Agriculture, Ecosystems and Environment 212 (2015) 94–105

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Relations between the design and management of Senegalese orchards and ant diversity and community composition

Lamine Diame[a,b,*], Rumsaïs Blatrix[c], Isabelle Grechi[d], Jean-Yves Rey[a,e], Cheikh Amet Bassirou Sane[a,b], Jean-François Vayssieres[e,f], Hubert de Bon[e], Karamoko Diarra[b]

[a] ISRA/CDH, BP 3120 Dakar, Senegal
[b] UCAD, BP 7925 Dakar, Senegal
[c] CEFE UMR 5175, CNRS, Université de Montpellier, Université Paul Valéry Montpellier, EPHE, 1919 route de Mende, 34293 Montpellier Cedex 5, France
[d] CIRAD, UPR HortSys, F-97410 Saint-Pierre, La Réunion, France
[e] CIRAD, UPR HortSys, F-34398 Montpellier Cedex 5, France
[f] IITA, 08 BP 0932 Cotonou, Benin

ARTICLE INFO

Article history:
Received 26 January 2015
Received in revised form 29 June 2015
Accepted 4 July 2015
Available online 17 July 2015

Keywords:
Ants
Formicidae
Bioindicators
Sahelian agroecosystem
Mango and citrus-based orchards
Senegal
Sustainable agriculture

ABSTRACT

Although agriculture is a major factor in environmental change, the level of its impact is likely to vary with farming practices. Thus, we sought to determine how farming practices might affect the natural compartment of agroecosystems and the sustainable use of land. In particular, we examined ant biodiversity and community composition as related to orchard design and management practices in the mango- and citrus-based orchard agroecosystems of Senegal. Ants were collected using pitfall traps in 49 orchards classed in four types based on their design and management. The results showed that the effect of practices was significant, albeit weak, and a typology of orchards based on design and management practices was congruent with a typology based on the composition of ant communities. The different types of orchard were seen to differ in the richness and diversity ant species. Moreover, ant richness and diversity was positively correlated with tree richness. We were also able to identify some ant species as being related to agricultural practices. For instance, *Monomorium salomonis* (L.) was closely associated with high irrigation, fertilization and pesticide use, whereas *Paltotyreus tarsatus* was associated with greater tree richness, high local ground coverage by the tree canopy, more leaf litter and great variation in the local tree planting density. This study appears to be the first attempt to characterise the relations existing between orchard design and management practices and the functioning of Sahelian fruit-based agroecosystems thereby furthering the goal of providing recommendations for sustainable management strategies.

1. Introduction

Agricultural activities are responsible for most landscape degradation, including the loss of plant and animal biodiversity. The simplification and destruction of natural habitats in agroecosystems are usually the main factors of such landscape degradation (Matson et al., 1997; Altieri, 1999; Benton et al., 2003; Burel et al., 2013). According to Philpott and Armbrecht (2006), intensive agricultural practices accelerate the loss of biodiversity. Changes in vegetation complexity, such as simplification or a decrease in biotic resources, commonly lead to a change in species interactions and ecosystem processes (Tilman et al., 1997; Hooper and Vitousek, 1997) and this can have potentially drastic consequences for ecosystem services. Nowadays, studies of ecosystem functioning are increasingly being used in efforts to promote biodiversity conservation. Examples include studies of the impact of human management practices on ecological processes in cropping systems (Weibull and Östman, 2003). In Senegal, it is known that orchard agroecosystems are very diverse in their varietal composition, their planting design and their management practices (Vannière et al., 2004; Grechi et al., 2013),

---

[*] Corresponding author at: ISRA/CDH, BP 3120 Dakar, Senegal.
E-mail addresses: diamelamine99@gmail.com (L. Diame), rumsais.blatrix@cefe.cnrs.fr (R. Blatrix), isabelle.grechi@cirad.fr (I. Grechi), jean-yves.rey@cirad.fr (J.-Y. Rey), cheikh84amet.bass@gmail.com (C.A.B. Sane), j.vayssieres@cgiar.org (J.-F. Vayssieres), hubert.de_bon@cirad.fr (H. de Bon), karamoko.diarra@ucad.edu.sn (K. Diarra).

http://dx.doi.org/10.1016/j.agee.2015.07.004
0167-8809/© 2015 Elsevier B.V. All rights reserved.

but no prior study has examined the relations existing between orchard design and management practices and underlying ecological processes.

Biodiversity is known to have important functions in agroecosystems, affecting the stability, productivity, and sustainability of farms (Giller et al., 2009; Vandermeer et al., 2010), and the management of crop resources can have a major impact on the environment (Wardle et al., 2001; Hooper et al., 2005). To reduce that impact, it is necessary to understand the effect of orchard design and management on animal communities, including arthropods.

In Senegalese orchards, it was necessary to identify ecological indicators in order to understand how orchard design and management might impact ecological processes. An ecological indicator can be defined as any species "that demonstrates the impact of a stressor on biota or that monitors longer term stressor-induced changes in biota" (Mcgeoch, 1998). Soil organisms, such as earthworms and ants, are often used as ecological indicators. They play a crucial role in organic decomposition, soil nutrient balancing, soil formation and the renewal of soil fertility (Thomsen et al., 2012; Folgarait, 1998). Ants have been studied in many climate zones (Hoffmann and Andersen, 2003; Perfecto and Armbrecht, 2003) and have been successfully used as ecological indicators in a wide range of land-use situations (Andersen et al., 2002; Andersen and Majer, 2004). Ant communities have been investigated in studies of land management systems, natural systems, rehabilitation processes and changing agroecosystems (New, 2000). The robustness of ants as ecological indicators has been demonstrated, and is supported by an extensive understanding of their community dynamics in relation to disturbance (Andersen and Majer, 2004; Andersen et al., 2004). Moreover, ants can provide invaluable information, e.g. for detecting (1) invasive species; (2) trends affecting threatened or endangered species, (3) impacts on keystone species and also for (4) evaluating land management actions, and (5) assessing the impact of long-term ecosystem changes in disturbed habitats. All can be done in a relatively short time and for a low cost (Underwood and Fisher, 2006). Ant communities have been shown to respond quickly to changes in vegetation stages (Wike et al., 2010). In addition, ants are good biodiversity indicators because their diversity is representative of overall diversity and the assemblage composition of other groups, and can be characterised in a specified area relatively quickly and easily (Majer et al., 2007).

The consequences of ant activity and diversity for pest and disease control, and thus for agriculture, can be beneficial or detrimental depending on the local context and the identity of the ants. High ant activity has a top-down effect reducing communities of herbivorous arthropods in agroforest systems (Philpott and Armbrecht, 2006; Philpott et al., 2004). This is particularly true for dominant ants that have a marked predatory behaviour. However, high ant activity can also reduce communities of predatory arthropods (James et al., 1999), and thus be detrimental to agriculture. A beneficial effect of ant diversity on pest control is not well established, but is expected because, for instance, the more diverse a community is, the more chances it has of including a predator of a particular pest (Philpott and Armbrecht, 2006; Gove, 2007).

No prior studies have examined ant communities in Senegalese orchards. The agroecosystems, which are in the semi-arid climatic zone, possibly require specific ecological indicators that differ from those used in temperate or tropical zones. Thus, our aim was to identify representative ant communities, if any, in a wide range of Senegalese orchard types and then find out whether ants in general or specific ant species could be used as bioindicators of the impact of orchard design and management on their diversity, richness and community composition. To do this, we tested the hypotheses that ant diversity, ant richness and ant community composition are related to (i) orchard design and (ii) human management practices in orchard agroecosystems.

2. Materials and methods

2.1. Study area

The study was carried out in 49 orchards which were widely dispersed across the whole study area, were easily accessible and encompassed the diversity of orchard design and management found within the study area. They were located in four localities: 'Notto', 'Ndoyenne', 'Pout' (Pout town and Pout sigelec) in the *Niayes* region and 'Thiès' (Thiès East and Thiès West) in *Plateau de Thiès* region (Fig. 1). The two regions belong to the same semi-arid agroecological zone. The favourable climate mitigated by a cool and humid trade wind during the hot season makes the regions the major fruit and vegetable production areas of Senegal. Both regions are characterized by ferralic arenosols and a Sudano-Sahelian climate with unimodal rainfall from July to September (between 600 mm and 750 mm per year between 2008 and 2012). 'Ndoyenne' and 'Notto' benefit from oceanic winds that lower the ambient temperature for longer periods than in 'Pout' and 'Thiès'.

2.2. Orchard sample and characterisation of orchard types based on design and management practices

In a previous study carried out on 64 orchards sampled within the *Niayes* and *Plateau de Thiès*regions, an orchard typology was built based on 26 variables describing orchard design and management practices (Grechi et al., 2013). Orchard typology was obtained by a Hierarchical Multiple Factor Analysis (HMFA) performed on the variables of the 'orchard design' and 'orchard management' groups (Table 1). This HMFA was followed by an Agglomerative Hierarchical Clustering (AHC) with the Euclidean distance metric and Ward's agglomeration method. It resulted in four main orchard categories. These orchards were also characterized with seven additional variables classed in a third group regarding 'orchard vegetation state' (Table 1). These variables were not used for the cluster analysis but to describe the categories instead. Of the 49 orchards analysed in the present study, we used 31 from the previous study (we could not use the 64 for logistical reasons) and we added 18 new ones in order to have approximately the same number of orchards for each locality. Orchard categories for the remaining 18 new orchards were defined based on a same approach. For these additional orchards, HMFA was performed on the variables of the 'orchard design' and 'orchard management' groups. Then, the 18 additional orchards were assigned to the category for which the Euclidian distance between orchard coordinates and the category barycentre was minimal on the principal components of the HMFA.

