Impact of Land-Use Change on Earthworm Diversity and Activity: the Consequences for Soil Fertility and Soil Erosion

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Abstract

Earthworms are considered useful indicators for monitoring different farming practices, landscape structures and transformations because they respond quickly to land-use change. Many articles have been written on the effects of soil macrofauna (termites and earthworms) on soil properties and the functioning of ecosystems. These soil animals are usually considered to have a positive influence on soil organic matter decomposition and nutrient cycling. They increase the concentration of nutrients in their biogenic structures (casts, sheetings, nests, galleries etc.) and promote the growth and diversity of plants. However, there is a lack of data concerning their impact on tropical ecosystems with steep slopes. This study is part of the Management of Soil Erosion Consortium (MSEC) project, which examines the effects of land-use changes on soil erosion on a southeast Asian regional scale. The aim of the study was to evaluate the recovery potential of earthworms and their effects on soil conservation in areas where cassava crops were replaced by four different types of vegetation cover. It was conducted in an experimental watershed in Hoa Binh province, a mountainous area of northern Vietnam. Results showed that land-use change affects earthworm diversity and that this has significant consequences in terms of soil fertility, water infiltration and soil erosion. In plots planted with eucalyptus, large amounts of plant litter and probably higher soil moisture levels favour *Pheretima leucocirca* activity. These worms produce surface casts, which then became free aggregates, and galleries which are sometimes open at the surface. Casts, galleries and aggregates increase water infiltration and thus reduced water runoff and soil erosion. Cassava, fallow and fodder, however, favour *Metaphire californica* worms, which do not make casts. A soil crust is formed, which leads to a decrease in water infiltration and increased soil erosion. The data clearly shows that biological parameters such as earthworm diversity and activity must not be neglected in studies of the determinants of soil erosion after land-use change. Upland land-use systems with vegetation that produces lots of ground litter may help encourage beneficial worm species (such as *Ph. leucocirca*) and thus help reduce soil erosion and accelerate restoration of degraded land.

Keywords: land-use change, earthworms, erosion, soil fertility, water infiltration.

1. Introduction

Earthworms have been described as a keystone species as their activity helps regulate soil fertility, water infiltration and soil detachability in agroecosystems (Lavelle and Spain, 2001; Shipitalo and Le

Bayon, 2004). Earthworm burrows facilitate water and gas transport through the soil, and by producing surface casts they modify soil nutrient cycling and increase soil rugosity, which in turn decreases the velocity of runoff water and thus promotes water infiltration (Roose, 1999). Casts deposited on the soil surface may also be carried away in surface water runoff after rain, leading to increased on-site soil erosion and perhaps also affecting soil properties downstream of the worm's actual home (Shipitalo and Le Bayon, 2004). Earthworms are also considered to be interesting 'bioindicators': because they respond quickly to land-use changes they can be used to monitor the effects of farming practices, landscape structures or transformations on the soil environment (Paoletti, 1999). Soil erosion is a widespread land degradation problem in Southeast Asia and has dramatic consequences on soil fertility and water quality (Lal, 1998; Maglinao and Leslie, 2001). In northern Vietnam most of the moist forest was destroyed during the 1970s and deforestation is still continuing today (Sharma, 1992; Teck AwBeng, 1997; Castella et al., 2006). Forests were cut to expand cultivated areas for cropping cassava, arrowroot, taro, maize and eucalyptus in the uplands. Due to decreasing soil fertility, upland farmers have progressively replaced these annual crops with fallow, common grazing land, or tree plantations (mainly acacias) (Tran Duc et al, 2003; Clement et al, 2006). The aim of this study was to evaluate the recovery potential of earthworms in areas where cassava crops were replaced by four different types of vegetation cover: pasture, two kinds of fallow and tree plantations. The consequences of earthworm recovery on water infiltration and soil detachability were also investigated.

