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## **Do morphological traits of ground dwelling-ants respond to land use changes in a neotropical landscape?**

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1 **Do morphological traits of ground-dwelling ants respond to land use changes in a**  
2 **neotropical landscape?**

3 **Abstract**

4 Analyzing the impacts of agricultural activities on biodiversity requires a full knowledge of the  
5 ecology of the studied species. Using a trait-based approach may improve our ability to  
6 understand land use impacts on less well-studied species in order to establish general trends that  
7 will facilitate the prediction of these impacts. In this study, we applied a trait-based approach to  
8 understand the impact of land use change on ant communities in the Colombian Llanos region.  
9 Five common land uses were considered (annual crops, rubber plantations, oil palm plantations,  
10 improved pastures and semi-natural savannas) to test whether some morphological traits respond  
11 to soil properties and land uses. An RLQ analysis shows a significant common structure between  
12 species distribution, environmental factors, and morphological ant traits. This indicates that  
13 morphological traits could be used to predict the response of ant communities in different land  
14 uses since they respond to environmental characteristics as vegetation complexity, composition  
15 and management. Based on the selected morphological ant traits, three groups of land uses were  
16 differentiated: grazing-based systems, agroforestry plantations and annual crops. Agroforestry  
17 plantations, especially rubber plantations tend to host larger and specialized ant species, while  
18 grazing-based systems (*i.e.* improved pastures) mainly host small and generalist ants, and annual  
19 crops host more pigmented ants. These findings suggest that certain morphological traits can  
20 reflect the ability of ant species to settle down and survive in a given land use system. Our study  
21 shows that improving knowledge about trait-environment associations could be a useful way to  
22 better understand how ecological filtering shape neotropical ant communities and how they  
23 respond to landscape transformation and land use changes.

1 **Keywords:** Land uses; ant species; soil management; soil properties; RLQ analysis.

2

### 3 **1. Introduction**

4 Agriculture often involves large-scale shifts in nutrient flux and plant productivity and is a major  
5 driver of biodiversity change and habitat (Marta et al. 2021). The growing need for food  
6 production and energy resources continues to increase the pressure to expand agricultural lands,  
7 such that “agricultural frontiers” are now reaching the last unprotected natural areas in many  
8 regions of the world (Hubert et al. 2010; Decaens et al. 2018). In the Eastern Plains (Llanos) of  
9 Colombia, diverse agricultural activities have exerted growing pressure on natural ecosystems  
10 during the last 50 years (Romero-Ruiz et al. 2012). The widespread conversion of natural  
11 ecosystems to intensive agriculture results in habitat loss and fragmentation, which subsequently  
12 impacts the integrity and function of biological communities, from weeds, large mammals and  
13 birds to small soil-dwelling animals (Altieri and Nicholls, 2003; Fischer et al. 2006). In tropical  
14 countries, predicting how land uses and land use changes affect these communities remains  
15 challenging, but new approaches based on species traits may be used to describe them and their  
16 dynamics in order to tackle these issues.

17 Many methods to predict the impacts of agricultural activities on biodiversity have been  
18 developed (Carvalho et al. 2020; Schmidt and Diehl, 2008). The most obvious is to describe  
19 taxonomic diversity and use it to predict the impact of land uses on species. However, this  
20 restricts predictions to species that have been identified and thoroughly studied (Moretti et al.  
21 2013; Vandewalle et al. 2010). Instead, the trait-based approach uses different types of traits (*i.e.*  
22 morphological, eco-physiological and life history characteristics) (Wong et al. 2019). This

1 approach could be used to better understand the impact of land use change and agriculture on  
2 biological communities (Carvalho et al. 2020; de Bello et al. 2010) and to explain general  
3 patterns that could allow for improved prediction and mitigation of these impacts (Pey et al.  
4 2014; Linksvayer and Janssen, 2009; Webb et al. 2010). In this sense, species traits can be used  
5 to predict species distribution and community composition (Gibb and Parr, 2013; Sarty et al.  
6 2006) and can help to clarify what different bioindicator groups are actually indicating  
7 (Carvalho et al. 2020). Traits are comparatively easy to describe but it is necessary to define and  
8 standardize the methodologies to assess them (Pey et al. 2014; Ribera et al. 2001; Vandewalle et  
9 al. 2010, Wong et al. 2019).

10

11 Ant communities provide a good model to examine relationships between environmental  
12 characteristics, communities (Gotelli and Ellison, 2002) and traits (Campbell and Crist, 2016).  
13 They constitute a diverse and abundant group in most terrestrial communities of ground-dwelling  
14 organisms (Hölldobler and Wilson, 1990). They are also involved in a range of important  
15 ecological functions, such as the modification of the physical-chemical environment (Cammeraat  
16 et al. 2002). Ants can also affect plant communities and a range of other soil organisms  
17 (Folgarait, 1998; del Toro et al. 2013). They nest in different substrates (soil, ground, litter, etc.)  
18 and have very diverse diets (scavengers, predaceous, granivorous, herbivorous, etc.) (Hölldobler  
19 and Wilson, 1990; Retana et al. 2015).

20

21 Land use clearly influences the distribution of neotropical ant species in agricultural landscapes  
22 of Colombian Llanos (Sanabria et al. 2016). Different land uses have distinct vegetation types

1 and influence ants through a variety of factors: microclimatic effects, resource availability, the  
2 abundance of predators and the intensity and frequency of disturbances (Gotelli and Ellison,  
3 2002; Sanders et al. 2007). Soil properties also represent a key component of the ant  
4 environment and can have marked impacts on abundance and distribution those insects (de  
5 Bruyn and Conacher, 1990; Sanabria et al. 2016). It has been demonstrated that microclimatic  
6 conditions, such as soil moisture or temperature, may also affect ant distributions at various  
7 spatio-temporal scales (Jacquemin et al. 2012). For example, niche partitioning between ant  
8 species can be based on temperature preferences for their brood (Mezger and Pfeiffer, 2010;  
9 Mezger and Pfeiffer, 2011), while soil moisture can influence foraging activity, food abundance,  
10 suitability of nest sites, and predation by other ants (Levings, 1983).

