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Soil carbon and plant diversity distribution at the farm level in the savannah region of Northern Togo (West Africa)

M.-T. Sebastià[1,2], E. Marks[1], and R. M. Poch[2]

[1]Forest Technology Centre of Catalonia (CTFC), Pujada del Seminari s/n, 25280 Solsona, Spain
[2]University of Lleida, Av. Rovira Roure 191, 25198 Lleida, Spain

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Correspondence to: M.-T. Sebastià (teresa.sebastia@ctfc.es)

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Abstract

In western Africa, soil organic matter is a source of fertility for food provision and a tool for climate mitigation. In the Savannah region, strong soil degradation linked to an increase in population threatens organic matter conservation and agricultural yield. Soil degradation is also expected to impact biodiversity and, with it, increase the vulnerability of ecosystem goods and services, including the storage of soil organic carbon. Studies of land use, plant species composition and soil fertility were conducted for a conservation project at a demonstration farm in Northern Togo (West Africa), host to various management regimes. Results showed a low organic matter content of the surface soil horizons, often around 0.5%. The highest values were found in a sacred forest within the farm (2.2%). Among crops, rice had the highest soil organic matter, around 1%. In a survey of grasslands, pastures showed the highest organic matter content, with vegetation composition differing from grazed fallows and abandoned grasslands. Plant species richness showed a positive relationship with soil organic matter (R^2_{adj}=41.2%), but only by the end of the wet season, when species richness was also highest. Sampling date had a strong effect on vegetation composition. Results showed a strong influence of human activity on soil formation and distribution, and also on plant diversity. The soil characteristics found under the permanent forest suggest a high potential of the soils of the region for improvement of both agricultural yields and as a potential carbon sink relevant to global change policies.

1 Introduction

Soil organic matter has long been recognized as a source of fertility because of its capacity for nutrient storage (Jenny, 1980; Herrick and Wander, 1997). Nowadays, soil organic matter stabilization is perceived as a mechanism for organic carbon storage in the soil in the context of current climate change (Goh, 2004). Indeed, soil carbon is the main terrestrial carbon pool (Batjes, 1996). In western Africa, both roles of soil organic matter, as a fertility source and as a tool for climate mitigation, are particularly relevant (Marks et al., this volume). In the Savannah region, soil degradation in the form of erosion is recognized as a constraint to soil quality and agricultural development (Poch and Ubalde, 2006). Soil degradation processes have been linked to an increase in population (locally exceeding 300 inhabitants km^{-2}), with consequences of the loss of soil organic matter and decreases in agricultural yield (Brabant et al., 1996). Increased human population also has an impact on land use change and deforestation, which in turn affects the carbon cycle (Canadell et al., 2007). However, since soil organic matter contents can be improved through human management, there is high potential for carbon sequestration activities in the West African region (Lal, 2002; Tschakert et al., 2004; Parton et al., 2004). In addition, a relationship between soil carbon storage and biodiversity is expected (Chapin, 1997). Biodiversity is expected to protect the resilience and productivity of grasslands and improve ecosystem service provision on the local scale (Hooper et al., 2005). Increased biodiversity has been found to increase primary productivity (Hector et al., 1999), change plant allocation patterns (Tilman et al., 2007), and reduce invasibility by unsown species thus changing herbage composition (Kirwan et al., 2007) in sown grassland, all of which are expected to affect the quantity and quality of soil carbon inputs. In turn, land use, erosion and soil organic matter dynamics affect biodiversity (Dobson et al., 1997; de Bello et al., 2007).

Current farming practices have been attributed to deplete soil carbon, degrade soil quality, reduce productivity, and result in the need for more fertilization, irrigation, and pesticides (Lal et al., 2004). Furthermore, in the West Africa Sahel, climatic perturbations have led to decreased human carrying capacity to below actual population densities (Gonzales, 2001), further encouraging farming practices which deplete soil quality and result in per-area productivity losses. In order to improve soil carbon management in agricultural land it is important to first assess the impact of current practices and land uses for organic matter conservation. In this study our aim was to assess the effect of land use on soil quality using fertility indicators such as organic matter. Secondly, because it is believed that ecosystem resilience is related to the species diversity of the plant community, we explored the effect of management on vegetation composition, plant diversity, and the relationship between soil quality and diversity in grasslands.