2. Materials and methods

2.1 Study site

The MSEC project Dong Cao experimental watershed (50 ha) is located in the northeast of Vietnam, approximately 50 km southwest of Hanoi (20°57'N, 105°29'E). The Dong Cao watershed is surrounded by hills with slopes averaging 40%, but reaching 100% in some areas. Annual rainfall ranges from 1,300-2,000 mm. The humidity is always high, at between 75-80%. Daily temperature varies from 15°-25°C (Tran Duc et al, 2004) while the dominant soil type in the landscape is an acrisol (World Reference Base for soil resources, 1998) or ultisol (Soil Survey Staff, 1999). Soils are generally thick, at over a metre deep, but the depth is quite variable. They are over 50% clay in content and are very porous, with a bulk density of 1g cm^{-3}. The clay is almost exclusively kaolinite with a low CEC and a pH of below 5 (Tran Duc et al, 2004). From 1998-2002, the studied watershed was mainly covered with cassava crops and some areas of eucalyptus. From 2002 onwards, land-use practices changed rapidly because of decreases in soil fertility and land-use policies favouring tree plantations on steep slopes (Clement et al, 2006). Five land-use systems were set up in 2005: 1) young fallow following a final cassava planting in 2001 (FAL); 2) a mixed *Acacia mangium* and *Venicia montana* plantation planted in 2002 after cassava (FOR); 3) a fodder plantation of *Bracharia ruzziensis*, which replaced cassava in 2003 (BRA); 4) a very young fallow associated with eucalyptus tree regrowth following a forest cut in 2003 (EUC); 5) a small area of cassava (CAS).

2.2 Earthworm sampling

Earthworms were sampled from ten large sample plots in each different land-use system (1x1 m x 50 cm deep monoliths). Sampling was done during the rainy season (August 2005), when communities were assumed to be at peak abundance. Soil samples were collected at randomly distributed sites in the plots. Earthworms were rapidly hand-sorted after soil excavation and identified at the species level. Cluster analysis and indicator value tests were then carried out in order to determine the relative abundance of each species in each plot.

2.3 Soil analyses

Above-ground soil macroaggregates over 5 cm in diameter were collected in 25 x 25 cm plots (n=9) and separated into four morphological groups: i) above-ground casts (CAST); ii) free biogenic aggregates (rounded shape macroaggregates that were clearly identified as belonging to old casts: ROUND); iii) angular to subangular rocky macroaggregates (ANG); iv) unidentified aggregates (UND). Soil aggregates were air-dried and weighed to determine their relative mass contribution (n=10). Basic soil analyses were carried out on samples from the soil surface and earthworm casts, (n=3) to measure: C and N content (%); pH; clay content (%); CO2 release and microbial enzymatic activities after a 24-hour incubation period (acid- and alkaline-phosphatase, α- and β-Glucosidase and N-acetyl-glucosidase); dissolved organic carbon; and mineral nitrogen contents (NO_3^- and NH_4^+) after 1 and 21 days of incubation. More details on these analyses can be found in Jouquet et al. (2007).

Soil structural stability was determined according to Le Bissonnais's 1996 test (n=18). Aggregate soil stability was assessed by measuring the Mean Weight Diameter (Le Bissonnais, 1996). This method was adapted to the field samples and determined on 12-15 mm diameter air-dried aggregates. This method combined measurements of three types of alteration to the soil structural stability: 1) a breakdown (fast wetting), simulating the behaviour of dry material under heavy rain; 2) a disaggregation test (mechanical breakdown), to analyse the behaviour of damp materials; 3) a slow wetting testing the behaviour of dry, or slightly damp materials, when subjected to moderate rain.

