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Expanding networks of field hedges in densely populated landscapes in the Sahel

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Abstract

Changing woody plant density across agricultural landscapes of the Sudano-Sahelian region is a debated issue. This paper reports the results of an investigation on the contribution of field hedges to overall woody plant density. Hedges separating individual cropped parcels were studied within village agropastoral territories in the Dantiandou district in western Niger. In 1992, field hedges were mapped over the study area using aerial photography and in 2016, using high resolution Google Earth imagery. In 1992, field hedge length was equal to 1006 km within 435 km^2 of croplands, equivalent to 2.3 km km^{-2}. In 2016, 17.5% of these hedges had disappeared, but 1591 km of new hedges were observed resulting in an increased density of hedges to 5.6 km km^{-2}. In 24 years, hedges had increased at a mean annual rate of 3.7% likely associated with the splitting of crop fields by inheritance.

The composition and productivity of hedges were also monitored in 1996, 2010 and 2015. All trees (maximum height ≥4m), shrubs (<4m) and tussock perennial grasses were recorded within twelve field hedge samples of 200m each. Field measurements were used to estimate basal area, crown area, foliage mass and wood mass of each woody plant within the sampled hedges. No significant trends were found between 1996 and 2015 in woody plant density, basal area, crown cover, wood and foliage masses across all monitored hedges. However, overall means hide a slight decrease in tree contributions, while shrub contributions first increased and then decreased. They also mask contradictory trends among sites most likely related to different rates of shrub coppicing and tree cutting. The woody species composition of the hedges is poor with an increase of *Combretum glutinosum* to the detriment of *Guiera senegalensis* over the study period.

Multiplying the hedge sample statistics by the changing lengths of field hedges in the study area provides estimates of the contribution of the hedge woody plants to the woody plant population at a landscape scale. Between 1992 and 2016, field hedges contributed to increases of woody plant density by 3.9%, basal areas by 5.4% , crown cover by 2.7% , leading to 6.1% annual increase in foliage mass and 8.8% increase in wood mass.

Key words: agroforestry; hedgerow; land tenure; deforestation; bocage; tropical Africa

Introduction

The trend of woody plant populations in Sahelian West Africa is a topic of considerable uncertainty and controversy. Many publications have referred to alarming deforestation (Chamard and Courel 1999) caused by cropping or forestry exploitation to provide fuel to urban centers (Peltier et al. 2009). However, a recent remote sensing work has found that woody plant cover has generally increased across Sahel from 2000 to 2014 with a few exceptions (Brandt et al. 2016). Within this debate, a major area of uncertainty is how woody plant populations have changed on agricultural landscapes that represent a significant proportion of the land area in the region.

The landscapes of the southern Sahel are strongly shaped by a long history of agrarian management (Raynaut 2001; Ballouche and Rasse 2007). Human management reshapes rural landscapes through land use (**Fig. SI 1**) with a major distinction being between rangelands and agricultural lands, reviving the ancient distinction between saltus and ager (Poux et al 2009). Rangelands are defined by their pastoral management under communal access, but also by their marginal potential for cropping associated with shallow or infertile soils, or with increased flood risks in low lying areas. Moreover, rangelands cannot be distinguished from agricultural lands simply by the presence of grazing since all portions of the rural landscape are open to grazing after crop harvest (Turner et al. 2005). Gathering and wood collection also extend to the whole landscape and are regulated by specific use rights (Sidikou 1997). Agricultural lands include all the arable lands cropped or fallowed centered around villages. Two components constitute the woody population in agricultural lands: 1. the large trees and coppiced bushes of the agrarian parkland within fields and fallows (Boffa 1999), and 2. the web of hedges that delineates fields, tracks and paths. Less spectacular and studied than the trees (Gijsbers et al. 1994; Boffa 1995; Nouvellet et al. 2006; Yossi et al. 2006) and coppiced bushes (Diack et al. 2000; Achard et al. 2001; Dick et al. 2010; Diakhaté et al. 2016) of the agrarian parkland, the woody field hedges frame some of the most densely populated agro-pastoral landscapes in West Africa (Pélissier 1953; Portères 1965; Seignobos 1980; Levasseur 2003).

The objective of this paper is to quantify changes over the past two decades in the woody population of field hedges within a study area located within western Niger. Western Niger is one of the areas of the Sahel where woody plant cover has been found not to have increased from 2000 to 2014 (Brandt et al. 2016). Within this area, woody plant cover has declined on plateau rangelands[1], declined slightly or remained the same on slopes, and increased slightly in valleys and near villages. While slight positive trends have been observed locally (San Emeterio et al. 2013), one would expect a decline of woody cover on agricultural land due to the progressive expansion of the land cropped to the detriment of fallows (Bouzou Moussa et al 2011; Tong et al 2017). Still, the coarse resolution of the satellite imagery used in assessments of woody plant cover at the regional scale does not allow a distinction of the contribution of field hedges from that of the parkland within field or fallows.

In Western Niger, the trees, shrubs, and certain perennial grasses, which constitute the field hedges, are not planted like in other regions of the Sahel (Yossi et al. 2006). Instead, hedges are formed by selective sparing of woody plants at field edges when fields are cleared (**Fig. SI 2**). The initial objective of this protection is to mark the field limits. The management of hedges is conducted largely independently of the management within the surrounding fields or fallows.

Landscape-level changes in the woody population of field hedges were estimated by combining detailed ecological monitoring work of the composition and density of field hedges with their mapping, using aerial photos and high resolution satellite imagery. Woody populations of rangelands, fields and fallows in the region have most commonly been assessed through either exhaustive census on sampled areas (Hiernaux et al. 2009) or by distance methods (Picard and Bar-Hen 2007). However, the linear and dense arrangement of the woody plants along field hedges is not compatible with either of these methods and therefore, a more appropriate assessment method was developed for this research, as reported below. Finally, observed changes in the spatial pattern of hedges will be related to changes in land use and land tenure as documented by surveys of families farming fields in the study area.

Materials and method

1.1. The study site

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[1] In western Niger, deforestation on the plateaus has often been observed within the patterned woody vegetation type known as ‘tiger bush’ or ‘spotted bush’(d’Herbes et al. 1997). Degradation of tiger bush has been observed elsewhere in the Sahel (Abdourhamane Touré et al. 2010, Trichon et al. 2018).

To better understand the evolving ecology and contribution of field hedges to the overall woody population in the Sahel, research was conducted within a 499 km^2 area in the Dantiandou district of southwestern Niger (**Fig. 1**). In the study area, rangelands are confined to the Oligocene ferricrete that caps the sedimentary plateaus at the highest elevations of the landscape. Rangeland also extends along the edges of the plateau and on a few shallow soils on the Pleistocene ferricrete downslopes (d'Herbès and Valentin 1997). Cropping is prevalent on the sandy soils on the slopes and in the valleys, and on sandy clay soils lying in flats and stream beds (Turner and Hiernaux 2015). Agricultural lands are composed of a minority of permanently cropped fields, close to villages and to pastoral camps, and a majority of shifting crop fields and fallows further away (Osbahr 2001). Indeed, permanent cropping requires fertilization that is most commonly achieved by corralling livestock on the fields during the dry season (Hiernaux and Diawara 2014) with or without the application of domestic wastes carried to the field by carts. The capacity to manure depends on the size of the family herd and on the extent of seasonal transhumance of the herd away from the village. The soil fertility of shifting fields is managed by alternating cropping for five years with fallowing that lasts typically three years but may last much longer especially on lands marginal for cropping (Hiernaux and Turner 2002). Fallow duration also depends on the field's tenure status (Turner and Moumouni 2018a). Agricultural lands are clustered around villages the locations of which are where lands were free to crop and ground water was accessible to hang-dug wells (more recently, boreholes) at the time of settlement (Favreau et al. 2002).

