



## Woody plant population dynamics in response to climate changes from 1984 to 2006 in Sahel (Gourma, Mali)

Pierre Hiernaux, L. Diarra, Valérie Trichon, E. Mougin, N. Soumaguel, F. Baup

### ► To cite this version:

Pierre Hiernaux, L. Diarra, Valérie Trichon, E. Mougin, N. Soumaguel, et al.. Woody plant population dynamics in response to climate changes from 1984 to 2006 in Sahel (Gourma, Mali). *Journal of Hydrology*, Elsevier, 2009, S0022-1694(09)00135-8, pp.HYDROL 16508. <10.1016/j.jhydrol.2009.01.043>. <ird-00406590>

**HAL Id: ird-00406590**

**<http://hal.ird.fr/ird-00406590>**

Submitted on 24 Jul 2009

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## Accepted Manuscript

Woody plant population dynamics in response to climate changes from 1984 to 2006 in Sahel (Gourma, Mali)

Pierre Hiernaux, Lassine Diarra, Valérie Trichon, Eric Mougín, Nogmana Soumaguel, Frédéric Baup

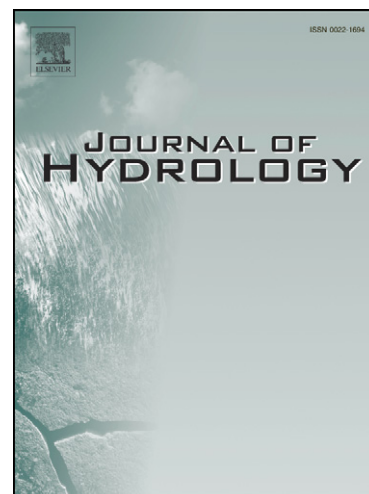
PII: S0022-1694(09)00135-8  
DOI: [10.1016/j.jhydrol.2009.01.043](https://doi.org/10.1016/j.jhydrol.2009.01.043)  
Reference: HYDROL 16508

To appear in: *Journal of Hydrology*

Received Date: 16 May 2008  
Revised Date: 17 October 2008  
Accepted Date: 27 January 2009

Please cite this article as: Hiernaux, P., Diarra, L., Trichon, V., Mougín, E., Soumaguel, N., Baup, F., Woody plant population dynamics in response to climate changes from 1984 to 2006 in Sahel (Gourma, Mali), *Journal of Hydrology* (2009), doi: [10.1016/j.jhydrol.2009.01.043](https://doi.org/10.1016/j.jhydrol.2009.01.043)

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.



1 **Woody plant population dynamics in response to climate changes from**  
2 **1984 to 2006 in Sahel (Gourma, Mali)**

3

4 Pierre Hiernaux<sup>a,\*</sup>, Lassine Diarra<sup>b</sup>, Valérie Trichon<sup>c</sup>, Eric Mouglin<sup>d</sup>, Nogmana Soumaguel<sup>e</sup>  
5 and Frédéric Baup<sup>a</sup>

6

7 \*Corresponding author: [pierre.hiernaux@cesbio.cnrs.fr](mailto:pierre.hiernaux@cesbio.cnrs.fr)

8 <sup>a</sup> *Centre d'Etudes Spatiales de la BIOSphère (CESBIO) UMR 5126 - UPS*

9 *18 avenue Edouard Belin b.p.i. 2801, 31401 Toulouse Cedex 9. France.*

10 <sup>b</sup> *Institut d'Economie Rurale (IER) B.P. 258, rue Mohamed V, Bamako, Mali*

11 <sup>c</sup> *EcoLab UMR 5245 UPS-CNRS-INPT Université Paul Sabatier, 118 route de Narbonne,*

12 *31062 Toulouse, France*

13 <sup>d</sup> *Centre d'Etudes Spatiales de la BIOSphère (CESBIO) UMR 5126 - CNRS*

14 <sup>e</sup> *Institut de Recherche pour le Développement (IRD) B.P.2528, Hippodrome 238 rue 234,*

15 *Bamako, Mali*

16

17 **Abstract**

18 The patterns of the changes in woody plant population densities, size and species composition  
19 is documented and discussed for 24 rangeland sites monitored from 1984 to 2006 in Gourma  
20 (Mali). The sites are sampled along the North-South bioclimatic gradient on each of the main  
21 soils and levels of grazing intensity. Site woody plant populations range from extremely  
22 sparse on shallow soils, to scattered on sandy soils, to open forest in temporarily flooded  
23 clayed soils, and to narrow thickets on hard pans. Three different methods contributed to  
24 assess and monitor woody plant density and canopy cover.

1 In the short term woody populations were struck by the 1983-84 droughts irrespective of their  
2 edaphic situation and location along the bioclimatic gradient. Drought induced mortality was  
3 not more severe under drier climate within the Sahel gradient but occurred sooner after  
4 drought in shallow soils, and with a lag of a year or two on flooded clay soils. No evidences  
5 were found of higher mortality rates in stands with history of intense grazing. Although  
6 rainfall remained below average for a decade after the drought, active recruitment of woody  
7 plants occurred in all sites starting as soon as 1985. Recruitment proceeded by successive  
8 cohorts, often with short-living perennial undershrubs and pioneer shrubs settling first. *Acacia*  
9 species were among the first to settle or re-establish, especially on the sites most intensively  
10 grazed. The release of competition due to drought induced mortality and to the reduction of  
11 herbaceous cover contributed to the success of the recruitment. The species composition  
12 change that resulted could first be interpreted as a shift toward a more arid tolerant flora, then  
13 some diversification occurred since the mid 90's that could indicate a possible return to  
14 previous composition in the long term, confirming the resilience Sahel vegetation.

15 **Keywords:** Sahel, Mali, climate change, drought, woody plant population, vegetation  
16 dynamics, tree recruitment, resilience.

## 1 **Introduction**

2 In the Sahel that extends over 6000 km East-West at the southern edge of the Sahara, two  
3 catastrophic droughts occurred in 1972-73 and in 1983-84 within a dry period of 25 years,  
4 from 1968 to 1993, which followed a relatively wet period of 20 years from 1948 to 1968  
5 (Nicholson, 2001). Since 1994, rains fluctuate up and down the century average (Frappart et  
6 al. this issue) at least in eastern and central Sahel (Nicholson, 2005). Both droughts had severe  
7 impact on the vegetation, crops, livestock and rural populations. Alarming reports of massive  
8 mortality of woody plant populations are made through out Sahel (Boudet, 1972; Poupon,  
9 1980; Sinclair and Fryxell, 1985; Miede, 1998; Andersen, 2007) associated to warnings of  
10 severe risks of diversity losses (Larwanou and Saadou, 2005). The woody plant decimation is  
11 attributed to the climatic droughts or to their impact on water tables. It is also imputed to  
12 natural resource management by rural populations with increased tree pollarding to feed  
13 hungry livestock (Breman and Cissé, 1977), cutting trees for fuel, construction and clearing  
14 for expanding crop lands, especially in low lands (Lykke, 2000). Deforestation and soil  
15 erosion being major components of Sahel desertification, large efforts are locally invested in  
16 tree planting and contours building (Sumberg and Burke, 1991). However, since the 80's,  
17 some observations report contradictory evidence of strong regeneration of the woody  
18 populations (Boudet 1979; Couteron, 1997). Yet the amplitude, spatial extension and species  
19 composition of the post drought regenerations remain questioned. Unlike with herbaceous  
20 annuals (Hiernaux et al. this issue), the study of woody plant dynamics requires monitoring  
21 over large areas because of the low density and patchy pattern of populations, and because of  
22 the large size of some individual plants. The monitoring should also be conducted over  
23 several years or decades to cope with the long life cycle of most woody plants and the  
24 suspected sensitivity of their demography to rare events (Breman and Kessler, 1995).

1 The monitoring of 24 rangeland sites in Gourma (Mali) from 1984 to 2006 documents the  
2 pattern of the changes in woody plant population density, size, mass and species composition.  
3 Sites are sampled along the North-South bioclimatic gradient (Fig. 1) on main soils and levels  
4 of grazing intensity in order to represent the rangelands encountered across the region. The  
5 sites were initially described in 1984, and regularly monitored till 1993 (Table 1) to assess the  
6 impact of the 1983-84 droughts on forage resources available in this region of Sahel  
7 (Hiernaux et al., 1984; 1993). The monitoring was resumed from 1998 onwards to study the  
8 ecosystem response to climate changes in the framework of the AMMA project (Redelsperger  
9 et al., 2006; Mougin et al. this issue).

10 This papers aims at describing the woody populations of 32 rangeland sites in Gourma (Table  
11 2) and analysing population dynamics in response to droughts on a subsample of 24 sites.  
12 Trends in woody plant populations are discussed and related to rainfall variations, taking  
13 forestry, pastoral and crop management into account. The interpretation of population  
14 dynamics also relies on the woody plant phenology monthly monitored for the main species  
15 on 13 of the rangeland sites (Hiernaux et al., 1994). A first hypothesis guiding the analysis is  
16 that the impact of droughts is more severe under drier climate, thus toward the north of the  
17 transect; and also in drier edaphic situations, thus more severe in shallow than in deep soils,  
18 and in coarse textured than in fine textured soils (Grouzis, 1988; Dembélé et al., 2006) or the  
19 reverse: more severe on fine textured than on sandy soils (Scholes, 1985). A complementary  
20 hypothesis is that woody plant populations suffer more from drought when subjected to heavy  
21 browsing by livestock or pollarding, which intensity has increased due to the desperate search  
22 of additional fodder by the herders facing drought (Bille, 1977; Hillerislambers et al., 2001).  
23 Another hypothesis highlighting the competition for water predicts that woody plants suffer  
24 more from drought if herbaceous plants do grow and use a large fraction of the soil moisture

1 (Knoop and Walker, 1985; Belsky, 1994; Akpo and Grouzis, 1996; Scholes and Archer, 1997;  
2 Picard et al., 2005).

