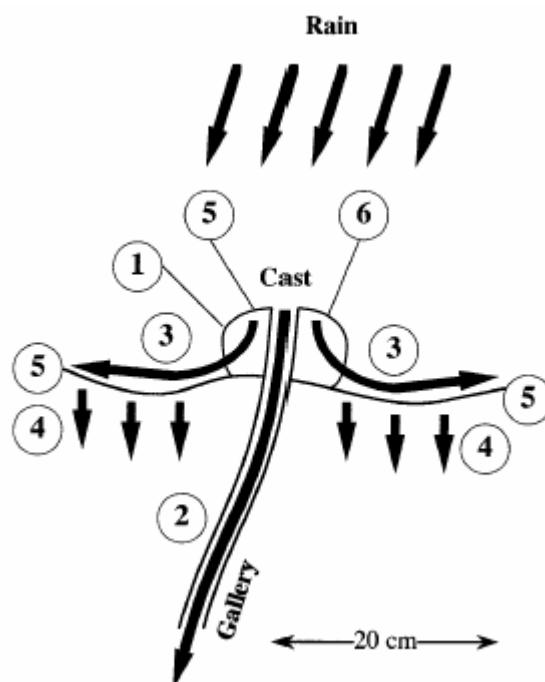
Figure 6. Model of N dynamics in earthworm casts and the nearby soil. The arrows indicate the direction of water flow, numbers refer to a chronological order: (1) high NH4+ release in fresh casts plus NO3- production, (2) vertical drainage in the gallery, (3) lateral runoff from the cast and the soil surface, (4) vertical leaching in the soil profile, (5) denitrification plus root and microbial uptake, (6) N immobilisation in dry casts (Decaëns et al. 1999a).

A significant contribution to the overall N budget in these agroecosystems derives from the enormous quantities of casts deposited in the soil surface by this earthworm. It has been estimated that, 3 and 34 kg ha^{-1}.year^{-1} inorganic N may be released in fresh casts of _Martiodrilus_ sp., in the savanna and the pasture, respectively (Decaëns et al. 1999a).
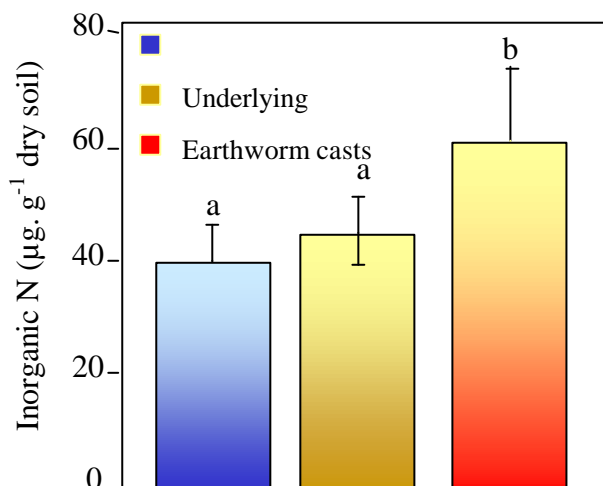

Figure 7. Mean values of inorganic N in the soil and the casts of the introduced grass-legume pasture in Carimagua (different letters indicate significant differences at P<0.05). _ppm mg g^{-1}_ (Decaëns et al. 1999a).

But this species also produces underground casts, and the overall production of casts (surface plus below ground) was estimated at 14 t dry casts. ha^{-1}. year^{-1} in the savanna and 114 t. ha^{-1}. year^{-1} in the pasture (calculated after Rangel et al., 1999). In the case of the pasture, inorganic N release