11 Several studies have pointed out that ant species have specific morphological traits that are  
12 correlated with environmental characteristics in which they live, which can be explained by the  
13 ecology or behavior of the species (Kaspari, 1993; Schilman et al. 2007, Wong et al. 2019). For  
14 example, leg length has been shown to be negatively correlated with vegetation cover and could  
15 allow species to forage for food in the upper part of the litter to discover food resources more  
16 quickly (Wiescher et al. 2012). Weber's length has been found to be associated with habitat  
17 complexity, and scape length and ocular index to associate with mobility (Gibb and Parr, 2013;  
18 Yates et al. 2014). Some studies have demonstrated strong relationships between ant  
19 morphological traits (*i.e.* pilosity, presence of spines, leg length) and habitat complexity and  
20 disturbance (Bihn et al. 2010; Chown and Gaston, 2010; Ribera et al. 2001; Silva and Brandao,  
21 2010; Yates et al. 2014). However, the relationship between a set of traits and a set of  
22 environmental characteristics has been rarely tested for neotropical ants. Ultimately, because ants  
23 should be adapted to the habitat where they preferentially occur, ants found in different land uses

1 and types of soil should exhibit particular morphological characteristics (Costa-Milanez et al.  
2 2017; Salas-Lopez et al. 2018; Linksvayer and Janssen, 2008). In this study, we expect that field  
3 management expressed as soil characteristics and landscape scale-simplification expressed as  
4 land use, are both filtering some morphological traits in soil ants. Thus, morphological traits as  
5 pigmentation, small size, etc., are linked with a higher adaptability to extreme conditions,  
6 perturbation and should be more frequent in less complex land uses.

## 7 **2. Materials and Methods**

8 *2.1 Study area.* Fieldwork was carried out in three municipalities: Puerto López (PL), Puerto  
9 Gaitán (PG) and Carimagua (CAR), in the eastern plains of Colombia (between 3°55'21"N–  
10 71°01'43"W and 4°38'07"N–72°53'55"W), between June and August 2011. The Llanos region  
11 extends to the northeast from the Meta department to the Venezuelan border and is bounded to  
12 the north-west by the Andean Eastern Cordillera. At roughly 200 m in elevation, the region has a  
13 humid tropical climate, with an average annual temperature of 26°C, rainfall totaling 2500 mm  
14 per year and a marked dry season between December and March (Decaëns et al. 2001; Sanabria  
15 et al. 2014).

16 *2.2 Sampling scheme.* Five representative land uses were sampled in the region: 1. annual crops  
17 (including rice, maize and soybeans (AC), 2. improved pastures (*Brachiaria* spp. (IP) 3. oil palm  
18 plantations (*Elaeis guineensis* (OP), 4. rubber plantations (*Hevea brasiliensis* (R), and 5. semi-  
19 natural savannas (S) (See Appendix A, supplementary material). Although it was not possible to  
20 get precise information on the age and history of the cultivated plots, some general information  
21 could be collected on land uses. The original savanna has been disturbed for a long time with a  
22 clear management intensity gradient from Carimagua, where best-preserved savannas with rather  
23 dense tree cover are found, to Puerto Lopez where nearly all of the trees have been eliminated

1 and grazing pressure is high. Improved pastures are rather heterogeneous, since the oldest ones  
2 may have been established 10–15 yrs. before sampling and in many cases are degraded with  
3 relatively high densities of weeds and compacted soils. Annual crops were implemented  
4 relatively recently since cropping is usually maintained for only 2–4 yrs. before perennial tree  
5 crops or improved pastures were installed. Rubber and oil palm plantations had been installed 3–  
6 10 yrs. prior to sampling in all cases. These systems are typically installed in fields following  
7 annual crops, while some rubber plantation plots, mainly in Carimagua were directly converted  
8 from savannas (Lavelle et al. 2014).

9 For each one of the five land uses, fifteen replicates were taken (75 fields were sampled in total).  
10 In each sampled field, one transect of three sampling points was implemented, leading to a total  
11 of 225 sampling points. At each sampling point, a modified Tropical Soil Biology and Fertility-  
12 TSBF protocol (Anderson and Ingram, 1993) was used to collect soil macrofauna. Each  
13 sampling point consisted in the excavation of a central monolith (25 x 25 cm x 20 cm deep) and  
14 two adjacent monoliths (25 cm x 25 cm x 10 cm deep) located 10 m to the North and South of  
15 each central monolith leading to a total of 675 fauna samples (225 sampling points x 3  
16 monoliths). All the macrofauna from the litter and soil of each monolith was hand-sorted.  
17 Standing plant biomass was cut 2-3 cm above the soil surface, and removed prior to sampling  
18 (Sanabria et al. 2014, Sanabria et al. 2016).

19 *2.3 Ant identification.* At each sampling point, ants were collected along with other groups of soil  
20 macrofauna (only ant data was use here). In the laboratory, ants were separate from other  
21 macrofauna taxa and were preserve in 96 % Ethanol. Identification of ants to the genus level was  
22 made following keys by Bolton (1994), Palacio and Fernández (2003), Lozano-Zambrano et al.  
23 2008 (keys therein). When possible, species were identified using a variety of sources including



1 AntWeb (2016; and references therein), Longino's ants of Costa Rica (2004), and Pheidole  
2 working group (Longino 2013). Additionally, some species were compared with voucher  
3 specimens at Museo de Entomología de la Universidad del Valle (MEUV). A reference  
4 collection of material from this study was deposited in the MEUV.

5 In total, 92 ant species belonging to 35 genera and 9 subfamilies were identified, 70.3 % to the  
6 species level and the remaining 29.7 % to the morphospecies level (28). However, only soil-  
7 dwelling ant species were taken into account in analyses: a total of 43 ant species belonging to  
8 22 genera (see Appendix B, supplementary material for the complete list of species).