### 3 **Material and methods**

#### 4 **The Gourma region and the Sahel bioclimate**

5 Rainfall, soil and woody population data from 1984 to 1995 are provided by the ILCA  
6 (International Livestock Centre for Africa) and IER (Institut d'Economie Rurale) research  
7 project data base (Hiernaux and Diarra, 1993), while data from 1998 to 2006 are recorded  
8 under the long term observation program of the AMMA (African Monsoon Multidisciplinary  
9 Analyses) research project (Redelsperger et al., 2006; Mougin et al., 2008). Historical rainfall  
10 data are provided by the Mali meteorological service. Sites are sampled in four bioclimatic  
11 groups set along the South-North climate gradient in Gourma (Fig. 1 and Table 2). The  
12 gradient spans over most of the Sahel bioclimatic zone (Le Houérou and Popov, 1981) with a  
13 gradual decrease of mean total rainfall with latitude from 500 mm rainfall to the South, at the  
14 Burkina Faso border, to 150 mm to the North, by the Niger River close to Gourma Rharous  
15 (Frappart et al., this issue). The climate gradient is chiefly explained by a reduction in the  
16 number of rain events occurring over a shorter season, mostly because of the later start of the  
17 monsoonal rains (Le Barbé and Lebel, 1997) and secondarily by a reduction of mean size of  
18 rain events at the drier end of the gradient (Frappart et al. this issue).

19 Within each bioclimatic group three main edaphic situations are sampled: deep sandy soils,  
20 deep loamy-clay soils, shallow soils on rock or hard pans (Table 2). On the sandy soils that  
21 extend over about half the landscape (Kammerud, 1996), three level of grazing intensity are  
22 systematically sampled: low, medium and high (Table 3). Grazing intensity is determined by  
23 the proximity, size and seasonal duration of neighbour water points and associated villages  
24 and encampments. Grazing intensity is systematically high in sites with deep loamy-clay soil

1 because they are close to water points, at least temporary pools, while grazing is generally  
2 low in shallow soil sites because of the poor forage resources offered.

### 3 **Woody plant population record methods**

4 Three different methods are used to monitor the woody plant populations depending on years  
5 and sites (Table 1). The aims of the three methods differ but they all contribute to assess some  
6 parameters of the woody plant population: plant density, crown cover, projected crown cover,  
7 foliage and wood masses, species composition. Plant species are named according to the Flora  
8 of West Tropical Africa second edition (Hutchinson and Dalziel, 1954-1972).

9  
10 Crown Linear Intercept method (CLI). The linear intercept method initially aimed at studying  
11 the influence of woody plants on the herbaceous layer. As the herbaceous layer is stratified  
12 and sampled along the 1000 m long and 1m large linear transect (Hiernaux et al., this issue),  
13 woody plants which crown overcast the transect line are recorded with the exact position and  
14 length of the crown intercept with the transect line. The sum of these intercepts provides an  
15 estimate of the site canopy cover and projected canopy cover depending if crown overlaps are  
16 accounted for or not. The species name, height, longest and perpendicular crown diameters,  
17 and the base (avoiding bottom when it is swollen) circumference of the trunks of each of  
18 woody plant intercepted are recorded. Fast to record and needed to analyse impact on  
19 herbaceous distribution anyway, crown linear intercept records were carried out almost every  
20 year from 1984 to 1990 ( $n=24$  sites), in 1993 ( $n=19$ ) and again in 2005-06 ( $n=22$ ), (Table 1).

### 21 22 Circular Plots Census method (CPC)

23 This method was initiated in 1988 to better assess woody plant density contributing together  
24 with allometric functions established by species (Cissé, 1980) to the assessment of wood and  
25 foliage masses. It is a straightforward method that consists in recording the species name and



1 size parameters (height, crown diameters, number and base circumference of the trunks) of  
2 each individual found within a set of 4 circular plots centred 200 meters apart along the  
3 1000m linear transect that define the site (Hiernaux and Gérard, 1999). Because woody  
4 populations largely differ in densities, the radius of the circular plots is adapted to the  
5 expected (by visual estimate) density. The target is to ensure a minimum sampling of 10  
6 individuals per plot, so a total of 40 per transect for each category of woody plants recorded  
7 separately. As a result, plot sizes used to record woody plants in Gourma sites range from 312  
8 to 10 000 m<sup>2</sup>. When the plant types or species that compose a population at a site contrast  
9 strongly by their sizes, densities or distribution patterns, they are recorded in two categories  
10 separately, i.e. on two series of plots of different sizes centred on the same points. Such  
11 circular plot census were performed on most of the Gourma sites (Table 1) at least once  
12 between 1988 and 1990 ( $n=24$ ), once between 1993 and 1995 ( $n=22$ , sites 37 and 38 are  
13 missing) and once recently between 2002 and 2006 ( $n=23$ , site 22 is missing). Plot means and  
14 standard deviations are calculated for density, height, canopy cover (both total and projected  
15 thanks to the systematic record of the fraction of crown overcast by any other crown), basal  
16 areas by species, plant types, and for all woody plants.

17

#### 18 *Distance from Point Centred Quadrant method (PCQ)*

19 The PCQ method was initiated in 1988 in parallel with the CPC. It aims assessing woody  
20 plant density especially when plant distribution is patchy, which question representativeness  
21 of the samples described with the CPC method (Engeman et al. 1994; Picard and Bar-Hen,  
22 2007; White et al., 2008). In the PCQ method, the plant density of individual species or plant  
23 type is estimated by the mean distance of the closest individual to sampling points (20 or 10)  
24 taken systematically every 50 or 100 meters along the transect depending on plant density . At  
25 each sampling point, mean distance is calculated between the shorter distances measured for

1 each four quadrants defined by the linear transect and the line perpendicular to transect line at  
 2 the sampling point (Cottam and Curtis, 1956). The four individuals for which the distance is  
 3 measured are described as in CPC: species name, height, crown perpendicular diameters, base  
 4 circumference of trunks. As in CPC woody plants are recorded in two categories, i.e. two  
 5 series of distances measured in same quadrants for the same series of points, when plant types  
 6 or species contrast strongly by their sizes, densities or distribution patterns. For each category,  
 7 the woody plant density (D) i.e. the number of individuals per unit area (ha) is estimated  
 8 following two alternative algorithms:

9 
$$(3) D_1 = \frac{10000}{\bar{d}^2}$$
 with  $\bar{d}$  the mean distance in the 4 sectors (Cottam and Curtis, 1956).

10 
$$(4) D_2 = 10000 \frac{4(kn - 1)}{\pi \sum_{j=1}^n \sum_{k=1}^4 d_{kj}^2}$$
 with  $d_{kj}$  the distance (m) in the  $k$  ( $j = 1$  to 4) sectors,  $n$  ( $n = 1$  to  $n$ ) the number of sampling points (Pollard 1971).

11  
 12 The PCQ method has been applied to most of the Gourma sites once in 1988 ( $n=17$ ) and once  
 13 recently in 2005-2006 ( $n=20$ ), (Table 1). Site canopy cover by species, plant types, and for all  
 14 woody plants are derived from respective density and mean crown area.

15

## 16 **Results**

17

### 18 **Contrasted woody plant populations of Sahelian rangelands**

19 The woody plant populations of 25 sites differ strongly in density, size of individual plants  
 20 (Table 3) and species composition. They range from extremely sparse low shrub stands on  
 21 shallow soils, to scattered stands of shrubs and low trees on sandy soils, to open *Acacia* or  
 22 *Anogeissus* forest in temporarily flooded clay soils, and to the narrow and dense thickets of  
 23 the ‘tiger bush’ on hard pans (Nasi and Sabatier, 1988). Indeed, site canopy cover of woody  
 24 populations on shallow soils at most reaches 1% with plant density inferior to  $50 \text{ ha}^{-1}$ , except

1 on the tiger bush type of vegetation in which the distribution extremely patchy. In tiger bush  
2 woody plants are organised in facieses that alternate along the gentle slope: extremely open  
3 stands on impluvium ( $0.4 \pm 0.2\%$  canopy cover with  $21 \pm 12$  plants  $\text{ha}^{-1}$ ) covering 90% of site  
4 area at Ortondé site (# 22) and dense thickets ( $124.3 \pm 61.1\%$  canopy cover with  $1568 \pm 583$   
5 plants  $\text{ha}^{-1}$ ) covering 10%, resulting in weighed averages of 12.8% canopy cover and plant  
6 density of  $176 \text{ ha}^{-1}$  (Hiernaux and Gérard, 1999). The woody plant populations in valleys and  
7 depressions with loamy-clay soils are taller and denser than on shallow soils as they benefit  
8 from run-off water and deep fertile soils (# 9). The distribution of woody plants in valleys is  
9 also very patchy with large extents almost deprived of woody plants either at the edges of the  
10 valley or else in the deepest part of the depressions with temporarily flooded cracking clay  
11 soils. On the other hand, dense and narrow thickets are found along streams and around  
12 pools, and open forests occur in temporarily flooded plains with clay soils such as the *Acacia*  
13 *seyal* (# 20, 21) or *Acacia nilotica* (# 7, 15) dominated forests. Woody populations on sandy  
14 soils present intermediary traits both in distribution pattern, plant density and canopy cover.  
15 Indeed, the canopy cover of monitored sandy soil sites averages 4.3 %, and plant densities  
16  $127 \text{ ha}^{-1}$  with the low and aphyllous shrub *Leptadenia pyrotechnica* accounting for 1.8%  
17 cover and  $63 \text{ plant ha}^{-1}$  in average but highly variable proportions from site to site (Table 3).  
18 Moreover, the distribution pattern of woody plants range from apparent random (# 1, 4, 6, 10,  
19 12, 18, 30, 31, 38) with coefficient of variation of between mean canopy cover and plant  
20 density equal to 20.7 and 20.3 respectively, to patchy distribution in relation with the  
21 repetitive pattern of dune and inter-dune (# 5, 14, 17, 25, 37) with corresponding coefficient  
22 of variations equal to 42.0 and 26.9%.

