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### ► To cite this version:

Pierre Hiernaux, Kalilou Adamou, Oumarou Moumouni, Matthew S Turner, Xiaoye Tong, et al.. Expanding networks of field hedges in densely populated landscapes in the Sahel. *Forest Ecology and Management*, 2019, 440, pp.178-188. 10.1016/j.foreco.2019.03.016 . ird-02117954

**HAL Id: ird-02117954**

**<https://ird.hal.science/ird-02117954>**

Submitted on 8 Jul 2019

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

3  
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24

25 **Abstract**

26 Changing woody plant density across agricultural landscapes of the Sudano-Sahelian region is  
27 a debated issue. This paper reports the results of an investigation on the contribution of field  
28 hedges to overall woody plant density. Hedges separating individual cropped parcels were  
29 studied within village agropastoral territories in the Dantiandou district in western Niger. In  
30 1992, field hedges were mapped over the study area using aerial photography and in 2016,  
31 using high resolution Google Earth imagery. In 1992, field hedge length was equal to 1006  
32 km within 435 km<sup>2</sup> of croplands, equivalent to 2.3 km km<sup>-2</sup>. In 2016, 17.5% of these hedges  
33 had disappeared, but 1591 km of new hedges were observed resulting in an increased density  
34 of hedges to 5.6 km km<sup>-2</sup>. In 24 years, hedges had increased at a mean annual rate of 3.7%  
35 likely associated with the splitting of crop fields by inheritance.

36 The composition and productivity of hedges were also monitored in 1996, 2010 and  
37 2015. All trees (maximum height  $\geq 4\text{m}$ ), shrubs ( $< 4\text{m}$ ) and tussock perennial grasses were  
38 recorded within twelve field hedge samples of 200m each. Field measurements were used to  
39 estimate basal area, crown area, foliage mass and wood mass of each woody plant within the  
40 sampled hedges. No significant trends were found between 1996 and 2015 in woody plant  
41 density, basal area, crown cover, wood and foliage masses across all monitored hedges.  
42 However, overall means hide a slight decrease in tree contributions, while shrub contributions  
43 first increased and then decreased. They also mask contradictory trends among sites most  
44 likely related to different rates of shrub coppicing and tree cutting. The woody species  
45 composition of the hedges is poor with an increase of *Combretum glutinosum* to the detriment  
46 of *Guiera senegalensis* over the study period.

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

52

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

## 54 **Introduction**

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

63 The landscapes of the southern Sahel are strongly shaped by a long history of agrarian  
64 management (Raynaut 2001; Ballouche and Rasse 2007). Human management reshapes rural  
65 landscapes through land use (**Fig. SI 1**) with a major distinction being between rangelands  
66 and agricultural lands, reviving the ancient distinction between saltus and ager (Poux et al  
67 2009). Rangelands are defined by their pastoral management under communal access, but also  
68 by their marginal potential for cropping associated with shallow or infertile soils, or with  
69 increased flood risks in low lying areas. Moreover, rangelands cannot be distinguished from  
70 agricultural lands simply by the presence of grazing since all portions of the rural landscape  
71 are open to grazing after crop harvest (Turner et al. 2005). Gathering and wood collection also  
72 extend to the whole landscape and are regulated by specific use rights (Sidikou 1997).  
73 Agricultural lands include all the arable lands cropped or fallowed centered around villages.  
74 Two components constitute the woody population in agricultural lands: 1. the large trees and  
75 coppiced bushes of the agrarian parkland within fields and fallows (Boffa 1999), and 2. the  
76 web of hedges that delineates fields, tracks and paths. Less spectacular and studied than the  
77 trees (Gijsbers et al. 1994; Boffa 1995; Nouvellet et al. 2006; Yossi et al. 2006) and coppiced  
78 bushes (Diack et al. 2000; Achard et al. 2001; Dick et al. 2010; Diakhaté et al. 2016 ) of the  
79 agrarian parkland, the woody field hedges frame some of the most densely populated agro-  
80 pastoral landscapes in West Africa (Pélissier 1953; Portères 1965; Seignobos 1980; Levasseur  
81 2003).

82 The objective of this paper is to quantify changes over the past two decades in the  
83 woody population of field hedges within a study area located within western Niger. Western  
84 Niger is one of the areas of the Sahel where woody plant cover has been found not to have  
85 increased from 2000 to 2014 (Brandt et al. 2016). Within this area, woody plant cover has

86 declined on plateau rangelands<sup>1</sup>, declined slightly or remained the same on slopes, and  
87 increased slightly in valleys and near villages. While slight positive trends have been  
88 observed locally (San Emeterio et al. 2013), one would expect a decline of woody cover on  
89 agricultural land due to the progressive expansion of the land cropped to the detriment of  
90 fallows (Bouzou Moussa et al 2011; Tong et al 2017). Still, the coarse resolution of the  
91 satellite imagery used in assessments of woody plant cover at the regional scale does not  
92 allow a distinction of the contribution of field hedges from that of the parkland within field or  
93 fallows.

