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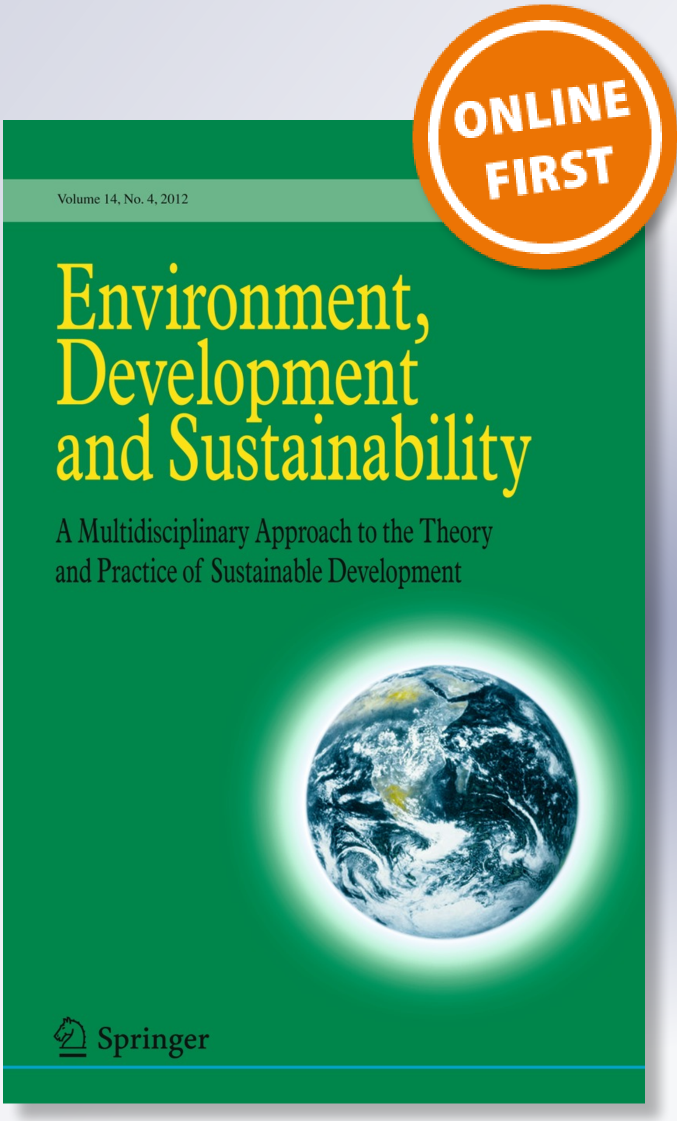

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Do protected areas really work to conserve species? A case study of three vulnerable woody species in the Sudanian zone of Burkina Faso

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Abstract Natural vegetation and native plant species contribute significantly to the daily needs of local people especially in developing countries. This exerts a high pressure on local species and jeopardizes the conservation of the most vulnerable plants. In Burkina Faso, conservation measures, such as the creation of protected forests, have been taken to safeguard the remaining indigenous vegetation. However, little is known about the effectiveness of these protected areas in conserving biodiversity. This study assessed and compared the population structures and regeneration potential of three vulnerable woody species—*Diospyros mespiliformis* Hochst., *Prosopis africana* (Guill. & Perr.) Taub. and *Sterculia setigera* Del.—in protected and unprotected areas in the Sudanian zone of Burkina Faso. The population structure and regeneration pattern of each species were compared between the North and South Sudanian sectors of Burkina Faso. The populations of all three species were unstable in both protected and unprotected areas. *D. mespiliformis* and *P. africana* displayed relatively good regeneration while *P. africana* lacked regeneration in unprotected areas. Regeneration was poor for *S. setigera,* regardless of protection status. The results suggest that the populations of the targeted species are unstable, regardless of the protection status of the area considered. This is probably due to the high anthropogenic pressure facing natural resources and raises serious concerns about the effectiveness of the protected areas in conserving biodiversity. Urgent measures are needed

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to ensure effective and efficient management and conservation of biodiversity in the protected areas of Burkina Faso.

Keywords Multipurpose species · Population dynamics · Regeneration · Size-class distribution · Protected areas · Conservation

1 Introduction

In many developing countries, wooded ecosystems provide a range of goods and services to local communities. This is especially true for Burkina Faso where the majority of the population depends on plant species as sources of fuel, timber, food, medicine, fodder, and other products of cultural value (Sop et al. 2012). In the West African Sahel in general, and Burkina Faso in particular, firewood is the major source of energy for cooking and heating, and 90 % of the total energy consumption is from sources such as wood and charcoal (Brocard et al. 1998; Nygard et al. 2004). Wooded landscapes are also being cleared for subsistence agriculture, which supports 80 % of the total population of Burkina Faso (INSD 2008). Another factor in land degradation is livestock production: based on natural pastures in the savanna-woodlands of the country, it has been one of the main livelihoods for indigenous people for centuries. Grazing effects include impacts on seedlings and tree regenerative capacity. These pressures on the land resources are exacerbated by an exponential increase in population growth: from 1960 to 2012, the population of Burkina Faso increased fivefold from 3.5 to more than 17 million (CIA 2012). The resulting high demand for plant resources raises concerns about the ecological impacts of exploitation on biodiversity and ecosystem processes (Pote et al. 2006).

Diospyros mespiliformis Hochst., *Prosopis africana* (Guill. & Perr.) Taub. and *Sterculia setigera* Del. are among the species most commonly used by the local people in the Sahelian area of West Africa (Belem et al. 2007; Vodouhê et al. 2009; Paré et al. 2010; Traoré et al. 2011; Sop and Oldeland 2011). This results in a rapid decline in their populations (Tchoundjeu et al. 1998; Weber et al. 2008; Traoré et al. 2011), and in western Burkina Faso, these species are among the most vulnerable (Traoré et al. 2011). In the light of projections for ever-growing human and livestock populations, the pressure exerted on these multipurpose species is expected to increase. This will probably compromise the regenerative capacity and thus conservation of these species, with major ecological, economic and social consequences.

In the 1930s, a large part of the Sudanian zone of West Africa was delimited and protected by the colonial administration to create wildlife sanctuaries and prevent the expansion of shifting cultivation (Zida 2007). Following political independence, forests and woodlands were preserved through the establishment of state forests for wood production and biodiversity conservation (Zida 2007). In Burkina Faso, such reserves represent 25 % of the total area of forest and woodland, covering 7.1 million ha or 26 % of the country's land area (Savadogo 2007; Zida 2007).

Several ecological studies have considered anthropogenic and climate impacts on the population structure and dynamics of multipurpose tree species in many parts of Burkina Faso (Ouédraogo et al. 2006; Bognounou et al. 2009; Sop et al. 2011), but not the potential influence of management status (protected vs. unprotected). Such knowledge is crucial for assessing the ecological impact of forest protection on plant populations and for making recommendations on sustainable conservation and management of woody plant resources.

This study analyzed population structure and regeneration patterns of three economically important woody species, *D. mespiliformis*, *P. africana,* and *S. setigera*, in protected and unprotected areas in the Sudanian zone of Burkina Faso. It was hypothesized that the population structure and regenerative ability of these three species would be enhanced within protected areas.

2 Materials and methods

2.1 Study area

This research was carried out in the Sudanian phytogeographical zone in western Burkina Faso, West Africa. The study area is situated between 9°30′–13°30′N and 5°30′–2°30′W (Fig. 1). The Sudanian zone consists of the North Sudanian (NS) and the South Sudanian (SS) sectors (Fontès and Guinko 1995).