2.4 Water runoff experiment

Water runoff simulation was carried out by running 1.5 l of methylene blue water (5 g l-1) with a constant flow of 75 ml s-1 on the top of a 50cm x 30cm Plexiglas plate. The plate was laid on the ground so the water reached the soil with a uniform, 30 cm wide, front. Given the pronounced impact of slope gradient on runoff and detachment, the slope of the set-up was set at around 40%, which is the mean slope of the catchment. The methylene blue water dyed the soil so that we could determine the precise distance and surface covered by the runoff water. Different parameters were measured to describe soil surface properties. Surfaces (%) covered by macro-aggregates (CAST, ROUND and ANG) and vegetation were visually estimated in a 25cm x 25cm frame placed 3 cm beneath the Plexiglas plate. The maximum distance covered by water runoff (cm) was measured while the overall area covered by water runoff (cm^2) was visually estimated. Soil moisture was measured in the surrounding environment. This experiment was performed in each land use type in areas without macro-aggregates (control plots: CAS, FAL, BRA), with CAST and ROUND aggregates, areas with only ROUND aggregates or only ANG aggregates (CAS) on the soil surface. The quantity of UND aggregates was too low to study their effect on water runoff.

2.5 Aggregate displacement

To simulate aggregate transport by rain events, the ROUND and CAST soil aggregates (n>100) were dyed red, put back randomly on the soil in each plot (every land use type) and then observed to see if they moved down the slope. Their path was recorded after each rainfall event of the 2005 rainy season.

2.6 Statistical analyses

Prior to analyses the data was inspected for homogeneity of variance using Levene's test, and log-transformed when required. Differences between treatments were tested through analysis of variance. Principal component analysis (PCA) was conducted using a matrix of 27 samples and 15 variables. A permutation test was used to assess the significance of the groupings suggested by PCA. All statistical calculations were carried out using the R statistical software package (R Development Core Team, 2007). Differences were considered significant, only when *P* (probability) values were lower than 0.05.

3. Results and discussion

3.1 Earthworm diversity and soil surface properties

Earthworm densities in the five land-use systems are shown in figure 1. Seven species were found over-all. Of these, four species were completely absent from CAS suggesting that cassava cropping affects the soil in a way that influences earthworm diversity. The most abundant species in all the plots was *Metaphire californica*. Cluster analysis and indicator value (indval) statistical tests selected *M. californica* as an indicator of a broad cluster including CAS, BRA and FAL (indval score = 0.82), and of a smaller cluster including BRA and FAL only (indval score = 0.75) (figure 2). *Pheretima leucocirca*, the second most common earthworm species, was mainly found in EUC and FOR, and was given as an indicator of this cluster (indval = 0.48). These results are not very surprising because different types of earthworms are known to prefer different vegetation and soil characteristics. *Ph. leucocirca* is an epi-anecic type of worm (Bouché, 1977). By observing these worms in the field and laboratory,

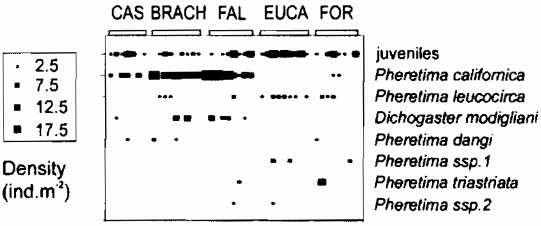

Figure 1: Earthworm diversity and density (individuals.m^{-2}) in the different land-use plots

researchers discovered that they prefer to feed on soil and decaying surface organic matter residues, so they need lots of plant litter and/or specific microclimatic conditions in the soil, such as surface temperature and soil moisture.

In contrast *M. californica* is an endogeic species (Bouché, 1977). These worms like to live deeper in the soil and feed on a mixture of soil minerals and organic matter. This species can therefore survive in areas with less plant cover and litter availability than *Ph. leucocirca*, and are a bioindicator of land use that leads to these conditions, for example cassava cropping .