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

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

111

## 112 **Materials and method**

### 113 ***1.1. The study site***

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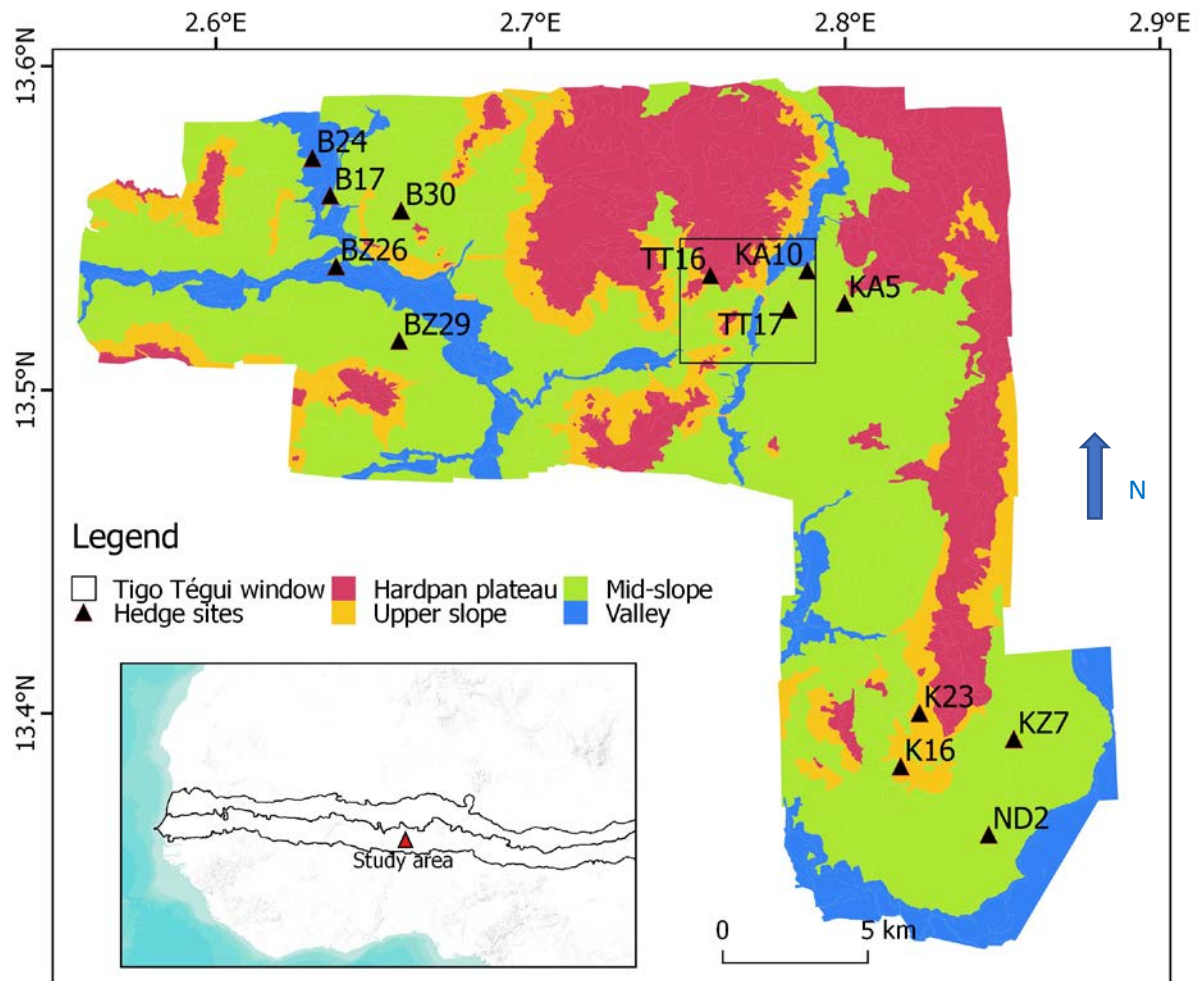
<sup>1</sup> In western Niger, deforestation on the plateaus has often been observed within the patterned woody vegetation type known as ‘tiger bush’ or ‘spotted bush’(d’Herbes et al. 1997). Degradation of tiger bush has been observed elsewhere in the Sahel (Abdourhamane Touré et al. 2010, Trichon et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