The North Sudanian sector has a mean annual rainfall between 700 and 800 mm. The mean annual temperature ranges from 15 to 40.8 °C. December and January are the coldest months while March and April are the warmest (Ky-Dembélé et al. 2007). The most frequently encountered soils are lithosols (Bognounou et al. 2009). Common woody species are *Acacia seyal* Del., *Combretum micranthum* G. Don, *C. glutinosum* Perr.ex DC, *C. nigricans* Lepr. ex Guill & Perr., *Guiera senegalensis* J. F. Gmel. and *Anogeissus leiocarpa* (DC.) Guill. et Perr. The grass layer is dominated by *Andropogon pseudapricus*

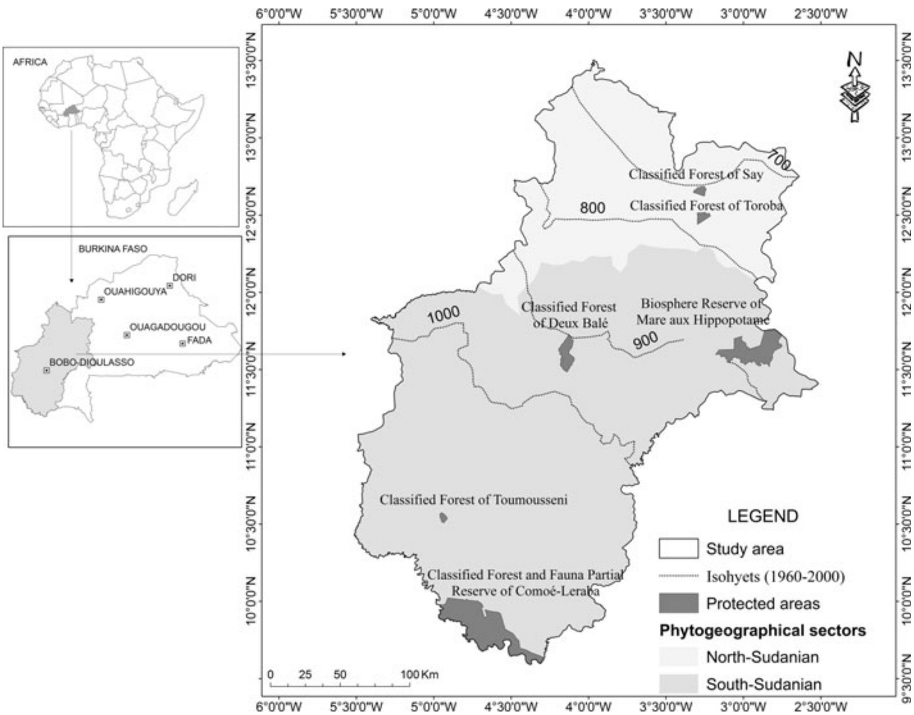

Fig. 1 The location of the study sites within the Sudanian zone, western Burkina Faso

Stapf., *Loudetia togoensis* (Pilg.) C.E. Hubb., *Andropogon gayanus* Kunth, *Elionurus elegans* Kunth, and *Cymbopogon schoenanthus* Spreng.

The annual rainfall in the South Sudanian sector varies from 900 to 1,000 mm (Fontès and Guinko 1995). The average annual temperature is 28 °C, with a mean maximum monthly temperature of 37.9 °C in April and a mean minimum monthly temperature of 17.6 °C in December. The dominant soils are ferralsols (Bognounou et al. 2009). Common woody species include *Acacia sieberiana* DC.*, Anogeissus leiocarpa* (DC.) Guill. et Perr.*, Burkea africana* Hook. F, *Daniellia oliveri* (R.) Hutch. & Dalz. C*, Diospyros mespiliformis* Hoschst. ex A. DC.*, Combretum glutinosum* Perr.ex DC*, C. nigricans* Lepr. ex Guill & Perr. and *Isoberlinia doka* Craib. & Stapf. The main herbaceous species were *A. gayanus*, *Diheteropogon amplectens* (Nees) Clayton, *Loudetia simplex* (Nees) C.E. Hubb. and *Vetiveria nigritana* Stapf.

Agriculture and cattle breeding are rather homogeneous and the whole Sudanian zone falls within the "cotton area," with agriculture based mainly on sorghum, millet, groundnuts, and some vegetables. Agricultural production in the South Sudanian zone is more intensive and more varied than in the North. This is especially due to the cultivation of yams and perennial food crops (mangoes, citrus fruits, cashew nuts, etc.), which is of vital importance for the country (Devineau 2010).

In this study, protected areas are defined as clearly delimited areas of natural savanna or forest, that have been set up—with appropriate legal status—by public authorities with the aim of restricting anthropogenic disturbances and ensuring protection of natural resources as well as ecosystem function and services. There are two types of public protected areas according to the Forestry act of 1997: areas managed under the authority of the government and areas managed by local public authorities (Konrad and Adouabou 2010). There are also private forests that belong to conservation areas, but we focused only on public forests. Numerous protected areas are present in the study zone, but the protected status tends to be only partially observed. There are incursions of local populations as well as their cattle into the reserves, and fires are commonly used by park managers as a management strategy. Due to the scarcity of natural pastures, livestock grazing in protected areas is more or less tolerated. Consequently, the environmental policy of Burkina Faso has moved from simple conservation to a sort of "management conservation" taking into consideration the inclusion of pastoral activities in the forest management policy (Savadogo 2007). Park managers of public protected areas are official forestry workers who are recruited and trained by the government for enforcing Forestry Act, either at the national or local level. Foresters are in charge of the security of protected areas. The Forestry Act of Burkina Faso of 31 January 1997 foresees sanctions such as financial penalties or imprisonment against any person taking off forest products from protected areas without prior authorization of the competent authorities. The application of these sanctions is rather a marginal phenomenon.

Data collection was carried out only in officially defined protected areas. Traditionally protected forests (sacred forests), without official protection status, were not considered in this study. The protected forests of Say and Toroba (Dédougou) were sampled in the North Sudanian sector. In the South Sudanian sector, the protected area of Balé (Boromo), the Biosphere Reserve of "la mare aux hipoppotames" (Bala), the forest reserve of Toumouséni/Soubakaniédougou (Banfora), and that of Comoé-Leraba were considered (Fig. 1). Like all the conservation areas, these protected forests show more diversity compared with the surrounding ecosystems (Belemsobgo et al. 2010).

The sampled protected areas obey to different management regimes. The classified forests of Toroba, Balé, and Toumousséni/Soubakaniédougou are fully controlled by state services. The protected area of Say is conceded (concession) to private operators, while the

Comoe-Leraba protected reserve is managed by local communities associations—also called territorial collectivities—through a concession with the State. When a concession has been attributed to communities' associations or to private operators, the role of the state forestry services is limited to the supervision and surveillance of the protected zones. Classified and partial fauna reserve of Comoé-Léraba is an experimentation of the direct management of a protected area by local communities that is being experienced since 2001.

The majority of classified forests today are experiencing destruction of a magnitude which varies from one location to another. Illegal logging and harvesting of non-woody forest products are frequent in all these protected areas. In addition, protected areas are subject to agricultural, pastoral, and bush fires (early and late fires) pressures (Belemsobgo et al. 2010). Early bush fires are controlled fires, that are frequently used in protected areas, especially at the beginning of the dry season (when the grass cover has just started to dry), as a mean to reduce the biomass load and therefore the risk and intensity of destructive late fires (Mäkelä and Hermunen 2007). Although prohibited for their destructive effects on vegetation and soils, late fires, which take place at the peak of the dry season, when the grass cover is already completely dry, are also observed in some protected areas, generally as a consequence of criminal activities within these zones (pers. observation).