The four orchard categories resulting from the HMFA and AHC analyses were: (1) 'no-input mango diversified orchards', (2) 'low-input mango orchards', (3) 'medium-input citrus-predominant orchards' and (4) 'medium-input large mango- or citrus-predominant orchards'.

Types 1 and 2 consisted of orchards with a large proportion of mango trees (86% on average), and a high diversity in mango cultivars for those of type 1. They were mostly planted with polyembryonic mango cultivars, such as cv. Boucodiékhal, and were dedicated to the local market or subsistence production. None of the type 1 orchards was managed or supplied with water, fertilizers and pesticides. The type 2 orchards displayed only low management levels. Vegetation in the type 1 orchards was dense. Type 3 consisted of orchards with a large proportion of citrus trees

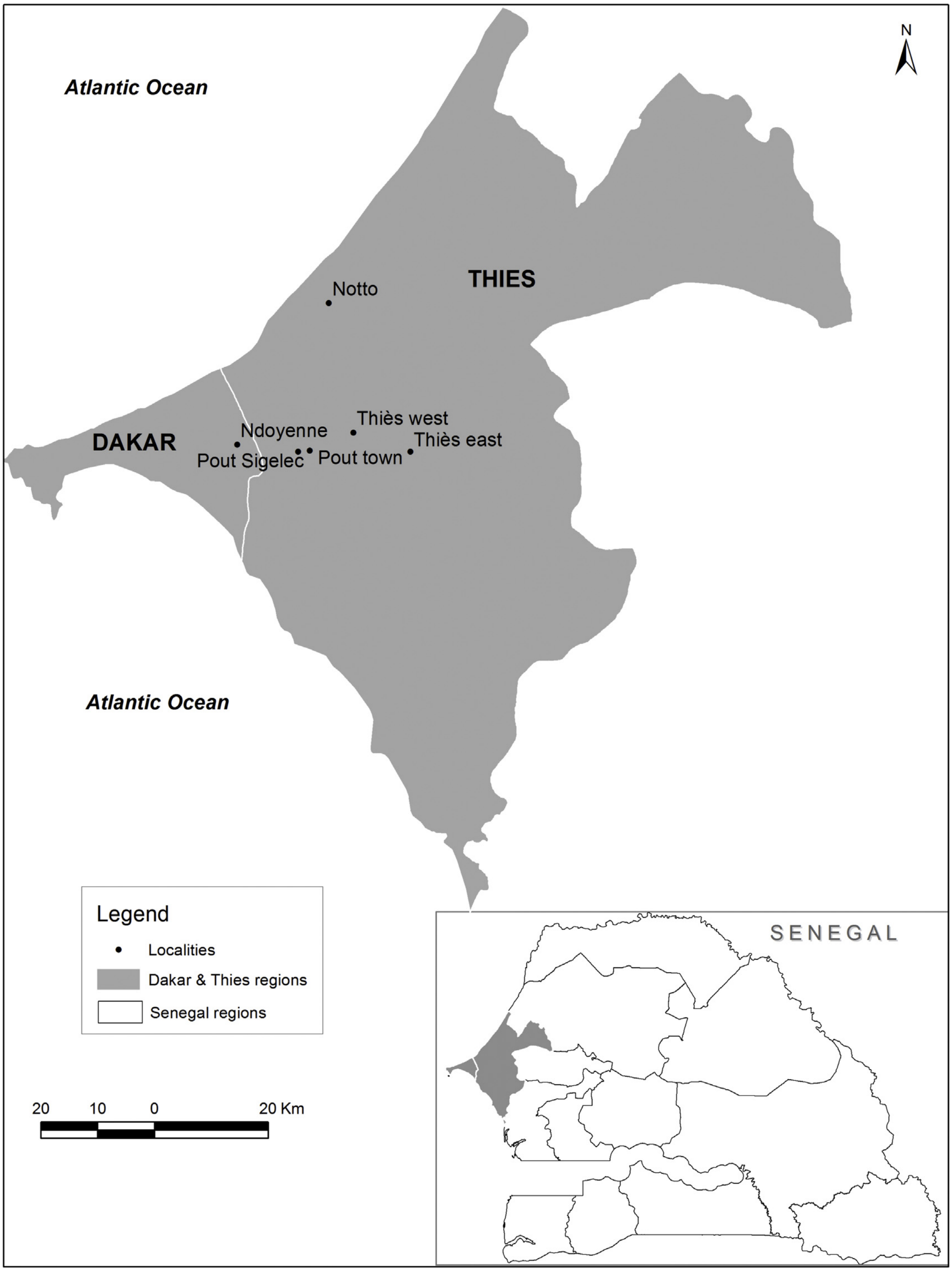

Fig. 1. Map of the study area in the *Niayes* and *Plateau de Thiès* regions, Senegal.

(65% on average), including grapefruit, orange and mandarin species, and a high diversity of tree species. Corossol, papaya, banana, guava and sapodilla were other species planted in these orchards, but citrus and mango trees formed the main crops. The planting density was high on average but tree spacing was irregular within the orchards. All orchards were irrigated and fertilized. Type 4 consisted of large orchards with a low diversity of tree species, and mango cultivars, and a regular tree spacing. Kent was the main cultivar followed by cv. Keitt. Most of them were mango mono-specific orchards whereas the others were citrus-predominant mixed orchards. They displayed the highest management levels in comparison with those of the others types. Mango mono-specific orchards of type 4 were dedicated more to the export market.

2.3. Ant sampling

Ants in each orchard were sampled in 2012, once during the dry period (March–June) and once during the rainy period (July–September). For each period, twenty pitfall traps per orchard

Table 1
List and definition of all the variables of the ‘orchard design’, ‘orchard management’ and ‘vegetation state’ groups used to describe the orchards. The asterisk indicates the variables used in the ant diversity and richness and RDA analyses. For details on the variables, see Grechi et al. (2013).

Sub-groups	Variables	Definition (unit)
Group 1. Orchard design		
Acreage	Acreage	Orchard acreage (ha)
Tree richness	*Tree richness	Number of tree species (called “Species” in Grechi et al. (2013))
Density	*Density	Mean local planting density of trees (ha^{-1})
DensityCV	*DensityCV	Coef. of variation of the local planting densities of trees
Cultivar	Cultivar	Number of mango cultivars
% Species		Orchard composition of tree species
	Mango	% of trees of mango species
	Orange	% of trees of orange species
	Grapefruit	% of trees of grapefruit species
	Mandarin	% of trees of mandarin species
	Lemon	% of trees of lemon species
	Papaya	% of trees of papaya species
	Guava	% of trees of guava species
	OtherFruit	% of trees of less frequent species
% Cultivar		Orchard composition of mango tree cultivars
	Kent	% of mango trees of cv. Kent
	Keitt	% of mango trees of cv. Keitt
	BDH	% of mango trees of cv. Boucodiékhal (BDH)
	DBG	% of mango trees of cv. Dieg bou gatt (DBG)
	Séwé	% of mango trees of cv. Séwé
	OtherMango	% of mango trees of less frequent cultivars
Group 2. Orchard management		
Pasture	*Pasture	Level of secondary use of the orchard for pasture by ruminants
OtherCrop	*OtherCrop	Level of secondary use of the orchard for cultivation of associated food or vegetable crops
Irrigation	*Irrigation	Irrigation intensity based on the amount of water supplied and mechanization level
SoilCare	*SoilCare	Shallow tillage and/or mechanical weeding for soil care
Pesticide	*Pesticide	Application frequency of natural or synthetic pesticides
Fertilization	*Fertilization	Fertilization intensity based on the amount and form of N supplied
FruitPicking	FruitPicking	Picking up frequency of fallen fruits for preventive fruit fly control
Group 3. Orchard vegetation state		
Mortality	Mortality	Mortality rate of trees
Height	*Height	Mean height of living trees (m)
HeightCV	HeightCV	Coef. of variation of the heights of living trees
Vigour	*Vigour	Mean vigour index of living trees
Cover	*Cover	Mean local ground coverage by the tree canopy (%)
CoverCV	*CoverCV	Coef. of variation of the local ground coverage by the tree canopy
Litter	*Litter	Mean litter abundance index of trees

were distributed within all microhabitats (sun-exposed habitats, shaded habitats and hedges). The traps were made of plastic pots (diameter 7.5 cm; height 8 cm), buried in the soil with their opening at soil level and half filled with soapy water. The traps remained in the field for 48 h. Collected ants were first sorted into morphospecies groups. Then, representative samples of morphospecies groups were assigned to species by Dr. Brian Taylor (using his on-line resource, “The Ants of (sub-Saharan) Africa”[1]).