2 Methods

2.1 Study area

The study area is located in Northern Togo, by the Gulf of Benin in western Africa. The vegetation belt in Northern Togo corresponds to the Savannah Region. Land use, vegetation and soils were sampled in Tami, a model farm of 100 ha located 20 km east from Dapaong, the capital of the region. The farm holds the *Centre de Formation Rurale de Tami* (CFRT), which trains local farmers. The region has Sudano-Guinean climate, characterized by a dry season from October to April and a rainy season from May to end of September. Mean annual precipitation is 1001 mm, with a maximum of 266 mm in August and a minimum of 0 mm in January. Mean annual temperature is 28.1°C, ranging from 25.2°C in August to 31.8°C in May (Fig. 1, see Poch and Ubalde, 2006). The Savannah region is characterised by a rolling landscape consisting of sequences of platforms, valleys and slopes, and the substrate is mainly of granites and gneiss with granodioritic composition (Collart et al., 1985).

The land area of the farm is covered mainly by crops (60%; Poch and Ubalde, 2006), mostly rain fed for self consumption (peanuts, soja, corn, sorghum, millet, rice) but also cash crops such as cotton. Fertilisation is very limited, mainly organic amendments from composting in the farm itself, which is applied only to corn. No burning is practised, and weeds are sometimes incorporated to the soil by plowing. Chemical NPK (15-15-15) fertilizers are applied at an approximate dose of 150 kg ha^{-1}. The remaining land consists of woody savannah, often used as pastureland, where dominant woody species are the trees *Parkia biglobosa* (Jacq.)G.Don. and *Butyrospermum parkii* (G. Don) Kotschy, and the shrub *Acacia sieberiana* DC. In addition, there is a small remnant of dry Sudanian forest preserved as “sacred forest” which hosts *Anogeissus* *leiocarpus* DC, *Butyrospermum parkii* (G. Don) Kotschy, *Bauhinia thonningii* Schum. and *Ziziphus mauritiaca* Lam.

2.2 Soil mapping

Soils of the farm were mapped at a 1:5000 scale (1 observation/10 ha). Geomorphological and vegetation units had been defined previously. Soil profiles were opened and described in the main pre-defined units (Poch and Ubalde, 2006). This map is also used as a reference for further discussions of land use and grassland distribution.

2.3 Soil sampling and land use

Twenty-two sites with different land use were sampled in the farm. Soil surface horizons were taken to a depth of 15 cm in homogeneous areas with a given land use or sown crop. Land use was recorded. Physico-chemical analyses were performed on the soil samples: particle-size distribution (coarse silt, fine silt, clay, sand; pipette method), organic carbon (OC; Walkley-Black method), phosphorus (P, Olsen method) and nitrogen content (N; Kjeldahl method), cation exchange capacity (CEC; ammonium-acetate method), cations (K, Mg, Ca, Na; atomic absorption), according to Porta et al. (1993). Soil organic carbon stocks (SOCS) were calculated for the modal profiles of the soil map, from the organic carbon concentration obtained by the Walkley-Black method of each horizon, the bulk soil density and respective horizon thicknesses, down to the profile depth, which varied between 0.5 and 1.5 m. Organic matter (OM) content was estimated from organic carbon using the Van Bemmelen conversion factor (1.72). The same procedure was used for the calculation of SOCS in the soil surface horizons (upper 15 cm).

2.4 Grassland sampling

Thirty-two grasslands were sampled in the farm in two different dates across the wet season, 17 at the beginning of the season, in June/July, and 15 different ones at the end of the season, in October. Three grassland categories were designated, according to current use: grazed grassland (pasture), pastured fallow (fallow), and abandoned grassland (abandoned). Transects 10 m long were placed in the middle of each grassland patch, and contacts of plant species on a 2 mm pin recorded every 10 cm following the point-quadrat method, totalling 100 sampled points per transect. Species frequencies per transect were calculated by adding up the contacts (for each species, frequency up to 100 per transect). The total number of species per transect, or species richness, was determined as a parameter measuring biodiversity. This is the simplest species diversity index. It has been found that different diversity parameters could behave in different ways to environmental factors (see de Bello et al., 2006 and 2007 for an example).

In order to explore the relationships between soils and vegetation, the sampled sites were located on the soil map, and the soil characteristics of the corresponding map unit were assigned to each sampled grassland patch. Other environmental variables (topography) were recorded in situ, but variation among those was very small, so they were ignored after some preliminary exploratory analyses.