The study area's population is dominated by the Djerma who also control agricultural land through village chieftaincies. Although Djerma families hold no formal land title, they have legal customary rights to their cropped field; rights which are generally inheritable by sons (Lavigne-Delville 2003; Turner and Moumouni 2018a). The founding Djerma families of the village enjoy chieftaincy rights on lands often arranged in sectors radial from the village. Among them, the village chief manages usufruct rights to the chieftaincy common lands. These usufruct rights are assignable by contract to new settlers, including agropastoral Fulani families who have settled in the vicinity of the villages within the study area dating back to the severe 1973-74 drought. These rights are restricted to cropping activity without exclusive rights to exploit woody plants or to graze livestock on the agricultural land.

The landscape is further structured by a web of tracks that radiate from each village to access the fields and travel to neighboring villages. In addition, there is a web of livestock paths that allow local livestock access to water points and rangelands, especially during the wet season when they are not authorized to cross cropped fields. These livestock paths also connect to a web of regional livestock paths allowing regional and international transhumance (Turner et al. 2014). The pastoral camps of settled Fulani families are positioned along these livestock paths just outside the edge of permanently cropped fields surrounding each village. Their positions reflect that cropped fields are off limits to livestock during the growing season and that pastoral families depend on village water resources during the dry season.

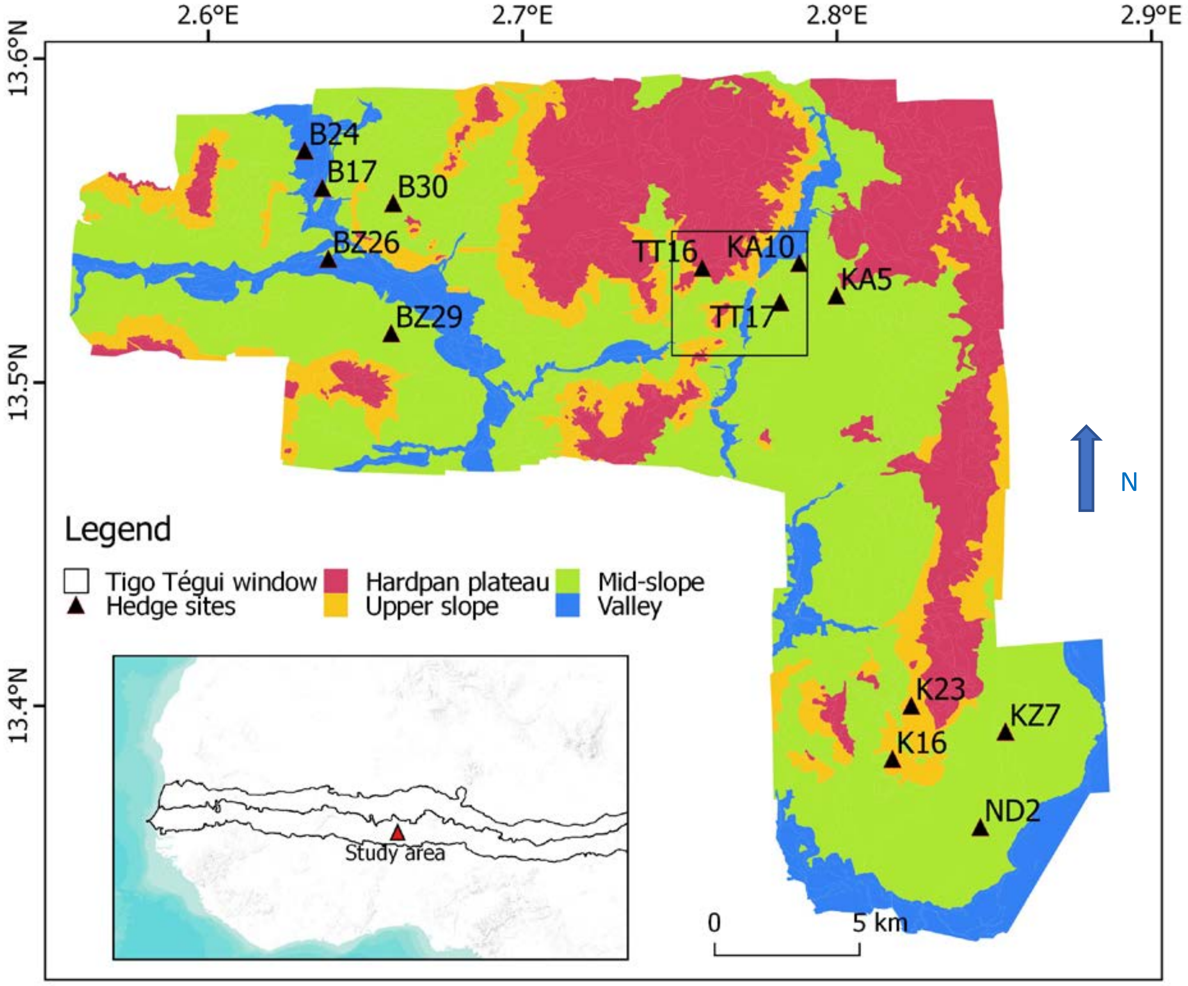

Figure 1 Geographic location of the study area (499km²) in the Dantiandou District of Niger. The three lines of the small maps figure isohyets 150, 300 and 600mm from CHIRPS data 1982-2014 delineating northern, central and southern Sahel bioclimates. Twelve field hedges monitored since 1996 (+ B17 only observed in 1996) are located relative to the main edaphic situations: hard pan plateau, top sandy slope, mid and bottom sandy slopes and valleys (Hiernaux and Ayantunde 2004). The black square frame locates the more detailed map of **Fig 6**.

The study area's climate is typical for the semi-arid monsoonal tropics with an average annual rainfall of 494 ± 30mm (1990-2018) at Banizoumbou, a village within the study area, distributed from June to October in 35 ± 6 rainy days most of which as convective storms (Panthou et al. 2014). There are large rainfall variations between years with series of wetter and dryer years such as the regional droughts of the early 1970's, mid 1980's and more recently between 2009 and 2011 (Lebel and Ali 2009). However, there is no overall trend in annual rainfall over the 1990-2018 period that encompass the monitoring period for this study (**Fig. 2**).

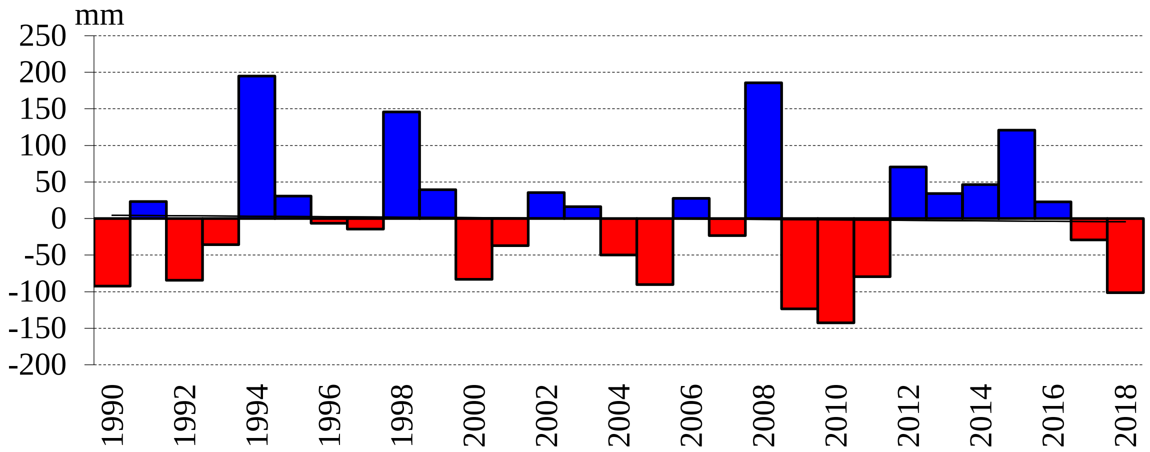

Figure 2 Annual rainfall departure from the mean over 1990 to 2018 (494 ± 30 mm) at Banizoumbou (13°32'N, 2°40'E).

