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Soil macroinvertebrate communities and ecosystem services in deforested landscapes of Amazonia

Raphael Marichal[a,b,e,*], Michel Grimaldi[b], Alexander Feijoo M.[c], Johan Oszwald[d], Catarina Praxedes[e], Dario Hernan Ruiz Cobo[c], Maria del Pilar Hurtado[f], Thierry Desjardins[b], Mario Lopes da Silva Junior[g], Luiz Gonzaga da Silva Costa[g], Izildinha Souza Miranda[g], Mariana Nascimento Delgado Oliveira[g], George G. Brown[h], Stéphanie Tsélouiko[a], Marlucia Bonifacio Martins[e], Thibaud Decaëns[i], Elena Velasquez[j], Patrick Lavelle[a,b,f]

[a] Université Pierre et Marie Curie (UPMC-Univ Paris 6), UMR BIOEMCO 211, Centre IRD Ile de France, 32 Av. Henri Varagnat, 93143 Bondy Cedex, France
[b] IRD, UMR BIOEMCO 211, Centre IRD Ile de France, 32 Av. Henri Varagnat, 93143 Bondy Cedex, France
[c] Universidad Tecnológica de Pereira, Apartado Aéreo 97, Pereira, Colombia
[d] Université de Rennes 2, UMR CNRS LETG 6554, Laboratory of Geography and Remote Sensing COSTEL, France
[e] Museu Paraense Emilio Goeldi (MPEG), Coordenação de Zoologia, Av. Perimetral, n° 1901, CEP 66077-530 Terra Firme, Belém, Pará, Brazil
[f] Centro Internacional de Agricultura Tropical (CIAT), TSBF_LAC, ap aereo, 6713 Cali, Colombia
[g] Universidade Federal Rural da Amazonia (UFRA), 2501 Av. Presidente Tancredo Neves, 66077-530 Bairro Montese, Belém, Pará, Brazil
[h] Embrapa Florestas, Estrada da Ribeira, Km. 111, C.P. 319, Colombo PR 83411-000, Brazil
[i] Université de Rouen, ECODIV, Faculté des Sciences & des Techniques, Bâtiment IRESE A, Place Emile Blondel, F-76821 Mont Saint Aignan Cedex, France
[j] Universidad Nacional de Colombia, Carrera 32 No 12-00 Chapinero, Vía Candelaria, Palmira, Valle del Cauca, Colombia

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ABSTRACT

Land use changes in the Amazon region strongly impact soil macroinvertebrate communities, which are recognized as major drivers of soil functions (Lavelle et al., 2006). To explore these relations, we tested the hypotheses that (i) soil macrofauna communities respond to landscape changes and (ii) soil macrofauna and ecosystem services are linked. We conducted a survey of macrofauna communities and indicators of ecosystem services at 270 sites in southern Colombia (department of Caqueta) and northern Brazil (state of Pará), two areas of the Amazon where family agriculture dominates. Sites represented a variety of land use types: forests, fallows, annual or perennial crops, and pastures. At each site we assessed soil macroinvertebrate density (18 taxonomic units) and the following ecosystem service indicators: soil and aboveground biomass carbon stock; water infiltration rate; aeration, drainage and water storage capacities based on pore-size distribution; soil chemical fertility; and soil aggregation. Significant covariation was observed between macrofauna communities and landscape metric data (co-inertia analysis: RV = 0.30, $p < 0.01$, Monte Carlo test) and between macrofauna communities and ecosystem service indicators (co-inertia analysis: RV = 0.35, $p < 0.01$, Monte Carlo test). Points located in pastures within 100 m of forest had greater macrofauna density and diversity than those located in pastures with no forest within 100 m (Wilcoxon rank sum test, $p < 0.01$). Total macroinvertebrate density was significantly correlated with macroporosity ($r^2 = 0.42$, $p < 0.01$), as was the density of specific taxonomic groups: Chilopoda ($r^2 = 0.43$, $p < 0.01$), Isoptera ($r^2 = 0.30$, $p < 0.01$), Diplopoda ($r^2 = 0.31$, $p < 0.01$), and Formicidae ($r^2 = 0.13$, $p < 0.01$). Total macroinvertebrate density was also significantly correlated with available soil water ($r^2 = 0.38$, $p < 0.01$) as well as other soil-service indicators (but with $r^2 < 0.10$). Results demonstrate that landscape dynamics and composition affect soil macrofauna communities, and that soil macrofauna density is significantly correlated with soil services in deforested Amazonia, indicating that soil macrofauna have an engineering and/or indicator function.