2.4. Relations between orchard characteristics and ant diversity and richness

As there were no missing traps, the Shannon diversity index (α-diversity) was calculated for each orchard using the total number of pitfall traps containing a given species (out of the 40 collected pitfalls) as the measure of ant species abundance in the focal orchard. Ant richness, which amounts to the number of species in each orchard was also determined. Variations in ant richness and diversity between the four orchard types were tested with a Kruskal–Wallis test. A Kruskal multiple test was used to separate factor modalities when a significant effect was detected.

The relation between orchard characteristics relative to orchard design, management practices and vegetation state (i.e. Tree richness, Density, DensityCV, Pasture, Irrigation, SoilCare, Pesticide, Fertilization, Vigour, Height, Cover, CoverCV, OtherCrop and Litter; see definition in Table 1) on ant diversity and richness was tested using the Generalized Linear Model (GLM) with Gaussian error distribution followed by a type-II analysis of the deviance with a F test. These 14 variables were chosen because the others were unlikely to influence ant biodiversity. These selected variables characterized vegetation structure and human management practices in orchards.

2.5. Characterization of orchard types based on ant communities

A typology of the 49 orchards was also built using the composition of the ant communities. As there were no missing traps, the abundance of each ant species in each orchard was computed as the total number of pitfall traps that contained the species. This typology and all other following analyses for ants were performed on data pooled for the two sampling periods in order to obtain a more accurate characterisation of the ant community of each orchard. We computed a Bray–Curtis dissimilarity matrix on log-transformed abundance data and we built a dendrogram of the orchards based on Bray–Curtis pairwise distances using Ward’s agglomeration method.

---

[1] http://antsofafrica.org/, revised and re-launched September 2013 and archived by the UK Web Archive http://www.webarchive.org.uk).

2.6. Relations between orchard characteristics and ant community composition

We first tested the congruence between orchard typologies based on the ant community and design and management practices using a Fisher exact test on a contingency table of the two orchard typologies.

Then, a redundancy analysis (RDA), which is a method combining regression and a principal component analysis, was performed to visualize the relation between the composition of the ant community and the 14 selected variables (i.e. Tree richness, Density, DensityCV, OtherCrop, Irrigation, Pesticide, Fertilization, SoilCare, Cover, CoverCV, Vigour, Height, Pasture and Litter, Table 1). These variables were the same as those used in the GLM analysis and were selected for the same reason. Hellinger transformation was applied to ant abundances for use in the RDA. As rare species can mislead interpretation of RDA results, we removed species detected in fewer than 10 pitfall traps over the 1960 sampled (49 orchards × 2 seasons × 20 pitfalls/orchard/season). This choice of 10 pitfalls was discretionary and depended on the consideration the collector gave to a rare species in the prospected area. Treatment of rare species is problematic because they can strongly influence the results of the analysis without being related to an effect of the environment on the communities.

All the statistical tests, models and figures were carried out with R statistical software (R Development Core Team, 2011). The "FactomineR" R package (Husson et al., 2011) was used to build the typology based on orchard design and management practices. The

Table 2
List of ant species collected in the 49 orchards in the dry and rainy periods in 2012. The species code is the code for the morphotypes used in statistical analyses.

Subfamily	Species code	Species	Rare species
Cerapachyinae	Cer	*Cerapachys longitarsus* (Mayr, 1879)	X
Dolichoderinae	Tap	*Tapinoma demissum* (Bolton, 1995)	
	Tap	*Tapinoma melanocephalum* (Fabricius, 1793)	
	Tec	*Technomyrmex senex* (Bolton, 2007)	
Dorylinae	Dor	*Dorylus aegyptiacus* (Mayr, 1865)	
Formicinae	Cam_ves	*Camponotus vestitus* (F Smith, 1858)	
	Cam_ser	*Camponotus sericeus* Fabricius, 1798)	
	Cam_oas	*Camponotus oasium* (Forel, 1890)	
	Cat	*Cataglyphis abyssinica* (Forel, 1904)	
	Cat	*Cataglyphis savignyi* (Dufour, 1862)	
	Lep_ach	*Lepisiota acholli* (Weber, 1943)	
	Lep_lae	*Lepisiota laevis* (Santschi, 1913)	
	Oec	*Oecophylla longinoda* (Latreille, 1802)	
	Par	*Paratrechina longicornis* (Latreille, 1802)	
	Tal_sim	*Tapinolepis simulans* (Santschi, 1908)	
	Tal_nsp	*Tapinolepis* sp.	
Myrmicinae	Car	*Cardiocondyla emeryi* (Forel, 1881)	
	Cre_bru	*Crematogaster brunneipennis* (André, 1890)	X
	Cre_coe	*Crematogaster coelestis* (Santschi, 1911)	X
	Cre_sen	*Crematogaster senegalensis* (Roger, 1863)	X
	Cre_kne	*Crematogaster kneri* (Mayr, 186)	
	Mer	*Meranoplus magrettii* (André, 1884)	X
	Mes	*Messor galla* (Mayr, 1904)	
	Mon_are	*Monomorium areniphilum* (Santschi, 1911)	
	Mon_bic	*Monomorium bicolor* (Emery, 1877)	
	Mon_dak	*Monomorium dakarense* (Santschi, 1914)	
	Mon_mt4	*Monomorium oscaris* (Bolton, 1987)	
	Mon_mt4	*Monomorium osiridis* (Santschi, 1915)	
	Mon_sal	*Monomorium salomonis* (Linnaeus, 1758)	
	Mon_von	*Monomorium vonatu* (Bolton, 1987)	
	Phe_aeb	*Pheidole aeberlii* (Forel, 1894)	
	Phe_beq	*Pheidole bequaerti* (Forel, 1913)	
	Phe_mt2	*Pheidole andrieui* (Santschi, 1930)	
	Phe_mt2	*Pheidole mentita* (Santschi, 1914)	
	Phe_mt2	*Pheidole rugaticeps* (Emery, 1877)	
	Phe_meg	*Pheidole megacephala* (Fabricius, 1793)	
	Phe_ter	*Pheidole termitophila* (Forel, 1904)	
	Phe_wel	*Pheidole welgelegensis* (Forel, 1913)	
	Tet_ang	*Tetramorium angulinode* (Santschi, 1910)	X
	Tet_sim	*Tetramorium simillimum* (F Smith, 1851)	
	Tet_ser	*Tetramorium sericeiventre* (Emery, 1877)	
	Tet_mus	*Tetramorium muscorum* (Arnold, 1926)	
	Tet_rot	*Tetramorium rothschildi* (Forel, 1907)	
Ponerinae	Ano_beq	*Anochetus bequaerti* (Forel, 1913)	
	Ano_rot	*Anochetus rothschildi* (Forel, 1907)	X
	Ano_sed	*Anochetus sedilloti* (Emery, 1884)	X
	Bra	*Brachyponera sennaarensis* (Mayr, 1862)	
	Pal	*Paltothyreus tarsatus* (Emery, 1899)	
Pseudomyrmicinae	Tetp	*Tetraponera claveaui* (Santschi, 1913)	X

"vegan" R package (Oksanen et al., 2011) was used to compute and build the dendrogram clustering the orchards based on the ant community and to perform the RDA analysis.

3. Results

3.1. Species richness and composition of ant samples

In all, 73,594 ants (43,296 in the dry period and 30,298 in the rainy period) belonging to 49 species, 21 genera and 7 subfamilies were collected. Some species of the same genus were however merged because it was too difficult to separate them in the pitfall samples (these species are identified with a same species code in Table 2). It led us to consider only 44 morphospecies for analysis. The most diverse subfamilies were Myrmicinae (27 species) followed by Formicinae (11 species), Ponerinae (5 species), Dolichoderinae (3 species) and Pseudomyrmecinae, Dorylinae, Cerapachyinae (1 species). The genera *Pheidole*,*Monomorium*, and *Tetramorium* showed the highest species richness (8, 7, and 5, respectively) whereas other genera comprised only 1–4 species. Among the 44 morphospecies, nine were considered as "rare" species (i.e. they were detected in fewer than 10 pitfall traps out of the total dataset).

3.2. Relations between orchard characteristics and ant diversity and richness

Ant richness was significantly different across orchard types based on orchard design and management practices ($\chi^2 = 10.02$; df = 3; $P < 0.05$; Fig. 2A). Ant diversity followed the same trend as ant richness but differences between the orchard types were only marginally significant ($\chi^2 = 7.58$; df = 3; $P = 0.055$; Fig. 2B). Orchards of type (3) 'medium-input citrus-predominant orchards' displayed the greatest ant diversity and ant richness out of the four orchard types, while orchards of type (4) 'medium-input large mango- or citrus-predominant orchards' displayed the lowest values. Ant diversity and ant richness were at intermediate levels in orchards of types (1) and (2). When considering only orchards of types (3) and (4) and classing these orchards according to their main tree species, it appeared that ant diversity and ant richness were greater in citrus-based orchards than in mango-based orchards, but the differences were only marginally significant (Fig. 3; $\chi^2 = 3.38$; df = 1; $P = 0.06$ for ant richness and $\chi^2 = 3.15$; df = 1; $P = 0.07$ for ant diversity). The GLM tests on the 14 variables indicated that tree richness and pesticides had significant effects on ant richness ($F = 8.04$; df = 1; $P < 0.01$ and $F = 3.29$, df = 1, $P < 0.05$, respectively). In addition, soil care showed a marginal significant effect on ant richness ($F = 3.29$; df = 1; $P = 0.08$). Tree richness showed a significant effect on ant diversity too ($F = 4.96$; df = 1; $P < 0.05$). Ant richness and diversity increased with tree richness, whereas ant richness tended to decrease when moving from orchards where there was not soil care to orchards treated with shallow tillage and/or mechanical weeding of soil (Fig. 4).