9 *2.4 Soil characteristics.* A total of eleven soil physical properties were used (Lavelle et al.  
10 2014): volumetric (VM) and gravimetric moisture (GM) content, microporosity (<0.03 µm;  
11 MIC), mesoporosity (0.03–3 µm; MES) and macroporosity (>3 µm; MAC), available water  
12 storage capacity (AWC), bulk density (BD), resistance to vertical penetration (POR), sand (Sa),  
13 and silt (Si) contents. Sixteen soil chemical properties were measured including total soil C and  
14 N content, cation exchange capacity (CEC), Al saturation (AIS), macro and micronutrient  
15 content (Ca, K, Mg, P Bray II (PBr), Al, B, Fe, Mn, Cu and Zn) (Table 1). All soil chemical  
16 measurements were conducted on soil excavated from the 0-20 cm layer, after sorting out  
17 macrofauna, while soil physical measurements were conducted using soil collected within metal  
18 rings removed from the vertical walls of the central monolith.

19 *2.5 Trait description.* Seven morphometric traits were described in the ants, including six  
20 measurements, an index, and a cuticle-associated trait (see Table 2 for full description of traits).  
21 The morphological measurements were taken using an ocular micrometer attached to a  
22 microscopy stereoscope (Nikon SMZ 500). Each of those traits was measured on five randomly  
23 selected workers of each species (Silva and Brandao 2010, Yates et al. 2014, Gibb et al. 2015,

1 Wong et al. 2019, among other authors) In the cases of morphological dimorphism (*i.e.*  
2 *Pheidole*) or polymorphism only minor workers were measured. Pigmentation (P) was coded  
3 with 0 for absence of pigmentation (white or very light yellow) and 1 for pigmented species  
4 (black, red, brown, etc.). All these morphological traits have been used previously for ants and  
5 the literature provides insight on the ecological significance of most of them and their links with  
6 the occupation of a heterogeneous agricultural landscape (Table 2).

7 *2.6 Data analysis.* Abundance data was converted into species occurrence tables (number of  
8 monoliths per field in which the species occurred). This is a common procedure for ants, due to  
9 the social nature of these insects allowing a single sample to contain an extremely high  
10 abundance of a rare species (Hölldobler and Wilson, 1990, Longino et al. 2010). This procedure  
11 provides consistent information on species presence and relative abundance inside the  
12 community. However, only species that occurred in more than five samples were included in the  
13 analysis. The morphological trait values of HW, HL, SL and EL were log-transformed to reduce  
14 the effect of extreme values and regressed against  $\log_e(WL)$ . Other authors when analyzing  
15 morphological traits in order to reduce correlation between body measures and body size widely  
16 use this procedure. We used the residuals of these regressions as traits, since they are  
17 independent of body size (Gibb et al. 2015, Martelo et al. 2018). HL was used in the Cephalic  
18 index computation, so we did not include it in the final statistical analysis.

19 To describe the relationships between traits and environmental variables we performed a RLQ  
20 analyzing the link between table R (environmental variables) and table Q (species traits) through  
21 the table L (abundance-based species distribution). The RLQ analysis (see Dolédec et al. 1996)  
22 consisted of analyzing the joint structure of these three tables in order to decompose the  
23 eigenvalue of the cross-matrix and provides the common ordination axes onto which traits and

1 environmental variables are projected. We used three data tables for the RLQ: the environmental  
2 characteristic table (R for physical and chemical parameters and land use types), the species table  
3 (L for species occurrence) and the morphological trait table (Q). First, each table was separately  
4 analyzed by specific multivariate analysis, which allowed the determination of the proportion of  
5 the total variance of each table represented in the RLQ. The species table (table L) was analyzed  
6 by correspondence analysis. Principal component analysis (PCA) was applied to quantitative  
7 morphometric traits + Pigmentation (table Q). A Hill-Smith ordination was applied to  
8 environmental site characteristics (table R), as this table included continuous (soil) variables  
9 together with land use. The significance of the relationship between the environmental attributes  
10 and morphological traits (Q) was tested using random permutations (Montecarlo permutation:  
11 N=9999 times). Here values of sites and traits were permuted (*i.e.*, permutes entire rows of tables  
12 R and Q; Dray and Legendre, 2008; Ter Braak et al. 2012). Finally, a Ward's hierarchical  
13 classification based on Euclidian distance between species along the first two RLQ axes allowed  
14 defining response groups of ant species. Each of them was further described by its trait  
15 distribution. The difference between species response groups was calculated using type II sums  
16 of squares for unbalanced in a linear model. Effects were compared using multiple comparisons  
17 of means (Tukey's Honestly Significant Difference).

18 All analyses were conducted using the ADE-4 (Thioulouse et al. 1997) and the car (Fox and  
19 Weisberg 2011) packages in the R environment software, version 3.1.1 (R Core Team 2017).

20

### 21 **3. Results**

#### 22 *3.1 Joint analysis of traits, environmental variables and ant community*

1 The RLQ is significant ( $P = 0.023$ ). The first two axes of the RLQ analysis extracts 83.89 % of  
2 the total variance (67.74 % and 16.15 % respectively). The proportion of variance attributed to  
3 each RLQ axis and the proportion of variance that they represent from the multivariate analyses  
4 done on environment characteristics of sites (Hill-Smith ordination), quantitative morphological  
5 traits (principal component analysis) and species distribution (correspondence analysis) are  
6 shown in Table 3.