23

24 **The dynamics of the canopy cover from CLI records**

1 When canopy cover assessed in CLI records are analysed for all sites together there is an  
2 overall trend over years. Canopy cover first decreased from 1985 to 1988, then increased  
3 slightly from 1988 to 1993, and increased markedly from 1993 to 2006 as indicated by the  
4 regressions established for each pairs of canopy cover data (Table 4). When the trends are  
5 analysed per site and per species within site (Fig. 2) three main behaviours are observed:

- 6     ▪ In a majority of sites (12 out of 22) canopy cover decreased in the years following the  
7         1983-84 drought till 1993-95 due to extensive tree mortality. The canopy cover kept  
8         decreasing between 1993 and 2006 in four of these sites. These four sites include three  
9         of the four shallow soil sites (# 8, 22, 28) and one of the heavy grazed dune (# 31, Fig  
10         2f). In that later site the woody plant population was initially dominated by a stand of  
11         *L. pyrotechnica* shrubs that developed following the 1973-74 drought and  
12         progressively thinned out from 1984 onwards. In the eight other sites canopy cover  
13         increased during the last decade, including sites on ungrazed but regularly burned  
14         sandy soil (# 30, Fig. 2e), heavily grazed dune (# 14), shallow soil (# 16, Fig. 2a) and  
15         clay soil (# 21, Fig. 2d).
- 16     ▪ In a minority of sites (7 out of 22), canopy cover maintained itself following the  
17         drought in spite of selective mortality affecting the more sensitive species such as  
18         *Acacia senegal* or senescent individuals. The cover then decreased in the last decade  
19         in two of these seven sites (# 5 on sand dunes and neighbour # 2 in a clayed plain) and  
20         maintained itself on the others three with sandy soils and very sparse woody  
21         populations (# 6, 10, 12), and on two with dense mature stands of *A. seyal* (# 20) or *A.*  
22         *nilotica* (# 15) on temporarily flooded clay soils.
- 23     ▪ In the three last sites (17, 18, 19), all on sandy soils, canopy cover increased rapidly  
24         following the drought, due to the strong encroachment of *L. pyrotechnica* that more  
25         than compensated the mortality of pre-established woody plant species, especially *A.*

1        *senegal*, *Combretum glutinosum* and *Guiera senegalensis* (Fig. 2b, 2c). Canopy cover  
2        further increased during the last decade in the almost pure stand of *L. pyrotechnica* (#  
3        19), while it decreased slightly in the more diverse stands (# 17, 18) as the initial  
4        population of *L. pyrotechnica* thinned in part due to wild fires.

5

#### 6        **Woody plant densities from CPC and PCQ records**

7        Although the first observations by CPC and PCQ were performed four to five years after the  
8        1983-84 drought, the distinction of alive from dead plants in the records done in 1988-89  
9        document the wave of woody plant mortality that resulted from the drought (Table 5). The  
10       proportions of dead woody plants vary largely between sites, and between species at each site.  
11       Actually, the wave of mortality affected all sites including sites in which no dead trees were  
12       recorded in 1989 (# 12, 18, 31), but with different timings and intensities. Among the faster  
13       and more intensively struck woody populations were the tiger bush and very sparse shrubby  
14       vegetation on shallow soils (# 8, 16, 22), but also the sparse *C. glutinosum* and *Acacia ssp.*  
15       dominated stands on sandy soils all over the bioclimatic gradient (# 1, 4, 5, 6, 10, 12, 14, 17,  
16       18, 25, 30, 37, 38). Tree mortality was locally high in some of the open forest on clay soils in  
17       low lands (# 2, 9, 15, 20, 21), but occurred with one or two year lag after the drought as  
18       observed in the *A. seyal* mature stand (# 20, 21).

19

20       Because of the four year gap between the drought and the first record, the drought induced  
21       mortality does not always translate in a decrease of the overall woody plant density between  
22       1988 and 1995. Indeed, after a wave of mortality, the drought was followed by active  
23       recruitment of woody plants in most sites. The recruitment started as soon as 1985 or 1988,  
24       explaining for the increase in plant density, followed by a slower increase in canopy cover (#  
25       6, 14, 17, 19, 21; Fig. 3c, 3d). The trends observed on total plant density and canopy cover

1 between 1988 and 1993 result from the combination of the wave of mortality and the  
2 recruitment. However, the exact timing and the magnitude of tree mortality and recruitment  
3 vary between sites (Fig. 3 and 4). It explains, for example, the sharp increase of plant density  
4 and slower increase of canopy cover observed from 1988 onwards on some clay soil (# 21,  
5 Fig. 3c, 3d) and sandy soils (# 6, 14, 19, 17; Fig. 4c, 4d).

6  
7 Woody plant recruited mostly from new seedlings often for a few species only. The seedling  
8 species are either already established in the stand or relatively short life cycle species that may  
9 have been present in the stand but in very small numbers and suddenly recruit massively and  
10 are thus considered pioneers. Among the most prominent pioneers, *L. pyrotechnica* recruits  
11 actively on sandy soils, especially in the district of Hombori (# 17, 18, 19) and more recently  
12 further north (# 3, 6, 14). *Calotropis procera* recruits on more loamy or clayed soils (# 9, 16,  
13 22, 28, 40) and in the interdune (# 5, 25). While *A. ehrenbergiana* and *Commiphora africana*  
14 recruits on shallow sandy-loam soils (# 2, 8, 16, 22, 28). For example, in addition to the 48 ha<sup>-1</sup>  
15 established woody plants on heavy grazed sand soil (# 14), 28 ha<sup>-1</sup> young *L. pyrotechnica*  
16 and 87 ha<sup>-1</sup> seedlings were recorded in 1989. In some of the sites, the pioneer shrubs  
17 succeeded to a population of short-living under-shrubs such as *Chrozophora senegalensis* (#  
18 10, 17, 19, 31), *Aerva lanata* (# 1, 2, 4), and *Sphaeranthus senegalensis* (# 9) that settled just  
19 following the drought starting in 1985 and disappeared after a couple of years. The temporary  
20 colonisation by *Chrozophora senegalensis* was particularly spectacular on the dune of  
21 Hombori Hondo (# 19), starting in 1985 with a peak in 1989 at a density of 4347 ha<sup>-1</sup> with  
22 4.4% cover and standing dry mass of 217 kg ha<sup>-1</sup>.

23  
24 Among the species that were established prior to the drought, thinned out and then recruited  
25 actively there are several acacia species: *A. raddiana* in sandy soils (# 1, 5, 6, 10, 14, 17, 18,

1 31; Fig 4e, 4f), *A. senegal* in loamy sands (# 17, 18, 25), *A. laeta* in sandy loams (# 12, 28) and  
2 *A. seyal* in clay soil (# 20, 21). The recruitment of *A. seyal* in the stand gaps that resulted from  
3 the mortality of adult *Acacia* trees in 1984, developed in three main cohorts which germinated  
4 in 1985, 1988 and 1995 as noticed on the records of *A. seyal* densities (Fig. 3d) and  
5 distribution in classes of size for canopy area and basal area (Fig. 5) in 1989, 1993 and 2002.  
6 *Euphorbia balsamifera* also recruited progressively on sandy-loam soils or shallow sandy  
7 soils to the dryer end of the bioclimatic transect (# 4, 5). Some progressive recruitment were  
8 also observed for evergreen *Maerua crassifolia* (# 2, 10, 16; Fig. 3a, 3b), *Boscia senegalensis*  
9 (# 1, 4, 22, 28), *Maytenus senegalensis* and *C. aculeatum* (# 25, 28, 30; Fig. 4a, 4b), and *C.*  
10 *glutinosum* (# 38). The life duration of the new recruited woody plants depends on species,  
11 and could be relatively short with the pioneer shrubs which density already drop between  
12 1995 and 2005 for *L. pyrotechnica* (# 6, 19, 17; Fig. 4c, 4d), *Calotropis procera* (# 40, 16;  
13 Fig. 3a, 3b), *Commiphora africana* (# 8, 22) and *Euphorbia balsamifera* (# 5). Thinning also  
14 affected some of the other species that recruited, especially *Balanites aegyptiaca* (# 5, 10, 12),  
15 *Boscia senegalensis* (# 5, 10) and *A. raddiana* (# 12), but this does not impede the canopy  
16 cover to progress.