2.5 Data analysis

We used restricted multivariate methods, in particular Canonical Correspondence Analysis (CCA), to explore the relationships between soil characteristics and land use. We defined various current land uses (in 2003): orchard, fallow, corn, soy, sorghum (plus one sward with millet), rice, and forest. In addition, as crops are usually rotated, we added three variables representing previous use, considering the year before sampling as well as the main use applied in the previous six years (1997 to 2002): fallow (usually used as pasture), legume crop (legume0; including soy and peanut), and non legume crop (cereal0; usually cereals, including sorghum, millet and rice). We used soil parameters as the descriptor variables of the samples, and land use – current and past, introduced as dummy variables (0/1) – as environmental explanatory variables. F-ratios and P-values were generated for explanatory variables from randomization tests by 499 Monte Carlo permutations in the analysis (see Leps and Smilauer, 2003 for details). We used the same procedure in a second CCA in which the forest sample was removed, and only crops and fallows were compared.

We used another CCA to explore the relationships between plant species composition, sampling date and grassland management. The descriptor variables in the CCA analysis were species frequency per transect, and the environmental variables were sampling date as a semi-quantitative variable (July: 1/October: 2), and management type as dummy variables (0/1): pasture, fallow, abandoned.

We performed ANOVA to assess the relationship between soil organic matter and land use; and between the number of species per transect in grassland and sampling date. In addition, we modelled total soil organic content in the grasslands according to date, management type and the number of species, plus the first and second order interactions. Only the interaction date x number of species was significant, and therefore was kept in the final model.

3 Results

3.1 Land use and soils

Multivariate analysis (CCA) revealed three different land uses clearly differentiated according to soil characteristics: forest, rice paddocks and other crops (Fig. 2a). The first two uses have a tendency to present higher organic matter and cation contents (Fig. 2a), particularly the forest (Fig. 3). Indeed, rice and forest were the first explanatory variables entering the CCA model, followed by fallow as previous use, based on randomization tests by Monte Carlo permutations (Table 1). A second CCA performed on samples from cropland only (Fig. 2b) showed, once again, rice paddocks being the most differentiated in terms of soils from the other crops, with higher organic matter and cation contents (on axis 1; Fig. 2b). Among the other crops, those usually sown with cereals – including corn, sorghum and millet – were differentiated from others, par-

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ticularly those with legume crops (on axis 2; Fig. 2b). Indeed, legume swards showed the lowest soil organic matter content (Fig. 3), with high intra-treatment variability and a low number of samples (n=2).

3.2 Relation between grassland management, vegetation and soil organic carbon

Vegetation composition differed with management; in addition, vegetation changed with the seasons (Fig. 4). Species composition of pastured grasslands were more dissimilar from pastured fallows and abandoned grassland than were the latter two when compared one against the other (Fig. 5). The number of species at the end of the wet season was higher than that at the beginning of the wet season (Fig. 4; P=0.005), but we did not find any effect of management on species richness (P=0.713).

Organic carbon content of the surface horizons ranged from 0.12 to 1.56% in croplands and reached 2.16% under forest. Total soil organic carbon stocks (SOCS) were also highest under forest (22.7 kg m^{-2}). It was significantly related to the number of plant species, but this relationship was dependent on sampling date (Table 2). SOCS increased with increased species richness, but only in July, at the beginning of the wet season. Furthermore, SOCS depended on grassland management; pastured fallows had lower SOCS than pastured grassland and abandoned farmland. This simple SOCS model was highly explanatory (R^2_{adj}=41.2%).

4 Discussion

4.1 Land use and soils

The forest soils provided the baseline for the potential fertility in the area (Poch and Ubalde, 2006). The significant differences in terms of quality between the cropland and forest soils have already been noted, and the loss of soil fertility as a consequence of agricultural practices has been emphasized (Poch and Ubalde, 2006). It is important

