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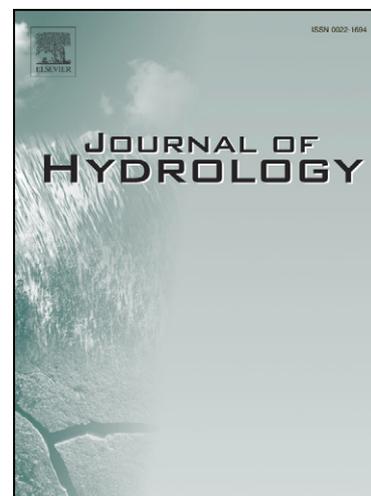
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1 **Woody plant population dynamics in response to climate changes from**
2 **1984 to 2006 in Sahel (Gourma, Mali)**

3

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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 m². 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
$$(4) D_2 = 10000 \frac{4(kn - 1)}{\pi \sum_{j=1}^n \sum_{k=1}^k d_{ij}^2}$$
 with d_{ij} the distance (m) in the k ($j = 1$ to 4) sectors, n (i
 11 $= 1$ to n) the number of sampling points (Pollard 1971).

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 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 ± 12 plants ha^{-1}) covering 90% of site
4 area at Ortondé site (# 22) and dense thickets ($124.3 \pm 61.1\%$ canopy cover with 1568 ± 583
5 plants ha^{-1}) covering 10%, resulting in weighed averages of 12.8% canopy cover and plant
6 density of 176 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 ha^{-1} with the low and aphyllous shrub *Leptadenia pyrotechnica* accounting for 1.8%
17 cover and 63 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⁻¹
15 established woody plants on heavy grazed sand soil (# 14), 28 ha⁻¹ young *L. pyrotechnica*
16 and 87 ha⁻¹ 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⁻¹ with
22 4.4% cover and standing dry mass of 217 kg ha⁻¹.

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; Miede
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

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- 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 | → | | | | | | |
| Grazing pressure | → | Low | Moderate | High | Crop | High | Low |
| Range of annual rainfall (mm) | 250-150 | 5 | 1, 3, 4 | 6 | | 9 | 2, 8 |
| | 350-250 | 10 | 12, 32 | 14 | | 15 | 16, 40 |
| | 450-350 | 18 | 17, 19 | 31 | 41 | 20, 21 | 22, 42 |
| | 450-550 | 30, 38 | 25, 27 | 37 | 23 | 28 | 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 ⁻¹ | | | | basal area m ⁻² | |
|---------|------|-------|--------|------|----------------|------|--------------|------|--------------------------------|------|--------------|------|----------------------------|------|
| | | | | | 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 (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 ha^{-1} | | Density of dead woody plants 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.