from casts is equivalent to $\approx 22\%$ of the total annual N uptake by grasses (about 155 kg. ha^{-1}. year^{-1}, Fisher and Kerridge, 1996). This is also equivalent to $\approx 48\%$ of the total N inputs generally used in upland rice monocultures (70 kg. ha^{-1}. year^{-1}, Thomas et al., 1995). These estimates on N mineralisation may be even higher, due to the presence of significant populations of other species (Jiménez et al., 1998b).
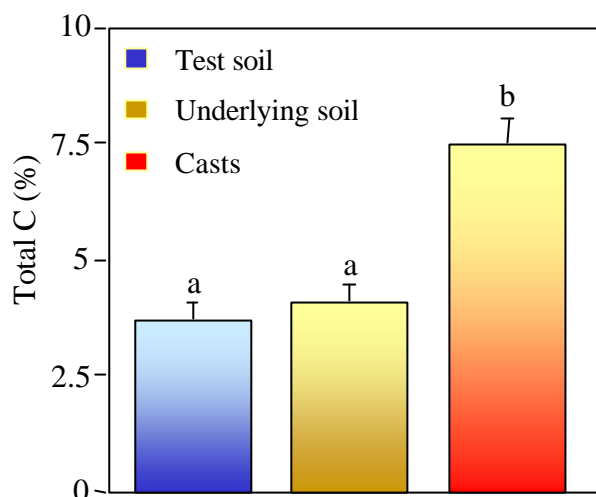

Figure 8. Mean values of total C in the soil and the casts of the introduced grass-legume pasture in Carimagua (different letters indicate significant differences at P<0.05). *ppm mg g^{-1}* (Decaëns et al. 1999a).

The capacity of <u>*Martiodrilus*</u> sp. to select a food substrate with high organic contents might be the reason why total C and N contents highly significant in casts than in the control soil in both systems ($\approx + 100\%$). Several factors may explain these results (Decaëns et al., 1999a): fixation of atmospheric CO_2 by algae or nitrification bacteria (autotrophic microorganisms); the colonisation of casts by cast-dwelling macroinvertebrates and the accumulation of organic material and/or the production of carbon-enriched faecal pellets.

A possible effect of the concentration of organic C in the casts is the build-up of a physically protected and active C pool. The further disintegration of the casts leads to the release of this C that plant could uptake. Earthworm-induced C accumulation in stable aggregates may be considerable due to the enormous quantities of soil egested as casts. These have been estimated at 0.6 t ha^{-1}. year^{-1} and 8.6 t ha^{-1}. year^{-1} in the savanna and the pasture, respectively. Part of this C (83% and 62% in the savanna and the pasture, respectively) corresponded to the C increase in fresh casts compared with soil, and may have been due to the selective ingestion by earthworms of organic-rich food substrates. The total quantity of C concentrated in the casts of *Martiodrilus* sp. represented 2 and 30% of the total soil C in the top 10 cm (based on a bulk density of 1.0 g. cm^{-3}), respectively, in the savanna and the pasture. The implication of this process in C sequestration deserves further attention.

Positive effects of earthworms on plant growth have been widely documented, especially in short-term studies on plants grown in pots (see review by Brown et al. 1999; Lavelle, 1997). Casting activity by *Martiodrilus* sp. first enhances the mobilisation of nutrients (e.g. of NH_4^+ and NO_3^- in our study) that are not generally available in the soil (Rangel et al. 1999), and a greater availability of P (Jiménez et al. 2003). Moreover, as this species is most-ly active at the beginning of the wet season (Jiménez et al. 1998b), the timing of earthworm-induced mineralization may coincide with high nutrient requirements of plants.

Root biomass in the upper soil layer of the pasture significantly responded to the presence of casts at the soil surface (Figure 7). Root biomass increased by a factor of 2 below casts that were deposited recently and 5 when located under aged casts, when compared with the control soil without casts.