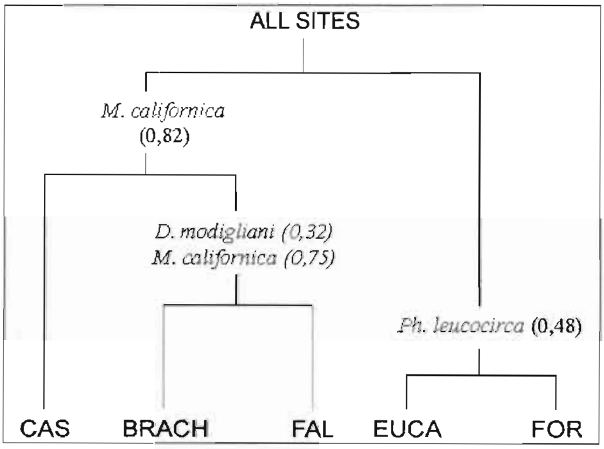

Figure 2: Earthworms are bioindicators of land-use change. Indicator earthworm species determined by indval tests are shown for the different clusters (indval values in brackets). Indval is a statistical test comparing the density of different species in different environments to determine which species is an indicator of specific environmental conditions.

The size and species composition of earthworm communities are important because any shifts in earthworm community may result in significant changes in soil properties. *M. californica* are mainly active 10 cm below the surface. This species does not produce casts on the soil surface and forms extensively branched, subhorizontal networks that are never open to the soil surface. *Ph. leucocirca* live in semi-permanent burrows that are connected with the soil surface. Above-ground casts produced by this species can be very large, sometimes reaching more than 20 cm in length (figure 3). These casts are produced through an accumulation of faecal

Figure 3: Casts produced by *Pheretima leucocirca*. **Fecal aggregates are deposited one on top of the other**

Photo by P. Jouquet.

aggregates that are deposited one on top of the other.

As a consequence, while *M. californica* does not significantly alter the soil surface, casts produced by *Ph. leucocirca* highly modify soil surface properties. It was also observed in the field that these CAST appear to become fragmented probably due to weathering (drying or raindrop impacts), water runoff and livestock trampling and are then dispersed or released as free biogenic aggregates (ROUND). The quantities of CAST, ROUND, ANG and UND aggregates are shown in table 1. The high activity of *Ph. leucocirca* in EUC and FOR had strong consequences on the soil surface properties. These two land-use systems were covered by functional and old CAST and by ROUND aggregates. More than 20 and 10 kg.m^{-2} of these biogenic aggregates were found in EUC and FOR respectively. As a consequence, the soil in EUC was characterised by a typical granular horizon, up to 5 cm thick with high roughness and macroporosity. This type of soil horizon was found less often in FOR and was absent in BRA and FAL, where few biogenic aggregates were found. In these plots the soil surface was more heterogeneous and earthworm activity, and thus casts, were concentrated in small areas. Finally, while the absence of *Ph. leucocirca* in CAS meant that CAST and ROUND were missing, many ANG aggregates were found. These may have been produced by farmers tilling the soil.

Table 1: Weight of air-dried macroaggregates found on the soil surface (kg.m^{-2})

	CAST	ROUND	ANG	UN
CAS	0.00 (± 0.00)	0.00 (± 0.00)	0.93 (± 0.59)	0.00 (± 0.00)
FAL	0.88 (± 1.18)	2.15 (± 1.74)	0.31 (± 0.28)	0.33 (± 0.37)
BRA	0.11 (± 0.11)	0.82 (± 1.03)	0.20 (± 0.28)	1.61 (± 1.36)
EUC	11.57 (± 2.80)	11.24 (± 4.42)	0.00 (± 0.00)	0.68 (± 0.35)
FOR	4.42 (± 1.10)	3.27 (± 0.77)	0.00 (± 0.00)	0.43 (± 0.20)

Mean ± standard error, n=9.