17

## 18 **Discussion**

19

### 20 **The short term impact of droughts on woody plant populations**

21 In all three edaphic situations, populations were struck by the droughts irrespective of their  
22 location along the bioclimatic gradient (Table 5, Fig. 2). The hypothesis that drought induced  
23 mortality would be more severe under drier climate within the Sahel gradient, is not verified  
24 by the observations. However, the first observations followed the drought with a gap of one to  
25 four years and the record of dead individuals may have been incomplete because of some logs

1 were harvested for fire wood or charcoal in the mean time (Benjaminsen, 1996; Andersen et  
2 al., 2007), this would lead to an underestimate of wood mortality. Moreover, the survey was  
3 only initiated after the second major drought of 1983-84, yet sites had suffered from a major  
4 drought a decade earlier that had already decimated woody populations (Boudet, 1972).  
5 Although there are evidence that woody populations were struck by the 1972-73 drought all  
6 along the Gourma bioclimatic transect (Boudet, 1977; Benoît, 1984), the impact may have  
7 been unequal, more severe at the drier end, and this could explain that the second drought is  
8 relatively less severe on woody population more severely struck the first time because of the  
9 reduced competition between adult trees that escape the first drought (Mueller et al., 2005),  
10 and lower sensitivity of young individuals that established after the first drought (Boudet  
11 1979, Slik 2004).

12  
13 The results do not support either the associated hypothesis along which drought induced  
14 mortality would be relatively more severe in shallow than in deep soils and in coarse texture  
15 than in fine texture soils (Togola et al. 1975; Grouzis, 1988; Couteron 1997). However, as  
16 already observed by Boudet (1979) after the 1972-73 drought, mortality seems to occur faster  
17 in shallow soils followed by deep sandy soils, than in the fine texture soils of low lands.  
18 Indeed, the peak of tree mortality in the *A. seyal* stands (# 20, 21) only occurred in the dry  
19 season 1984-1985, while it had already occurred the previous year in sandy and shallow soils.  
20 However, as for previous hypothesis, a more severe impact of the first drought in edaphically  
21 dry situations could have masked the gradient of impact observed during the second drought.

22  
23 Contrary to observations in Senegal (Bille, 1977; de Wispelaere 1980; Poupon, 1980; Miehle  
24 1998) the woody plant mortality observed in the sandy soil sites subjected to high grazing  
25 pressure by livestock (# 6, 14, 31, 37) are not superior to that observed in the other sandy soil



1 sites (Table 5). No evidence was found to support the hypothesis that woody plant  
2 populations would suffer more of droughts when subjected to heavy browsing by livestock or  
3 pollarding by herders as suggested by Boudet (1979). Yet, not all species are subjected to  
4 browsing and pollarding (Piot et al., 1980), and the density of woody plant stands may have  
5 been affected by the history of grazing long before the droughts, masking droughts effect by  
6 the selection of poor quality browse species. However, the species composition of the woody  
7 population of the sites exposed to high stocking rates include high proportions of good quality  
8 browse such as *A. raddiana*, *A. senegal*, *A. laeta*, *Balanites aegyptiaca*, which seed dispersion  
9 is facilitated by livestock (Le Houerou, 1980). On the other hand, in some of these sites (# 19,  
10 31, 37) the density of woody plants (except *L. pyrotechnica*) is very low, perhaps reflecting  
11 the effect of a long history of high pastoral use or ancient clearing for crops (Fig. 2f, 4e, 4f).

### 13 **The mid term impact of droughts on woody plant populations: stand recruitment**

14 Although rainfall remained below average several years after the drought, active recruitment  
15 of woody plants occurred in most sites (Fig. 3 and 4). This recruitment often started as soon  
16 as 1985 or 1988, by new seedlings in successive cohorts. This recruitment first increased  
17 woody plant densities, while canopy cover was still decreasing at many sites, and only  
18 contributed to enhance canopy cover from the 90's onwards. In most sites, only a few species  
19 contributed to recruitment, at least to the first cohorts (Miehe, 1998). Among the first settlers,  
20 a number of short-living perennial undershrubs and tussock grasses and sedges, colonized  
21 temporarily some of the sites (Hiernaux and Le Houérou, 2006). *Chrozophora senegalensis*  
22 and *Aristida sieberiana* established at the edges of deflation patches on sandy soils recently  
23 eroded by wind as a consequence of two consecutive years of soil denudation because of the  
24 drought, while *Colocynthis vulgaris*, occasionally biannual, and *Cyperus jemicus* helped  
25 trapping sands of the micro-dunes as already observed by Boudet following the first drought

1 (1977). Temporary colonization by short-living perennial also extended to other soil types in  
2 some sites, with *Aerva lanata* on sandy loam soils and *Sphaeranthus senegalensis* on clay  
3 soils. Simultaneously, the first cohorts of pioneer shrubs settled, among which *L.*  
4 *pyrotechnica* on sandy soils, *Euphorbia balsamifera* on loamy sands and *Calotropis procera*  
5 on all type of soils, are dispersed by wind (Breman and Kessler, 1995). *Acacia* species were  
6 among the first to settle or re-establish, especially on the sites the most heavily grazed by  
7 livestock. Even if particular changes in soil surface may have facilitated the development of  
8 the seedlings of species which seeds are dispersed by wind or by livestock, their simultaneous  
9 and wide spread appears as a response to the opening of the woody layer due the drought  
10 induced wave of tree mortality. For example, the recruitment of *A. seyal* in the low land clay  
11 soil sites only occurred in the gaps made in the previous mature stand by patchy mortality of  
12 trees or at the edges of the previous stand. This is in contradiction with the higher seedling  
13 density observed at the shade of trees by Akpo and Grouzis (1996) in Senegal.

14  
15 An additional hypothesis is that the release of competition by the herbaceous could have  
16 contributed, as well, to the success of the recruitment (Belsky, 1994; Couteron, 1997; Picard  
17 et al., 2005). As indicated previously, the denudation of the soil during the drought, resultant  
18 activation of wind erosion and changes in soils surface features, certainly facilitated the  
19 installation of pioneer shrubs. The reduction in herbaceous cover due to grazing during the  
20 wet season and the trampling by livestock may have contributed also to dense recruitment by  
21 *Acacia* species observed in some of the sites submitted to high stocking rates (# 6, 14, 20).  
22 This observation is in contradiction with reduction in woody plant, and seedling densities,  
23 observed by Dembélé et al. (2006) as distance to water point decreased in a sandy area right  
24 to the North of Gourma but agrees with the increase woody plant densities observed by the  
25 authors as the distance to the Niger valley is reducing. It also contradicts higher seedling

1 recruitment observed in fenced plots partially of totally protected from grazing in Senegal  
2 (Miehe, 1998).

3

4 Although, some thinning were observed during seedling development, especially among the  
5 pioneer shrub populations, the recruitment overall resulted in an increase in population  
6 density and canopy cover despite overall below average rainfall conditions. At the same time,  
7 species composition evolved in favour of a limited number of species dominated by the  
8 pioneer shrubs, *Acacia sp.*, and species adapted to drier climate such as *Balanites aegyptiaca*,  
9 *Maerua crassifolia* and *Commiphora africana*. This trend in species composition could  
10 initiate a latitudinal shift in species distribution in response to the reduction in rainfall  
11 observed since the late 60's (Breman and Cissé, 1977; Boudet, 1979). However, this shift  
12 could also only reflect the relatively dry period during which the recruitment took place.  
13 Indeed, the improvement in rainfall observed since the mid 90's triggered the recruitment of  
14 species that had not recovered yet from the drought such as *C. aculeatum*, *C. glutinosum* and  
15 *Guiera senegalensis* in the southern sandy sites. In shallow soil sites however, the changes in  
16 soil surface features and hydric functioning following the drought are so severe (Leprun,  
17 1992; Ichaou, 2000; Leblanc et al., 2007) that the reestablishment of the previous woody plant  
18 flora is unlikely.

19

## 20 **Conclusion and perspectives**

21

22 In response to the 1983-84 drought woody plant mortality reduced population density and  
23 canopy cover in all Gourma sites irrespective of the soils, topography, grazing pressure and  
24 location along the bioclimatic gradient. However, active recruitment of woody plants  
25 occurred in most sites starting as soon as 1985 and in spite of below average rainfalls. The

1 recruitment proceeded by successive cohorts, often with short-living perennial undershrubs  
2 and pioneer shrubs settling first. *Acacia* species were among the first to settle or re-establish,  
3 especially on the sites most heavily grazed. It seems that the release of competition due to  
4 drought induced mortality and also to the temporal reduction of herbaceous cover contributed  
5 to the success of the recruitment particularly vigorous in the stand gaps and sandy sites  
6 subjected to heavy grazing. After twenty years, post drought woody plant recruitment resulted  
7 for a large majority of sites in an increase of population density and canopy cover in spite of  
8 the overall below average rainfall conditions. The change in species composition that resulted  
9 from mortality and recruitment could first be interpreted as a botanic shift toward more arid  
10 tolerant species flora, however some recruitment diversification observed since mid 90's  
11 could prelude a long term return to previous composition, at least in sites that were not too  
12 severely affected by soil erosion. The mid term response to drought of the woody plant  
13 population sampled along the bioclimatic gradient in Gourma, on main soils types under an  
14 array of grazing pressure conditions, come in support of the resilience of the Sahel vegetation.  
15 In a context of progressive trends and extreme events of climate and land use, the study of  
16 woody plant dynamics in Sahel requires that field data be recorded over long series of years.  
17 To better understand population dynamics there is need to improve on the data quality and the  
18 representativeness of the woody plant population monitored. A critical study of the sampling  
19 and observations methods used in woody population monitoring in the Gourma should be  
20 conducted. Because of the long time scale on which woody plant population evolves there is  
21 also a need to better document local climate and land use histories (fire, clearing for cropping,  
22 camp settlement) using interviews and remote sensing tools. Aerial photographs such as the  
23 IGN coverage over Gourma in 1954, Corona photos in 1965 should also be used to document  
24 past woody population canopy cover and densities. It would, for example, help verifying how

1 far the woody plant decimation following the first drought (1972-73) has conditioned the  
2 woody population response to the second drought analysed in this paper.