1.2. ***Mapping land use and field hedges***

Woody field hedges were initially mapped by stereoscopic photointerpretation of 1992 panchromatic aerial photos (**Table SI 1**) over the study area. The map was digitized in ATLAS-GIS and geometrically corrected using 150 GPS readings (Trimble Pathfinder Basic Plus GPS receiver) under a UTM projection with a WGS-84 datum. Yet, when the file was overlaid on Google Earth small shifts in random directions were observed and these were corrected manually. The woody field hedges in 1992 were mapped along with six classes of land use (built-up area, manured cropland, unmanured cropland, recent fallow, old fallow, rangeland) together with tracks, cattle paths, pastoral camps, granaries, isolated trees, ephemeral water courses, ponds, wells and boreholes (Hiernaux and Ayantunde 2004). The woody field hedges in 2013-16 were mapped using available Google Earth imagery (**Table SI 1**). The hedges mapped in 1992 were first overlaid on the google map imagery and the hedges that had disappeared were identified and erased from the 2016 file. Then the hedges not mapped in 1992 but present in 2013-2016 were mapped in a separate file. To document the land use changes, the categories of land use mapped in 1992 plus an additional category of "pristine savanna" (no sign of cropping at least during the previous century) were mapped over the same area covered by historical aerial photo coverages of 1950 (IGN) and 1975 (IGNN). Land use mapping was also performed on low altitude aerial color slides taken in 1994, 1995 and 1996. Finally, land use mapping was extended to high resolution multispectral satellite data (SPOT images) by supervised classification in 2007, 2008, 2009, and 2010.

1.3. ***Monitoring woody plant and tussock grasses in field hedge samples***

Twelve samples of field hedges were selected in 1996: three on plateau dunes or on sandy upper slopes; three on sandy mid-slopes; three on loamy-sand bottom-slopes; and three on alluvial soils in valleys (**Fig. 1**). Only one of the sites (K23) is located along permanently cropped fields.All the others are along fields that are managed in a crop-fallow cycle. First measured in 1996, the hedges were revisited in 2010 and 2015. One of the hedges described in 1996 had disappeared in 2010 due to land erosion on a stream bank (B17) and was replaced by a different hedge (BZ26).

The monitored field hedge sections were 200m long, subdivided into eight segments of 25m. The perennial grasses (*Andropogon gayanus*, *Aristida sieberiana*), shrubs (maximum crown height below 4m) and trees (crown height above 4m) along the hedges are systematically measured. For each woody plant, the following were recorded: the species, crown height, largest crown diameter (D, m), crown diameter perpendicular to the largest diameter (d, m), and the circumference (C, cm) of each stem at 10 cm above ground level.

The density of shrubs and trees was calculated by simply counting individual plants along the hedge section. Errors are very unlikely, limited to the possibility of inadequately distinguish individual shrubs when highly intertwined. The basal area (Ba, cm^2) of each woody plant was calculated by summing the basal area of each stem calculated as :

$$Ba = C^2/(4.\pi) \qquad (1)$$

Risks of error in assessing basal areas are minor as well, limited to missing small stems, especially after recent shrub coppicing, and to imprecise measurements of the stem circumferences, especially for low branching trees or shrubs.

The foliage dry mass (Fm) and wood dry mass (Wm) are estimated using existing species-specific allometric functions of the circumference of each stem (Cissé 1980; Henry et al. 2011):

$$Fm = \alpha.C^{\beta} \quad (2)$$

$$Wm = \gamma.C^{\delta} \quad (3)$$

The species-specific coefficients α, β, γ and δ are provided in **Table SI 2** . Error associated with the use of allometric functions such as these is likely if the sizes of woody plants sampled fall outside the range of circumferences used to generate the function. Unfortunately, such ranges are not systematically documented for the allometric functions used but it is unlikely that the size distribution of woody plants sampled here are outside the ranges used to develop these functions.

The crown area (Ca, m²) is estimated as the area of the ellipsoid shape defined by the largest crown diameter (D, m) and the perpendicular diameter (d, m):

$$Ca = \pi \,.\, (D.d)/4 \quad (4)$$

There is a possible observer bias tied to the crown diameter estimation being either measured in 1996 and 2015, as the extreme longest diameters, between the more remote branchlets, while in in 2010, the diameter estimated from a rounded ellipsoid fitting the crown.

Densities, basal areas, crown areas, wood and foliage masses are expressed per 100m of hedge. The contribution of field hedge woody plants to the overall woody plant population is assessed in two different ways. The first approach estimates the contribution per unit area (ha) by relating the measurements expressed by 100m of hedge to the 10 m-wide band surrounding the hedge, i.e. 5 meters on either side of the hedge axis. This is justified by the observation that the maximum crown diameter of the trees in monitored hedges did not exceed 10 meters. Using this approach, leaf and wood masses per hectare equivalent are estimated by simply multiplying by 10 the values given for 100 meters of hedge. The second way is to estimate the absolute number of woody plant individuals contributed by hedges by multiplying the hedge woody plants values expressed by 100 meter of hedge by the length of field hedges mapped on the same date.

1.4. *Surveying land tenure and human population*

The land-use maps in 1994 to 1996 were used as background to survey and map land tenure, identifying the family managing each field and under which tenure status: primary rights to the land generally held by members of chieftaincy lineage and the few purchases of land, or secondary rights which characterizes the rights held by those outside of the chieftaincy lineage (Hiernaux and Ayantunde 2004). An additional survey was conducted in 1998 on the history of each field, establishing the ancestor of the actual family head that had first cleared the field for cropping, the year of that clearing and the list of the names of the successive managers since clearing. The land tenure status of crop fields and land rights of families in three major villages have been further studied and characterized recently (Turner and Moumouni 2018a, b). The composition of families were surveyed in 1994, 1998 and 2013 (Zezza et al. 2016) that allows an assessment of demographic growth and changes in family composition. These population surveys were compared with the more recent administrative population census performed in 2008 and 2013 (INS-Niger 2013).

2. Results

2.1. Field hedge and land use mapping

Field hedge mapping

The total length of woody field hedges in the study area in 1992 equals 1006 km over 499 km² of land (equivalent to 2.02 km km^{-2}) and over 435 km² of agricultural land (2.31 km km^{-2}) when the unarable rangelands, without field hedges, are excluded (**Fig. 3, Table 1**). In 2016, 174.1km (17.5%) of these 1992 field hedges had disappeared, but 1591.3 km of new hedges were observed so that the resulting density of woody field hedges per area of agricultural land reached 5.56 km km^{-2} (**Fig. 4**). Woody field hedges had thus increased by a factor 2.4 equivalent to a mean annual increase rate of 3.7% from 1992 to 2016.