3.2 Earthworm activity and soil organic matter mineralisation

A PCA was carried out using the data obtained describing the physical, chemical and biological properties of the soil (figure 4). PCA is a simple non-parametric test for extracting relevant information from complex data sets. Axes F1 and F2 account for 29.8% and 18.9% of the total variance respectively. This PCA highlights how land-use change and earthworms affect soil fertility, and especially the mineralisation of soil organic matter and retention or leaching of mineral nitrogen nutrients. Casts were characterised by higher nutrient content compared to the surrounding soil (C, N and mineral nitrogen contents). Table 2 summarises soil organic matter mineralisation after a 21-day incubation period. No difference occurred between casts and the control surrounding soil ($P>0.05$), except in BRA, where mineralisation increased ($P<0.05$). However, the nitrification rate and consequently the loss of mineral nitrogen (NH_4^+ plus NO_3^-) through leaching increased in FAL, EUC and FOR and decreased in BRA.

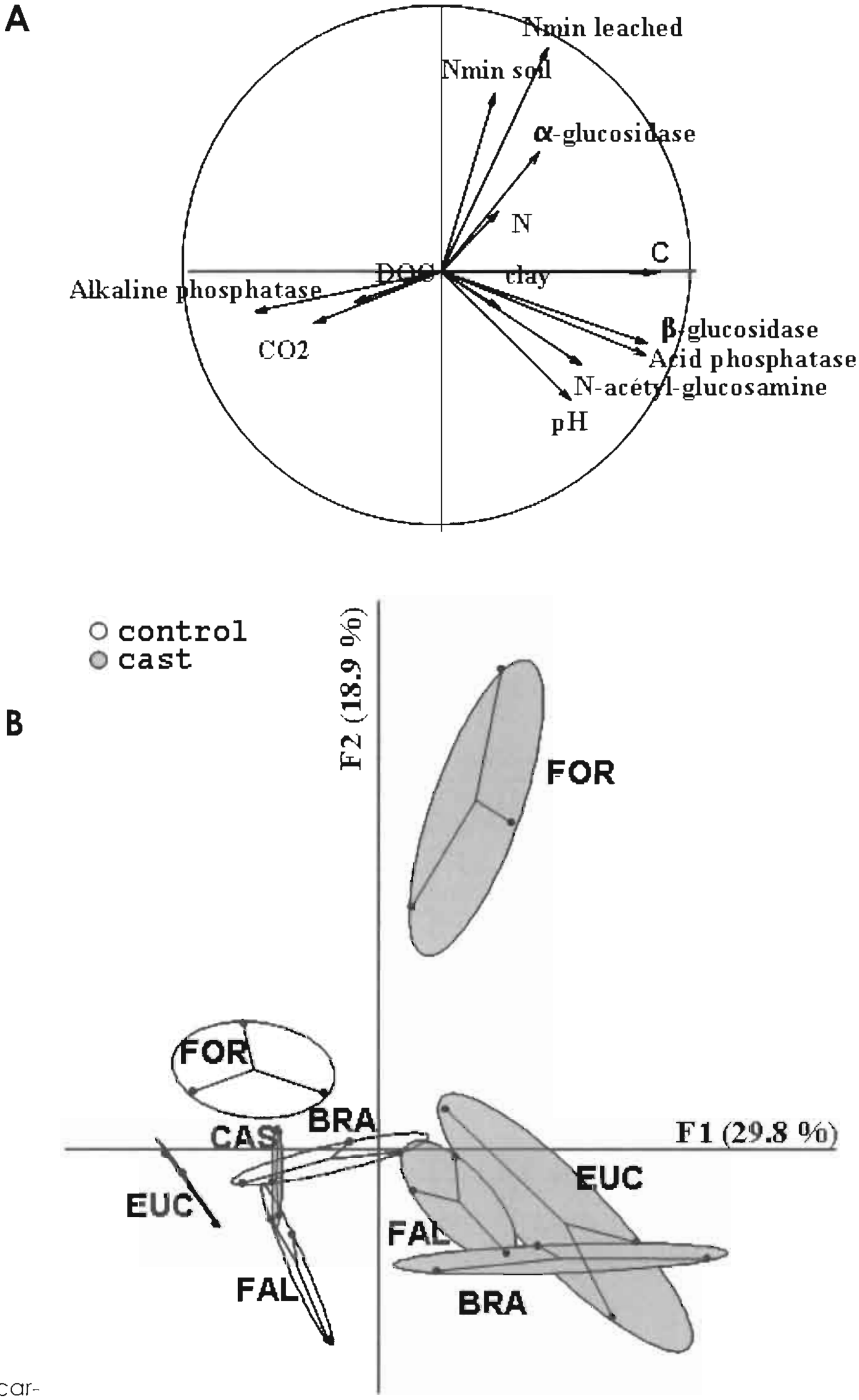

Figure 4: Principal components analysis on initial soil and aggregate properties

Clay (%); carbon (C) and nitrogen (N) (%); pH; Nmin in soil and in leachate (µg N.g-1); dissolved organic carbon (µg C.g-1); available C (%); acid- and alkaline-phosphatase; a- and β-glucosidase and N-acetyl-glucosidase activities (U.g-1). **(A)** Correlation circle: positive and negative correlations between parameters are represented by the direction of the arrow, the length of the arrow describes the importance of the parameter within the data set. **(B)** Order of the samples in the plane defined by axes 1 and 2 (first dimension) of the PCA. The circles represent the multidimensional averages plus variance of all values determined for each land use (CAST or control soil). A distinct grouping of control and CAST samples is seen.

Table 2: Comparison of nitrogen mineralisation (production of NH_4^+ plus NO_3^-), nitrification rate (NH_4^+ to NO_3^-) and remaining mineral nitrogen content (NH_4^+ plus NO_3^-) in casts compared to the surrounding soil after a 21-day incubation period (n=3)

	Mineralisation	Nitrification	Mineral nitrogen content
FAL	n.s. ($p>0.05$)	Increase ($p<0.05$)	Decrease ($p<0.05$)