3

4

5 **Acknowledgments.** This work was carried out within the African Monsoon Multidisciplinary  
6 Analysis research project funded by a large number of agencies with a major contribution of  
7 the European Community's Sixth Framework Research Program. Information on AMMA  
8 scientific coordination and funding are available on the web site (<https://amma-eu.org/>). The  
9 first author benefited from a grant by INSU CNRS. The authors acknowledge the Malian  
10 agriculture research institute, IER, contribution to data collection and analysis as well as the  
11 International Livestock Research Institute (formally ILCA) program in Mali under which the  
12 first decade of the data base was recorded. They would like to thank ILCA and IRD staff in  
13 Mali for their major contribution in data collection over many years.

1 **References**

- 2 Akpo, L.-E., Grouzis, M., 1996. Influence du couvert sur la régénération de quelques espèces  
3 ligneuses sahélienne (Nord Sénégal, Afrique occidentale). *Webbia*, 50, 2 : 247-263
- 4 Andersen, G.L., 2007. Long-term dynamics of wadi trees in a hyper-arid cultural landscape.  
5 Dis. Dr. scient., Univ. of Bergen, Sweden, 42 p.
- 6 Belsky, A.J., 1994. Influences of trees on savanna productivity: test of shade, nutrients, and  
7 tree-grass competition. *Ecology*, 75: 922-932.
- 8 Benjaminsen, T.A., 1996. Bois-énergie, déboisement et sécheresse au Sahel: le cas du  
9 Gourma malien. *Sécheresse*, 3: 179-85.
- 10 Benoit, M., 1984. Le Séno ne doit pas mourir. Ed. O.R.S.T.O.M., Paris, coll. Memoires 103,  
11 143 p.
- 12 Bille, J.C., 1977. Étude de la production primaire nette d'un écosystème sahélien. Ed.  
13 O.R.S.T.O.M., Paris, Trav. et Doc. 65, 82 p.
- 14 Breman, H., Cissé, A.M., 1977. Dynamics of sahelian pastures in relation to drought and  
15 grazing. *Oecologia*, 28: 301-15.
- 16 Breman, H., Kessler, J.J., 1995. Woody Plants in Agro-Ecosystems of Semi-Arid Regions,  
17 with an Emphasis on the Sahelian countries. Springer-Verlag, Berlin-Heidelberg,  
18 340 p.
- 19 Boudet, G., 1972. Désertification de l'Afrique tropicale sèche. *Adansonia*, ser. 2, 12, 4: 505-  
20 524.
- 21 Boudet, G., 1977. Désertification ou remontée biologique au Sahel. *Cahiers O.R.S.T.O.M.*,  
22 série biol., 12: 293-300.
- 23 Boudet, G., 1979. Quelques observations sur les fluctuations du couvert végétal sahélien au  
24 Gourma Malien et leurs conséquences pour un stratégie de gestion sylvo-pastorale.  
25 *Bois et Forêts des Trop.* 184: 31-44.

- 1 Cissé, M.I., 1980. Production fourragère de quelques arbres sahéliens : relation entre la  
2 biomasse foliaire maximale et divers paramètres physiques. In Le Houérou (ed.) Les  
3 fourrages ligneux en Afrique : état actuel des connaissances, I.L.C.A., Addis Abeba:  
4 203-208.
- 5 Cottam, G., Curtis, J.T., 1956. The use of distance measures in phytosociological sampling.  
6 Ecology, 37: 451-460.
- 7 Couteron, P., 1997. Contractions du couvert végétal et sècheresse. Exemples au nord-ouest du  
8 Burkina Faso? In D'Herbès J.M., Ambouta J.M.K. and R. Peltier (eds),  
9 Fonctionnement et gestion des écosystèmes forestiers contractés sahéliens. John  
10 Libbey Eurotext, Paris: 69-79.
- 11 Dembélé, F., Picard, N., Karembé, M., Birbaum, P., 2006. Tree vegetation patterns along a  
12 gradient of human disturbance in the Sahelian area of Mali. J. Arid Envir. 64: 284-297.
- 13 Engeman, R.M., Sugihara, R.T., Pank, L.F., Dusenberry, W.E., 1994. A comparison of  
14 plotless density estimators using Monte Carlo simulation. Ecology, 75, 6: 1769-1779.
- 15 Frappart, F., Hiernaux, P., Guichard, F., Mougin, E., Kergoat, L., Arjounin, M., Lavenu, F.,  
16 Koité, M., Paturel, J.-E., Lebel, T.. Rainfall regime over the Sahelian climate gradient  
17 in the Gourma, Mali. J. Hydrology, this issue.
- 18 Geerling, C., 1985. The status of the woody species of the Sudan and Sahel zones of west  
19 Africa. For. Ecol. Management, 13: 247-255.
- 20 Grouzis, M., 1988. Structure, productivité, et dynamique des systèmes écologiques Sahéliens  
21 (Mare d'Oursi, Burkina Faso). Ed. O.R.S.T.O.M., Coll. Etudes et Thèses, 318 p.
- 22 Hiernaux, P., Ayantunde, A.A., Kalilou, A., Mougin, E., Gérard, B., Baup, F., Grippa,  
23 M., Djaby, B.. Resilience and productivity trends of crops, fallows and rangelands in  
24 Southwest Niger: impact of land use, management and climate changes. J. of  
25 Hydrology, this issue.

- 1 Hiernaux, P., Cissé, M.I., Diarra, L., 1984. Bilan d'une saison des pluies 1984 très déficitaire  
2 dans le Gourma (Sahel malien). Première campagne de suivi et télédétection  
3 expérimentale. I.L.C.A., Addis Ababa, Doc. Progr. 140, 44 p.
- 4 Hiernaux, P., Cissé, M.I., Diarra, L., de Leeuw, P.N., 1994. Fluctuations saisonnières de la  
5 feuillaison des arbres et des buissons sahéliens. Conséquences pour la quantification  
6 des ressources fourragères. Rev. d'Elev. et de Méd. Vét. des Pays Trop., 47, 1: 117-  
7 125.
- 8 Hiernaux, P., Diarra, L., 1993. Dynamique de la végétation des terres de parcours sahéliennes.  
9 Un bilan du suivi des sites pastoraux du Gourma en 1992. I.L.C.A., Addis Ababa, Doc.  
10 Progr. 1/93, 46 p.
- 11 Hiernaux, P., Gerard, B., 1999. The influence of vegetation pattern on the productivity,  
12 diversity and stability of vegetation: The case of 'brousse tigrée' in the Sahel. *Acta*  
13 *ecologica*, 20: 147-58.
- 14 Hiernaux, P., Le Houérou, H.N., 2006. Les parcours du Sahel. *Sécheresse*, 17(1-2): 51-71
- 15 Hiernaux, P., Mougin, E., Diarra, L., Soumaguel, N., Lavenu, F., Tracol, Y., Diawara, M..  
16 Sahelian rangeland response to changes in rainfall over two decades in the Gourma  
17 region, Mali. *J. Hydrology*, this issue.
- 18 Hillerislambers, R., Rietkerk, M., van den Bosch, F., Prins, H.H.T., de Kroon, H., 2001.  
19 Vegetation pattern formation in semi-arid grazing systems. *Ecology*, 82: 217-226.
- 20 Hutchinson J., Dalziel, J.M., 1954-1972. Flora of West Tropical Africa. 2<sup>nd</sup> edition, Keay  
21 R.W.J., Hepper, F.N., (eds), Crown Agents for Overseas Gov. and Adm., London, vol  
22 1-2-3, 828-544-574 p.
- 23 Ichaou, A., 2000. Dynamique et productivité des structures forestières contractées des  
24 plateaux de l'ouest nigérien. PhD dis., Univ. Paul Sabatier, Toulouse III, 230 p.



- 1 Kammerud, T.A., 1996. Soil impact on satellite based vegetation monitoring in Sahelian Mali.  
2 Geogr. Ann. 78, A, 4: 247-259.
- 3 Knoop, W. T., Walker, B.H., 1985. Interactions of woody and herbaceous vegetation in a  
4 Southern Africa savanna. J. Ecol., 73: 235-253.
- 5 Larwanou, M., Saadou, M., 2005. Biodiversity of ligneous species in semi-arid to arid zones  
6 of southwestern Niger according to anthropogenic and natural factors. Agric., Ecosyst.  
7 And Envir., 105: 267-271.
- 8 Le Barbé, L., Lebel, T., 1997. Rainfall climatology of the central Sahel during the years 1950-  
9 1990. J. of Hydrology 188/189: 43-73.
- 10 Leblanc, M., Favreau, G., Massuel, S., Tweed, S., Loireau, M., Cappelaere, B., 2007. Land  
11 clearance and hydrological change in the Sahel : SW Niger. Global and Planetary  
12 Change, 61, 3-4: 135-150.
- 13 Le Houérou, H.N., 1980. Chemical composition and nutritive value of browse in tropical west  
14 Africa. In Le Houérou H.N. (ed.) Browse in Africa. The current state of knowledge,  
15 I.L.C.A., Addis Ababa: 261-289.
- 16 Le Houérou, H.N., Popov, G.F., 1981. An eco-climatic classification of inter-tropical Africa.  
17 F.A.O., Roma, Plant Production and Protection Paper, 33, 40 p.
- 18 Leprun, J.C., 1992. Etude de quelques brousses trigrées sahéliennes : structure, dynamique,  
19 écologie. In Le Floc'h, E., Grouzis, M., Cornet, A., Bille, J.C., (eds) L'aridité une  
20 contrainte au développement, Ed. O.R.S.T.O.M., Paris: 221-244.
- 21 Lykke, A.M., 2000. Vegetation changes in Sahelian valley system in Burkina Faso. Proc.  
22 I.A.V.S. symposium, Upulus Press, Uppsala: 245-248.
- 23 Miehe, S., 1998. Inventaire et suivi de la végétation dans le périmètre expérimental à Windou  
24 Thiengoly dans le cadre du Projet Sénégal-Allemand d'autopromotion pastorale dans  
25 le Ferlo. G.T.Z., PAPF, Saint-Louis, Senegal, 49 p.