Table 1. Inventory of woody field hedges over the study area (499 km² out of which 435 km² of agricultural lands) in 1992 and 2013-2016. The density of hedges is calculated at the full landscape (499 km^2) or at the agricultural land (435 km^2) scale.

Year	Type of hedges	Number # 	Total length Km	Mean length m	Density within study area km/km²	Density in study area's agricultural land km/km²
1992	Hedges	1981	1005.7	507	2.02	2.31
2013-16	1992 Persistent	1716	829.6	483	1.66	1.91
2013-16	New hedges	4682	1591.3	340	3.19	3.66
2013-16	All hedges	6398	2420.9	378	4.85	5.56

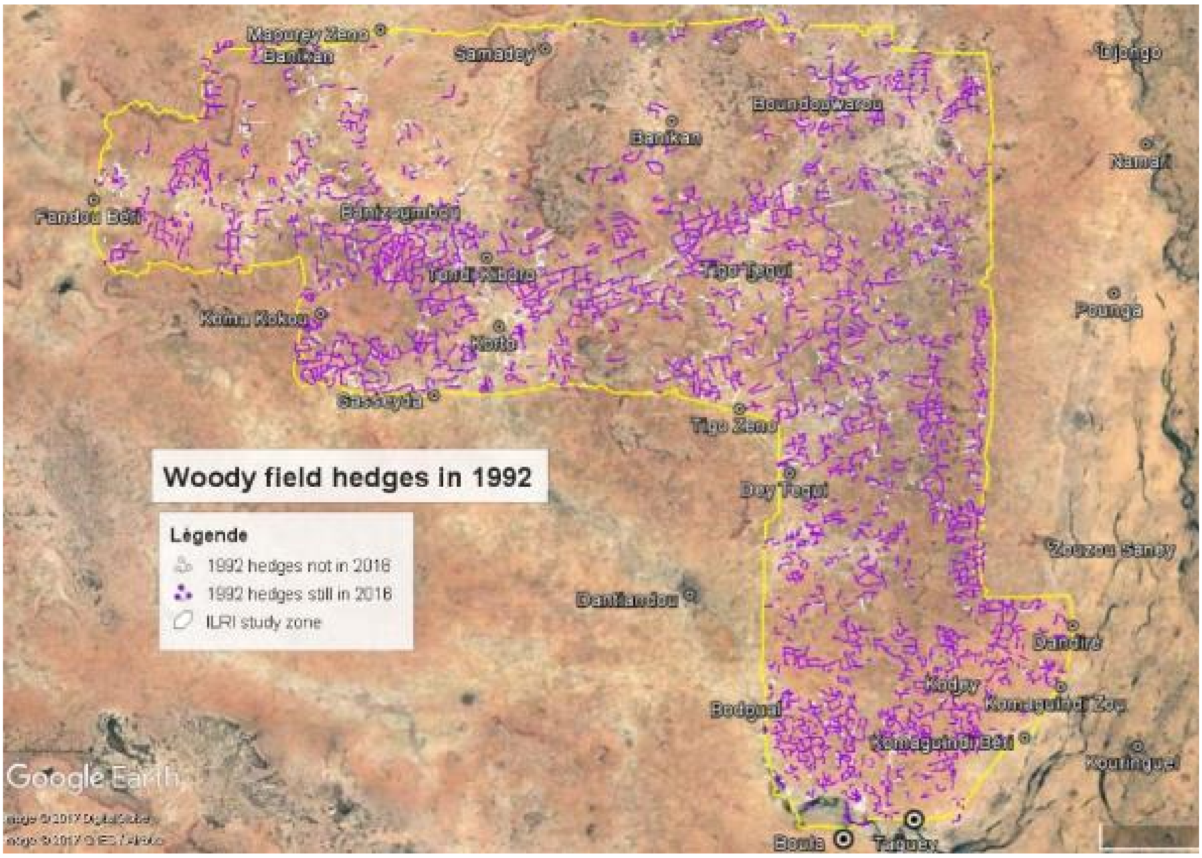

Figure 3. Map of the woody field hedges in 1992 overlaid on Google Earth image. Hedges that were eliminated (white) and maintained (purple) by 2013-16 are delineated with the study area delineated in yellow.

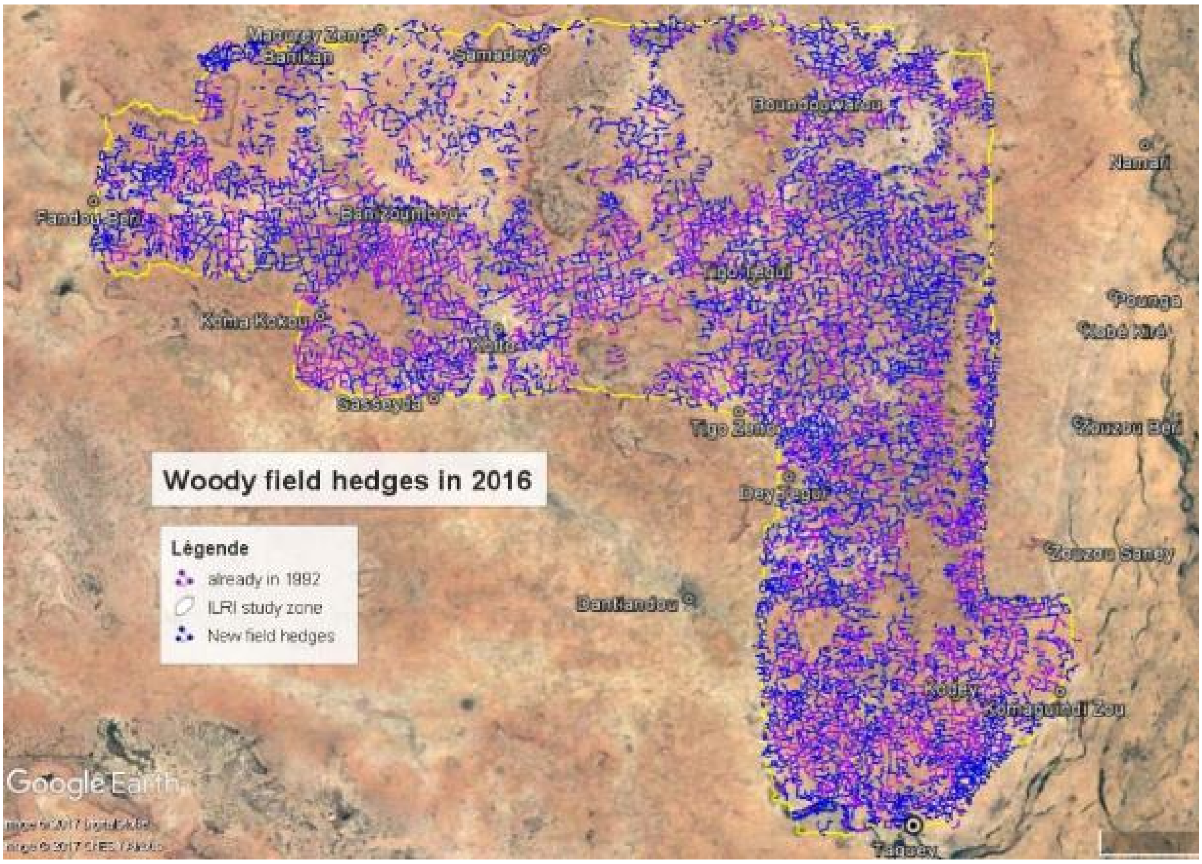

Figure 4. Map of the woody field hedges in 2013-16 from Google earth imagery of 11/11/2016 (70% East side), 31/01/2016 (10%, Mid-Center), or 28/09/2013 (20%, West). Hedges that were already present in 1992 (purple), new hedges (blue) are delineated with study area delineated in in yellow.