BRA	Decrease ($p<0.05$)	Decrease ($p<0.05$)	Increase ($p<0.05$)
EUC	n.s. ($p>0.05$)	Increase ($p<0.05$)	Decrease ($p<0.05$)
FOR	n.s. ($p>0.05$)	Increase ($p<0.05$)	Decrease ($p<0.05$)

n.s. = not significant.

3.3 Earthworms and water infiltration

Figure 5 shows how CAST, ROUND and ANG aggregates affect water infiltration. Data showed that the reduction of runoff water was more efficient with CAST ($y= -7.42x + 595.73$, $R^2=0.259$, $P<0.001$) than with ROUND ($y= -5.28x + 757.30$, $R^2= 0.490$, $P<0.001$), and that ANG aggregates did not significantly affect water infiltration ($R^2=0.01$, $P=0.198$). By producing casts and consequently modifying soil surface characteristic, *Ph. leucocirca* significantly influenced water infiltration. In producing casts, earthworms enhance surface roughness, modify the shape of water runoff, reduce runoff velocity, and as a consequence improve water infiltration. Surface roughness increases the time that water resides in soil irregularities before forming a free connected surface able to runoff. Galleries beneath casts might partially explain this more efficient reduction of runoff. However, in the field it was observed that galleries were not always the preferential flow path for water, especially when casts were still functional (i.e. used by earthworms) or when casts blocked galleries. Casts deposited by *Ph. leucocirca* are anchored in the soil and there is continuity between below-ground galleries and above-ground casts. Since casts were not broken, this continuity may have impeded the infiltration of water into the galleries.

3.4 Earthworms and soil erosion

Measurements of soil structural stability (i.e. the capacity of soil aggregates to resist water disturbance), showed that soil macroaggregates from all the plots, including CAS ,were very stable and not easily dispersed by raindrops or water runoff. This result might be explained by the very high kaolinite clay content in these soils (more than 50%, Jouquet et al, 2007) which does not shrink and swell much with variations in soil surface moisture. It seems likely therefore that these water-stable aggregates could be transported downstream by surface water runoff during the intense rainfall events that occurred in the study field, thus leading to a significant loss of soil and associated nutrients.