- 1 Mougine, et al.. The AMMA Gourma observatory site in Mali: An overview of research  
2 activities. *J. Hydrology*, this issue.
- 3 Mueller, R.C., Scudder, C.M., Porter, M.E., Talbot Trotter, R. III, Gehring, C.A., Whitham,  
4 T.G., 2005. Differential tree mortality in response to severe drought : evidence for  
5 long-term vegetation shifts. *J. of Ecology*, 93: 1085-1093.
- 6 Nasi, R., Sabatier, M., 1988. Projet d'inventaire des ressources ligneuses au Mali. Rapport de  
7 synthèse, première phase : les formations végétales. BDPA/SCET-AGRI, CTFT-  
8 CIRAD, Nogent-sur-Marne, 215 p.
- 9 Nicholson, S.E., 2001. Climate and environmental change in Africa during the last two  
10 centuries. *Climate Research* 14:123-144.
- 11 Nicholson, S.E., 2005. On the question of the 'recovery' of the rains in the West African  
12 Sahel. *J. of Arid Envir.* 63: 615-641.
- 13 Picard, N., Bar-Hen, A., 2007. Estimation of the density of a clustered point pattern using a  
14 distance method. *Env. and Ecol. Stat.*, 13, 3: 341-353.
- 15 Picard, N., Guéguen, K., Abdoulaye, H.A., Diarisso, D., Karembé, M., Birnbaum, P., Nasi,  
16 R., 2005. Tree formation in relation with soil land grasses in a dry savanna in Mali,  
17 West Africa. *Afr. J. of Ecol.*, 43: 201-207.
- 18 Piot, J., Nebout, J.P., Nanot, R., Toutain, B., 1980. Utilisation des ligneux sahétiens par les  
19 herbivores domestiques. Etude quantitative dans la zone de la mare d'Oursi (Haute  
20 Volta). GERDAT, CTFT, Nogent-sur-Marne, IEMVT, Maison Alfort, 213 p.
- 21 Pollard, J. F., 1971. On distance estimators of density in randomly distributed forests.  
22 *Biometrics*, 27: 991-1009.
- 23 Poupon, H. 1980. Structure et dynamique de la strate ligneuse d'une steppe sahélienne du  
24 Nord-sénégal. Ed. O.R.S.T.O.M., Paris, Trav. et Doc., 115, 351 p.

- 1 Redelsperger, J.L., Thorncroft, C., Diedhiou, A., Lebel, T., 2006. African Monsoon  
2 Multidisciplinary Analysis (AMMA): an international research project and field  
3 campaign. *Bul. Amer. Meteor. Soc.*, 87, 12: 1739-1746.
- 4 Scholes, R.J., 1985 Drought related grass, tree and herbivore mortality in a southern African  
5 savanna. in Totthill, J.C. and J.J. Mott (eds) *Ecology and Management of the World's*  
6 *savannas*. Austr. Acad. of Sc., Canberra: 350-353.
- 7 Scholes, R.J., Archer, S.R., 1997. Tree-grass interactions in savannas. *Annu. Rev. Ecol. Syst.*,  
8 28: 517-544.
- 9 Sinclair, A.R., Fryxell, J.M., 1985. The Sahel of Africa: ecology of a disaster. *Can. J. Zool.*  
10 63: 987-994.
- 11 Slik, J.W., 2004. El Niño droughts and their effects on tree species composition and diversity  
12 in tropical rain forest. *Oecologia*, 141: 114-120.
- 13 Togola, M., Cissé, M.I., Breman, H., 1975. Evolution de la végétation du ranch de Niono  
14 depuis 1969. In *Inventaire et cartographie des pâturages tropicaux africains*. Actes  
15 colloque, I.L.C.A., Addis Ababa: 195-201.
- 16 Sumberg, J., Burke, M., 1991. People, trees and projects: a review of CARE's activities in  
17 West Africa. *Agroforestry Systems*, 15: 65-78
- 18 White, N.A., Engeman, R.M., Sugihara, R.T., Krupa, H.W., 2008. A comparison of plotless  
19 density estimators using Monte Carlo simulation on totally enumerated field data sets.  
20 *BMC Ecology*, 8, 6, 11 p.
- 21 Wispelaere (de), G., 1980. Les photographies aériennes témoin de la dégradation du couvert  
22 ligneux dans un géosystème sahélien sénégalais. Influence de la proximité d'un forage.  
23 *Cahiers O.R.S.T.O.M.*, ser. Sci. Hum., 17: 155-166.
- 24



**Table 2.** Sampling grid of 32 rangeland sites monitored in Gourma (Mougin, et al., this issue). The sites are figured by their code number (as in Fig. 1, except site 37 and 38 located at the South West of the area mapped). The woody plant populations of sites # 3, 23, 27, 32, 36, 40, 41, 42 have not been described until 2005 and are thus not included in the analysis of population dynamics that only consider the sites with historical data (codes in bold).

Hydrology	→	Endoreic systems				Structured watershed	
		Sandy and loamy-sands				Clay, loam	Rock, gravels
Top soil texture	→	Low	Moderate	High	Crop	High	Low
Grazing pressure	→					High	Low
Range of annual rainfall (mm)	250-150	<b>5</b>	<b>1, 3, 4</b>	<b>6</b>		<b>9</b>	<b>2, 8</b>
	350-250	<b>10</b>	<b>12, 32</b>	<b>14</b>		<b>15</b>	<b>16, 40</b>
	450-350	<b>18</b>	<b>17, 19</b>	<b>31</b>	41	<b>20, 21</b>	<b>22, 42</b>
	450-550	<b>30, 38</b>	<b>25, 27</b>	<b>37</b>	23	<b>28</b>	36

**Table 3.** Characterisation of woody plant population in 25 Gourma sites arranged by class of soil texture (Soil), climate aridity (Arid: increasing from 1=south Sahel to 4= north Sahel) and grazing intensity (increasing from 1= light to 4 = intense, 5 = crops, intensively grazed in dry season only). Mean (m.) and standard deviation (s.d.) of the mean canopy cover (%) with or without *Leptadenia pyrotechnica* (L.p.), woody plant density with or without L.p., and basal area without L.p. as calculated from circular plots census done on the indicated year.

Soil	Arid	Graze	Site #	year	canopy cover %				plant density ha <sup>-1</sup>				basal area m <sup>-2</sup>	
					all species		without L.p.		all species		without L.p.		without L.p.	
					m.	s.d.	m.	s.d.	m.	s.d.	m.	s.d.	m.	s.d.
Sandy	1	1	30	2002	1.9	0.6	1.9	0.6	36	14	34	12	0.32	0.11
	1	1	38	2005	3.7	0.3	3.7	0.3	17	2	17	2	0.50	0.02
	1	2	25	2002	1.8	0.6	1.8	0.6	118	36	118	36	0.79	0.29
	1	4	37	2005	0.6	0.3	0.6	0.3	8	4	8	4	0.14	0.07
	2	1	18	2002	6.9	1.1	1.5	0.5	182	32	32	5	0.23	0.07
	2	3	17	2005	3.1	0.9	1.5	0.3	106	27	30	9	0.39	0.11
	2	3	19	2002	10.2	1.9	0.0	0.0	173	105	1	0	0.00	0.00
	2	4	31	2002	7.1	1.2	0.8	0.3	237	46	17	8	0.16	0.07
	3	2	10	2002	2.0	0.6	1.8	0.6	85	11	59	10	0.42	0.12
	3	3	12	2002	3.1	0.9	3.0	0.9	30	5	24	5	0.55	0.16
	3	4	14	2002	13.0	6.6	10.5	5.2	672	69	428	139	2.44	1.14
	4	1	5	2005	2.9	1.3	2.8	1.3	36	8	34	8	0.11	0.02
	4	2	1	2005	0.6	0.2	0.5	0.2	25	2	12	2	0.11	0.07
	4	3	4	2005	2.1	0.4	2.0	0.4	45	10	40	8	0.33	0.19
	4	4	6	2005	5.5	0.8	5.3	0.7	132	43	108	38	0.89	0.15
Shallow	2	2	22	1993	12.8	-	12.8	-	176	-	176	-	1.70	-
	2	2	40	2005	0.7	0.3	0.7	0.3	15	5	15	5	0.20	0.14
	3	2	16	2002	0.6	0.2	0.6	0.2	25	4	24	4	0.11	0.04
	4	2	8	2005	0.3	0.2	0.3	0.2	49	19	46	17	0.16	0.07
	4	2	2	2005	1.0	0.1	1.0	0.1	31	2	31	2	0.27	0.04
Clay	1	3	28	2002	10.7	1.4	10.7	1.4	384	66	384	66	2.59	0.47
	2	4	20	2002	32.1	3.0	32.1	3.0	88	16	88	16	5.29	0.64
	2	4	21	2002	89.6	29.1	89.6	29.1	533	269	533	269	7.39	2.31
	3	4	15	2002	22.8	1.8	22.8	1.8	65	8	65	8	6.74	1.07
	4	3	9	2005	3.3	1.0	3.3	1.0	37	13	37	13	0.64	0.13

**Table 4.** Linear regressions established between the canopy cover of woody plants (Crown Linear Intercept method) in 85 (C85), 1988 (C88), 93 (C93) and 2005-06 (C06), rangeland sites in Gourma (Mali).