Land use mapping.

There were significant changes in land use within the 499km² study area since 1950. There has been a rapid extension of the cropped area from 1950-1975 with the disappearance of 'pristine' savannas (**Fig. 5**). Since 1992, cropped area continued to increase to the detriment of fallows with interannual variations due to farmers adjusting their sowing and weeding practices to observed rainfall received by individual fields (**Fig. 2**). The land use dynamics from 1950 to 2018 is also illustrated by series of aerial views centered over the northern portion of one village's fields located in the center of the study area (**Fig SI 2**).

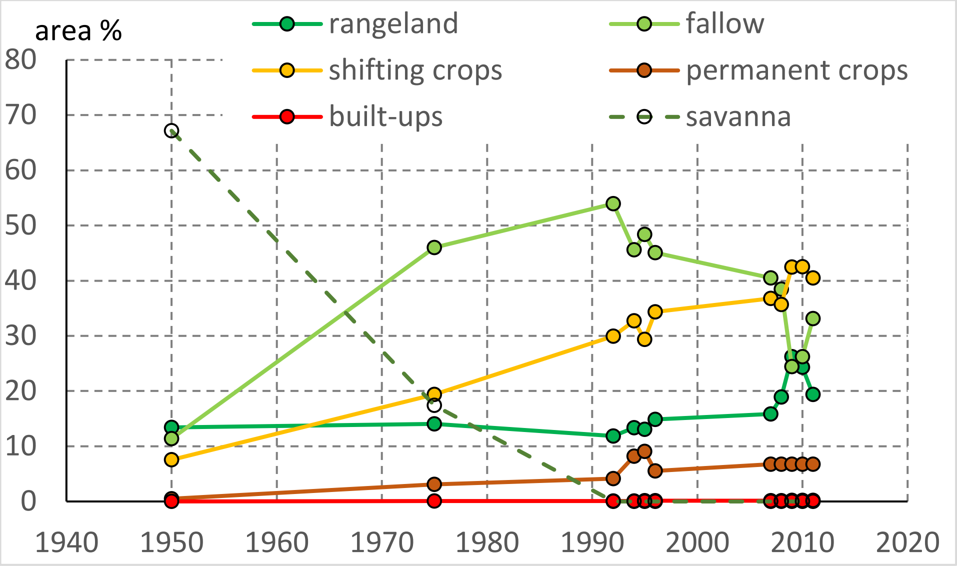

Figure 5. Changes in land use over the study area (499km²). Areas are estimated from classification of aerial photos (1950-1996) and supervised classifications of SPOT imagery (2007 onwards). The cropland is categorized as either shifting crop fields or permanently cropped fields.

Land tenure mapping and recording field management history

Using the 1994 land-use map, interviews of farmers produced a land tenure map as described above. **Figure 6** shows a portion of the land tenure map, overlaid on the map of the woody field hedges for an area lying northwest of a village in the center of the study area (see inset of **Figure 1** for this figure's location within study area). The process of agricultural land splitting through intergenerational inheritance is illustrated by a few fields identified on this portion of the land tenure map (with fields attached to certain families designated by family codes 19 to 26 described more fully in **Fig SI 9**). In 1998 these fields were separately managed by eight families (seven brothers and one of their sons) -- all descendants from a common ancestor, Boulymane K., grandson of Koutoubi H. who founded the village in 1906 (Turner and Moumouni 2018a). Boulymane K.'s only son, Moussa B., had seven sons who shared his rights to the land he inherited (**Fig. SI 9**). The next generation currently in charge of field management is composed of 26 family heads, associated with further splits of the land parcels by a factor 3.7 on average. Some of these plot partitions generate new field hedges, either already established in 2016 (in light green in **Fig. 6**) or just outlined (in light blue). Indeed, the split of fields between brothers is sometimes initiated before the father's death (8.1± 4.7 years before, on average) but more commonly. after the father's death (13.4±16.6 years after, on average) (Turner and Moumouni, 2018b).

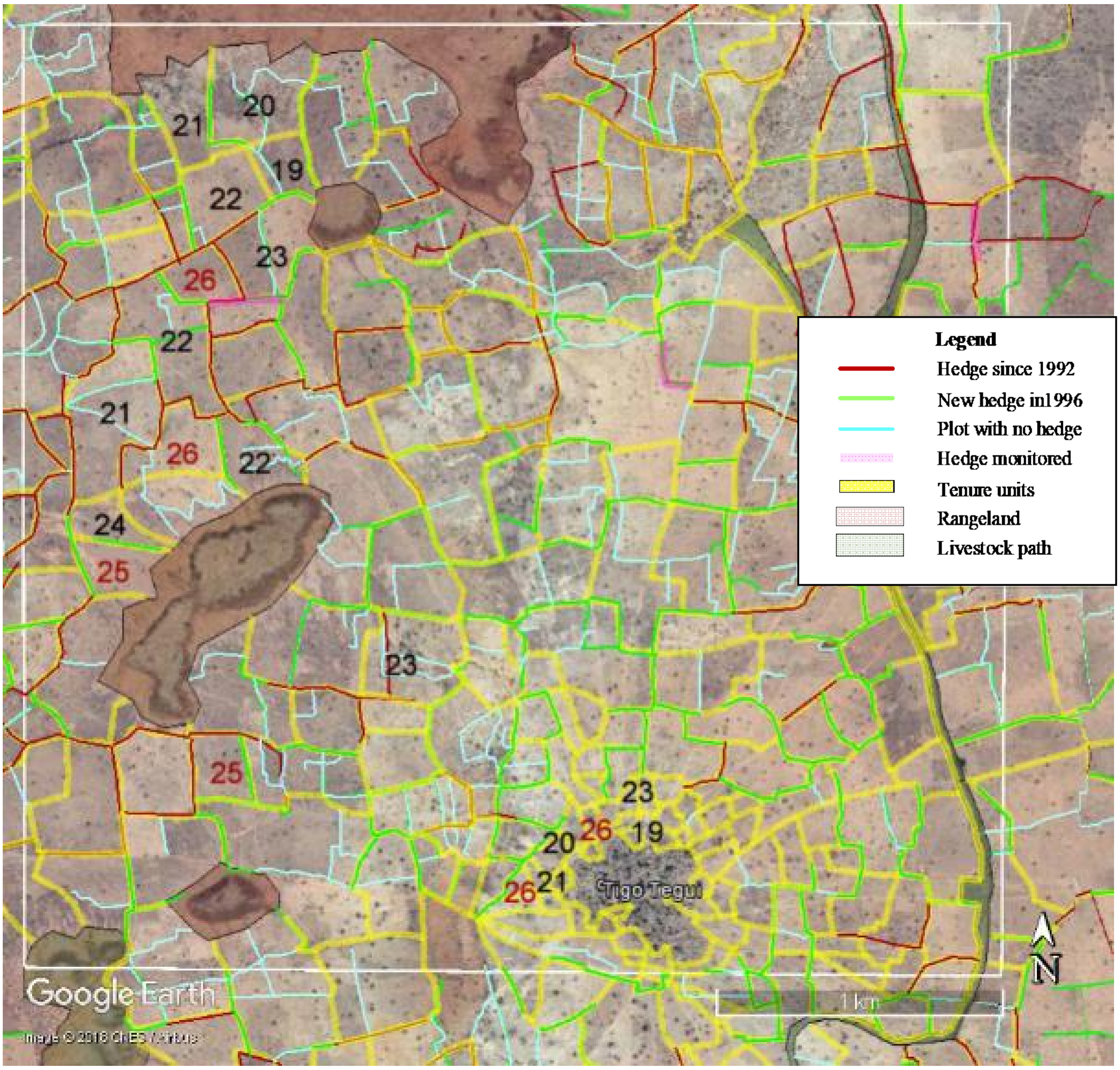

Figure 6. Land tenure (yellow thick polygons as recorded in 2002), woody field hedges (since 1992 in dark red and new in 2016 in green), and recent field partition with no hedge yet (light blue), to the northwest of a village within the study area. The numbers refer to related farmer families (**Fig. SI 9**). The map is overlaid on high resolution Google Earth satellite image dated 11/11/2016.