7 The first axis of the RLQ accounts for 70 % of the eigenvalue of the first axis of the Hill-Smith  
8 ordination performed on environmental characteristics and represents 73 % of the variability of  
9 the PCA ordination performed on the morphological traits table. This is evidence of a good  
10 representation of the environmental characteristics and the set of morphological traits on the first  
11 RLQ axis. When considering the two first axes of the RLQ, the representation of environmental  
12 characteristics and morphological traits is still very good, as they account for 66% of the  
13 eigenvalue of the first two axes of the Hill-Smith ordination on environmental characteristics and  
14 for 86% of the variability of the first two axes of PCA ordination done on the morphological  
15 traits. However, the strength of the relationship between environmental characteristics and  
16 morphological traits is relatively low (correlation between the two new sets of factorial scores  
17 projected onto the RLQ axes = 0.26 on the first RLQ axis and 0.19 on the second RLQ axis). The  
18 first RLQ axis represents a major co-structure between the three tables R, L and Q. Figure 1  
19 shows the projection of axes for each separate analysis (*i.e.* the Hill-Smith performed on  
20 environmental characteristics, R1 and R2, and the PCA performed on morphological traits, Q1,  
21 Q2 and Q3, on the first two RLQ ordination axes).

22 The results of the RLQ analysis are best summarized by representing the scores of the  
23 environment, species and trait variables on the RLQ axes (Figure 2). The first axis of the RLQ

1 (RLQ1; Fig. 2a) is positively associated with rubber (LU.R), oil palm plantations (LU.OP),  
2 Available Water Capacity (AWC), Mesoporosity (MES), pH and Sand (Sa). This axis is  
3 negatively associated with improved pasture (LU.IP), savanna (LU.S), microporosity (MIC),  
4 cation exchange capacity (CEC), copper total (Cu) and sulfur total (S). Considering the traits, the  
5 first axis of the RLQ1 is positively associate with Weber's length (WL) and negatively  
6 associated with eye length (EL) (Figure 2c). The RLQ1 axis opposes species with larger body  
7 size from those with larger eyes. Meanwhile, annual crop was the factor that determines the  
8 second axis of the RLQ (positive side of the RLQ2). This axis is positively associated with  
9 aluminum total (Al), magnesium total (Mg), manganese total (Mn) and macroporosity (MAC). In  
10 addition, it is possible to observe that improved pastures (LU.IP) and savannas (LU.S), which are  
11 the land uses with high microporosity and high CEC are placed in opposite position to annual  
12 crops (LU.AC) which correspond to the land use with the high Mn, Mg and Al contents. This  
13 axis was also positively associated with more pigmented ants (P) and negatively associated with  
14 ants having larger antennae and heads (CI and HW) (Figure 2). The RLQ2 axis represents a  
15 gradient of species distribution according to their pigmentation.

16 The distribution of land uses along the factorial plane of the RLQ (Appendix C in supplementary  
17 material) showed that rubber (R) and oil palm (OP) plantations were on the positive side, while  
18 annual crops (AC), improved pastures (IP) and savannas (S) were on the negative side of that  
19 axis. RLQ1 separated on the positive side agroforestry plantation (*i.e.* land uses with trees such  
20 as rubber and oil palm plantations) that have soils capable of storing water, from grazing-based  
21 systems (improved pastures) and annual crops located on the negative side that have more fertile  
22 soils (based on presence of most macro and micro nutrients).

### 23 *3.2 Classification of species based on environmental variables and species traits*

1 Four species groups were define based on the mean position of the species on the first two RLQ  
2 axes. Each group were represented on the RLQ factorial plan (Figure 2b) and described through  
3 the distribution of morphological traits (Figure 3) and it is important to notice that the description  
4 of the response groups is based on general tendencies, but particular species of a group might not  
5 follow the general pattern (see Appendix B, for further information of the species).

6 *Species response group A* – This group is formed by 25 species (included *Acanthostichus*  
7 *sanchezorum*, *Brachymyrmex longicornis*, *Cyphomyrmex rimosus*, *Paratrechina longicornis*,  
8 *Pheidole vallifica*, *Nylanderia fulva*, *Solenopsis picea*, etc.), which represents 60.47% of the soil-  
9 dwelling ant species collected. It is not easy to indicate the characteristics that the species in this  
10 group have in common due to its position near the origin of the RLQ factorial plan. This group  
11 was however mainly comprised of small and medium size species (Figure 3).

12 *Species response group B* – With 5 species (*Acropyga palaga*, *Solenopsis geminata*, *Pheidole* sp.  
13 2, *Pheidole subarmata* and *Pheidole inversa*), this group is characterized by more proportionate  
14 heads (+/- as long as wide) and were mainly less pigmented species (Figure 3).

15 *Species response group C* - This group comprises 10 species (*Hypoponera opacior*, *Hypoponera*  
16 *punctatissima*, *Hypoponera creola*, *Hypoponera* sp. 2, *Pachycondyla* sp.1, *Ectatomma ruidum*,  
17 *Labidus praedator*, *Neivamyrmex punctaticeps*, *Centromyrmex brachycola*, *Rasopone arhuaca*).  
18 This group is mainly characterized by large and more pigmented species with narrow and smaller  
19 eyes (Figure 3).

20 *Species response group D* - This group contains only two species (*Dorymyrmex goeldii* and  
21 *Solenopsis* sp. 4) that are small species with big eyes (Figure 3).

22 The barycenter of species response group D is on the negative side of the first RLQ axis, while

1 species response group C is on the positive side of this axis. In addition, species response group  
2 B is on the negative side of the second RLQ axis and the species response group A is close to the  
3 axis origin (Figure 2b). In land uses dominated by grasses and with higher chemical fertility  
4 (negative side of RLQ1), species response group D is dominated by more generalist species.  
5 Meanwhile, on the positive side of RLQ1 species response group C is associated to rubber  
6 plantations and is mainly composed by species categorized as hunter ants (*Hypoponera*  
7 *punctaticeps*, *Centromyrmex brachycola*, *Rasopone arhuaca*, *Hypoponera opacior*, etc.) and  
8 army ants (*Neivamyrmex punctaticeps* and *Labidus praedator*). In general, these species tend to  
9 be specialists with a carnivorous diet. Additionally, species group B contained species belonging  
10 to genera such as *Pheidole* and *Solenopsis* that commonly nest in disturbed soils and that were  
11 located between oil palm plantations and savannas on the RLQ. In summary, these results  
12 suggest that RLQ1 represented a gradient of species specialization according to the  
13 presence/absence of tree cover and soil properties (i.e. chemical fertility, water availability, pH,  
14 mesoporosity and soil litter).