Number of sites	Linear regression	$r^2$
19	$C88 = 0.6900 C85 + 1.0318$	0.45
22	$C93 = 1.0765 C88 + 0.4251$	0.88
21	$C06 = 1.4692 C93 - 0.7530$	0.89

**Table 5.** Woody plant mortality following 1983-84 drought assessed by the density of living and dead plants ( $\text{ha}^{-1}$ ) observed in 1989 in 24 rangeland sites in Gourma using CPC.

Site N°	Soil texture	Climat aridity	Grazing pressure	Density of living woody plants $\text{ha}^{-1}$		Density of dead woody plants $\text{ha}^{-1}$		Dead plants %
				mean	s.d.	mean	s.d.	
30	Sandy	1	1	35	12.7	9	4.4	20.5
38		1	1	25.5	4.9	5	2.1	16.4
25		1	2	19.5	9.6	0.3	0.3	1.3
37		1	4	7.9	4.3	39.7	5.7	80
18		2	1	70	20.8	0	0	0
17		2	3	17	4	2.5	1.2	12.8
19		2	3	17.8	3.6	0.5	0.5	2.7
31		2	4	116.7	26.6	0	0	0
10		3	2	33	19.5	5	3	13.2
12		3	3	23	4.4	0	0	0
14		3	4	94	40.7	4	4	4.1
5		4	1	62	23.4	1	1	1.6
1		4	2	15	7.2	2	1.4	11.8
4		4	3	36.5	6.2	3	2.4	7.6
6	4	4	46	11.5	21	6	31.3	
16	Shallow	3	2	37	31.9	9	7.7	19.6
8		4	2	52	16.6	18.5	8.6	26.2
2		4	2	29.5	8.2	5	0.6	14.5
28	Clay	1	3	125	43.9	3	3	2.3
20		2	4	48	4.6	10	6	17.2
21		2	4	34	9	6	3.5	15
15		3	4	45	5	3	1	6.3
9		4	3	28	6.3	1	0.6	3.4
7	4	4	66	13.2	41	10.1	38.3	



## Figure captions

**Figure 1.** Location of the monitored rangeland sites along the bioclimatic gradient and on the main soil types in Gourma, Mali, and on the main soil types. The sites to the North of Niger River and the sites # 3, 23, 27, 32, 40, 41, 42 which woody populations were not described until 2005 are not included in the analysis of the population dynamics.

**Figure 2.** Trends in canopy cover (Cover %) of alive (diamond, solid line) or dead woody plants (square, dashed line) in Gourma sites between 1985 and 2006 as observed with the crown linear intercept method. Example of overall constant (# 16, 17), increasing (# 19, 21) or decreasing trends (# 30, 31).

**Figure 3.** Trends in canopy cover (Cover %) and in plant density (density  $\text{ha}^{-1}$ ) per woody plant species in Gourma sites from 1988 to 2006, from circular plot census, sites 16, 21.

**Figure 4.** Trends in canopy cover (Cover %) and in plant density (density  $\text{ha}^{-1}$ ) per woody plant species in Gourma sites from 1988 to 2006, from circular plot census records: sandy soils sites lightly grazed (# 30), moderately grazed (# 17) and intensely grazed (# 31).

**Figure 5.** Dynamics over the years 1989, 1993 and 2002 of the distribution of the crown areas in  $\text{m}^2$  (a,b,c) and basal areas in  $\text{cm}^2$  (d,e,f) of the *Acacia seyal* individuals recorded over 1 ha at Kelma (# 21). Histograms figure the frequency distribution ( $\text{ha}^{-1}$ ) while dashed lines figure cumulated distributions (%).

Figure 1.

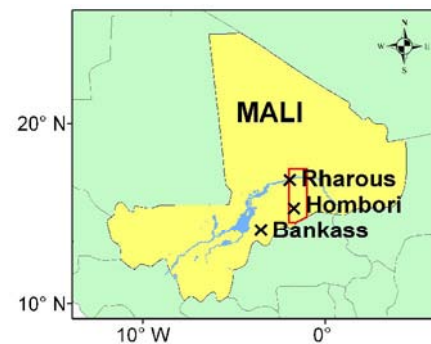
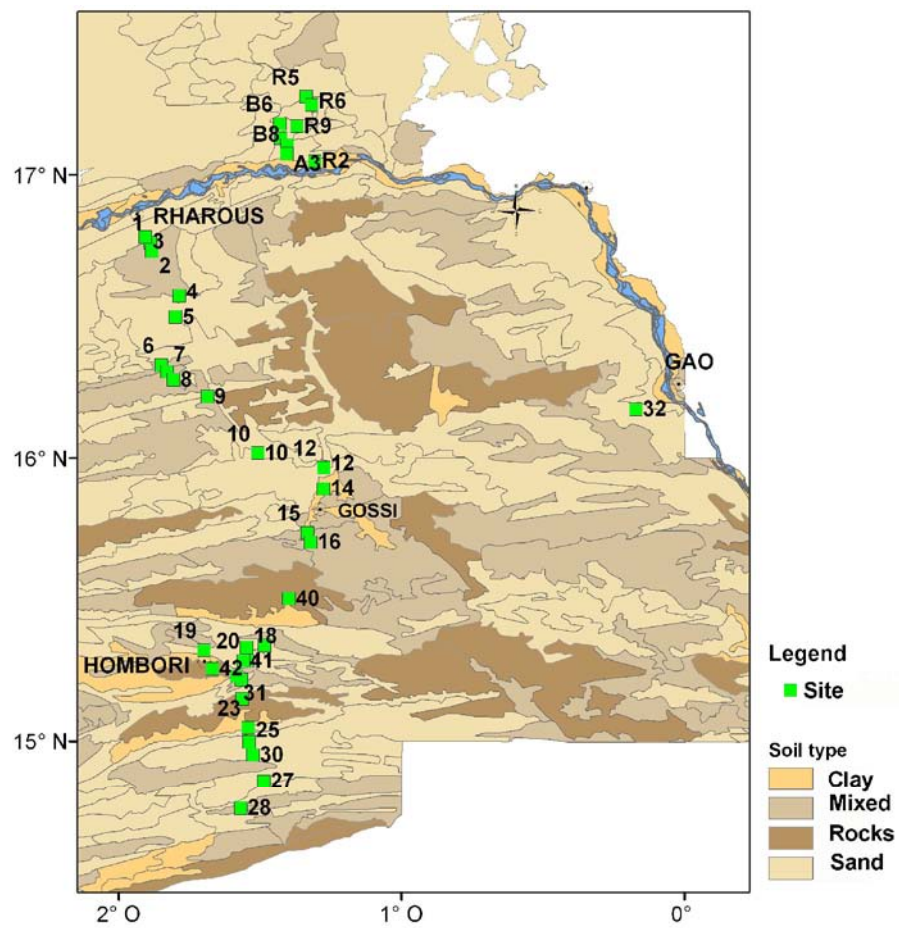