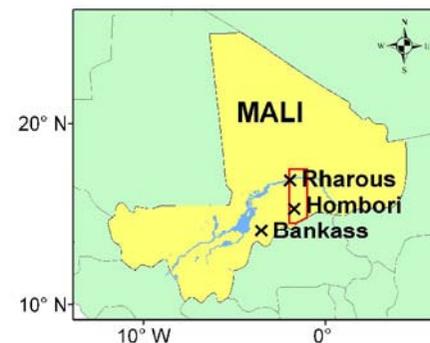
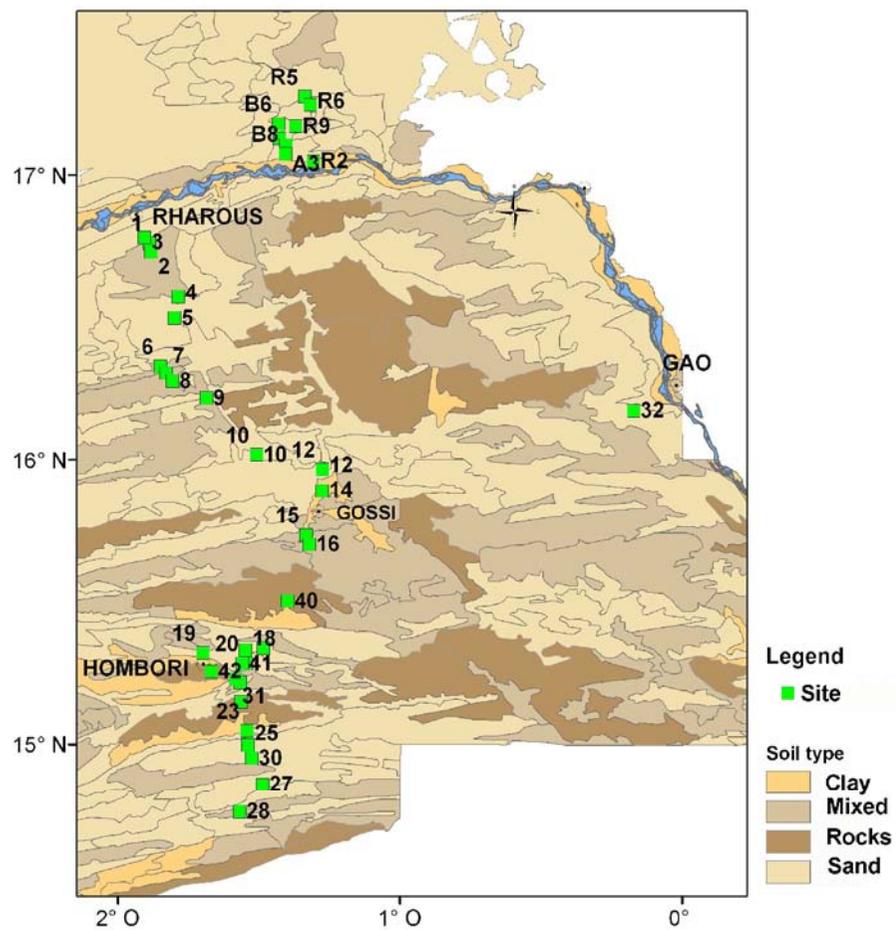
Figure 2. Trends in canopy cover (Cover %) of alive (diamond, solid line) or dead woody plants (square, dashed line) in Gourma sites between 1985 and 2006 as observed with the crown linear intercept method. Example of overall constant (# 16, 17), increasing (# 19, 21) or decreasing trends (# 30, 31).

Figure 3. Trends in canopy cover (Cover %) and in plant density (density 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 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 m^2 (a,b,c) and basal areas in cm^2 (d,e,f) of the *Acacia seyal* individuals recorded over 1 ha at Kelma (# 21). Histograms figure the frequency distribution (ha^{-1}) while dashed lines figure cumulated distributions (%).

Figure 1.