3.3. Relations between orchard characteristics and ant community composition

The results for the categorization of orchards based on orchard design and management practices led to the 49 orchards being classed in 9 orchards of type (1), 14 of type (2), 14 of type (3) and 12 of type (4).

The results for the categorization of orchards based on ant community composition revealed four groups: (A), (B), (C) and (D) composed of 22, 11, 8 and 8 orchards, respectively (Fig. 5). A comparison of ant species composition between orchard groups is shown in Fig. 6. Group (A) was dominated by *Monomorium bicolor* (Mon_bic), followed by *Camponotus oasium* (Cam_oas), and *Tetramorium sericeiventre* (Tet_ser). Group (B) was dominated by *Pheidole aeberlii* (Phe_aeb) followed by *Monomorium salomonis* (Mon_sal). Group (C) was dominated by *Monomorium bicolor* followed by *Pheidole aeberlii*, *Tetramorium sericeiventre*, and *Monomorium*spp (Mon_mt4). Group (D) was dominated by

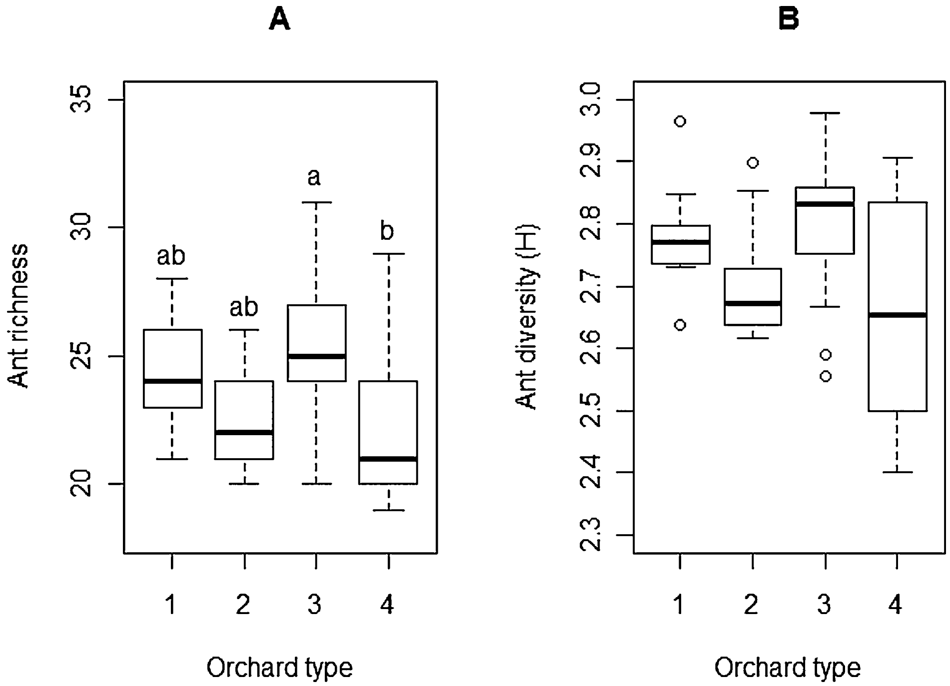

Fig. 2. Ant richness (A) and ant diversity (B) in the four orchard types: (1) "no-input mango diversified orchards", (2) "low-input mango orchards", (3) "medium-input citrus-predominant orchards" and (4) "medium-input large mango- or citrus-predominant orchards". Orchard types with different letters are significantly different (multiple comparison test after Kruskal–Wallis test; $P < 0.05$).

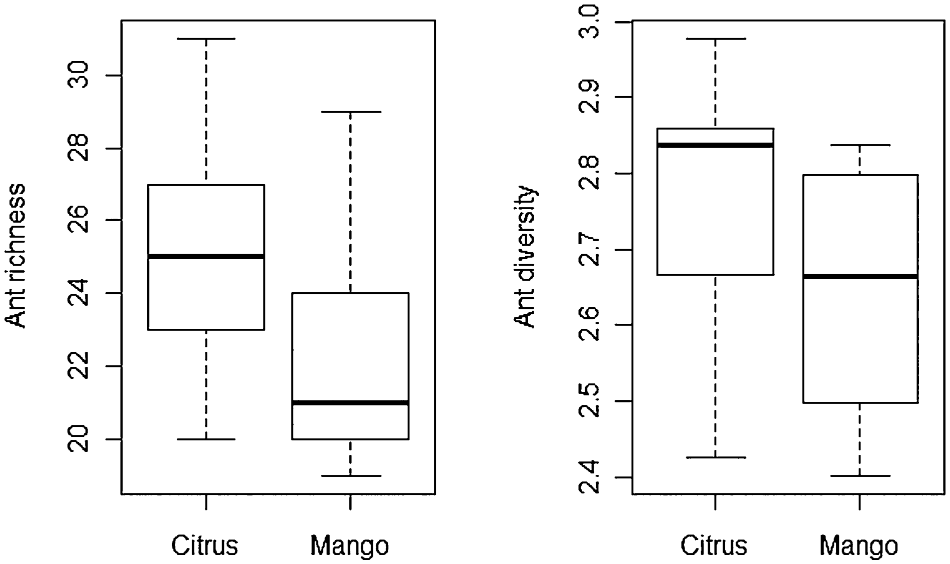

Fig. 3. Variation in ant richness and ant diversity depending on the main crop in the type 3 and type 4 orchards located in the localities of Ndoyenne and Notto. Citrus orchards were continuously irrigated and mango orchards were only irrigated for five months (January–May).

Tetramorium sericeiventre followed by *Pheidole aeberlii* and *Pheidole termitophila* (Phe_ter).

The two typologies of orchards based on ant community and design/management practices were significantly congruent (Fisher exact test: $P < 0.001$). Two groups of orchards were very characteristic: group (B), which was composed of 90.9% type (4) orchards and group (D) composed of 100% type (3) orchards (Fig. 5). The other two groups, (A) and (C) did not show any specific

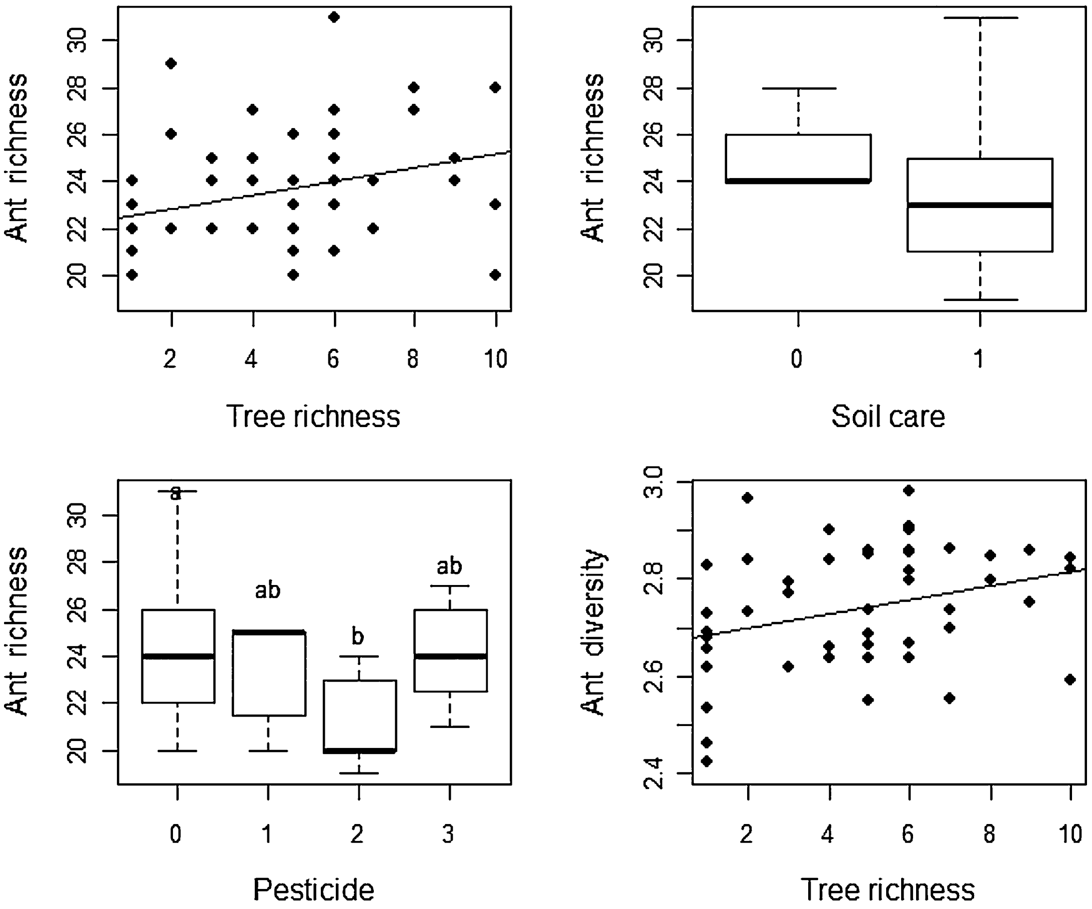

Fig. 4. Relations between ant richness, ant diversity and two variables relative to orchard design (tree richness) and management practices (soil care: 0 = no soil care, 1 = shallow tillage and/or mechanical weeding of soil; pesticide: 0 = no pesticide, 1 = 1–2 applications per year, 2 = 3–5 applications per year, 3 = more than 5 applications per year).