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to note that the fertility potential of the forest soil was not reached in any of the cropland soils (Fig. 2). Within cropland, the soils with highest organic matter content and fertility were those of rice paddocks (Fig. 3), with up to twice the amount of other crops. This was probably linked to their location on clayey soils (vertisols), which provide a higher CEC than sandy soils and have higher organic matter contents due to a better interaction of OM with soil mineral components. Given the sandy nature of most of the soils, the importance of organic matter management is key to improve the capacity of soils to prevent leaching. It is also interesting to note that, although crop rotation is a normal practice at the Tami farm, soils were highly differentiated between swards generally used for cereal crops, including corn, sorghum and millet, from other crops (Fig. 3), which include legumes such as soy. Legume crop utilization did not seem to contribute to increased soil fertility (Fig. 3), and those soils were not particularly related to the distribution of organic matter or N content (Fig. 2). This could be because of the utilization of inorganic fertilizers in the farm, which precludes symbiotic N-fixation, suggesting that a better use of the natural potential of legumes for N fertilization could be introduced. The results suggest that a potential for improved management practices (Lal et al., 2004) exists in the farm. However, contradictory results about the effect of legumes on soil fertility have been reported for cultivated African soils (Vanlauwe and Giller, 2006). In addition, the number of such samples in the farm was very low and therefore the potential for inference was weak. Other studies in Senegal report that SOC contents were not significantly different between plant communities, an observation that was attributed to under-replication (Woomer et al., 2004).

4.2 Grassland management, biodiversity and soil carbon

The relevance of biotic processes and biological diversity on soil organic carbon accumulation has been recognized, although the underlying mechanisms have yet to be identified (Schulze, 2006). Current ecological theory hypothesizes that biodiversity has a positive effect on the goods and services that ecosystems provide (Chapin et al., 1997; Hopper et al., 2005). Among those services, soil carbon storage has been found to relate to plant species richness in experimental grassland systems (Tilman et al., 2007). In this study we showed that soil carbon storage relates to biodiversity at the farm level (Table 2). Soil carbon storage was higher where plant species richness was higher, but the relationships between the two variables were complex (Table 2). Indeed, the relationship was expressed only at one of the two sampling times, when plant species richness was higher (Fig. 4). In addition, there was a strong shift in vegetation composition not only among the different management types of grassland, but also between the two sampling dates (Fig. 5).

Our results suggest that variation in species richness and vegetation composition could be among the mechanisms driving soil carbon storage. Soil carbon accumulation has been related to plant species composition and the functional groups to which they belong in experimental grasslands (Fornara and Tilman, 2008) and in boreal forests (Hollingsworth et al., 2008). In addition, our results show that the relationships between plant diversity and vegetation patterns with soil carbon storage could be complex, depending on the time of the year and the environmental conditions at that time, which would filter a given set of species (Fig. 5). Complex patterns linking plant species richness along precipitation gradients in geographically separated areas have been reported (de Bello et al., 2007), but less is known about the impact of temporal variation of vegetation in arid and semi-arid zones on ecosystem functioning. In addition, strong changes in plant functional types (de Bello et al., 2005) and species (Sebastià et al., 2008a) have been found with climate changes in grasslands, and those in turn could have an effect on soil carbon (Fornara and Tilman, 2008) and ecosystem nutrient dynamics (Sebastià 2007). Rainfall distribution in Northern Togo follows a hump-shaped curve over the rainy season from April to October (Fig. 1), and our results suggest that the vegetation as well as soil quality is sensitive to this curve, though more frequent sampling would be required to gain better resolution of changes in these systems in response to climate drivers. Caution is needed for interpretation, because soil carbon, biodiversity and vegetation composition are likely linked following intricate patterns, and feedback mechanisms must be at work (Sebastià, 2004; Sebastià et al., 2008b).

5 Conclusions

Our results showed that soil organic matter is highly dependent on land use and management. At the farm level, there was room for improvement of agricultural practices leading to increased organic matter stabilization. Those practices are likely to improve soil organic carbon content, species diversity and crop yields. We found a positive relationship between soil organic carbon accumulation and biodiversity. However, our model suggests that temporal as well as climatic interactions may be at work to influence apparent correlations between biodiversity and soil quality indicators such as soil organic carbon, and that these temporal variations in biodiversity and vegetation composition could have a role among the drivers in these systems.

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Table 1. Land use variables entering the CCA model based on soil parameters by automatic forward selection. F-ratios and P-values were generated for explanatory variables from randomization tests by 499 Monte Carlo permutations in the analysis.

Variable	F-ratio	P-value
Rice	8.49	0.002
Forest	2.14	0.104
Fallow0	1.37	0.234
Soy	1.22	0.292
Cereal0	1.48	0.196
Corn	1.52	0.214
Orchard	0.52	0.614
Fallow	0.28	0.796

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Table 2. Regression model relating log soil organic carbon stocks (SOCS) to sampling date (July, at the beginning of the wet season), management (fallow, abandoned), and the number of species per transect. The interaction term Date x No. species was significant and therefore was also included in the model.