Unprotected areas in this study are understood as agroforestry parklands, farms, fallows, freely accessible natural savannas, and rocky areas unsuitable for agriculture. Agroforestry parklands are very characteristic of the Sudanian zone and are characterized by the preservation of some important tree species (e.g., *Adansonia digitata, Parkia biglobosa*, and *Vitellaria paradoxa*) on croplands. Beside the parklands, some natural savanna sites exist and are not used for agriculture because of their unfavorable soil and habitat conditions (e.g., too dry, wet, or rocky). Unprotected areas are strongly affected by different types of anthropogenic activities, for example, extensive livestock grazing, fires, and various harvestings of natural products including fuel wood, thatching materials, poles for construction, and edible and medicinal plants.

Six main ethnic groups live in the study area: the Bobo, Bwaba, Samo, Mossi, Sénoufo, Goins, and Karaboro. Islam is the dominant religion in the area although the populations also practice African traditional religions that are deeply rooted in their ancestral customs. Extensive agriculture and cattle farming are the main occupations for local populations.

2.2 Study species

Diospyros mespiliformis (Ebenaceae) is a large tree, 15–20 m tall, distributed from Senegal to Cameroon, in tropical and East Africa. It is often associated with termite mounds and riverine fringes (Arbonnier 2004), and its leaves, bark, and roots have medicinal uses. The round and yellowish-brown fruits are consumed by humans and large frugivorous birds. The wood is used in construction and as a source of fuel. *D. mespiliformis* is highly prized by blacksmiths for making the handles of agricultural tools. Furthermore, its green fruits are used by female potters to increase the brightness of their pottery.

Prosopis africana (Leguminosae, sub-family Mimosoideae) is the only native species of its genus in tropical Africa (Tchoundjeu et al. 1998). It is a small or large tree of up to 20 m in height that occurs in semi-arid regions of sub-Saharan Africa (Weber et al. 2008). *P. africana* is common in Sudanian areas and found predominantly on deep sandy soils or stony and gravelly soils. The wood is resistant to insect attack, making it useful for the fabrication of poles, mortars, and handles for farm implements (Weber et al. 2008; Traoré et al. 2011). It is highly valued in the study area for firewood and charcoal (Traoré et al. 2011).

Sterculia setigera (Sterculiaceae) is a small tree of 5–12 m in height that occurs from Senegal to Angola. It is common and mainly found on rocky hills, where it forms isolated stands on stony, gravelly, or lateritic soils. *S. setigera* is in high demand by traditional healers and craftsmen for its bark and fibers.

2.3 Field sampling

Data were collected both inside and outside of selected protected areas of the North and South Sudanian phytogeographical sectors. The sample plots were implanted in the vegetation types where one of the targeted species was found. The main vegetation types encountered were tree/shrub, savanna, woody savanna, and woodlands in both phytogeographical sectors where the study was conducted.

Inventories of tree population stands were carried out during the rainy season (July–November) of the years 2009 and 2010. Species distribution maps (MECV 2008) and field visits were used to identify accessible populations of the studied species. Sampling units were plots of 1,000 m^2 (20 m $\times$ 50 m) in size. Depending on the stand size of the target species, between one and four plots were randomly laid out within each population. Overall, 10–15 plots per species and per phytogeographical sector were studied in each zone. A measuring tape was used to measure girth at breast height (GBH, at height 1.3 m), which was then converted to diameter at breast height (DBH) using the formula: DBH = GHB/Π. Within the 1,000 m^2 plots, all individuals of the target species of DBH $\geq$ 5 cm were sampled, following previously employed methods in the Sudanian area of Burkina Faso (Ouédraogo 2006; Sop et al. 2011).

2.4 Assessment of regeneration

Assessment of natural regeneration gives information on the regenerative capacity of a population (Obiri et al. 2002). Within each sampling unit of 1,000 m^2, two subplots of 25 m^2 (5 m $\times$ 5 m) were randomly laid out and geo-referenced with a Global Positioning System (GPS), to assess the regeneration capacity of each species. Individuals with a circumference <15.7 cm (i.e., DBH < 5 cm), being considered as juveniles, were counted and classified according to five height classes of 0.5 m intervals: 0–0.5, 0.51–1, 1.1–1.5, 1.51–2 m, and >2 m. This subdivision of the juveniles into height classes helps gain insight into the stages at which any growth and development problems occur among seedlings and saplings (Steven 1994 cited in Sop et al. 2011).

2.5 Data analysis

Mean population density was calculated for each species in protected areas (PAs) and in unprotected areas (UAs). T-tests were used to compare mean population density and mean seedling density between the two types of management regimes.

Owing to the fact that the data were not normally distributed, the Kolmogorov–Smirnov test was used to compare mean size-class distributions (SCDs) and height-class slopes of each of the three species within PAs and UAs. Results were considered significant at $p < 0.05$.

2.5.1 Size-class distribution

To establish the size-class distributions (SCDs), all individuals of the study species were assembled in ten diameter size-classes of 5-cm interval (5–10, 10–15, etc., and >50 cm). Ten classes are sufficient to allow the adjustment of Weibull theoretical distribution to the observed shape (Bonou et al. 2009).

The observed different diameter structures were adjusted to the 3-parameter Weibull. This is flexible and mathematically simple, covering diameter distributions that are strongly positively or negatively skewed as well as normally distributed (Lorimer and Krug 1983; Baker et al. 2005). The 3-parameter Weibull density function, *f*, is expressed for a tree diameter *x* as follows:

$$f(x) = \frac{c}{b}\left[\frac{(x-a)}{b}\right]^{c-1} \mathrm{e}^{-[x-a/b]^{c}}$$

where x = tree diameter, $a = 5$ cm for the diameter structure, b = scale parameter linked to the central value of diameters, and c = shape parameter of the structure. For each species, tree diameter was used to estimate the parameters b and c based on the maximum likelihood method (Zarnock and Dell 1985). The Weibull distribution accepts a wide variety of shapes as determined by the shape parameter c (Ryniker et al. 2006). When $c < 1$ the function has a reversed J shape, while when $c = 1$ it is a negative exponential distribution. For values of $c > 1$, the function is unimodal. If $1 < c < 3.6$, the distribution has a positive skew; when $c = 3.6$, it is approximately normal; and when $c > 3.6$, the distribution has a negative skew.

In each case, the log-linear analysis (Caswell 2001) was performed in SAS (SAS Inc. 1999) to test the fit of the observed structure to the Weibull distribution. The following model, described by Caswell (2001), was used:

$$\text{Log Frequency} = F + F_{\text{\_Class}} + F_{\text{\_adjustment}} + \varepsilon,$$

where F = mean frequency of the classes, $F_{\text{\_Class}}$ = non-random gap linked to the differences in frequency between classes, $F_{\text{\_Adjustment}}$ = non-randomly gap linked to differences between observed and theoretical frequencies, and ε = error of the model.

The fit between observed structure and Weibull distribution is accepted if the probability value of the test is higher than 0.05 (Bonou et al. 2009).