2.2.*Field hedge monitoring*

Woody plant density, basal area, crown cover and foliage masses in the field hedges.

Mean woody plant density of surveyed hedges varies little between 15.9 in 1996, 20.7in 2010 and 16.6per 100m of hedge in 2015 (**Table 2**; **Fig. SI 4a**). In other words, woody plants, on average, are standing 5 to 6 meters apart along the hedge (**Fig. SI 1**).

Table 2. Mean density, basal area, crown cover, foliage and wood masses per 100m of field hedge measured in 12 sites in 1996, 2010 and 2015.

Parameter for 100m of field hedge	Year	Trees		Shrubs		All woody	
		mean	Stdev	Mean	Stdev	mean	Stdev
Density (#)	1996	4.0	1.9	11.8	8.2	15.8	6.8
	2010	2.5	1.8	18.1	9.1	20.5	8.2
	2015	2.2	2.0	14.3	6.8	16.6	6.4
Basal area (m²)	1996	0.2	0.1	0.3	0.2	0.2	0.1
	2010	0.2	0.2	0.2	0.1	0.4	0.2
	2015	0.2	0.2	0.2	0.1	0.4	0.2
Cover (m²)	1996	167.9	115.5	73.3	55.0	234.1	101.9
	2010	52.3	47.4	60.8	38.4	110.5	37.0
	2015	77.2	77.7	112.0	84.0	185.1	85.3
Leaf mass (kg dry mass)	1996	49.6	33.5	16.9	14.1	66.6	29.3
	2010	59.4	78.5	61.2	38.2	120.6	48.7
	2015	57.8	76.7	52.5	41.7	110.3	50.1
Wood mass (kg dry mass)	1996	678.1	510.2	148.0	127.0	826.1	439.8
	2010	1576.9	2177.5	581.0	409.5	2157.9	1941.6
	2015	1821.2	2637.6	755.3	1004.0	2576.5	2318.3

Table 2 shows that across the years 1996, 2010, 2015, basal area and leaf mass of all woody plants first increased and then decreased as plant density while wood mass increases throughout the monitoring period. The opposite trend is seen for cumulative crown cover which first declines and then partially recovers over the same time period . This observation likely results from the bias in crown diameter measurements in 2010 described above and should be thus disregarded.

Among sites, contrasting trends were observed throughout the period. Woody plant density decreased at two sites, remained relatively stable at four sites and increased from 1996 to 2010 and then slightly decreased in 2015 at the other four sites (**Fig. SI 5a**). Similarly, the mean decrease in basal area hides an increase at five sites and a decrease at the other seven (**Fig. SI 5c**). Cumulative crown cover, leaf mass, and wood mass display much less inter-site variation with only one site in each case showing contrasting trends (**Figures S1 5d** and **S1 5e**).

Tree and shrub contributions

Crown cover, basal area, leaf mass, and wood mass show the same general trends for trees and shrubs across the monitored period. However, different trends in plant density were observed. The slight increase in woody plant density hides a decrease in the mean density of trees while shrub density strongly increased between 1996 and 2010, and then declined (**Fig SI 4a**). However, looking at each hedge, the overall decrease in tree density does not apply to sites K23, TT16 and BZ29 where tree density and aggregated basal area increased between 2010 and 2015 probably because some of the shrubs passed the threshold of 4m in height and were counted as trees (**Fig SI 6 a,c**). For the other hedges, the decrease in tree density, basal area, with associated decreases in tree wood and leaf masses could be due to selective logging, especially at B24, K16, KZ7 and ND2 (**Fig 6 a,c 7a,c**). Shrub coppicing, such as that experienced at hedges B24, TT16 and TT17 between 2010 and 2015 did not affect shrub density but reduced basal areas, wood and leaf masses. In contrast, the KA5 and ND2 hedges that were not coppiced during the same period, show opposite trends (**Fig 6 b,d 7b,d).**

Botanical composition of field hedge woody populations.

The number of woody plant species recorded in the 12 monitored hedges (**Table SI 3**) varied between 9 in 1996, 14 in 2010 and 12 in 2015 among which, three species largely dominate, together representing 93-98% of the total value depending on the parameter considered (**Fig. 8**): *Guiera senegalensis*, *Combretum glutinosum* and *Piliostigma reticulata*. As a shrub, *G. senegalensis* ranks first in density and crown cover. *C. glutinosum,* which may grow as a tree, ranks first in wood mass. *P. reticulata*, a small tree which is often coppiced, always ranks third. Although plant density did not change much over time, *C. glutinosum* increased in crown cover and basal area leading to increases in leaf and wood masses. On the contrary *G. senegalensis* decreased in both crown cover and basal area leading to decreases in leaf and wood masses from 1996 to 2015.