Legend
■ Site
Soil type
Clay
Mixed
Rocks
Sand

Figure 2

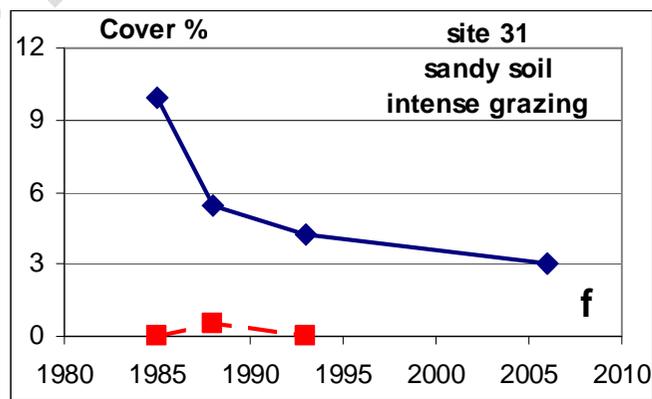
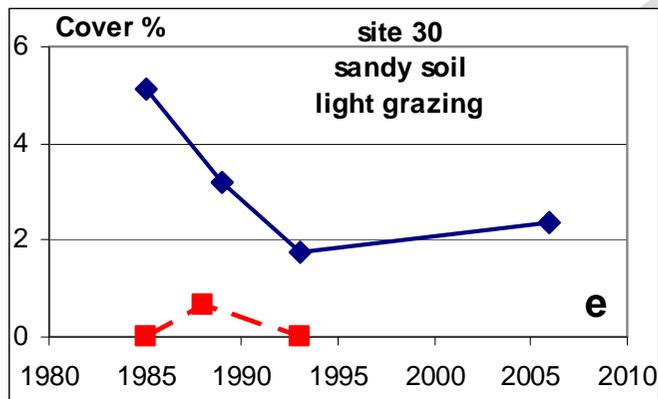
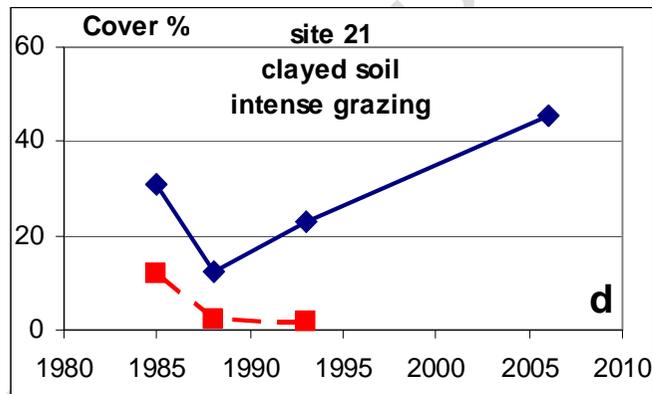
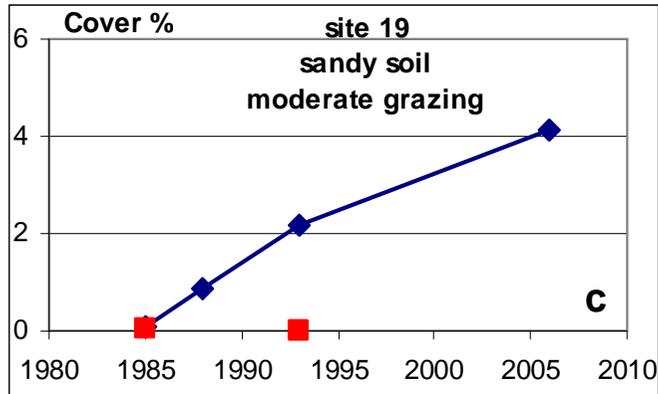
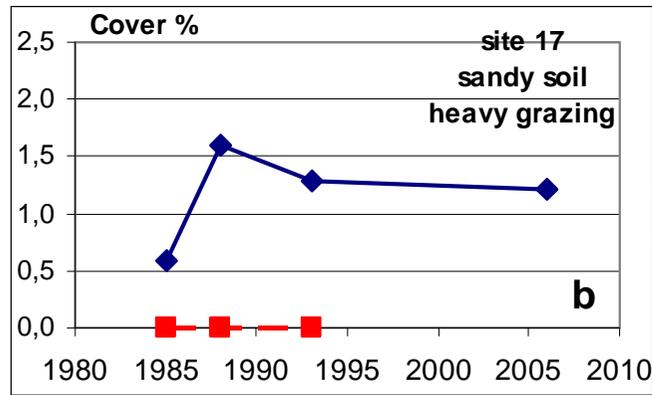
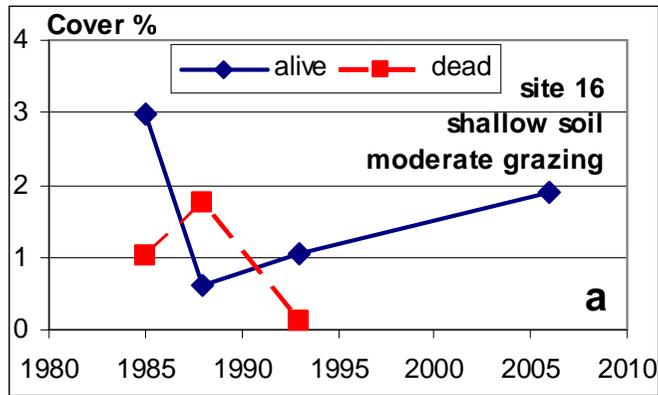