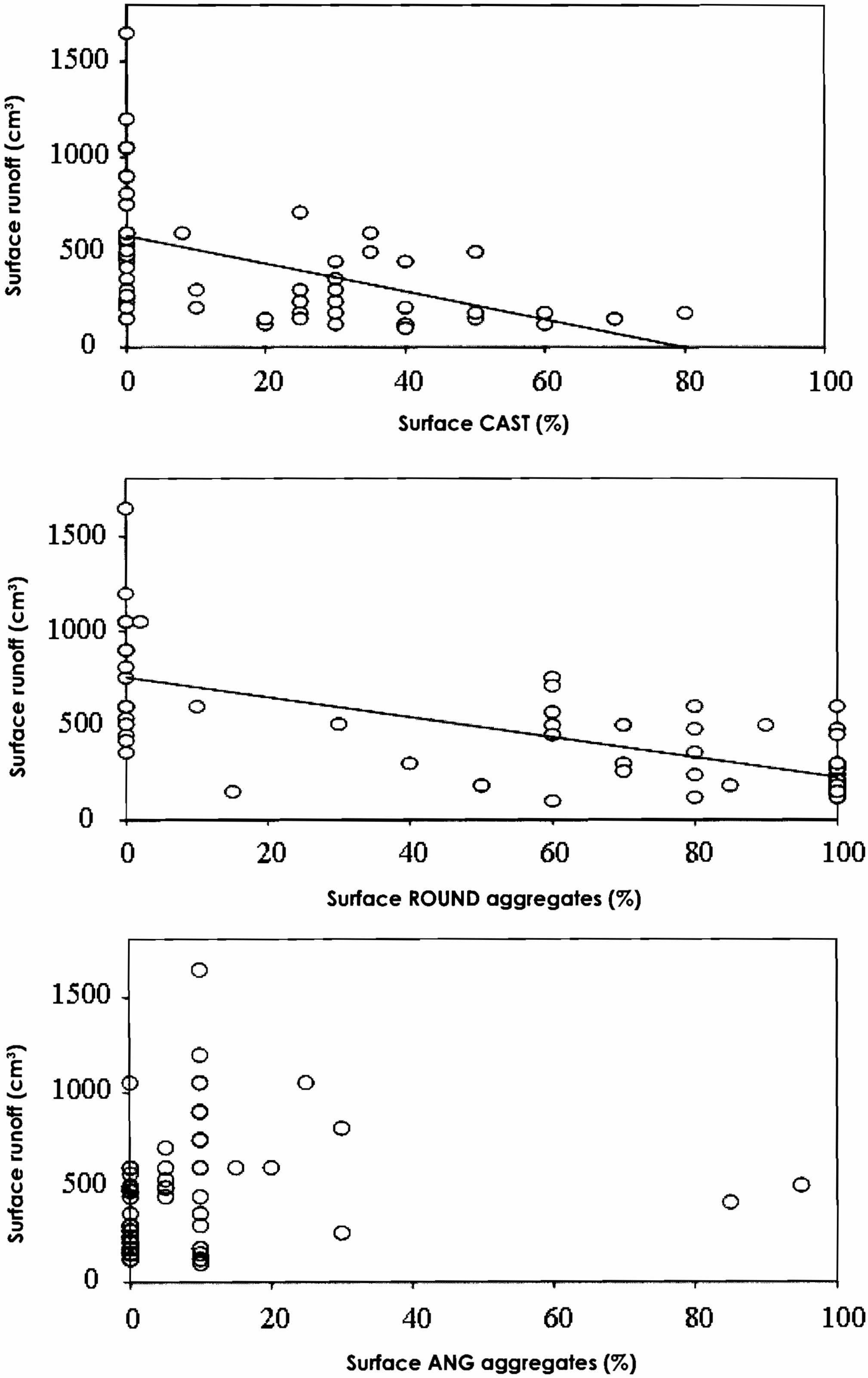

Figure 5: The effect of casts (CAST), free biogenic aggregates (ROUND) and angular rocky, possibly man-made macroaggregates (ANG) (% soil cover) on surface runoff (cm²)