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* Corresponding author at: CIRAD, UR 34 Perennial Crops, Av. de l'Agropolis, TA B-34/02, 34398 Montpellier Cedex 5, France. Tel.: +33 467616524.
E-mail address: raphael.marichal@cirad.fr (R. Marichal).

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1. Introduction

Deforestation is still intense in Amazonia (INPE-PRODES, 2010). Deforestation has diverse, though largely related, origins: road construction, wood exploitation, cattle ranching, and smallholder settlements (Le Tourneau, 2004). As forest is lost, landscape fragmentation increases (Ferraz et al., 2005), with significant negative effects on biodiversity (Laurance et al., 2001). Many studies have shown the importance of land use (Barros et al., 2002; Decaens et al., 2004; Lavelle and Pashanasi, 1989; Mathieu et al., 2004, 2005; Rossi et al., 2010) and the influence of spatial heterogeneity at small scales, from grass tufts to land use effects on soil macrofauna (Mathieu et al., 2009). The role of landscape properties has rarely been addressed (Decaëns, 2010). Carvalho and Vasconcelos (1999) showed that species richness and density of litter-dwelling ants decreases with forest fragmentation, while Louzada et al. (2010) observed that landscape configuration influenced dung beetle communities in Amazonian savannas. Beyond local effects at the plot scale, effects of landscape changes on soil macrofauna communities in deforested areas of Amazonia remain largely ignored.

The loss in diversity observed at small scales (Mathieu et al., 2005) likely affects ecosystem services, which are defined as the benefits people obtain from ecosystems (Millennium Ecosystem Assessment, 2005). Soil macrofauna has an acknowledged influence on soil formation, soil hydraulic properties, flood and erosion control, nutrient cycling, and primary production through direct and indirect plant stimulation and carbon dynamics (Brussaard et al., 2007; Lavelle, 2002; Lavelle et al., 1997, 2006). Earthworms, for example, are expected to greatly affect water-related services through their intense bioturbation and burrowing activities (Lavelle et al., 1997). Although soil macrofauna is broadly used as an indicator of soil quality (Rousseau et al., 2012, 2010; Ruiz-Camacho et al., 2009; Turbe et al., 2010; Vasconcellos et al., 2013; Velasquez et al., 2007a), few studies have directly assessed the link between soil ecosystem services and soil macrofauna communities in the field (van Eekeren et al., 2010).

To fill this gap, we tested the following two hypotheses:

(i) Soil macrofauna communities respond to landscape composition and dynamics. Abundance and diversity of soil macrofauna is expected to decrease with landscape degradation.
(ii) Soil macrofauna and the delivery of ecosystem services are correlated, mainly through the densities of soil engineers (earthworms, termites, ants) and soil processes.

To test these hypotheses, we surveyed macrofauna communities and ecosystem services in the diversity of landscapes found in a gradient of land-use intensification in deforested areas of Amazonia in Colombia and Brazil.