15

#### 16 **4. Discussion**

17 The RLQ analysis shows a strong gradient structuring both the environmental characteristics and  
18 the morphological species traits distribution. This gradient located along the X-axis is opposed  
19 on one side to agroforestry plantations (i.e. rubber and oil palm plantations. On the other side to  
20 pasture-based systems (i.e. sites with a significant grass component such as savanna and  
21 improved pastures), and it is possible to distinguish that all these systems are located away from  
22 annual crops (along the second RLQ axis). This study in the Llanos Orientales of Colombia  
23 supports that the morphological traits of ants are correlated both to land uses (Salas-Lopez et al.

1 2017, Martelo et al. 2018, Wong et al. 2019) and to soil properties (Schmidt et al. 2017, Wong et  
2 al. 2019).

### 3 *4.1 The response of traits to land uses*

4 Our results indicate that soil-dwelling ants with a more pigmented cuticle could be more  
5 frequently found in annual crops, although this land use is not clearly associated with a specific  
6 ant response group. This could be explained by the fact that annual crops have soils that are more  
7 exposed to sunlight and are the most disturbed of the study area (*e.g.* tillage and high fertilizer  
8 inputs; Sanabria et al. 2016). Such intensive agricultural practices lead to extremely disturbed  
9 conditions where few species can survive.

10 In agroforestry plantations, such as rubber plantations, ant communities tend to include some  
11 larger species (group C) that can use both the epigeaic and hypogaeic strata (Sanabria-Blandon  
12 and Chacon de Ulloa 2011) and have a more specialized diet. It is known that rubber plantations  
13 host fewer species than natural systems such as forests (Fayle et al. 2010; Fitzherbert et al. 2008,  
14 Martello et al. 2018) and in some cases also fewer than oil palm plantations (Sanabria et al.  
15 2014). However, these systems also host hunter and army ants which are considered as  
16 specialists (mainly predators) with particular requirements for microclimatic conditions (Kaspari  
17 and O'Donnell, 2003, Sanabria-Blandon and Chacon de Ulloa 2011). The presence of such  
18 species is likely explained by the presence of a permanent tree cover with a complex vertical  
19 structure and a thick litter layer which are known to these species (Chadab and Rettenmeyer,  
20 1975; Sanabria-Blandón and Chacon de Ulloa, 2011). At the same time, these agroforestry  
21 plantations, mainly oil palm plantations are monocultures that likely host abundant populations  
22 of pests (Andow 1983, Ali et al. 2012), which could constitute a large food supply for these  
23 predator ants. In contrast, grazing-based systems, such as savanna and improved pastures, were



1 related to ant response groups B and D. In general, the species of these groups are smaller, with  
2 variable coloration, larger heads, larger eyes and larger antennae. All these traits are all related to  
3 the ability to navigate and sense the environment, and they are found in more mobile ants that are  
4 common in open and disturbed habitats (Yates et al. 2014; AntWeb 2018, Sanabria *Pers. Obs.*)  
5 which are demanding from a practical point of view, possibly because these land uses are more  
6 complex and heterogeneous (Yates et al. 2018) than annual crops.

7 Based on our results, we can conclude that, when the response of ant community to land use is  
8 studied, a trait-based approach leads to a similar conclusion as a taxonomical approach, *i.e.* in  
9 neotropics, the community ants is constantly associated with the vegetation type (Philpott and  
10 Armbrrecht 2006, Sanabria and Ulloa-Chacon 2011, Sanabria et al. 2016).

11 Two general mechanisms may explain our results. First, ants are biological control agents and  
12 the presence of a tree cover provides different microhabitats allowing the presence of a diverse  
13 arthropod community, mainly pests that may be an important food source for these ant species  
14 (Schmitz et al. 2000; Perfecto and Vandermeer, 2002; Philpott and Armbrrecht, 2006). Second,  
15 due to the recent land use intensification history of the Llanos and the high level of disturbance  
16 (Lavelle et al. 2016), rubber tree and oil palm plantations can share many species with natural  
17 ecosystems such as disturbed forests and savannas (Sanabria et al. 2014). Thus, these  
18 agroforestry plantations could serve as refuges for some ant species and help the dispersal of  
19 these species between remaining fragments of natural ecosystems (Vandermeer and Carvajal,  
20 2001, Martello et al. 2018).

#### 21 *4.2 Response of traits to soil properties*

22 Our results corroborated that morphological traits give information on some aspects of the

1 relationship between ants and their environment, as it has been reported by other authors  
2 (Schilman et al. 2007; Menke and Holway, 2006; Wiescher et al. 2012; Sanabria et al. 2016). We  
3 found that less compacted soils tend to host ants with smaller body sizes, which can be  
4 considered as a characteristic allowing opportunistic ants to easily colonize environments  
5 (Kaspari and O'Donnell, 2003; Linksvayer and Janssen, 2008). In highly disturbed sites,  
6 opportunistic and generalist ants are often dominant, presumably because these species can  
7 easily take advantage of changes in the availability of various resource types (Hoffmann and  
8 Andersen, 2003; Kaspari et al. 2003). This is congruent with previous studies that reports clear  
9 relationship between traits and macrohabitats, where traits significantly differed between habitat  
10 types (Yates et al. 2014, Hevia et al. 2017).

11 It is known that ants depend on soils characteristics for their engineering activities (Lavelle and  
12 Spain, 2001). For example, soil texture determines the ease with which ants can tunnel in the soil  
13 and construct chambers (Boulton et al. 2005). In this study, we found that such relations could  
14 lead to associations between soil features and morphological ant traits: larger ants are present in  
15 soils with a higher water storage capacity, higher mesoporosity and a higher sand content. These  
16 characteristics allow ants to move more easily within the soil and establish their colonies.  
17 Moreover, high microporosity and high CEC values found in our grazing-based systems  
18 (improved pastures and savanna) are mainly associated with species with larger antennae and  
19 bigger eyes. Gibb and Parr (2013) have reported that these traits are known to be associated with  
20 species that are mobile, adapted to disturbed conditions and have a good capacity to settle down  
21 in new environments. In our opinion, there is no clear mechanistic relation between these traits  
22 and these soil features. The interpretation of these results would be, therefore, that these traits are  
23 associated with land use, which of course is correlated with soil characteristics due to

1 management (but see the first section of the discussion) (Sanabria et al. 2016, Martello et al.  
2 2018).