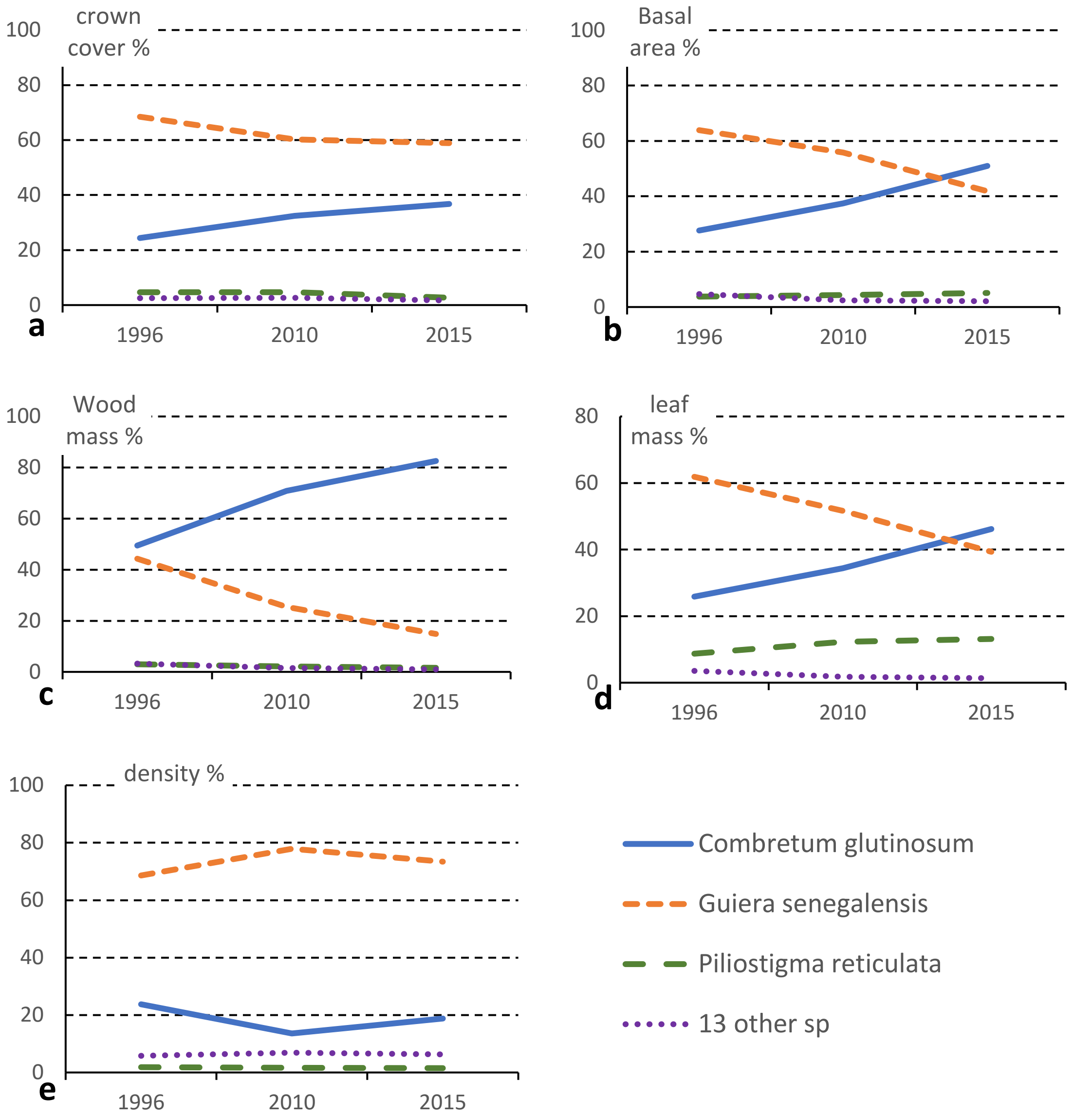

Figure 8. Species contribution (%) to the mean **a**) crown cover , **b**) total basal area, **c**) wood mass, **d**) leaf mass and **e**) woody plant density along 12 field hedges in 1996, 2010 and 2015.

Two perennial tussock grasses in the field hedges

Two perennial grass species are common in some of the field hedges, growing between woody plants. *Andropogon gayanus*, a 2-3m tall tussock grass, is protected by farmers in fields and particularly in the hedges because of its multiple uses (woven mats, thatch, chicken coops, beehives…) and the good fodder value of its dry season regrowth. *Aristida sieberiana* is not protected but its seed dispersion and germination is favored by soil disturbance associated with cropping. Both species' densities decreased during the study period with a faster reduction of *A. sieberiana* than *A. gayanus* (**Fig. 9**). The large standard deviation of density reflects quite different values among sites, the perennial grasses being more frequent either in more silty sands at the top of slopes or in depressions (**Fig. SI 8**). However a decrease in perennial grasses occurred in all sites.

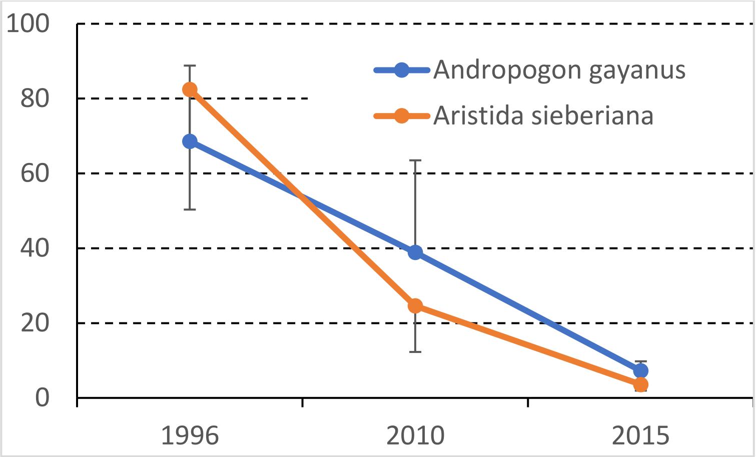

Figure 9. Mean and standard deviations of density (#/100 m of field hedge) of *Andropogon gayanus* and *Arisitida sieberiana* tussocks along 12 field hedges in 1996, 2010 and 2015.

2.3.*Contribution of field hedges to woody plant populations at the landscape scale*

Relating the woody plants described for 200m of field hedge to a band of land of 10m wide provides an estimate of the field hedge contribution to woody plant density, basal area, cover, leaf and wood masses per unit land. These contributions expressed per hectare are calculated by multiplying by 10 from the statistics expressed per 100 m of hedge (**Table 2**). Expressing hedge contributions in this way allows one to compare these values with those estimated within cropped or fallowed fields of the study area. The woody plant populations of the field hedges are much denser than that of cropped and fallowed fields (San Emeterio Cabañes et al. 2013; Brandt et al. 2016), with densities and cover closer to that of Sahelian open woodlands (Hiernaux et al. 2009).

Alternatively, multiplying the hedge statistics from field observations in 1995 (**Table 2**) by the density of hedges mapped in 1992 (**Table 1**) provides estimates of contribution of hedges over the study area's agricultural land in 1992-95 (**Table 3**). Similarly 2015 field statistics and 2013-2016 hedge map allows one to estimate the woody hedge contributions in 2013-16. Estimates of the parameter contributions of woody plants found within hedges across the study area all increased over the 24 years with mean annual growth rates varying between 3.9% for density, 5.4% for basal area, 2,7% for crown cover, resulting in annual increases by 6.1% in foliage mass and 8.8% wood mass. Shrubs are driving the increases in density, crown cover and foliage mass, while trees dominate the increase of basal area and wood mass.

Table 3. Mean and standard deviation of the contribution of the field hedges to the density (ha^{-1}), basal area (m² ha^{-1}), cover (%)), foliage and wood masses (kg ha^{-1}) of woody plant population on agricultural land within the study area in 1992-2005 and 2013-2016.

		Trees		Shrubs		All Woody	
Parameter	Interval	mean	Stdev	mean	Stdev	mean	stdev
Density ha^{-1}	1992-95	0.92	0.44	2.73	1.89	3.65	1.57
	2013-16	1.22	1.11	7.95	3.78	9.22	3.55
Basal area m² ha^{-1}	1992-95	0.04	0.03	0.06	0.04	0.06	0.03
	2013-16	0.1	0.09	0.11	0.06	0.21	0.09
Cover %	1992-95	0.39	0.27	0.17	0.13	0.54	0.24
	2013-16	0.43	0.43	0.62	0.47	1.03	0.47
Foliage mass kg ha^{-1}	1992-95	11.5	7.1	3.9	3.3	15.4	6.8
	2013-16	32.1	42.6	29.2	23.2	61.3	27.9
Wood mass kg ha^{-1}	1992-95	156.6	117.9	34.2	29.3	190.8	101.6
	2013-16	1012.6	1466.5	419.9	558.2	1432.5	1289

3. Discussion

Literature on field hedges is scarce in the Sahel. Their existence in the agrarian landscape is recognized (Pélissier 1953; Sanogo et al 2000; Levasseur 2003) but there have been no quantitative descriptions of densities, cover or wood masses. The literature has focussed more on the impact of woody hedges on biodiversity or agroecosystem processes (Burel 1996), with a particular attention to their potential to control either wind (Banzhaf et al. 1992; Michels et al. 1998) or run-off erosion (Valet 2000; Smolikowski et al. 2001). The role of hedges serving as land tenure markers (Pélissier 1995) is also mentioned. Moreover, there is an abundant technical literature on the agroforestry methods, best adapted woody species, planting or drafting practices to establish new live hedges, as if they were not part of the agrarian system already (Depommier 1991; Ayuk 1997; Yossi et al. 2006). Reflective of this, the woody plants growing in the hedges are generally excluded from the woody plant surveys carried out in forests and savannas, and also in cropped or fallowed fields. One reason for this disregard is the inability of standard survey methods to assess linear vegetation patterns. Yet, as demonstrated by this research, woody plants found within field hedges contribute significantly to the woody populations of agricultural landscapes.