2.5.2 Population dynamics

The population structure for each species in PAs and UAs was inferred by analyzing the slope of a linear regression of size-class distribution (SCD) parameters. For each of the three species, the ordinary least-squares regression (OLS) was calculated. The SCD midpoint (mi) was used as the independent variable and the mean number of individuals in each SCD (Ni), as the dependent variable. However, to derive straight line plots of SCD (Obiri et al. 2002; Sop et al. 2011), Ni in each size-class was subjected to a logarithmic transformation using ln(Ni + 1), as some size-classes had zero individuals. The regression was calculated between ln(Ni + 1) and ln(mi). The SCD slopes obtained from the regression were used as an indicator of population structure for each species (Condit et al. 1998; Lykke 1998; Obiri et al. 2002; Tabuti 2007). The interpretation of the SCD slopes is based on those described by Shackleton (1993), Everard et al. (1995) and Obiri et al. (2002): negative slopes indicate good rejuvenation and recruitment, with more individuals in smaller size-classes than in larger size-classes; flat slopes indicate equal numbers of regenerating trees and mature individuals; and positive slopes characterize poor recruitment with more individuals in the larger than in the smaller size-classes. The steepness of the slope was used to describe the regeneration trend for each species. Steep negative slopes indicate better recruitment than shallow slopes (Lykke 1998; Obiri et al. 2002; Mwavu and Witkowski 2009).

The quotient between successive diameter size-classes was calculated in order to determine the stability of populations in PAs and UAs. The results are usually expressed graphically (see Botha et al. 2002; Venter and Witkowski 2010). Constant quotients between successive size-classes indicate a stable population, while variable quotient values represent an unstable population (Botha et al. 2004; Mwavu and Witkowski 2009; Sop et al. 2011). To allow visual comparisons between PAs and UAs, quotient values were combined to generate a single graph for each species within the same site.

In order to assess the deviation of population from a monotonic decline, which would be expected in an "ideal" (undisturbed) population, the permutation index (PI) was computed for each species in the PAs and UAs (Wiegand et al. 2000; Botha et al. 2004). PI is expressed according to Botha et al. (2004) as:

$$P = \sum_{i=1}^{k} |J_i - i|; \quad J_i = 1, 2, \ldots, k$$

where Ji is the rank of size-class i ($i = 1$ for the smallest tree), with the highest rank ($Ji = 1$) given to the most frequent size-class. PI is higher in a discontinuous SCD than in a continuous, monotonically declining population. A monotonically declining population has PI $= 0$ and a population with a discontinuous SCD (disturbed population) will have PI > 0 (Venter and Witkowski 2010).

2.5.3 Analysis of regeneration data

Seedling density within PAs and UAs was computed for each species. All juveniles were divided into five height classes (0–0.5, 0.51–1, 1.1–1.5, 1.51–2 m, and >2 m). The analysis of the juvenile population was based on the extension of the method of Condit et al. (1998) developed by Sop et al. (2011). For regeneration structure, the slope of regression of the height class was computed for each species in the PAs and UAs. Height-class midpoint (mi) was treated as the independent variable, while the frequency of each class was the dependent variable. In this case, negative slopes were considered to indicate stable juvenile populations and positive slopes to indicate disturbed and unstable recruitment (Shackleton 1993; Everard et al. 1995; Obiri et al. 2002). The stability of height-class distribution for each species was also assessed within PAs and UAs.

3 Results

3.1 Effect of protection status on population parameters

The number of plots sampled, mean DBH, and mean density for each of the three species within the two Sudanian sectors are summarized in Table 1.

Mean DBH of trees did not significantly differ between PAs and UAs, except in the case of *P. africana* for which it was significantly larger in the UAs. This illustrates the tendency

Table 1 Difference in mean DBH (diameter at breast height, cm) and density (stems/ha) of stems >5 cm DBH of three vulnerable species (*D. mespiliformis, P. africana,* and *S. setigera*) in protected areas (PAs) and unprotected areas (UAs) in the Sudanian zone of Burkina Faso

Sites	Species	Protection status	No. plots	Mean DBH (cm)	SE (mean DBH)	*t*-Values	*p* Value	Density (stems/ha)	SE (mean density)	*t*-Values	*p* Value
North Sudanian	*Diospyros mespiliformis*	PAs	12	13.55	5.06	0.58	0.569	90.83	32.04	−2.05	0.053
		UAs	11	14.69	4.34			63.64	31.39		
	Prosopis africana	PAs	12	24.62	7.43	4.30	0.000	52.50	25.98	−1.82	0.081
		UAs	15	39.77	10.05			39.33	9.61		
	Sterculia setigera	PAs	11	45.60	8.29	−0.97	0.343	59.09	17	−1.32	0.199
		UAs	13	40.64	15.15			50.77	13.82		
South Sudanian	*Diospyros mespiliformis*	PAs	13	15.30	10.63	0.95	0.352	63.08	23.23	−0.14	0.886
		UAs	12	19.25	10.09			61.67	25.52		
	Prosopis africana	PAs	14	17.48	8.71	0.56	0.582	68.57	26.56	−1.89	0.071
		UAs	13	19.21	7.24			51.54	19.51		
	Sterculia setigera	PAs	12	19.59	7.17	1.95	0.065	42.50	9.65	0.57	0.573
		UAs	10	24.74	4.58			45	10.80		

DBH diameter at breast height, *SE* standard error, *PAs* protected areas, *UAs* unprotected areas

Significance level $p < 0.05$

toward aging within open areas. There was also no significant effect of protection on plant density. However, a clear tendency toward higher mean tree density was observed, for two of the three species, within protected areas in both phytogeographic domains (Table 1). A comparison of overall density of the three species between the two management regimes (in the whole study area) showed a significant difference for *Prosopis africana*. A high density of this species was observed in the PAs. The two others species did not show a significant difference between the two management regimes, but a clear tendency toward higher tree density within protected areas (Table 2).

3.2 Population structure

In the North Sudanian protected (NS-PAs) and unprotected areas (NS-UAs), the size-class profile of *D. mespiliformis* indicated a reverse J-shaped curve with the Weibull distribution c-value close to 1 (Fig. 2). This is typical of a relatively stable population. In both management regimes, the distribution of *P. africana* and *S. setigera* showed a positive skew distribution, that is, $1 < c < 3.6$ (Fig. 2), indicating unstable populations.

In the South Sudanian protected areas (SS-PAs) and South Sudanian unprotected areas (SS-UAs), the observed SCD for *D. mespiliformis* and *P. africana* showed a reverse "J" shape with Weibull shape parameter statistically smaller than 1, indicating a steeply descending monotonic distribution function (Fig. 2). *D. mespiliformis* in SS-UAs has $c = 1$, indicating a negative exponential distribution. *S. setigera* in SS-PAs and in SS-UAs has a positive skew distribution, indicative of an unstable population (Fig. 2).

Taking the study area as a whole, the SCD of *D. mespiliformis* (All-PAs and UAs) and *P. africana* (All-PAs) (Fig. 2) showed stable populations with c less than or close to 1. In contrast, *S. setigera* revealed a degraded profile (Fig. 2). Of particular note was the fact that *D. mespiliformis* had a stable distribution in both management regimes.

The log-linear analysis (computed for each structure) indicated a good fit of the data to the Weibull distribution ($p > 0.05$) (see Appendix).