The movement of dyed soil aggregates deposited on the soil surface was followed after each rainfall event throughout the rainy season. The results are shown in figure 6. It had been assumed that aggregates would be washed away and lost from the soil system following rainfall of a given intensity. However, the coloured aggregates either did not move at all or only moved a few centimetres regardless of rain intensity, slope or aggregate size. Therefore, this results suggests that biogenic aggregates (CAST and ROUND) are not eroded rapidly and do not seem to contribute to soil movement and particulate transfer.

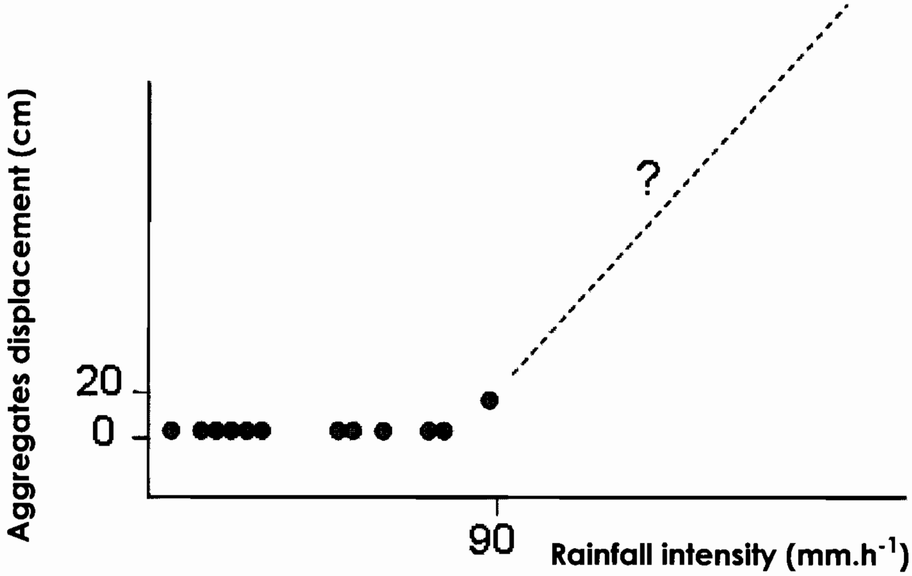

Figure 6: Influence of rainfall intensity on aggregate displacement. The dashed line corresponds to a hypothetical curve

4. Conclusion and recommendations

The results of this study suggest that land-use change affects earthworm diversity and that this has significant consequences in terms of soil fertility, water infiltration and soil erosion. In CAS, FAL and BRA, the presence of *M. californica* but not *Ph. leucocirca*, worms that do not make casts and thus directly influence soil surface properties, meant that a soil crust was formed, leading to a decrease in water infiltration and increased soil erosion. In contrast, large amounts of plant litter and probably higher soil moisture levels in EUC favoured *Ph. leucocirca* activity. These worms produced surface casts, which then became free biogenic aggregates (ROUND aggregates), and galleries which were sometimes open at the surface. Casts, galleries and also ROUND aggregates increased water infiltration and thus reduced water runoff and soil erosion. Free aggregates were observed to be very stable structures: they appeared not to be affected by runoff during the rainy season, and were not eroded or at least only very slowly and/or only during very intense events. Hence, it can be concluded that although soil cover plays an undisputed role in soil conservation, other biological parameters, especially earthworm diversity and activity, must not be neglected in studies of the determinants of soil erosion after land-use change. In uplands, land-use systems with vegetation that produces lots of ground litter may encourage beneficial worm species (such as *Ph. leucocirca*) and thus help reduce soil erosion and accelerate the restoration of degraded land.

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