Plate 3. The activities of soil organisms may enhance root development and consequently favour C sequestration in agricultural soils (picture from P. Lavelle).
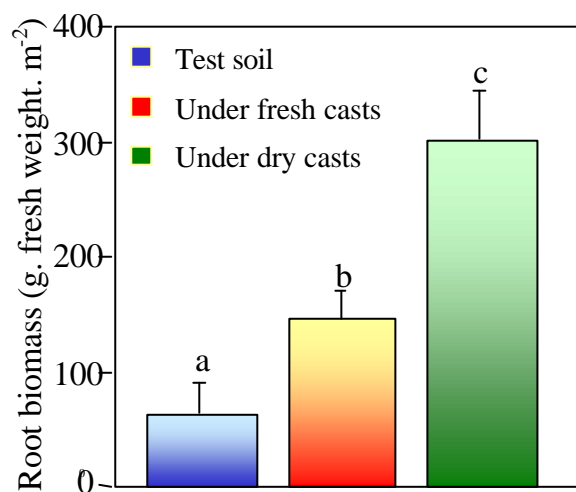

Figure 9. Average root biomass in the 0–15 cm superficial soil layer as affected by the presence of fresh and dry casts on the surface (different letters indicate significant differences at $P < 0.05$) (Decaëns et al. 1999a).

Removal of species and loss of positive ecosystem function

The selective elimination of this species and associated activity in the topsoil brings important changes and modifications in the physico-chemical properties of soil in a relatively short period of 18 months (Decaëns et al. 1999b). The decrease in earthworm biomass is associated with soil degradation (increased soil compaction and aluminum saturation, decreased carbon content) and

herbaceous biomass. Decrease of plant biomass, in turn, favored opportunistic weed species. The biomass of this earthworm species was associated with low soil compaction, high C contents, low Al saturation, high herbaceous biomass and low weed biomass. This experimental manipulation of soil organisms demonstrates that the disappearance of one species, when it is associated with an important decrease in biomass, result in significant losses in ecosystem functions that may lead to land degradation and consequently agricultural productivity reduction.

Attention must be paid to managing earthworm populations in tropical agroecosystems in order to profit from their impacts on soil fertility and enhance the sustainability of agricultural production. More information, however, is still needed, since very few tropical species (mostly peregrine endogeic species) have been intensively studied so far in relation to soil processes (Fragoso et al. 1997).

Guidelines for the management of soil beneficial biota

The brief presentation of the results obtained in these studies guards against making general guidelines for the management of soil macrofauna. Certain agricultural practices such as improved pastures can undoubtedly result in increased populations of soil macrofauna. However, these can be beneficial as in the case of the Colombian savannas or detrimental as in the Amazonian pastures, where the loss of a diverse soil macrofauna activity is responsible for pasture degradation.

The results obtained in these studies suggest the application of various alternatives to conserve and encourage the activities of soil macroinvertebrate communities. Conservation of native savanna areas and gallery forests plus integrated systems of short phases of crops with longer periods of pastures (3-5 years) are options to take into account for the sustainability of these large areas. By maintaining the third component, i.e. soil biodiversity of beneficial effects on soil physical and chemical parameters might be achieved. The ability of soil biota to respond to ecosystem disturbance might comprise a means to manipulate these communities for the farmer's benefit.

The spatial arrangement of pastures alongside cultured plots can result in a faster recovery of the macrofauna populations in the cropped plots. This management practice needs further exploration especially when the beneficial species, that can be more rapidly established, can also help reverse some of the degradative effects of cropping on the soil structure. This may help avoid the need for expensive machinery-intensive solutions to soil degradation problems.

However, one limitation that it is still present for giving recommendations and providing management guidelines, especially in tropical areas is that the main biological and ecological attributes of macrofauna in specific sites have not been addressed. This requires the assessment of at least one to two year studies focusing on the adaptive strategies, population dynamics, etc. by so doing, a better integrated knowledge of soil biological functions in agroecosystems will be achieved, and therefore a more rationale and sustainable farmer-decision making process for soil health management. These studies must be combined within a larger pluridisciplinar approach that gives emphasis to local knowledge, farmer experimentation, socioeconomic contexts and institutional organization, so that recommended agricultural practices can be adoptable and acceptable by end-users.

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