Figure 3

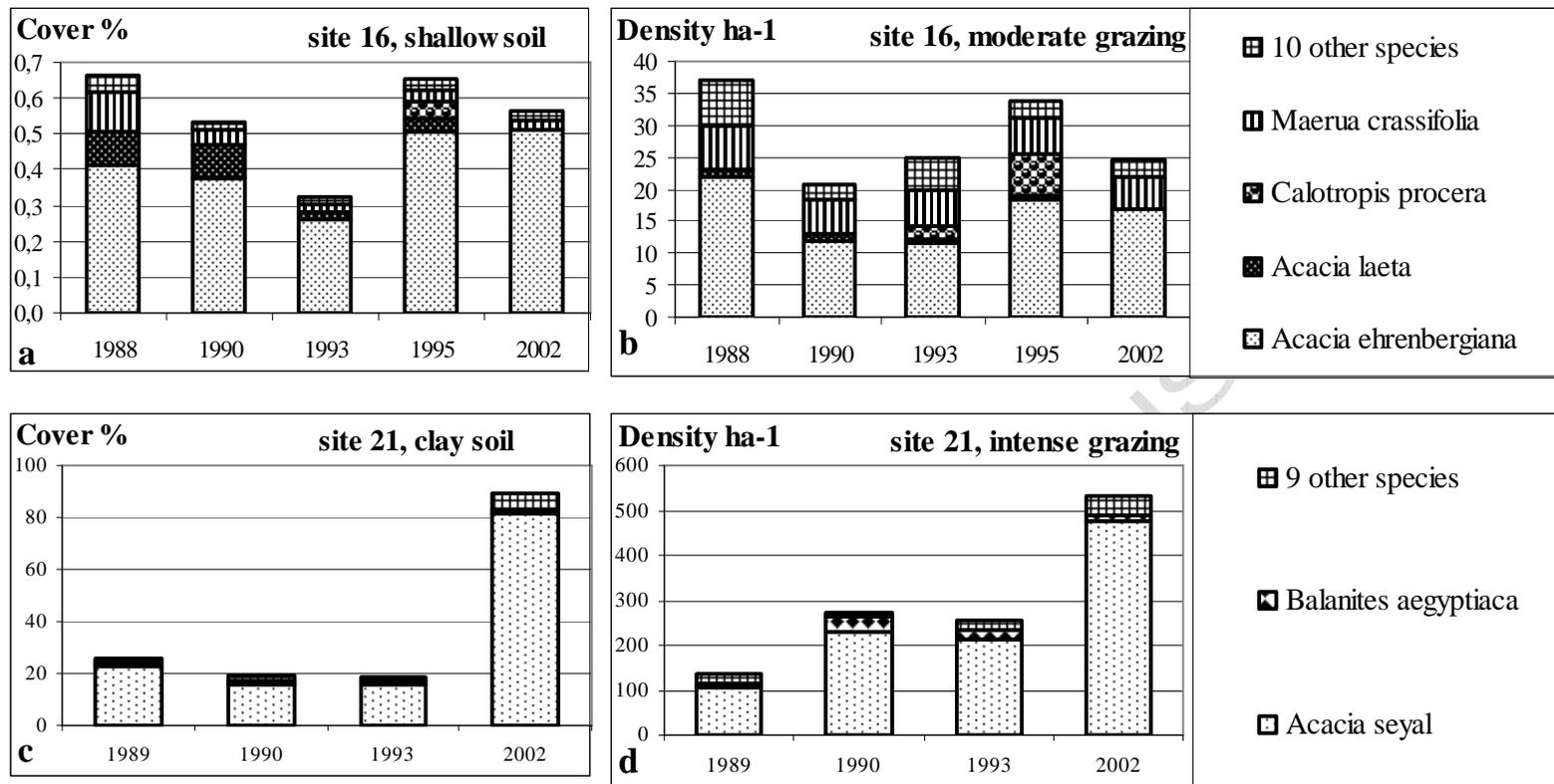