2. Materials and methods

2.1. Study sites

Sampling was conducted in two regions of Brazil and Colombia. In each country, three groups of nine farms were chosen that correspond to landscape units with different histories of colonization. Brazilian sites, located in the center of Pará State, were recently colonized: Palmares II is an old "*fazenda*" which was invaded by the "*Movimento dos Trabalhadores rurais sem Terra – MST*" (Landless Workers' Movement). Farms in Pacajá are located on a trail ("*Travessão Sul 338*") perpendicular to the Trans-Amazonian highway. The Maçaranduba region is occupied by a group of former agro-extractivist farmers who increasingly rely on cattle ranching. Deforestation started in 1990, 1994 and 1997 in the three landscape units, respectively. The three Colombian landscape units, located in the Caquetá Department (southwestern Colombia), are representative of three dominant farming systems: conventional livestock breeding in long-established degraded pastures, agrosylvo-pastoral and agro-forestry systems in the Canelos, Balcanes and Aguadulce regions, respectively. Deforestation started between 1940 and 1950 at all three Colombian sites.

On each of the 54 farms chosen, five sampling points were located equally along a transect corresponding to the longest diagonal of the farm, thus representing a total of 270 points (135 in each country). The distance between points (ca. 200 m) was equal to 1/6 of the transect length and varied according to farm area. Macrofauna and soil were sampled from April to June 2008.

2.2. Macrofauna sampling

The TSBF method (Anderson and Ingram, 1993) was used to sample soil invertebrates. At each of the 270 points, a central soil monolith (25 cm × 25 cm, 20 cm deep) was dug, and two additional soil monoliths (25 cm × 25 cm, 10 cm deep) were dug 5 m east and west from the central monolith. Thus, one sampled unit was composed of 3 monoliths. Overall, 810 monoliths were extracted and hand-sorted.

Macrofauna (groups in which more than 90% of individuals are visible to the naked eye) in the litter and soil was hand-sorted and preserved in 4% formaldehyde. All individuals were then sorted, counted and classified into the following taxonomic units: Formicidae, Isoptera, Blattaria, Diptera, Isopoda, Dermaptera, Hemiptera, Homoptera, Coleoptera (adults and larvae), Orthoptera, Lepidoptera (larvae), Diptera (larvae), Araneae, Opiliones, Chilopoda, Diplopoda, Gastropoda, and Oligochaeta.

2.3. Land use and landscape analysis

A remote sensing approach was used to characterize landscape dynamics from 1990 to 2007 for each site. Landsat TM and ETM+ (30-m spatial resolution, spectral recording adapted to land cover identification) were acquired during the dry season for each site (1990, 1994, 1998, 2002 and 2007). Field validation measurements were taken in 2007 and 2008 to classify landscape elements. Each geolocated measurement was linked to the spectral signature of each landscape element. A confusion matrix determined eight optimal classes of landscape elements.

For each site, supervised classification was performed with the 2007 Landsat image. The spectral signature of each landscape element allowed us to reconstitute previous images (1990, 1994, 1998, and 2002). Five classifications for each site from 1990 to 2007 were produced by supervised classifications.

Nine farms were analyzed on each site. Multivariate analysis was used to explain temporal dynamics of patches on each farm. Three-dimensional matrices were built with x (farm), k (land cover) and t (date). Then, the ACT (STATIS) method (Lavit et al., 1994) was used to identify the (in)stability of spatial patterns over time (each acquisition is integrated into a date-table). This method is based on a date-table correlation to identify a trade-off (inter-structural step). The second step (intra-structural step) identifies trade-off reproducibility within each date-table. Similar date-tables indicate similar landscape spatial structure. This method alone, however, cannot explain the complexity of spatial organization within the agricultural mosaic. Several landscape metrics were necessary to analyze the spatial organization of the landscape (Lausch and Herzog, 2002). Three groups of landscape metrics were identified: fragmentation metrics ("Total Area" (ha), "Edge Density" (m ha^{-1}), and "Mean Patch Density" (m ha^{-1})), diversity metrics ("Patch Richness", "Shannon's Diversity", "Shannon's Eveness", and "Dominance index") and fractal metrics ("perimeter/area", "Mean Shape