Figure 2

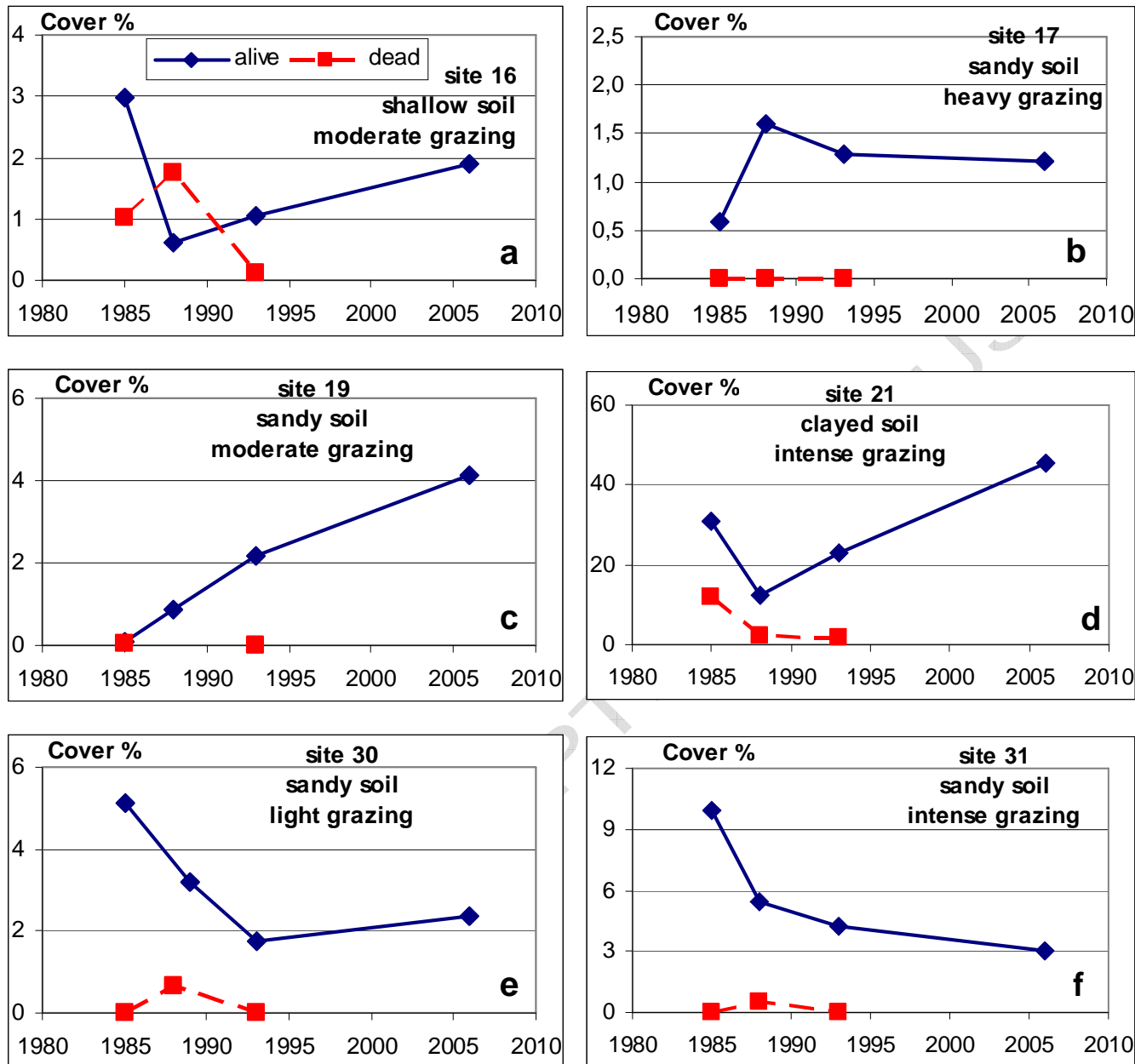


Figure 3

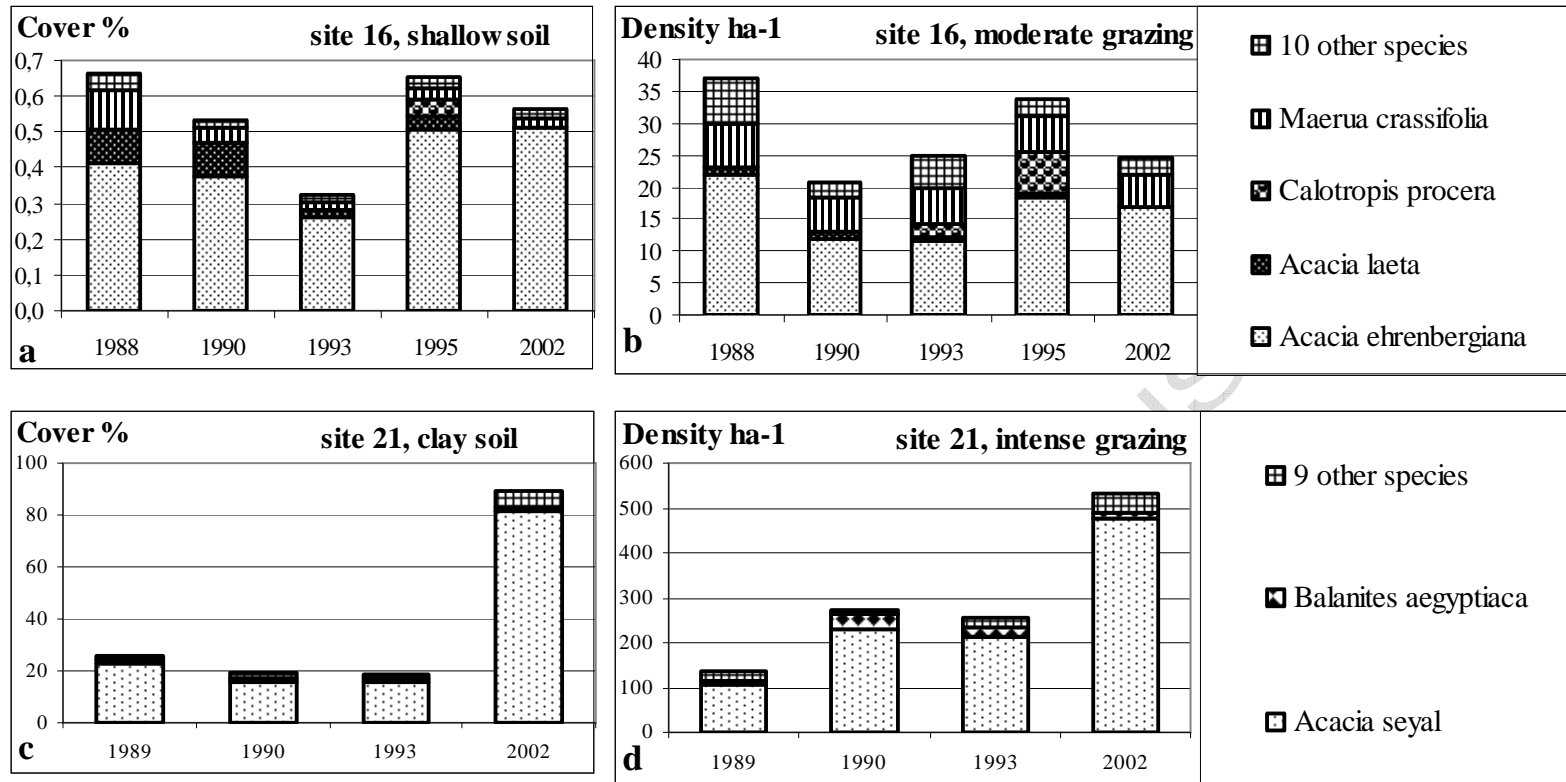


Figure 4

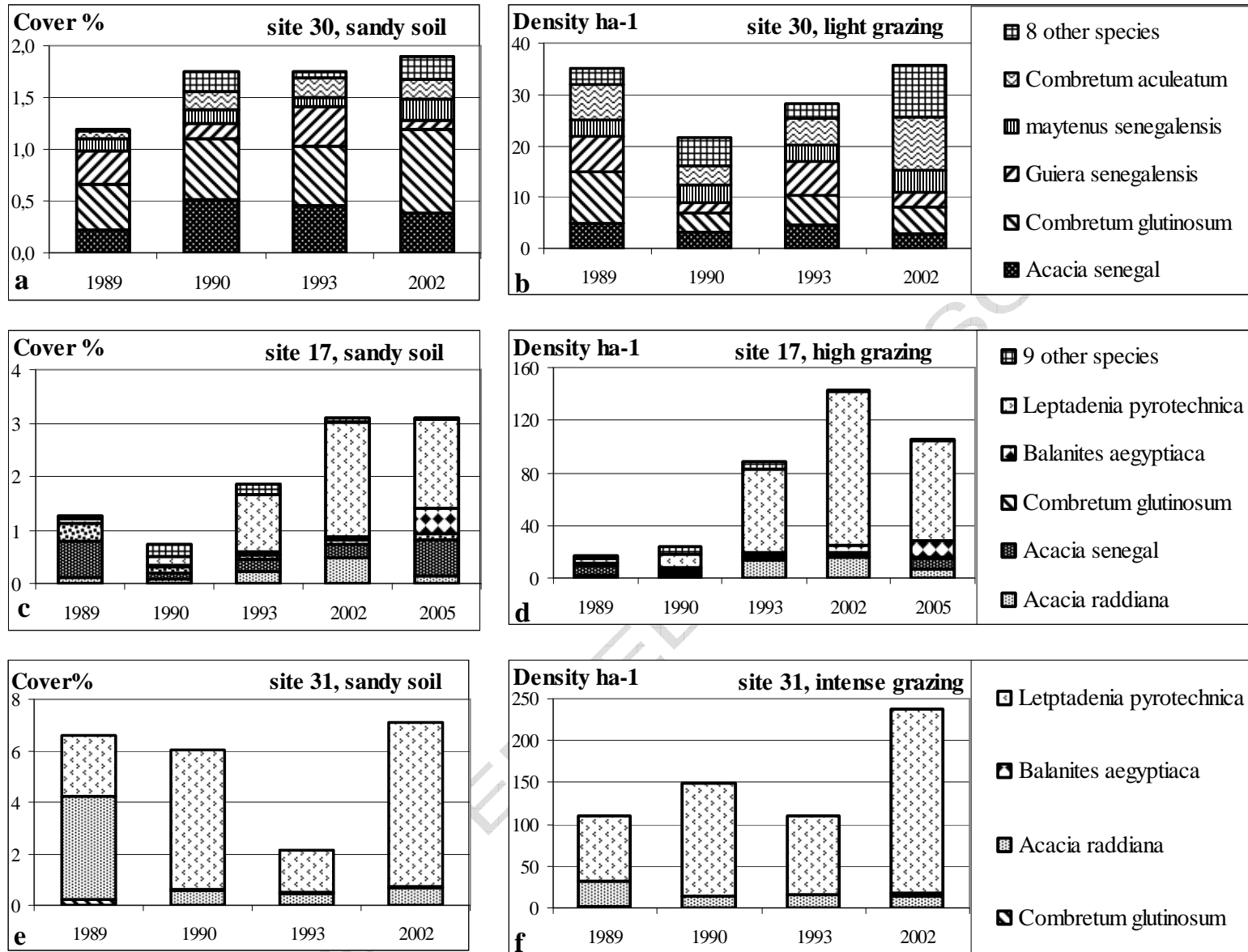


Figure 5