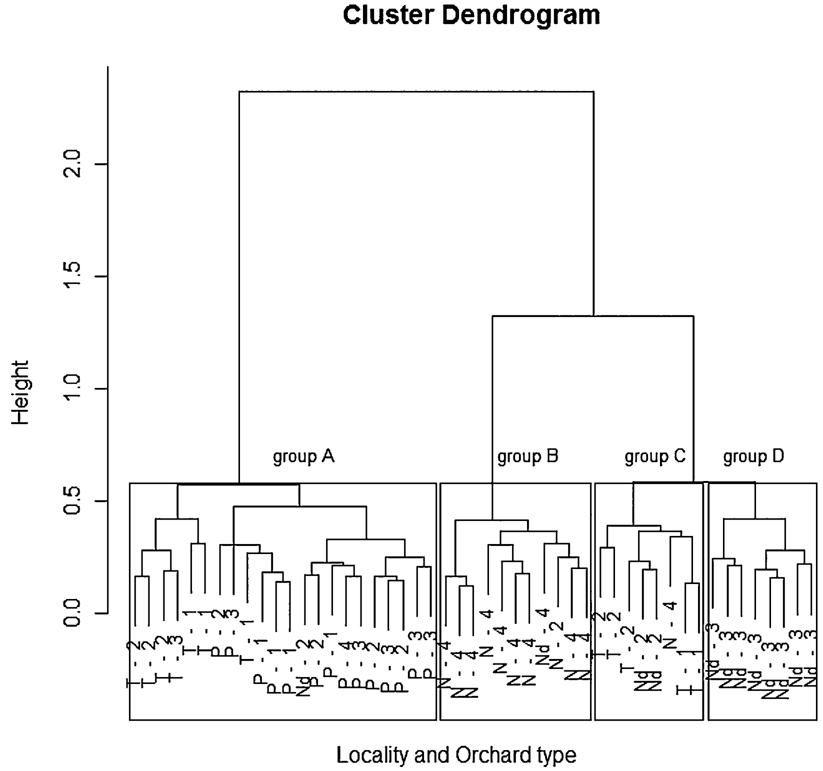

Fig. 5. Dendrogram clustering the Senegalese orchards in four groups (A, B, C and D) according to resemblances in their ant community composition. The orchard label is composed of letters indicating the localities in which the orchard is located (T = Thiès, P = Pout, N = Notto, Nd = Ndoyenne), followed by a number standing for the orchard type according to the typology based on orchard design and management practices: (1) 'no-input mango diversified orchards', (2) 'low-input mango orchards, (3) 'medium-input citrus-predominant orchards' and (4) 'medium-input large mango- or citrus-predominant orchards'.

orchard composition. Group (A) was composed of type (1) (31.8%), type (2) (36.3%) and type (3) (27.2%) orchards. Group (C) was composed of type (2) (62.5%), type (1) (25%) and type (4) (12.5%) orchards. The ant community was also significantly linked to the localities (Fisher exact test: $P < 0.001$). Groups (B) and (D) were composed of 90.9% and 100% orchards from Notto and Ndoyenne, respectively. In group (A), 63.3% of the orchards were located in Pout and 31.8% in Thiès. Group (C) comprised 62.5% of orchards from Thiès, 25% from Ndoyenne and 12.5% from Notto.

A redundancy analysis on all the orchards showed a relatively good adjustment model (adjusted $R^2 = 0.31$, meaning that 31% of the variability was explained by the model and 69% was not redundant), and the overall test was significant (10,000 permutations test on factorial axes, $P < 0.001$), indicating a relationship between the ant community and orchard characteristics. The first five axes of the RDA were significant (10,000 permutations on factorial axes), with 15% of the total variance explained by the first axis and 19% by the first two axes. The correlation plot of the design, management and vegetation state variables, ant species and orchard types with respect to the first two RDA axes, is shown in Fig. 7. Three groups of variables were individualized in the RDA plot: one group formed by pesticide use, fertilization and irrigation, one group formed by the level of litter, tree richness, local ground coverage by the tree canopy and the coefficient of variation of the planting density and another group formed by soil care and coefficient of variation of local ground coverage by the tree canopy. The variable called Cover indicates the overall ground coverage of the orchard by the tree canopy and not by mulch. Vigour was opposed to the first group of cited variables. The scatter of the orchards on the first two axes was mainly explained by these groups of variables (Fig. 7A). *Monomorium salomonis* (Mon_sal) was closely associated with high irrigation, fertilization and pesticide use. Conversely, *Brachyponera sennaarensis* (Bra), *Monomorium bicolor* (Mon_bic) and *Pheidole megacephala* (Phe_meg) were negatively associated with these variables but rather associated with vigour. *Camponotus sericeus* (Cam_ser), *Cataglyphis* spp. (Cat) and *Crematogaster kneri* (Cre_kne) were associated with high variation in of soil coverage by the tree canopy (CoverCV). *Paltothyreus tarsatus* (Pal) was associated with tree richness, abundant leaf litter and plenty of shade (Fig. 7B).

4. Discussion and conclusion

4.1. Ant diversity, ant richness and relations with orchard type

The ant richness in mango and citrus orchards in Senegal proved to be comparable to that found in other African agroecosystems. For instance, Kone et al. (2014) in Ivory Coast identified 43, 52, 57 and 73 species in four different cocoa agroecosystems. Tadu et al. (2014) in Cameroon identified 52, 53 and 61 species in three cocoa agroecosystems. Murnen et al. (2013) found 39 and 65 species from respectively low-shaded and high-shaded coffee in two American agroecosystems (Mexico).

Our results demonstrated that there is a link between ant biodiversity and orchard type characterized by design and management practices. Both ant diversity and richness varied depending on the orchard type. Type (4) orchards, which displayed higher intensification levels with a less diversified set of trees (Grechi et al., 2013), had the lowest ant diversity and richness. On the other hand, type (3) orchards, with the greatest tree richness, planting densities and variation in local planting density (Grechi et al., 2013), had the greatest ant diversity and richness. These results confirm previous studies showing the frequent increase in ant diversity and richness observed in heterogeneous landscapes