3.3 Population dynamics

The results of the OLS regression analysis of the SCDs revealed that protection status only had a significant effect on the regression slope for *P. africana* in the North and *S. setigera* in the South Sudanian sector. Although shallow, the mean SCD slopes were negative for *D. mespiliformis*, irrespective of zone or protection status of the area. *P. africana* in the South Sudanian sector had a flat slope in UAs (-0.07 ± 0.04) and a weak negative slope in PAs (-0.10 ± 0.08). However, in the North Sudanian sector, this species had a positive slope in UAs (0.05 ± 0.04) and a flat slope in PAs (-0.05 ± 0.06) (Table 3). *S. setigera* populations were apparently in steep decline in the North, as revealed by its positive slopes.

Moreover, the quotients calculated between numbers of trees in successive size-classes indicated that the populations of the target species within the study area were not evenly distributed (Fig. 3), suggesting unstable populations. The permutation indexes for *D. mespiliformis*, *P. africana,* and *S. setigera,* in both PAs and UAs, were greater than zero (Table 3), suggesting that something may have been disturbing the recruitment from one size-class to another.

The fluctuations of the quotient between successive diameter size-classes (Fig. 3) for all three species, and their high to very high permutation indices (PI > 0), irrespective of the management regime, point to the variously unstable population structures of these species (Table 4).

Table 2 Difference in density (stems/ha) of adult populations and seedlings from all protected areas (PAs) and unprotected areas (UAs) of both North and South Sudanian sectors

Species	Adult populations					Seedling			
	Protection status	Density (stems/ha)	SE (mean density)	*t*-Values	*p* Value	Density (stems/ha)	SE (mean density)	*t*-Values	*p* Value
Diospyros mespiliformis	PAs	76.40	30.67	1.62	0.112	4,092.30	2673.26	1.84	0.071
	UAs	62.60	23.83			2,625.00	2171.17		
Prosopis africana	PAs	61.15	27.02	2.69	0.009	2,240.00	1949.35	0.11	0.911
	UAs	45.00	15.98			2,168.42	2267.90		
Sterculia setigera	PAs	50.43	15.80	0.51	0.609	709.09	770.22	0.84	0.406
	UAs	48.26	12.66			523.07	252.17		

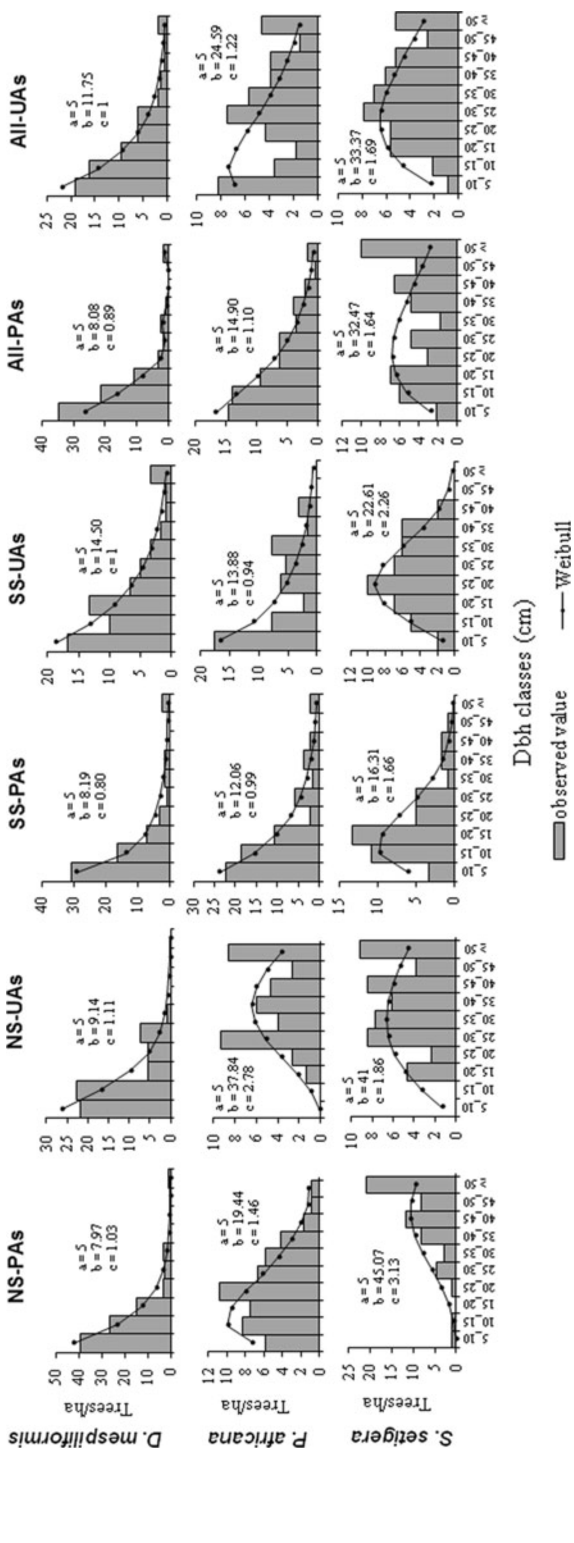

Fig. 2 The size-class distribution (SCD) of three vulnerable species (*D. mespiliformis*, *P. africana,* and *S. setigera*) in protected areas (PAs) and unprotected areas (UAs) of the North (NS) and South Sudanian (SS) sectors of Burkina Faso. *All* all plots, *PAs* plots in protected areas, *UAs* plots in unprotected areas

Table 3 Difference in OLS (ordinary least-squares regression) slopes of three vulnerable species in protected areas (PAs) and unprotected areas (UAs) in the Sudanian zone of Burkina Faso

Sites	Species	Protection status	Mean slope	SE slope	r^2	*p* Value	PI
North Sudanian	*Diospyros mespiliformis*	PAs	−0.14	0.06	0.44	>0.10	8
		UAs	−0.12	0.05	0.50		7
	Prosopis africana	PAs	−0.05	0.06	0.24	<0.005	8
		UAs	0.05	0.04	0.20		46
	Sterculia setigera	PAs	0.10	0.05	0.37	>0.10	48
		UAs	0.05	0.06	0.23		46
South Sudanian	*Diospyros mespiliformis*	PAs	−0.11	0.05	0.40	>0.10	10
		UAs	−0.09	0.05	0.37		10
	Prosopis africana	PAs	−0.10	0.08	0.42	>0.10	12
		UAs	−0.07	0.04	0.26		8
	Sterculia setigera	PAs	−0.05	0.05	0.25	<0.05	12
		UAs	−0.03	0.03	0.10		20