3 Finally, we consider that in the future it would be useful to include ecological traits such as  
4 nesting site, polymorphism, colony size, dispersal ability, competitive ability or trophic position.  
5 All of them have previously shown to be relevant predictors of species sensitivity to  
6 fragmentation and land use (Silvestre et al. 2003; Henle et al. 2004; Schweiger et al. 2005;  
7 Didham et al. 2007, Retana et al. 2015). Furthermore, it would be interesting to include other  
8 morphological traits that can be linked to micro-habitat specialization: jaw size, leg size, pilosity,  
9 cuticle sculpturing, etc., (Arnan et al. 2013, Wiescher et al. 2015). Those traits have been  
10 reported to be related to key environmental characteristics such as cover complexity (i.e. forest),  
11 ground cover, surface temperature and plant species richness (Satry et al. 2006; Schofield et al.  
12 2016). Third, it might be important to include other environmental features that had better  
13 describe ant habitat (i.e. percentage of bare ground, canopy cover, the depth and mass of leaf  
14 litter, soil and litter temperatures). These characteristics may be better linked to the ecology of  
15 ants and, therefore, could be more strongly associated with ant traits (Silvestre et al. 2003).

16

## 17 **5. Conclusion**

18 Agroforestry plantations are structurally less complex than natural forests, with homogeneous  
19 tree age, lower canopy, sparse undergrowth, and more frequent and stronger human disturbance,  
20 and they will never replace the role of natural systems. Nevertheless, due to its undeniable  
21 presence in tropical landscapes, conservation efforts should focus on ways to enhance  
22 biodiversity in those plantations (Fitzherbert et al. 2008). It has indeed been shown that on

1 neotropical agroforestry plantations management can be adapted to support a proportion of forest  
2 species. This can be accomplished maintaining high performance of the sites, high diversity,  
3 density and height of trees (Moguel and Toledo, 1999), improve the connectivity between  
4 fragments (Vandermeer and Carvajal, 2001), and may maintain metapopulation dynamics and  
5 long-term survival of forest species (Vandermeer and Carvajal, 2001; Perfecto and Vandermeer,  
6 2002, Philpot and Armbrecht, 2006).

7 Few studies have examined factors shaping the structure of ant assemblages at the landscape  
8 scale in the Colombian Llanos. As for many neotropical landscapes, the study of ant assemblages  
9 in this region can be problematic since many of the species that we encountered were new  
10 records and/or their ecology remains poorly understood. Nevertheless, some ant morphological  
11 traits can be used to analyze how ant species respond to land uses and land use change with  
12 distinct plant communities, vegetation cover and management intensity. Based on our data, we  
13 have been able to partially explain co-variation between ant morphological traits with land use  
14 and some soil characteristics. However, here we have only used morphological traits that are  
15 indirectly linked to the life-history strategies and ecological adaptations of ant species. In the  
16 future, using ecological traits could allow making important steps but this requires the  
17 documentation of ecological traits for ant species that have so far been poorly studied.

18 Overall, a trait-based approach helps to better understand ant ecology and better define the  
19 morphological traits that should be measured, as well as the different functional dimensions  
20 needed to describe the environments or niches of ant species (Arnan et al. 2014, Silva and  
21 Brandao 2014, Salas-Lopez et al. 2018). Our findings nevertheless suggest that the  
22 morphological traits we used in this study could reflect the ability of some ant species to  
23 establish and survive in a given environment. These morphological traits can be used to make

1 predictions about ant species distribution, the impacts of management and may also be used as a  
2 complementary tool for the conservation and management of ant communities in complex  
3 agricultural landscapes.