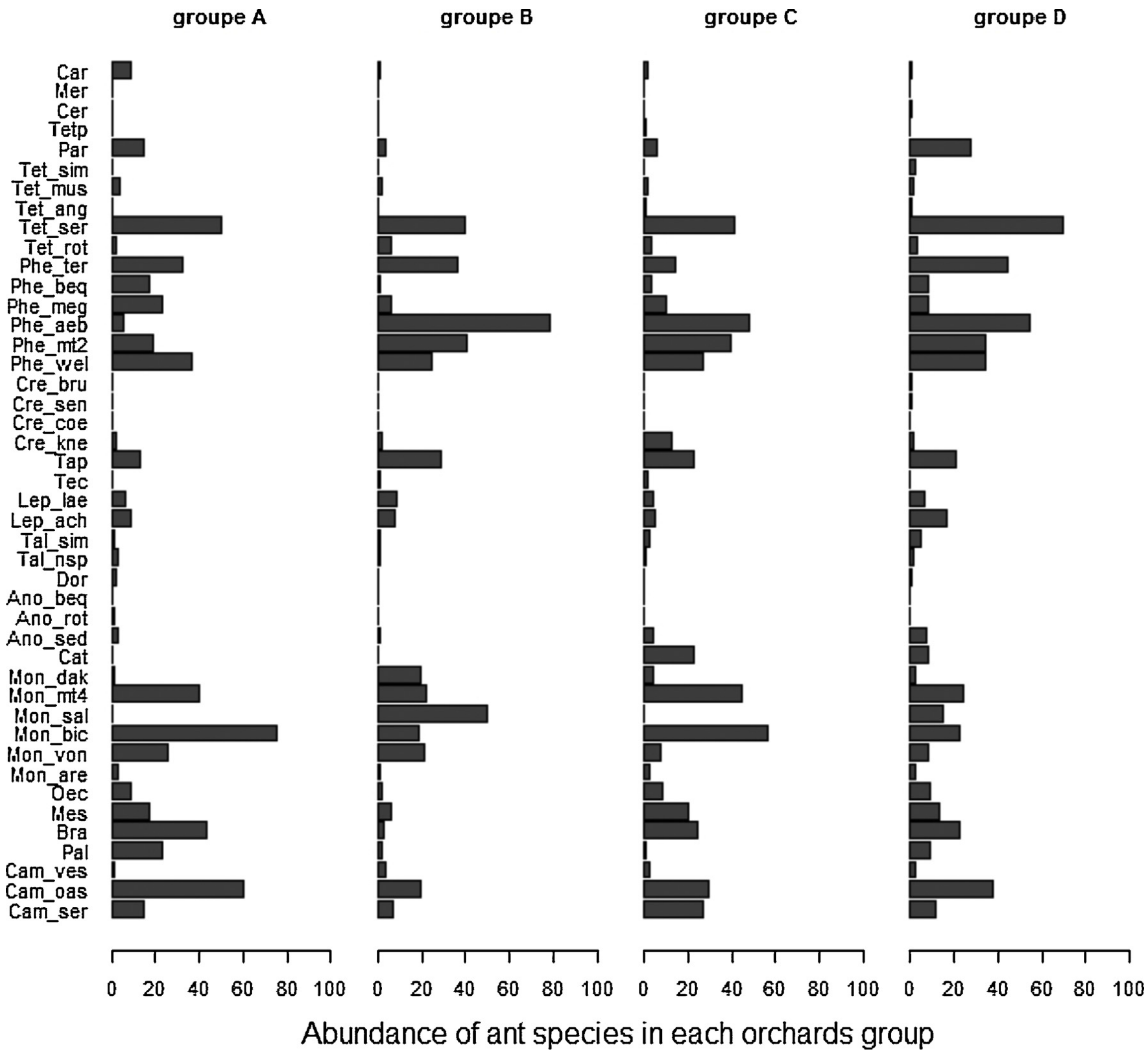

Fig. 6. Abundances of ant species in the four orchard groups (A), (B), (C) and (D) that were defined according to resemblances in their ant community composition. Values are the % of pitfalls in which a species was present out of the total number of pitfalls collected in all the orchards of the groups during the dry and rainy periods (i.e. 880, 440, 320 and 320 pitfalls in groups (A), (B), (C) and (D), respectively). For full names of ant species see Table 2.

(Ribas et al., 2003; Hill et al., 2008; Pacheco and Vasconcelos, 2012; De la Mora et al., 2013) and their decline in landscapes subject to high management intensity (Ribas and Schoereder, 2007; House et al., 2012). The greatest tree richness and coefficient of variation for the local planting density observed in the type (3) orchards created microenvironmental diversity generated by the existence of empty spaces and plant-mosaic portions in those orchards. A heterogeneous planting density in the orchards may have offered refuge to both shade-tolerant species and open ground-tolerant species (Reyes-Lopez et al., 2003), explaining the greater ant richness and diversity than in orchards with uniform planting density observed in our study, in a Mexican desert (Bestelmeyer and Schooley, 1999) and in Mediterranean pasturelands (Reyes-Lopez et al., 2003). Perfecto and Vandermeer (1996) showed the effects of microclimatic differences on ant diversity in coffee agroecosystems. Equally, the difference in ant diversity and richness observed between citrus and mango orchards might be explained by microclimatic differences in citrus and mango orchards. It is likely that they differed in moisture availability, since citrus trees were irrigated throughout the year, while the mango-based orchards were only irrigated for approximately four months (from flowering to the early rainy season).

4.2. Ant community structure depending on the locality and the orchard type

In our study, ant communities were related to the locality and the orchard type. The previous study by Grechi et al. (2013) in the same agroecosystems showed a close relation between the locality and the orchard type. A causal link between the climatic parameters of localities and orchard type is unlikely because the design and management of orchards in the same study zone were mainly based on historical, sociological and economic choices rather than on environmental grounds (Vannière et al., 2004). The association between ant communities and locality may thus simply result from the relationship that we found between orchard type and ant community. Alternatively, it may be due to environmental variation across localities. Indeed, large-scale geographical variables (latitude, longitude and elevation) and small-scale site variables (habitat area, vegetation composition, microclimate and light availability) are both factors reported as being able to affect ant diversity and/or richness (Gotelli and Ellison, 2002).

The ant communities of groups (B) and (D) were very typical of type (4) and type (3) orchards, respectively. The type (3) orchard

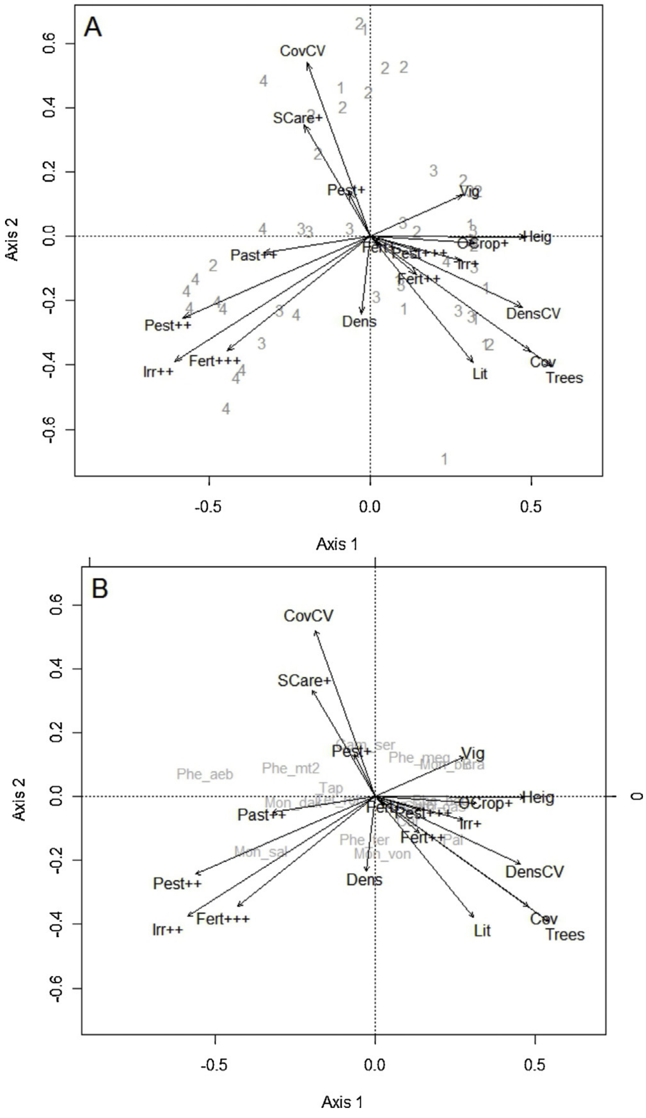

Fig. 7. Correlation plot of orchard design, management and vegetation state variables (arrows) and either orchard types (numbers in grey) (A) or ant morphotypes (grey) (B) with respect to the first two redundancy analysis (RDA) axes. For clarity, ant morphotypes with coordinates <0.1 on axes 1 and 2 have been removed.

Abbreviations for design, management and vegetation state variables mean Density (Dens), DensityCV (DensCV), Cover (Cov), CoverCV (CovCV), SoilCare (SCare), Pesticide (Pest), Fertilization (Fert), Irrigation (Irr), OtherCrop (OCrop), Litter (Lit), Tree richness (Trees), Vigour (Vig), Height (Heig), Pasture (Past).

Code for level of management practice:

SCare: (−) = no soil care, (+) = shallow tillage and/or mechanical weeding of soil.

Pest: (−) = no pesticide, (+) = 1–2 applications per year, (++) = 3–5 applications per year, (+++) = more than 5 applications per year.

Fert: (−) = no fertilizer, (+) = under 0.5 kg of N/year/tree only with manure, (++) = under 0.5 kg of N/year/tree in manure and/or mineral fertilizer, (+++) = over or equal to 0.5 kg of N/year/tree in manure or mineral fertilizer.

Irr: (−) = no irrigation, (+) = watering less than or equal to 200 l/tree/week, (++) = watering over or equal to 200 l/tree/week.

OCrop: (−) = no secondary use of orchard for other crops (food crop or market gardening), (+) = secondary use of orchard for other crops (food crop or market gardening).

Past: (−) = no pasture, (+) = occasionally or isolated animals, (++) = regular or flock.

associated with the Ndoyenne locality were dominated by citrus trees, which require a high level of watering and are irrigated continuously, while those of type (4), associated with Notto, were dominated by mango trees, which are only irrigated for a short period in the year. In such a situation, microclimatic conditions, which vary with irrigation regimes, can be indexed as potential factors involved in differences in ant communities. We put forward our hypothesis based on several studies that had already reported that ecosystem microclimates have an influence on ant community structures (Perfecto and Vandermeer, 1996; Retana and Cerdá, 2000; Castracani et al., 2010; Rosado et al., 2013). In the same way as it influences ant diversity and richness, moisture is an important factor in the of ant communities composition. Levings (1983) demonstrated the importance of soil moisture in structuring ant communities either through rainfall or through experimental watering during the dry season. However, in our case study, it was not possible to confirm that the collection of ant species under particular moisture conditions was due to a species preference for such ecological conditions, since the ecology of ant species collected in Senegal is relatively unknown.