PI permutation index

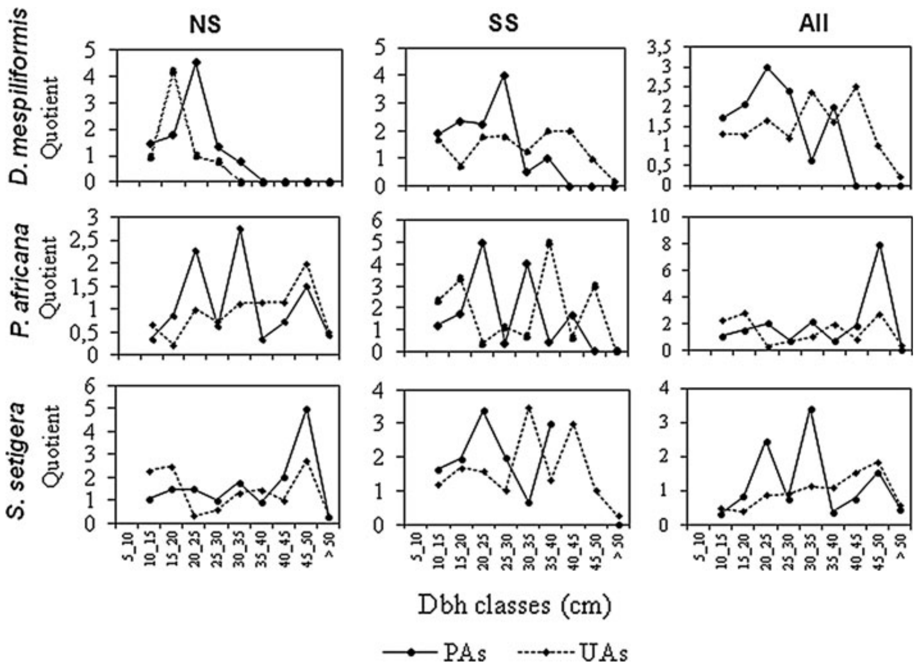

Fig. 3 Quotient between densities of *D. mespiliformis, P. africana,* and *S. setigera* in successive size-classes in protected areas (PAs) and unprotected areas (UAs) of the North Sudanian (NS) and the South Sudanian (SS) sectors of Burkina Faso

Table 4 Difference in OLS (ordinary least-squares regression) slopes of adult populations and seedlings from all protected areas (PAs) and unprotected areas (UAs) of both North and South Sudanian sectors

Species	Protection status	Adults population					Height class				
		Mean slopes	SE slopes	r^2	p Value	PI	Mean slopes	SE slope	p Value	r^2	PI
Diospyros mespiliformis	PAs	−0.13	0.06	0.42	$p < 0.05$	8	−0.39	0.15	$p > 0.10$	0.80	0
	UAs	−0.10	0.05	0.43		6	−0.28	0.16		0.65	0
Prosopis africana	PAs	−0.07	0.07	0.33	$p < 0.05$	9	−0.24	0.20	$p > 0.10$	0.52	2
	UAs	−0.01	0.07	0.23		28	−0.20	0.16		0.51	0
Sterculia setigera	PAs	0.02	0.08	0.30	$p > 0.10$	36	−0.24	0.22	$p > 0.10$	0.43	2
	UAs	0.01	0.06	0.17		36	−0.19	0.11		0.50	–

3.4 Seedling population structure

Protection status only had a significant effect on seedling density for *D. mespiliformis* in the North Sudanian sector and *P. africana* in the South Sudanian sector (with higher density in PAs). Regeneration was generally higher in PAs than in UAs for these species (Table 5). Negative height-class mean slopes (−0.44) and a permutation index equaling zero indicates good recruitment with stable regeneration in PAs of the North Sudanian sector for *D. mespiliformis*. Height-class plots show a perfect reverse J-shaped profile implying more juveniles in the smallest classes (Fig. 4). The permutation index (PI = 4) of *D. mespiliformis* in UAs suggests restricted seedling establishment and growth.

Compared with *D. mespiliformis,* regeneration capacity of *P. africana* was low with a mean seedling density ranging from 618.18 ind. ha^{-1} in the PAs to 755.55 ind. ha^{-1} in the UAs in the North Sudanian sector. The negative height-class slopes (ranging from −0.13 in the PAs to -0.17 in the UAs) show more juveniles in the classes 0–0.5 and 0.51–1 but an absence of them in the class 1.51–2 (Fig. 4). Thus, the permutation index (PI = 4 in the PAs) indicates irregular recruitment (Table 4). A similar result was observed for *S. setigera* in the North Sudanian sector (Fig. 4).

P. africana and S. *setigera* showed poor regeneration, as attested by the permutation index in the PAs ($p = 2$) in the South Sudanian sector. However, in the SS-UAs, these species had a relatively high number of juveniles in the first class (0–0.5), indicating poor recruitment with unstable regeneration (Fig. 4).

Table 2 presents the structural characteristics of the juvenile population (diameter < 5 cm) of the three targeted species in the whole study area. The standard error of seedling density in the whole study area for both management regimes was very high, indicating the unevenness of seedling spatial distribution. *D. mespiliformis* shows a similar level of recruitment under both management regimes, whereas *P. africana* and *S. setigera* present a non-significant higher mean density of seedlings between the management regimes. Furthermore, *D. mespiliformis* has a zero permutation Index, indicating that there is a stable and equal recruitment in all juvenile height classes for this species (Table 4). The positive permutation index for *P.africana* and *S. setigera* indicates perturbation in the recruitment and development of young individuals.

4 Discussion

4.1 Population parameters

In general, tree densities for the studied species were relatively low within the study area. The mean tree density of two out of three species was not significantly different between protected and unprotected areas. This might be an indication that protection measures did not significantly enhance species establishment. The observed low densities corroborate results from other studies, which found that the populations of these species are declining in many parts of West Africa (Tchoundjeu et al. 1998; Sambou 2004; Ouédraogo 2006; Weber et al. 2008). In fact, most protected areas are not entirely free from diverse anthropogenic intrusions. While generally being uncultivated lands, some of these areas have been affected by past conflicts including illegal occupancies and forced abandonments (Devineau 2010). In addition, poaching, wild harvesting, illegal logging, and grazing are frequent in the protected forests. Illegal grazing of large (mostly bovine) herds inside protected areas mainly takes place during the dry-season transhumance when herbs in open areas are scarce.

Table 5 Difference in seedling density and slope of height-class regression of three vulnerable species (*D. mespiliformis, P. africana,* and *S. setigera*) in protected areas (PAs) and unprotected areas (UAs) in the Sudanian zone of Burkina Faso

Sites	Species	Protection status	No subplots	Seedling stems/ha	SE	t-Values	p	Height class				PI
								Mean slopes	SE slopes	p Value	Mean $r^2 \pm$ ES	
North Sudanian	*Diospyros mespiliformis*	PAs	12	4,766.67	3,434.40	−2.42	0.027	−0.44	0.17	<0.01	0.81 ± 0.07	0
		UAs	6	1,266.67	854.79			−0.17	0.11		0.48 ± 0.28	4
	Prosopis africana	PAs	11	618.18	275.02	0.41	0.684	−0.13	0.09	>0.10	0.49 ± 0.23	4
		UAs	9	755.55	1,066.70			−0.16	0.11		0.49 ± 0.15	–
	Sterculia setigera	PAs	9	444.44	133.33	0.73	0.478	−0.10	0.09	>0.10	0.48 ± 0.14	4
		UAs	5	400.00	0			−0.13	0		0.50	–
South Sudanian	*Diospyros mespiliformis*	PAs	14	3,514.28	1,727.10	−0.08	0.929	−0.35	0.09	>0.10	0.80 ± 0.17	0
		UAs	10	3,440.00	2,341.50			−0.34	0.15		0.75 ± 0.15	0
	Prosopis africana	PAs	11	4,036.40	3,863.50	−2.56	0.018	−0.36	0.22	>0.10	0.55 ± 0.25	2
		UAs	12	1,066.66	1,056.00			−0.22	0.13		0.52 ± 0.07	–
	Sterculia setigera	PAs	13	892.30	968.21	−0.82	0.421	−0.13	0.16	>0.10	0.40 ± 0.22	2
		UAs	8	600.00	302.37			−0.17	0.05		0.50	–