4

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15

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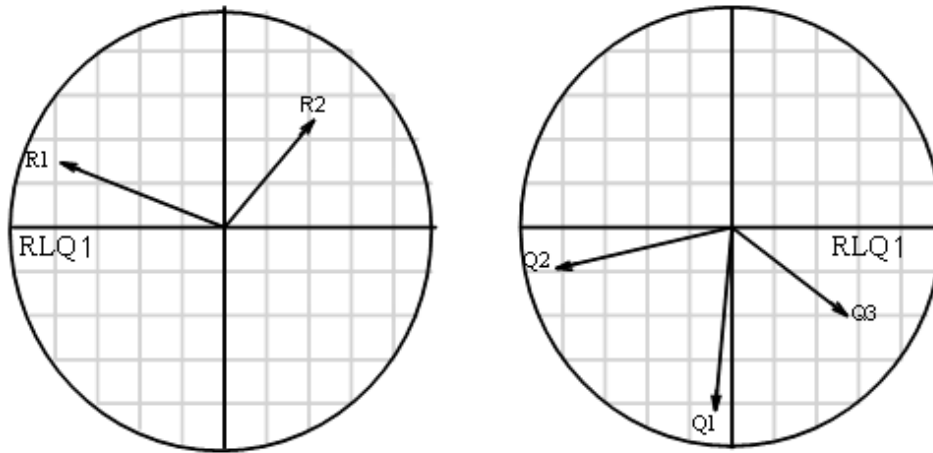
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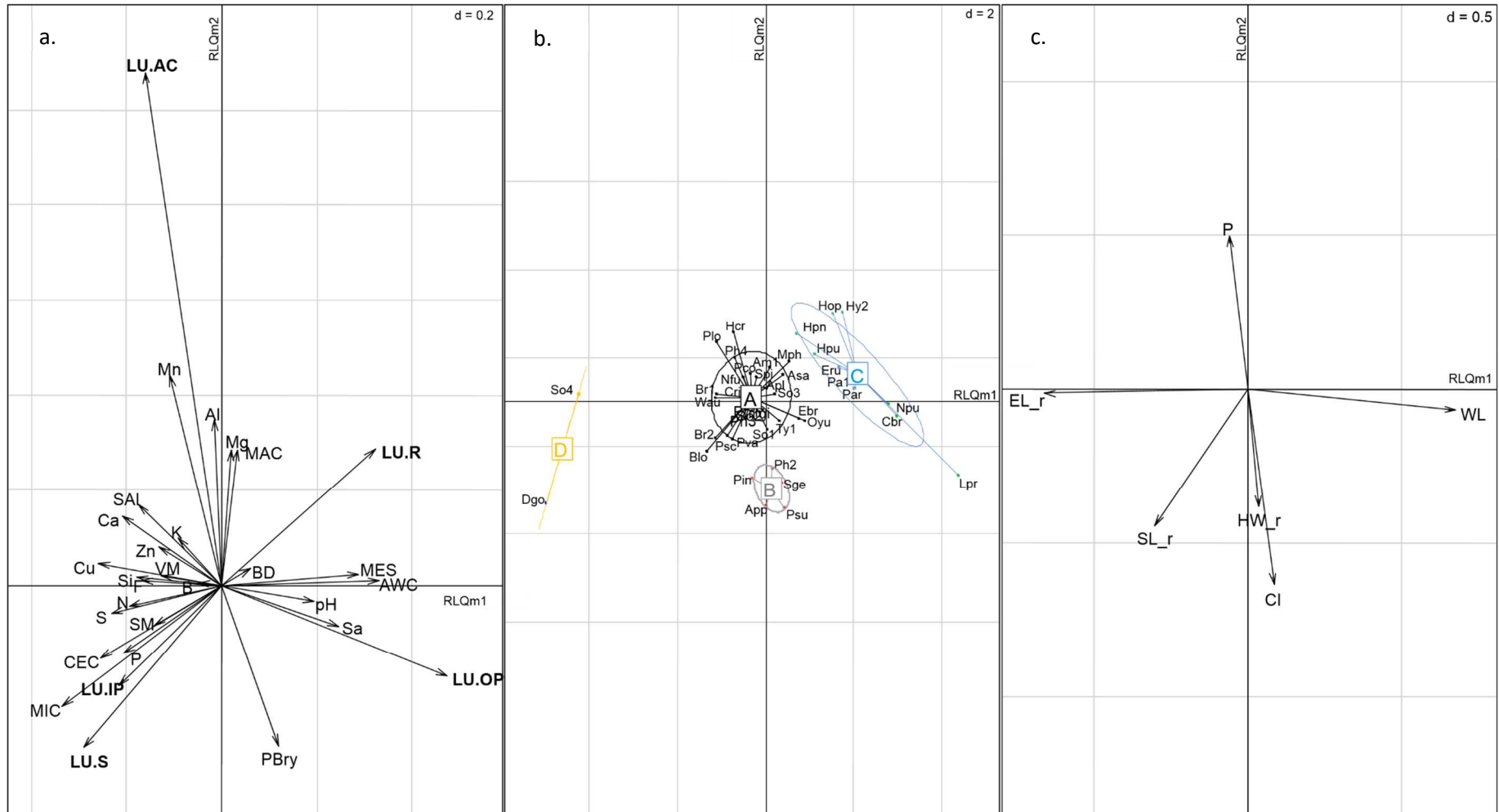


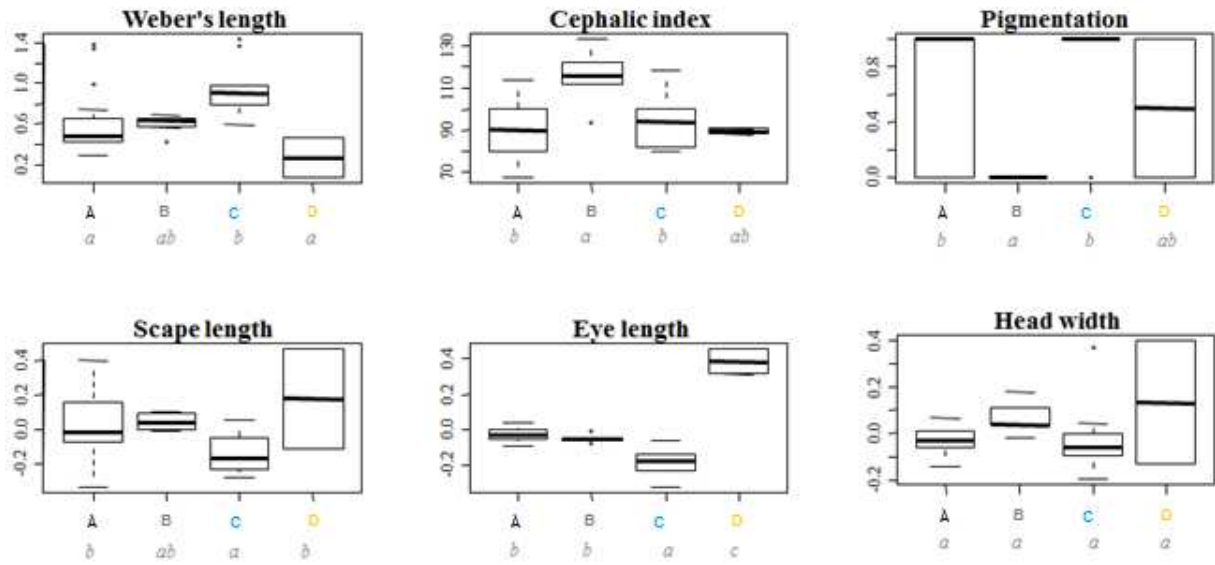
## Figures



**Figure 1.** Projection of the axes of the Hill-Smith ordinations done on R and the principal correspondence analysis done on Q, respectively on the first two RLQ joint ordination axes (RLQ1 and RLQ2). a) the two axes (R1 and R2 respectively) of the Hill-Smith on the environmental data and b) the first three axes (Qe1, Qe2 and Qe3, respectively) of the principal correspondence analysis on the morphological traits of ants collected in the Llanos Region of Colombia in 2011.