A different ant community assemblage was exhibited by group (A). In this case, the influence of limited management practices was more conspicuous since the orchards in the localities of Pout (Pout sigelec, Pout town), and Thiès (Thiès east, Thiès west), which formed this group (mostly type (1) and type (2)) were not subjected to particularly strong farming practices. These orchards were supplying local markets and showed no particular farming programme over the year. This was unlike those of type (4) in the locality of Notto, which grew fruits for the export market and displayed higher intensification levels (Ndiaye et al., 2012). The weak or non-existent technical interventions in type (1) and type (2) orchards were conductive to high leaf litter levels, no pesticide use and no fertilizer inputs that influenced ant diversity, ant richness or ant community structure, as reported by other studies demonstrating the sensitivity of ants to environmental conditions (Peck et al., 1998; New, 2000; Hernández-Ruiz and Castaño-Meneses, 2006; Torchote et al., 2010; Chen et al., 2011; Wiescher et al., 2012; Bernadou et al., 2013). For the group (A) orchards, one ecological factor able to influence the ant community was the vegetation stratum which determines the amount of leaf litter (Perfecto and Snelling, 1995; Ellison et al., 2002; Boulton et al., 2005), depending on whether or not there was orchard cleaning. We found that such orchards registered high levels of leaf litter due to a lack of cleaning practices.

The characteristic association between orchard type and some ant species strongly suggests that farming practices influence ant communities. The association of *Monomorium salomonis* with management variables such as pesticides, irrigation and fertilizers that are abundantly applied in type (4) orchards supports this finding. Indeed, this species is highly anthropophile and withstands a high level of environmental disturbance. In such a habitat, it is competitive and potentially dominant. Other species, such as *Camponotus sericeus, Cataglyphis abyssinica, Cataglyphis savignyi* and *Crematogaster kneri*showed a preference for open areas by virtue of their relative association with orchards having a high coefficient of variation for local ground coverage by the tree canopy. *Paltothyreus tarsatus* typified species found in orchards with greater tree richness, high local ground coverage by the tree canopy, more leaf litter and a large variation in local tree planting density, i.e. orchards with limited cleaning practices. This combination favoured ponerine ants such as *Paltothyreus tarsatus*, which is a forest or forest-savannah transition species foraging in the leaf litter. This ant species was very characteristic of group (A) orchards and might indicate orchards with high availability of ecological resources.

Our study confirmed the hypothesis that orchard design and management practices affect ant richness, ant diversity and ant community composition. It supported the concept that ecosystem diversity is a key element in biodiversity conservation (Petal, 1971; Dahms et al., 2005; Rizali et al., 2013). The study is relevant also in showing the way in which orchard design and management practices can affect ant diversity and composition even if the contrasts are less distinct compared to those usually found between open areas and forestry patches (Urrutia-Escobar and Armbrecht, 2013). In the same way as in temperate and tropical climatic regions, where the potential of ants to be used as biological and ecological indicators has already been demonstrated, ants can also be used similarly in the Sahelian regions. In Senegalese fruit-based agroecosystems, mainly dominated by mango and *Citrus* fruit crops, we identified two ant species that could be used as ecological indicators. *Monomorium salomonis* was characteristic of intensive agricultural practices that resulted in a high level of environmental disturbance. On the other hand, *Paltothyreus tarsatus* was characteristic of orchards with greater tree richness, high local ground coverage by the tree canopy, more leaf litter and a large variation in local tree planting density. This study is a first step in the development of biological indicators for African agroecosystems and provides evidence that ants may be good candidates.

The main findings from this study are that management practices are very likely to affect ant diversity and ant community structure. Among them, pesticide use, irrigation and fertilizers constitute the more obvious factors affecting ants. Ants are particularly sensitive to pesticides because they are central-place foragers, concentrating resources, and thus, pesticides gathered from a large area, in one point (the nest), and because they exchange food via trophallaxis, thus rapidly spreading pesticides potentially ingested across congeners (Rust et al., 2003), resulting in high mortality (Dong-Hwan and Rust, 2008). An ultimate goal for agroecosystem managers might not necessarily be to favour high ant diversity but rather a set of species that are efficient for crop protection. Integrated Pest Management (IPM) models are examples where low ant diversity, provided that the right species are present, can be beneficial for producers. In recommendations for sustainable farming practices, farmers need to be made more aware of how to control pests in agroecosystems by adopting environment-friendly approaches where environmental parameters involving trophic systems are taken into account (e.g. preservation of beneficial arthropods by reducing pesticide use in agroecosystems).

Acknowledgements

We are grateful to the PDMAS organisation which financially supported this research. Thanks also go to the orchard owners for their full collaboration and acceptance of experiments in their orchards. Thanks also to our field assistants (Moustapha Badj, Famara Badj, Christian Ndione and Pierre Ndione) and our laboratory assistants (Ardachir Yasmine and Ablaye Ndour). We are grateful to Diariétou Sambakhé (CERAAS-Thiès) for his advice on statistical analyses. We also thank Peter Biggins for revising the English of the article.

References

Altieri, M., 1999. The ecological role of biodiversity in agroecosystems. Agric. Ecosyst. Environ. 74, 19–31.

Andersen, A.N., Hoffmann, B.D., Müller, W.J., Griffiths, A.D., 2002. Using ants as bioindicators in land management: simplifying assessment of ant community responses. J. Appl. Ecol. 39, 8–17.

Andersen, A.N., Majer, J.D., 2004. Ants show the way Down Under: invertebrates as bioindicators in land management. Front. Ecol. Environ. 2, 291–298.

Andersen, A.N., Fisher, A., Hoffmann, B.D., Read, J.L., Richards, R., 2004. Use of terrestrial invertebrates for biodiversity monitoring in Australian rangelands, with particular reference to ants. Austral Ecol. 29, 87–92.

Benton, T.G., Vickery, J.A., Wilson, J.D., 2003. Farmland biodiversity: is habitat heterogeneity the key? Trends Ecol. Evol. 18, 182–188.

Bernadou, A., Céréghino, R., Barcet, H., Combe, M., Espadaler, X., Fourcassie, V., 2013. Physical and land-cover variables influence ant functional groups and species diversity along elevational gradients. Landsc. Ecol. 28, 1387–1400.

Bestelmeyer, B.T., Schooley, R.L., 1999. The ants of the southern Sonoran desert: community structure and the role of trees. Biodivers. Conserv. 8, 643–657.

Boulton, A.M., Davies, K.F., Ward, P.S., 2005. Species richness, abundance, and composition of ground-dwelling ants in Northern California grasslands: role of plants, soil, and grazing. Environ. Entomol. 34, 96–104.

Burel, F., Lavigne, C., Marshall, E.J.P., Moonen, A.C., Ouin, A., Poggio, S.L., 2013. Landscape ecology and biodiversity in agricultural landscapes. Agric. Ecosyst. Environ. 166, 1–2.

Castracani, C., Grasso, D.A., Fanfani, A., Mori, A., 2010. The ant fauna of Castelporziano Presidential Reserve (Rome, Italy) as a model for the analysis of ant community structure in relation to environmental variation in Mediterranean ecosystems. J. Insect Conserv. 14, 585–594.

Chen, Y.-q., Li, Q., Chen, Y.-l., Lu, Z.-X., Zhou, X.-y., 2011. Ant diversity and bio indicators in land management of lac insect agroecosystem in Southwestern China. Biodivers. Conserv. 20, 3017–3038.

Dahms, H., Wellsten, C., Wolters, V., Dauber, J., 2005. Effects of management practices on ant species richness and community composition in grasslands (Hymenoptera: Formicidae). Myrmecol. News 7, 9–16.

De la Mora, A., Murnen, C.J., Philpott, S.M., 2013. Local and landscape drivers of biodiversity of four groups of ants in coffee landscapes. Biodivers. Conserv. 22, 871–888.

Dong-Hwan, C., Rust, M.H., 2008. Horizontal transfer of insecticides in laboratory colonies of the argentine ant (Hymenoptera: Formicidae). J. Econ. Entomol. 101, 1397–1405.

Ellison, A.M., Farnsworth, E.J., Gotelli, N.J., 2002. Ant diversity in pitcher-plant bogs of Massachusetts. Northeast. Nat. 9, 267–284.

Folgarait, P., 1998. Ant biodiversity and its relationship to ecosystem functioning: a review. Biodivers. Conserv. 7, 1221–1244.

Giller, K.E., Witter, E., Corbeels, M., Tittonell, P., 2009. Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crops Res. 114, 23–34.

Gotelli, N.J., Ellison, A.M., 2002. Biogeography at a regional scale: determinants of ant species density in New England bogs and forests. Ecology 83, 1604–1609.

Gove, A.D., 2007. Ant biodiversity and the predatory function (A response to Philpott and Armbrecht, 2006). Ecol. Entomol. 32, 435–436.

Grechi, I., Sane, C.A.B., Diame, L., De Bon, H., Benneveau, A., Michel, T., Huguenin, V., Malezieux, E., Diarra, K., Rey, J.-Y., 2013. Mango-based orchards in Senegal: diversity of design and management patterns. Fruits 68, 447–466.

Hernández-Ruiz, P., Castaño-Meneses, G., 2006. Ants (Hymenoptera: Formicidae) diversity in agricultural ecosystems at Mezquital Valley, Hidalgo, Mexico. Eur. J. Soil Biol. 42, S208–S212.