3.1.**Heterogenous structures and homogeneous species composition**

Woody plant populations were found to differ significantly among the 12 sampled field hedges with coefficients of variation of the 12 hedge means between 40 and 43% for woody plant density, basal area, crown cover, foliage and wood masses (**Table 2**). The heterogeneity increases when shrubs and trees are separated with coefficients of variation for shrubs ranging between 55% for density and 71% for crown cover, and for trees between 71% for density and 87% for crown cover. The larger heterogeneity of crown cover could be related to the variations caused by the irregular coppicing of hedge shrubs. Because of their higher density, shrubs contribute about as much as trees to total basal area, crown cover and foliage mass. These variations are not explained by the geomorphic position nor related run-off/run-on balances (not shown).

The species composition of the field hedges of the study area is relatively poor by comparison with other woody populations in Niger (Mahamane et al. 2009; Idrissa et al. 2017) with only 16 species registered across the 12 sites over the three years of observation (**Table SI 3**). This poverty is reinforced by the fact that three species: *G. senegalensis, C. glutinosum* and *P. reticulata* together represent 93-94% of plant density, 96-97% of basal area, 97-98% of crown cover, wood and foliage masses. In Western Niger, the trees and shrubs of these field hedges are not planted, nor sown, but result from selective sparing of woody plants at field clearing. They are just the most common species found on the infertile acidic sandy soils in the southern Sahel (Hiernaux and Le Houérou, 2006)

3.2. **Weak trends in hedge woody plant and perennial grasses densities, cover and production over last two decades**.

There is no significant consistent trend between 1996 and 2015 in hedge woody plant density, basal area, crown cover, wood and foliage masses across the 12 hedges monitored. Moreover, the weak trends found for total woody plant population in the hedges result from different trends between trees and shrubs (**Fig. SI 4, 6, 7**) and between hedges (**Fig. SI 6, 7, 8**). The weakness of the overall trends, the contradictory trends among sites; between trees and shrubs, and between the two main species all argue in favor of a woody population dynamics more linked to site-specific management by selective shrub coppicing and tree cutting than to long term climate changes. Given that the prime objective of the woody hedge establishment is to delineate field boundaries, one would expect a greater level of conservation of hedge plants than within the field (Burel 1996; Louppe and Yossi 2000). Yet, the decreases in tree density and basal area over the last two decades may reflect an intensification of woody plant exploitation (Lericollais 1990). The trends observed in shrub density confirm population stability, but again the slight downward trend in density that occurred in the last decade and the progressive decrease in shrub basal area is consistent with an increase in coppicing and exploitation pressure in spite of reported adoption by local farmers of "Assisted Natural Regeneration" (RNA) management practices (Botoni et al. 2010). The density reduction of the two perennial herbaceous species, *A. gayanus* and *A. sieberiana,* is also consistent with an increase in exploitation pressure, by cutting the haulms of *A. gayanus* as construction material and grazing the dry season regrowth of both grasses. Indeed, these declines in perennial density over the last decade is inconsistent with the trend toward more frequent large rainfall events (Panthou et al. 2014) that should favor perennials to the detriment of annual herbaceous species.

3.3.**A denser web of field hedges resulting from land tenure fragmentation**.

Among the 12 sample hedges observed in 2015, all were already in place in 1992, 8 in 1975 and 3 in 1950 (**Fig SI 2**), field hedges are thus persistent features of the landscape. Only one of the hedges sampled in 1996 was dismantled by 2010 because of local soil erosion, and among the 1006 km of hedges mapped in 1992 only 176 km were not observed in 2013-2016 (**Table 1**). Merging neighbor fields may eliminate some hedges but more frequent splitting of fields generates new hedges and 1591 km of hedges were created between 1992 and 2013-shares2016. Splitting a field in two should geometrically increase hedge length by a quarter (in a square shaped field) to a third (in a rectangular field that is twice as long as wide). In 24 years, the overall length proportion of new versus old hedges reaches 1.58 which would correspond to a bit less than two splits of each existing field on average, resulting in the fragmentation of 1996 fields into 3 fields, on average. Indeed, when households divide, it is more common for all fields managed by the family to be split equally among successors to ensure that the quality of land is divided equally (Turner and Moumouni 2018a). Yet not all field splits result in a woody field hedge, a tacit agreement on a demarcation line may suffice. This appears to apply in the fields cropped by Fulani agro-pastoralists who do not have primary rights on the land they crop (Sidikou 1997).

3.4. The increased contribution of field hedges to agricultural land woody plant population.

The increased contribution of the hedges to the woody plants population at the landscape scale mainly comes from the densification of the web of hedges with their total length increasing by a factor of 2.4 in 24 years but is also influenced by the small changes in woody population structure as assessed on the sample of twelve hedge monitored from 1996 to 2015. The resulting contribution of hedges to woody plant density increased by 2.5, from 4.6 in 1995 to 9.2 plant ha^{-1}in 2016, mostly due to increasing shrub numbers with crown cover only increasing by a factor of 1.9 (**Table 3**). The hedge contribution to woody plant basal area tripled, so that leaf mass multiplied by 4.1 and wood mass multiplied by 12.7. Whether these increased contributions of field hedges to woody plant population compensate or not the reduction of trees and shrubs within fields and fallows still needs to be assessed. And if hedges do compensate for the losses within fields and fallows , would they further compensate, at the landscape scale, the decimation of the woody plants of the patterned vegetation of the plateau rangelands (Bouzou Moussa et al 2009; Abdourhamane Touré et al. 2010)?

4. Conclusions

In the monitoring of 12 sampled hedges from 1996 to 2015 no significant overall trends were found for mean density, crown cover or basal area of the woody plants. Instead opposite trends were observed between tree and shrubs, between dominant species and, above all, among hedge sites. Selective cutting and coppicing would explain these locally specific trajectories that are not explained by rainfall variations but likely from variable exploitation pressure over the last decade. Indeed, the hedge’s function as a land tenure marker that ensures long life to most hedges does not prevent their exploitation through gathering (fruits, dead wood, barks), pruning, and selective coppicing or cutting. The steady increase in rural human population density is leading to a fragmentation of the agricultural lands through the splitting of fields among successors at each generation. This fragmentation has led to an expansion of woody field hedges by a factor 2.4 over the 24 years of the survey, equivalent to a mean annual increase of 3.7%. The densification of the web of field hedges drives mean annual increases in the contribution of field hedges to the woody plant population of the agricultural land in the study area extending over 435 km^2. The field hedge woody plant increased density by 3.9%, basal areas by 5.4% , crown cover by 2.7% , leading to 6.1% annual increase in foliage mass and 8.8% increase in wood mass.

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