Factor	df	F	P-value
Date	1	23.1	<0.001
Management	2	5.4	0.0149
No. species	1	0.3	0.6079
Date x No. species	1	17.8	<0.001

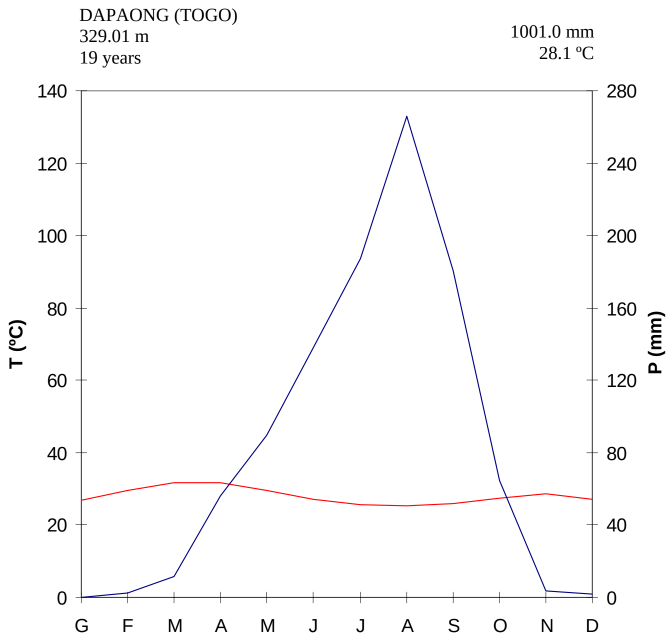

Fig. 1. Ombrothermic diagram of the meteorological station of Dapaong.

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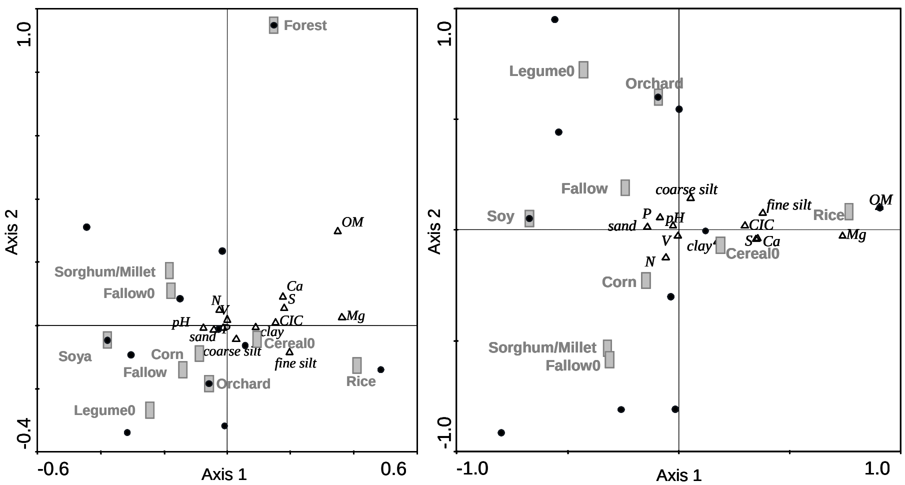

Fig. 2. Distribution of samples (black dots), soil parameters (open triangles) and land uses (grey squares) on the first two axes of a Canonical Correspondence Analysis on soil parameters per sample, with land use type as environmental variables. **(a)** (left): all uses included. **(b)** (right): only cropland uses included. Fallow0, previous use as fallow; Legume0, previous use as legume crop; Cereal0, previous use as non-legume crop, mainly cereal.