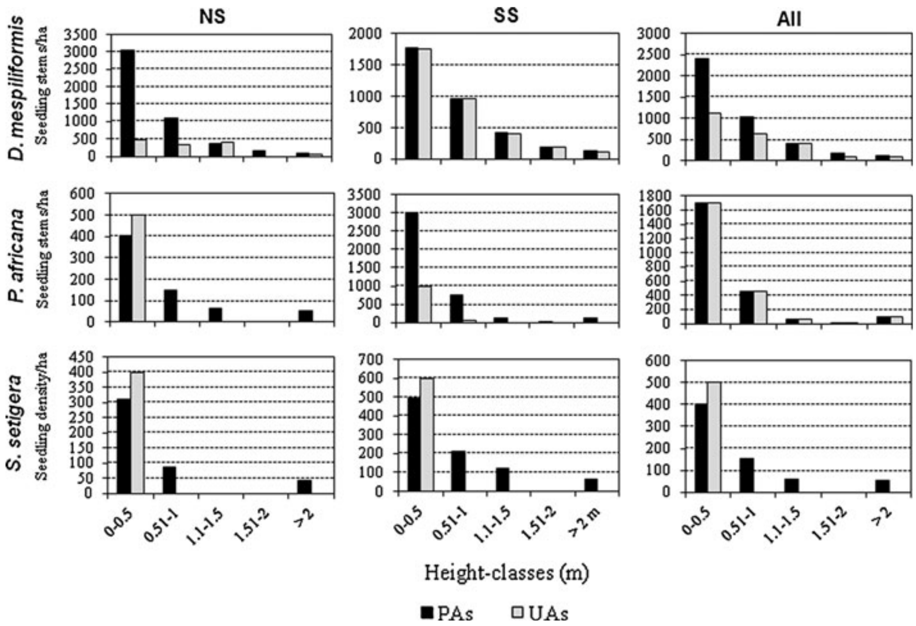

Fig. 4 Height-class distributions of seedlings of targeted species (*D. mespiliformis, P. africana,* and *S. setigera*) in protected areas (PAs) and unprotected areas (UAs) of the North Sudanian (NS) and the South Sudanian (SS) sectors of Burkina Faso

4.2 Population structure and species dynamics

D. mespiliformis exhibited a reverse J-shaped size-class profile in both sectors, irrespective of protection status. The pattern exhibited by *D. mespiliformis* in the UAs is uncommon for a particularly valuable woody species but may result from one or more of three causes. Firstly, the use of fallow-crop rotations in farming systems maintains and favors some of the useful species, notably woody species with edible fruits such as *D. mespiliformis* (Devineau et al. 2009; Devineau 2010). Secondly, in Sudanian areas, *D. mespiliformis* is one of the many species often associated with termite mounds and may have benefited from more suitable microsite conditions for its growth (Traoré et al. 2008). Finally, and possibly of most importance, *D. mespiliformis* is not used as fuel wood in most of the study area for cultural reasons. Indeed, some ethnic groups in the area (e.g., the Bobo) consider *D. mespiliformis* as a sacred plant (Taita 2003) while some others (e.g., the Senoufo) believe it might lead to infertility problems (Traoré et al. 2011). The taboo surrounding the use of this species is a key advantage for its conservation in the Sudanian zone, an area where human populations principally rely on woody resources for energy. Furthermore, *D. mespiliformis* is capable of vegetative reproduction through sucker roots, and this is an important adaptation strategy to hostile environments that might also explain the reverse J-shape observed for this species in both protected and unprotected areas. In addition, *D. mespiliformis* is often present in refuge habitats such as thickets and abandoned termite mounds that are considered as spaces where saplings can be relatively protected from fires (Traoré et al. 2008).

For all three studied species, the fluctuation observed in successive size-classes (indicated by the quotients), and the positive permutation index encountered, suggest perturbations to their populations across the study area. This is probably the effect of anthropogenic factors such as wild harvesting and illegal wood cutting, which are frequent practices in Sudanian ecosystems, even in protected areas (Devineau et al. 2009; Devineau 2010).

The observed flat SCDs observed for *P. africana* and *S. setigera* is possibly the results of trees' removal. However, flat SCDs can also be caused by factors such as lack of rejuvenation, rapid growth in small size-classes, and high survival rate overall (Condit et al. 1998; Lykke 1998). The importance of fires on the dynamics of savanna ecosystems is well known. The high density of herbaceous is likely to limit the establishment of new shrub. These ecological and environmental factors conditions are limiting factors.

P. africana showed unstable populations (with a bell shape profile) in both protected and unprotected areas in the North Sudanian sector and an imperfect reverse J-shape under both management regimes in the South Sudanian sector (Fig. 2). However, the more accentuated bell-shaped profile in the North Sudanian sector suggests that both anthropogenic and climatic factors (particularly the rainfall regime) may be involved in the observed trend. The "holes" in the SCD profile of *P. africana* in the South Sudanian sector certainly resulted from logging of trees for construction purpose. This has been observed to negatively affect the SCDs of woody vegetation in Senegal (Lykke, 1998). In both sectors, the SCDs of *P. africana* do not differ much between management regimes, suggesting that protection has only a limited impact on the dynamics of this species. Indeed, *P. africana* is highly valued in the region for firewood and charcoal production, and it is one of the most preferred species by blacksmiths (Traoré et al. 2011). Populations of this species are in more rapid decline in the North than in the South where the climate is more favorable. The weak SCDs and positive PI values for this species under both management regimes across the study area (see Table 4) are consistent with previous research reporting that *P. africana* is seriously threatened throughout the entire Sahelo-Sudanian region of West Africa (Tchoundjeu et al. 1998; Sambou 2004; Ouédraogo 2006; Weber et al. 2008; Ahoto et al. 2009). We did, however, record a perceptible effect of management regime on the dynamics of this species.

S. setigera showed a J-shaped distribution in the North Sudanian sector in both protected and unprotected forests. This is a typical trend for a declining species with aging populations, as evidenced by the lack of individuals in the small diameter classes (Fig. 2). A bell shape is instead observed in the South Sudanian sector for both management regimes (Fig. 2). *S. setigera* is very sought-after by traditional healers for its bark. The fibers of this species are used for rope-making, which shepherds use to immobilize their animals. The unfavorable population dynamics of *S. setigera* in this study are in line with the findings of Touré et al. (2009) who reported that the populations of this species face a high mortality and are characterized by an irregular profile dominated by old individuals.

4.3 Seedling population structure and regeneration patterns

It is widely acknowledged that populations of species with reverse J-shaped SCD distributions tend to be stable, with senesced individuals being naturally replaced by seedlings (Obiri et al. 2002; Tabuti 2007; Mwavu and Witkowski 2009). This is the case for *D. mespiliformis* in the North and South Sudanian sectors. Indeed, *D. mespiliformis* showed relatively good regeneration with a high number of individuals in the lowest height classes (Fig. 4), and this may be explained by both biological and environmental factors. *D. mespiliformis* seeds have a good germination rate (Zida 2009) and, as already mentioned, this species grows on or near termite mounds that are habitats where seedlings and saplings can be relatively protected from fires and where favorable soil and moisture conditions may favor the establishment of seedlings and saplings (Traoré et al. 2008).