Hill, J.G., Summerville, K.S., Brown, R.L., 2008. Habitat associations of ant species (Hymenoptera: Formicidae) in a heterogeneous Mississippi landscape. Environ. Entomol. 37, 453–463.

Hoffmann, B.D., Andersen, A.N., 2003. Responses of ants to disturbance in Australia with particular reference to functional groups. Austral Ecol. 28, 444–464.

Hooper, D.U., Vitousek, P.M., 1997. The effects of plant composition and diversity on ecosystem processes. Science 277, 1302–1305.

Hooper, D.U., Chapin III, F.S., Ewel, J.J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J. H., Lodge, D.M., Loreau, M., Naeem, S., Schmid, B., Setälä, H., Symstad, A.J., Vandermeer, J., Wardle, D.A., 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. Ecol. Monogr. 75, 3–35.

House, A.P.N., Burwell, C.J., Brown, S.D., Walters, B.J., 2012. Agricultural matrix provides modest habitat value for ants on mixed farms in eastern Australia. J. Insect Conserv. 16, 1–12.

Husson, F., Josse, J., Le, S., Mazet, J., 2011. FactoMineR: Multivariate Exploratory Data Analysis and Data Mining with R. http://factominer.free.fr.

James, D.G., Stevens, M.M., O'Malley, K.J., Faulder, R.J., 1999. Ant foraging reduces the abundance of beneficial and incidental arthropods in citrus canopies. Biol. Control 14, 121–126.

Kone, M., Konate, S., Yeo, K., Kouassi, P.K., Linsenmair, K.E., 2014. Effects of management intensity on ant diversity in cocoa plantation (Oumé, centre west Côte d'Ivoire). J. Insect Conserv. 18, 701–712.

Levings, S.C., 1983. Seasonal, annual, and among-site variation in the ground ant community of a deciduous tropical forest: some causes of patchy species distributions. Ecol. Monogr. 53, 435–455.

Majer, J.D., Orabi, G., Bisevac, L., 2007. Ants (Hymenoptera: Formicidae) pass the bioindicator scorecard. Myrmecol. News 10, 69–76.

Matson, P.A., Parton, W.J., Power, A.G., Swift, M.J., 1997. Agricultural intensification and ecosystem properties. Science 277, 504–509.

Mcgeoch, M.A., 1998. The selection, testing and application of terrestrial insects as bioindicators. Biol. Rev. 73, 181–201.

Murnen, C.J., Gonthier, D.J., Philpott, S.M., 2013. Food webs in the litter: effects of food and nest addition on ant communities in coffee agroecosystems and forest. Environ. Entomol. 42, 668–676.

New, T.R., 2000. How useful are ant assemblages for monitoring habitat disturbance on grasslands in south eastern Australia? J. Insect Conserv. 4, 153–159.

Ndiaye, O., Vayssières, J.-F., Rey, J.-Y., Ndiaye, S., Diedhiou, P.M., Ba, C.T., Diatta, P., 2012. Seasonality and range of fruit fly (Diptera: Tephritidae) host plants in orchards in Niayes and the Thiès Plateau (Senegal). Fruits 67, 311–331.

Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Wagner, H., 2011. Vegan: Community Ecology Package. R package version 2.0-2. http://CRAN.R-project.org/package=vegan.

Pacheco, R., Vasconcelos, H.L., 2012. Habitat diversity enhances ant diversity in a naturally heterogeneous Brazilian landscape. Biodivers. Conserv. 21, 797–809.

Peck, S.L., Mcquaid, B., Campbell, C.L., 1998. Using ant species (Hymenoptera: Formicidae) as a biological indicator of agroecosystem condition. Environ. Entomol. 27, 1102–1110.

Perfecto, I., Snelling, R., 1995. Biodiversity and the transformation of a tropical agroecosystem: ants in coffee plantation. Ecol. Appl. 5, 1084–1097.

Perfecto, I., Vandermeer, J., 1996. Microclimatic changes and the indirect loss of ant diversity in a tropical agroecosystems. Oecologia 108, 577–582.

Perfecto, I., Armbrecht, I., 2003. The coffee agroecosystem in the neotropics: combining ecological and economic goals. In: Vandermeer, J.H. (Ed.), Tropical Agroecosystems. CRC Press, Boca Raton, London, New York, Washington, D.C, pp. 159–194.

Petal, J., 1971. The effect of mineral fertilization on ant populations in meadows. Pol. Ecol. Stud. 2, 209–2018.

Philpott, S.M., Armbrecht, I., 2006. Biodiversity in tropical agroforests and the ecological role of ants and ant diversity in predatory function. Ecol. Entomol. 31, 369–377.

Philpott, S.M., Greenberg, R., Bichier, P., Perfecto, I., 2004. Impacts of major predators on tropical agroforest arthropods: comparisons within and across taxa. Oecologia 140, 140–149.

R Development Core Team, 2011. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria ISBN 3-900051-07-0, URL http://www.R-project.org/.

Retana, J., Cerdá, X., 2000. Patterns of diversity and composition of Mediterranean ground ant communities tracking spatial and temporal variability in the thermal environment. Oecologia 123, 436–444.

Reyes-Lopez, R., Ruiz, R., Fernández-Haeger, J., 2003. Community structure of ground-ants: the role of single trees in a Mediterranean pastureland. Acta Oecol. 24, 195–202.

Ribas, C.R., Schoereder, J.H., Pic, M., Soares, S.M., 2003. Tree heterogeneity, resource availability, and larger scale processes regulating arboreal ant species richness. Austral Ecol. 28, 305–314.

Ribas, C.R., Schoereder, J.H., 2007. Ant communities, environmental characteristics and their implications for conservation in the Brazilian Pantanal. Biodivers. Conserv. 16, 1511–1520.

Rizali, A., Clough, Y., Buchori, D., Hosang, M.L.A., Bos, M.M., Tscharntke, T., 2013. Long-term change of ant community structure in cacao agroforestry landscapes in Indonesia. Insect Conserv. Divers. 6, 328–338.

Rosado, J.L.O., Gonçalves de Gonçalves, M., Dröse, W., Ely e Silva, E.J., Krüger, R.F., Loeck, A.E., 2013. Effect of climatic variables and vine crops on the epigeic ants fauna (Hymenoptera: Formicidae) in the Campanha region, state of Rio Grande do Sul, Brazil. J. Insect Conserv. 17, 1113–1123.

Rust, M.K., Reierson, D.A., Klotz, J.H., 2003. Pest management of Argentine ants. J. Entomol. Sci. 38, 159–169.

Tadu, Z., Djiéto-Lordon, Yede, C., Messop Youbi, E.B., Fomena, A., Babin, R., 2014. Ant diversity in different cocoa agroforest habitats in the Centre Region of Cameroon. Afr. Entomol. 22, 388–404.

Tilman, D., Knops, J., Wedin, D., Reich, P., Ritchie, M., Siemann, E., 1997. The influence of functional diversity and composition on ecosystem processes. Science 277, 1300–1302.

Thomsen, M., Faber, J.H., Sorensen, P.B., 2012. Soil ecosystem health and services—evaluation of ecological indicators susceptible to chemical stressors. Ecol. Indic. 16, 67–75.

Torchote, P., Sitthicharoenchai, D., Chaisuekul, C., 2010. Ant species diversity and community composition in three different habitats: mixed deciduous forest, teak plantation and fruit orchard. Trop. Nat. Hist. 10, 37–51.

Underwood, E.C., Fisher, B.L., 2006. The role of ants in conservation monitoring: if, when, and how. Biol. Conserv. 132, 166–182.

Urrutia-Escobar, M.X., Armbrecht, I., 2013. Effect of two agroecological management strategies on ant (Hymenoptera: Formicidae) diversity on coffee plantations in southwestern Colombia. Environ. Entomol. 42, 194–203.

Vandermeer, J., Perfecto, I., Philpott, S., 2010. Ecological complexity and pest control in organic coffee production: uncovering an autonomous ecosystem service. BioScience 60, 527–537.

Vannière, H., Didier, C., Rey, J.-Y., Diallo, T.M., Kéita, S., Sangaré, M., 2004. La mangue en Afrique de l'Ouest francophone: les systèmes de production et les itinéraires techniques. Fruits 59, 383–398.

Wardle, D.A., Yeates, G.W., Bonnera, K.I., Nicholson, K.S., Watson, R.N., 2001. Impacts of ground vegetation management strategies in a kiwifruit orchard on the composition and functioning of the soil biota. Soil Biol. Biochem. 33, 893–905.

Weibull, A.-C., Östman, Ö., 2003. Species composition in agroecosystems: the effect of landscape, habitat, and farm management. Basic Appl. Ecol. 4, 349–361.

Wiescher, P.T., Pearce-Duvet, J.M.C., Feener, D.H., 2012. Assembling an ant community: species functional traits reflect environmental filtering. Oecologia 169, 1063–1074.

Wike, L.D., Martin, F.D., Paller, M.H., Nelson, E.A., 2010. Impact of forest seral stage on use of ant communities for rapid assessment of terrestrial ecosystem health. J. Insect Sci. 10 (77) Available online: insectscience.org/10.77.