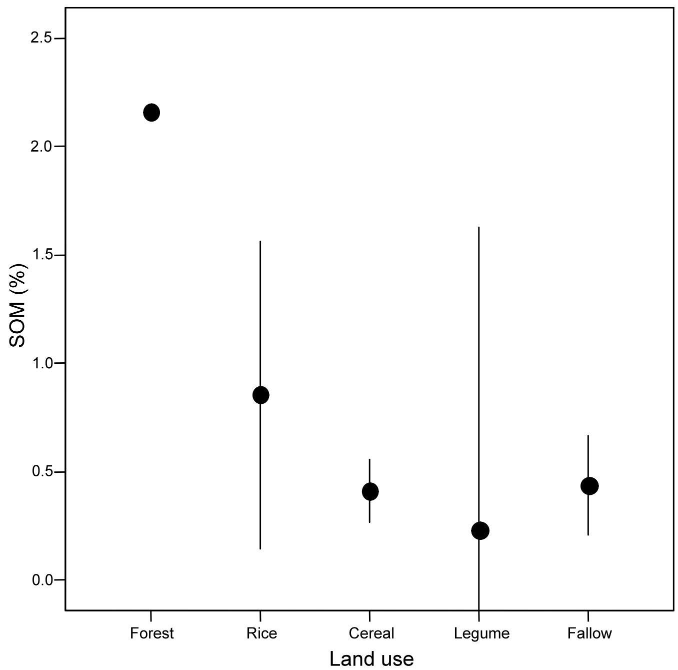

Fig. 3. Distribution of soil organic matter (OM) in the surface horizons (upper 15 cm) in Tami according to land use. Dots and bars indicate the mean and 95% confidence interval respectively. Forest land use has only one observation.

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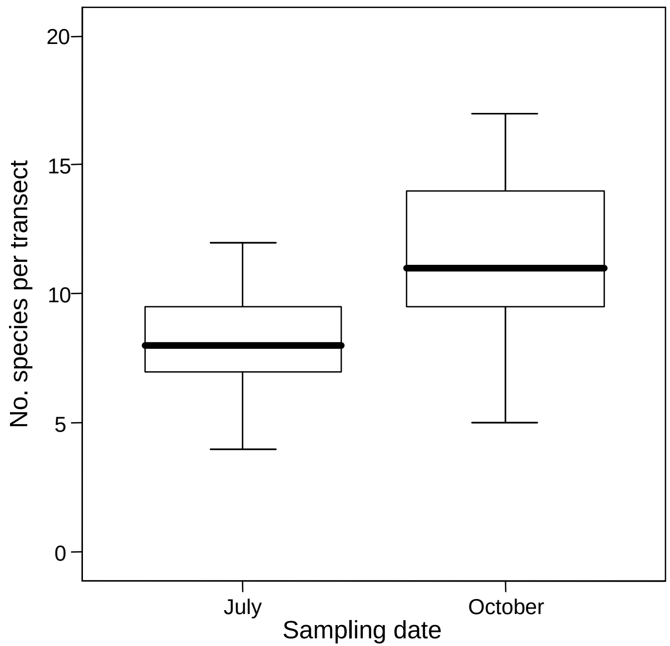

Fig. 4. Box-plot showing the distribution of the number of species per transect in the two sampling dates, July and October (at the beginning and end of the wet season respectively). Solid line, boxes and whiskers indicate the median, second and third quartiles, and first and fourth quartiles respectively.

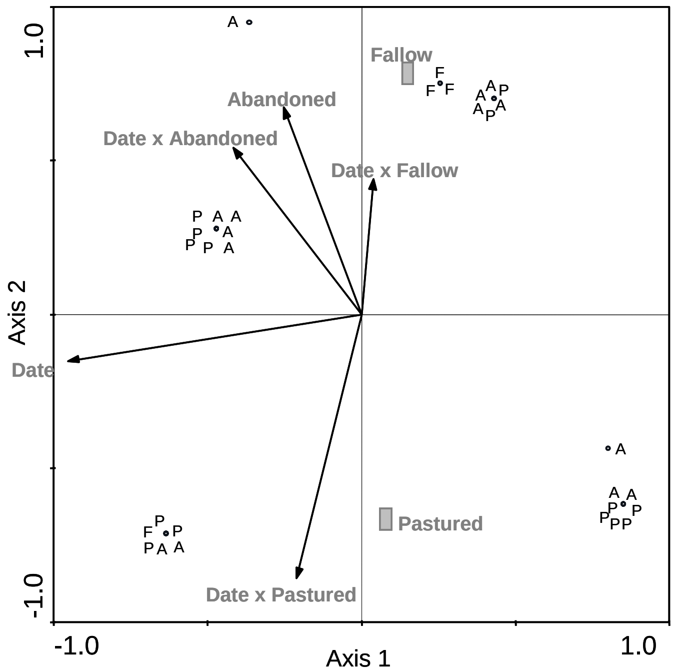

Fig. 5. Distribution of grassland samples (black dots and letters) on the first two axes of a Canonical Correspondence Analysis based on species frequencies per transect and including land use variables, sampling date, plus their interactions as explanatory environmental variables (grey squares). Grassland uses per sample: P, pastured grassland; A, abandoned grassland; F, pastured fallow. For factors including sampling date, the arrows show the direction of variation.