Figure 4

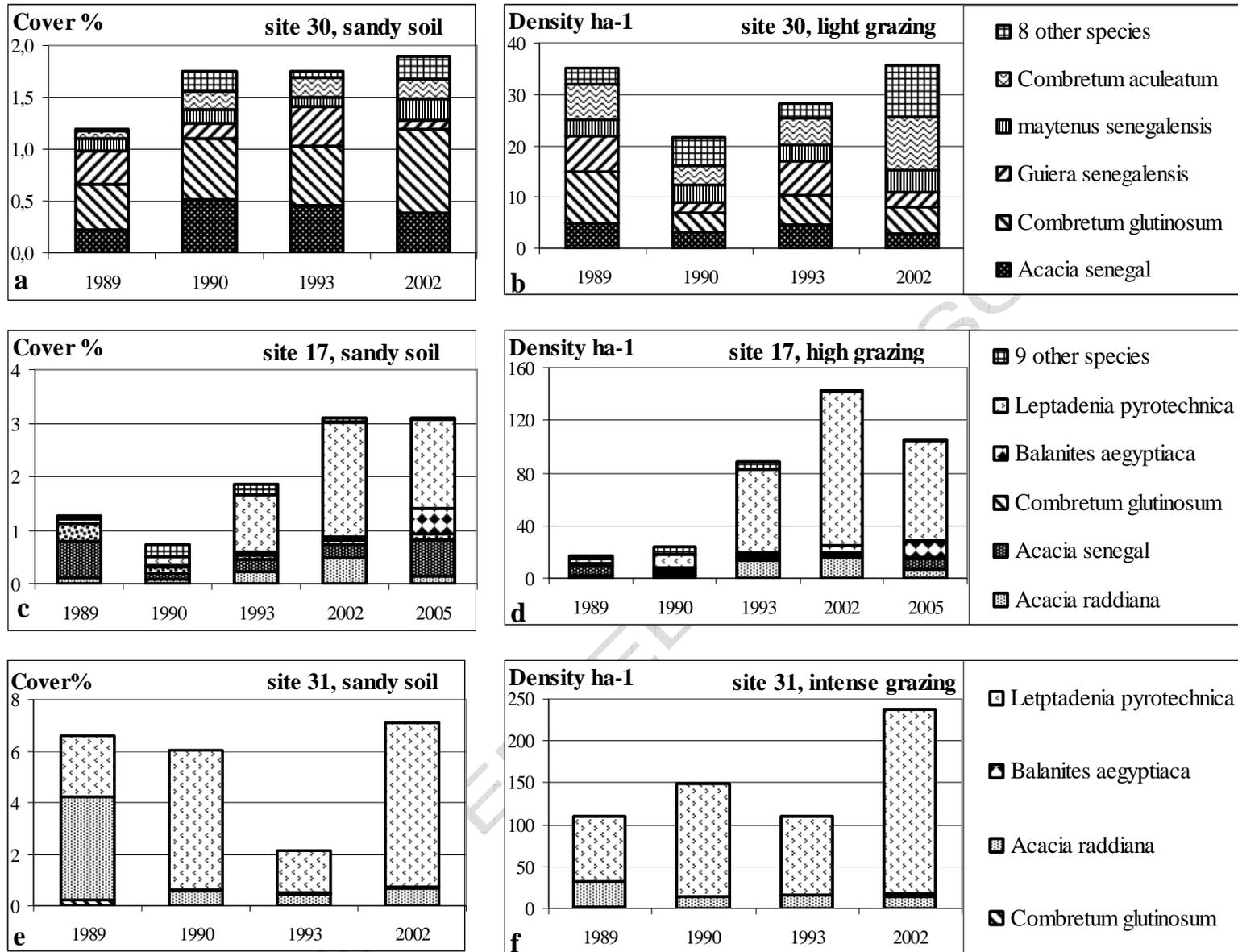


Figure 5