- 1 **Figure 2.** Multiple representations of the RLQ ordination on the first two axes: a) environmental variables, b) mean position of species and species response groups, c) morphological traits (see Tables 1 and 2 for full names of variables and Appendix B for species names). Projected inertia: 67.74%, 16.15% for axes 1 to 2 respectively. The *d* value refers to the grill size.





**Figure 3.** Morphological traits distribution in response groups. Uppercase letters (A, B, C and D) correspond to the four species response groups. Lowercase letters (a, b) indicates the statistical differences among species response groups. (see Table 2 and Appendix B, for further information about traits and species).

## Tables

**Table 1.** Physical-chemical soil parameters (see Lavelle et al. 2014 for more details) evaluated from soils collected in the Llanos Region of Colombia in 2011.

	Variables	Names	Units
Chemical	pH	Hydrogen potential	--
	N	Nitrogen Total	g kg <sup>-1</sup>
	C	Carbon Total	g kg <sup>-1</sup>
	P <sub>Bry</sub>	Available Phosphorus Total	mg kg <sup>-1</sup>
	K	Potassium Total	mg kg <sup>-1</sup>
	Ca	Calcium Total	mg kg <sup>-1</sup>
	Mg	Magnesium Total	mg kg <sup>-1</sup>
	Al	Aluminum Total	mg kg <sup>-1</sup>
	CEC	Cation Exchange Capacity	cmol kg <sup>-1</sup>
	SAI	Aluminum Saturation	%
	S	Sulfur Total	mg kg <sup>-1</sup>
	B	Boron Total	mg kg <sup>-1</sup>
	Fe	Iron Total	mg kg <sup>-1</sup>
	Mn	Manganese Total	mg kg <sup>-1</sup>
	Cu	Copper Total	mg kg <sup>-1</sup>
	Zn	Zinc Total	mg kg <sup>-1</sup>
Physical	SM	Soil Moisture	g 100 g <sup>-1</sup>
	VM	Volumetric Moisture	cm 100 cm <sup>-1</sup>
	BD	Bulk density	g cm <sup>-3</sup>
	AWC	Available Water Capacity	%
	MAC	Macropores (>3μm)	%
	MES	Mesopores (0.03–3μm)	%
	MIC	Micropores (<0.03μm)	%
	Sa	Sand,	%
Si	Silt	%	

**Table 2.** Morphological traits, abbreviations given and measures taken for soil-dwelling ant communities collected in the Llanos Region of Colombia in 2011. All lengths were measured in five minor workers and in those polymorphic species; we attempt to select randomly small, medium, and large workers.

<b>Trait name</b>	<b>Code.</b>	<b>Measure</b>	<b>Trait functional significance</b>
Weber's length	<b>WL</b>	Viewing mesosoma in lateral profile, distance from approximate inflection point, where downward sloping pronotum curves into anteriorly projecting neck, to posteroventral propodeal lobes	Indicative of worker body size (Weber, 1938), correlates with metabolic function and habitat complexity.
Head width	<b>HW<sup>a</sup></b>	Maximum width of head in face view, including eyes if they project beyond the sides of the head	Size of gaps through which worker can pass (Sarty et al. 2006); mandibular musculature.
Scape length	<b>SL<sup>a</sup></b>	Length of scape shaft from apex to basal flange, not including basal condyle and neck	Mechanical and chemoreception. Sensory abilities, longer scapes facilitate following of pheromone trails (Weiser and Kaspari, 2006).
Eye length	<b>EL<sup>a</sup></b>	Measured along maximum diameter	Eye size indicates feeding behavior, predatory ants have smaller eyes, and activity times (Weiser and Kaspari, 2006).
Head length	<b>HL<sup>b</sup></b>	Perpendicular distance from line tangent to rearmost points of vertex margin to line tangent to anterior most projections of clypeus, in full face view	May be indicative of diet; longer length may indicate herbivory (Gibb and Cunningham 2011, Silva and Brandao 2010).
Cephalic index	<b>CI</b>	100*HW/HL	Frequently used as index of overall size and to construct ant community morphospace (Weiser and Kaspari, 2006)
Pigmentation	<b>P</b>	Presence or absence of pigmentation in workers	More pigmented species, have higher ability to withstand sunlight (Yates et al. 2014).

<sup>a</sup>: As many size related characteristics are correlated, in the statistical analysis these features were considered as residuals based on the regression with Weber's length.

<sup>b</sup>: Because HL is used in the cephalic index computations, we don't included it in the statistical analysis.

**Table 3.** Statistical results from RLQ Analysis. Total inertia: 0.982. *Inertia %*: percentage of total variance accounted for by each RLQ axis. *Covariance*: covariance between the two new sets of factorial scores projected onto the first two RLQ axes (square root of eigenvalue). *Correlation*: correlation between the two new sets of factorial scores projected onto the first two RLQ axes.

<b>Eigenvalues decomposition</b>	<b>Eigenvalues</b>	<b><i>Inertia %</i></b>	<b><i>Covariance</i></b>
RLQ axis 1	0.62	67.74	0.79
RLQ axis 2	0.14	16.15	0.38
<b>Inertia &amp; coinertia R</b>	<b>Inertia</b>	<b>max</b>	<b>ratio</b>
Axis 1	6.34	9.05	0.70
Axes 1 and 2	8.85	13.33	0.66
<b>Inertia &amp; coinertia Q</b>	<b>Inertia</b>	<b>max</b>	<b>Ratio</b>
Axis 1	1.44	1.96	0.73
Axes 1 and 2	3.07	3.57	0.86
<b>Correlation L</b>	<b><i>Correlation</i></b>	<b>max</b>	<b>Ratio</b>
Axis 1	0.26	0.81	0.32
Axes 1 and 2	0.19	0.78	0.24