The improvement of soil physical and chemical properties, as well as water content in soil, by termite mounds is well documented (Konaté et al. 1999). In addition, *D. mespiliformis* is endowed with the capacity to reproduce vegetatively through sucker roots (Noubissié-Tchiagam et al. 2011), allowing this species to quickly form extensive patches in the Sudanian environments. Vegetative multiplication is a recruitment strategy developed by many species in difficult environments, helping to overcome limitations imposed on sexual reproduction. Asexual reproduction therefore constitutes an advantage for plant regeneration (Bellefontaine et al. 2000; Bognounou et al. 2010; Ouédraogo and Thiombiano 2012). Furthermore, *D. mespiliformis* exhibits an epigeous-cryptogeal germination type (Zida 2009), which protects seedlings from different types of threats (e.g., drought, fire and browsing) to which many species are exposed in the earlier stages of their development (Bationo et al. 2010).

On the contrary, *P. africana* appeared to have relatively poor regeneration. Most of the seedlings are concentrated in the lowest height classes, irrespective of protection status and phytogeographical sector. Low numbers of seedlings seem to survive the first class (0–0.5 cm), which is the phase of recruitment and seedling establishment (Fig. 4). A wide variety of factors may regulate regeneration and recruitment into the adult population (Ryniker et al. 2006). These factors could include erratic seed production, fruit consumption, browsing damage, low-light conditions under the canopy, and climatic variability (Russell and Fowler 2002). In the particular case of *P. africana*, grazing and earlier bush fires, which increase seedling mortality just after their establishment, might be enough to explain poor seedling recruitment into the second height class. In addition, *P. africana* appears to be sensitive to bushfire (Devineau et al. 2010), and in the context of fire-dominated environment where the study was done, some individuals will inevitably die before arriving at maturity. (Ouédraogo and Thiombiano, 2012) stressed that the capacity for rapid growth at the beginning of the rainy season is an advantage for many plants in semiarid environments, but the fire recurrence in the dry season quashes the efforts of saplings to grow, restricting them to a cycle of perpetually restarting growth. In this context, the recruitment pattern into the adult population become unpredictable, because the resprouts may have firstly to establish a fire-resistant perennial trunk, which will allow further growth in height in the following year (Gignoux et al. 1997). Niang-Diop et al. (2010) observed in a study in Senegal that grazing and fires were the major constraints to natural regeneration of *P. africana*. They also pointed out that the hard and impermeable tegument surrounding the seeds imposes a long dormancy that exposes the seeds to infestation by insects. In some areas of West Africa, excessive branch lopping and pod harvesting have seriously reduced natural regeneration of *P. africana* (Weber et al. 2008). Tchoundjeu et al. (1998) and Niang-Diop et al. (2010) pointed out that *P. africana* pods are also consumed by insects, and according to Ahoto et al. (2009), seedlings of this species show a high mortality rate under humid conditions, generally in the rainy season.

Seedling establishment and growth are the main factors that determine woody plant regeneration. *S. setigera* regeneration is hampered by the absence or weakness of recruitment. In the entire study area, *S. setigera* showed poor regeneration patterns, characterized by a relative large number of seedlings in the first height class, which do not survive into the next juvenile stages. Moreover, the gravelly habitats where *P. africana* and *S. sterculia* often grow do not favor recruitment and establishment of shrub, because these kinds of soils correspond mainly to fire-prone savannas (Devineau 2010). Ouédraogo and Thiombiano (2012) noticed that *S. setigera* had a high seed production in the field but that its regeneration potential was jeopardized by a high rate of infertility and resulting lack of seedling recruitment. In addition, sexual reproduction may also be highly reduced by pruning, which lowers fruit production as observed in the case of *Pterocarpus erinaceus* in communal (unprotected) areas in eastern Burkina Faso (Ouédraogo et al. 2006; Nacoulma et al. 2011). Low *S. setigera* seedling numbers have also been observed in Senegal (Traoré 1998) and are commonly reported across its range (Ouédraogo and Thiombiano 2012).

Among the three studied species, only *D. mespiliformis* showed good regeneration owing to the favorable environmental conditions in which the plant grows and the plant's intrinsic capacity for vegetative regeneration, which is an advantage in semi-arid environments such as Burkina Faso. The benefits of vegetative propagation are low-cost renewal of populations and rapid growth of sucker shoots (Bellefontaine et al. 2000, Ouédraogo and Thiombiano 2012). In savanna ecosystems, fires are known to be the most important stress factor and were observed to be more intense and frequent inside than outside protected areas (Caillault, 2011). However, the effect of fire depends on its intensity; for instance, high frequency of fires, especially early in the dry season, is typical of the savannah woodlands in the western part of Burkina Faso (Devineau et al. 2010; Caillault 2011). This may hamper the recruitment and establishment of small tree in adult stratum. The direct effect of fire on small trunks is to kill the cambium of the tip of the stem beyond a certain diameter, or above a certain height (Gignoux et al. 1997) which a drawback for many species.

5 Conclusion and recommendations

The aim of this study was to assess the impact of protected areas on the population structure and dynamics of three multipurpose species in the Sudanian zone of Burkina Faso. The outcome of the study did not completely meet our assumption that protection would enhance species status within protected areas. Indeed, except for *P. africana*, our results did not show significant difference in population structure, plant density, and regeneration patterns between protected and unprotected areas. The reason for this is the persistence of diverse anthropogenic intrusions in conservation areas. Furthermore, the management of protected areas with fire episodes is questionable as fire is known to jeopardize the regeneration and seedling growth for many species.

It is therefore recommended that: (a) forest authorities should be encouraged to build efficient cooperation with local people to ensure sustainable management of protected areas. This might be done though providing neighboring communities with significant incentives, particularly access to resources under an agreed sustainable level of harvesting. (b) managers of protected areas should be prevented using fire for management of protected areas; (c) sensitization of local populations through environmental education programs should be carried out on the importance of protected areas.

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Appendix

See Table 6.

Table 6 Results of log-linear analysis (in SAS Inc., 1999) applied to diameter class frequency

	The CATMOD Procedure						
	Maximum Likelihood Analysis of Variance						
	Protected areas				Unprotected areas		
	Source	DF	Chi-Square	Pr > ChiSq	DF	Chi-Square	Pr > ChiSq
North Sudanian							
Diospyros mespiliformis	Class	5	109.75	<0.0001	6	73.78	<0.0001
	Distr	1	0.01	0.9371	1	2.99	0.0840
	Class*Distr	5	3.31	0.6523*	4	5.79	0.2155*
Prosopis africana	Class	10	59.87	<0.0001	8	23.97	0.0023
	Distr	1	0.14	0.7117	1	1.74	0.1867
	Class*Distr	9	3.34	0.9492*	7	12.94	0.0737*
Sterculia setigera	Class	9	77.79	<0.0001	9	9.71	0.3741
	Distr	1	6.73	0.0095	1	2.88	0.0895
	Class*Distr	7	12.90	0.0745*	7	7.18	0.4101*
South Sudanian							
Diospyros mespiliformis	Class	9	182.49	<0.0001	9	102.04	<0.0001
	Distr	1	1.54	0.2150	1	0.04	0.8463
	Class*Distr	7	4.66	0.7014*	9	5.64	0.7749*
Prosopis africana	Class	9	130.40	<0.0001	9	102.35	<0.0001
	Distr	1	0.91	0.3414	1	0.09	0.7674
	Class*Distr	8	6.13	0.6327*	7	12.86	0.0756*
Sterculia setigera	Class	8	86.98	<0.0001	9	53.62	<0.0001
	Distr	1	0.00	0.9896	1	0.17	0.6757
	Class*Distr	8	7.63	0.4708*	7	1.53	0.9814*

An interaction «class*Distr» significant ($p > 0.05$) shows that the conformation between observed structure and Weibull distribution is accepted

* See values

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