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

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

144 The landscape is further structured by a web of tracks that radiate from each village to  
145 access the fields and travel to neighboring villages. In addition, there is a web of livestock  
146 paths that allow local livestock access to water points and rangelands, especially during the  
147 wet season when they are not authorized to cross cropped fields. These livestock paths also

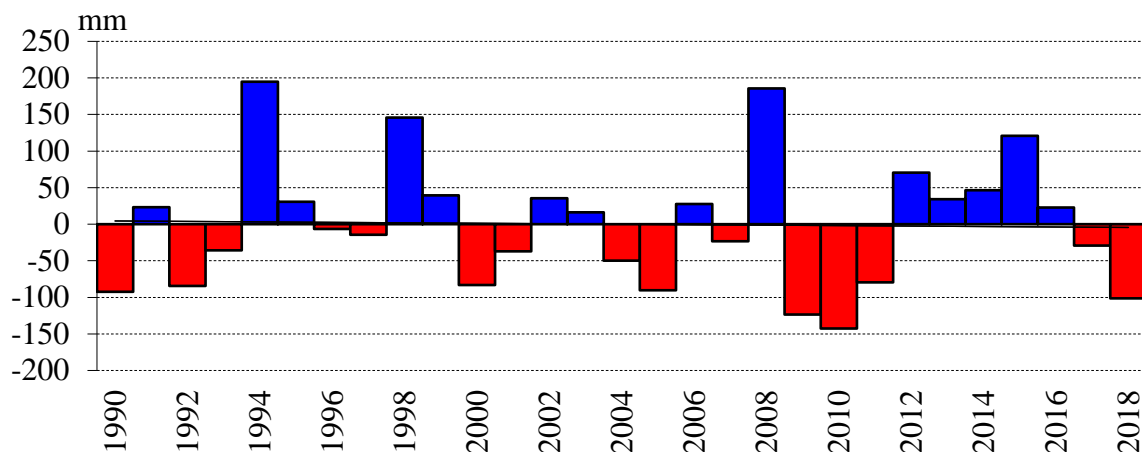
148 connect to a web of regional livestock paths allowing regional and international transhumance  
 149 (Turner et al. 2014). The pastoral camps of settled Fulani families are positioned along these  
 150 livestock paths just outside the edge of permanently cropped fields surrounding each village.  
 151 Their positions reflect that cropped fields are off limits to livestock during the growing season  
 152 and that pastoral families depend on village water resources during the dry season.



**Figure 1** Geographic location of the study area (499km<sup>2</sup>) 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**.

153 The study area's climate is typical for the semi-arid monsoonal tropics with an average  
 154 annual rainfall of  $494 \pm 30$ mm (1990-2018) at Banizoumbou, a village within the study area,

155 distributed from June to October in  $35 \pm 6$  rainy days most of which as convective storms  
 156 (Panthou et al. 2014). There are large rainfall variations between years with series of wetter  
 157 and dryer years such as the regional droughts of the early 1970's, mid 1980's and more  
 158 recently between 2009 and 2011 (Lebel and Ali 2009). However, there is no overall trend in  
 159 annual rainfall over the 1990-2018 period that encompass the monitoring period for this study  
 160 (Fig. 2).



**Figure 2** Annual rainfall departure from the mean over 1990 to 2018 ( $494 \pm 30$  mm) at Banizoumbou ( $13^{\circ}32'N$ ,  $2^{\circ}40'E$ ).

161 **1.2. Mapping land use and field hedges**

162 Woody field hedges were initially mapped by stereoscopic photointerpretation of 1992  
 163 panchromatic aerial photos (**Table SI 1**) over the study area. The map was digitized in  
 164 ATLAS-GIS and geometrically corrected using 150 GPS readings (Trimble Pathfinder Basic  
 165 Plus GPS receiver) under a UTM projection with a WGS-84 datum. Yet, when the file was  
 166 overlaid on Google Earth small shifts in random directions were observed and these were  
 167 corrected manually. The woody field hedges in 1992 were mapped along with six classes of  
 168 land use (built-up area, manured cropland, unmanured cropland, recent fallow, old fallow,  
 169 rangeland) together with tracks, cattle paths, pastoral camps, granaries, isolated trees,  
 170 ephemeral water courses, ponds, wells and boreholes (Hiernaux and Ayantunde 2004). The  
 171 woody field hedges in 2013-16 were mapped using available Google Earth imagery (**Table SI**  
 172 **1**). The hedges mapped in 1992 were first overlaid on the google map imagery and the hedges  
 173 that had disappeared were identified and erased from the 2016 file. Then the hedges not  
 174 mapped in 1992 but present in 2013-2016 were mapped in a separate file. To document the  
 175 land use changes, the categories of land use mapped in 1992 plus an additional category of



176 “pristine savanna” (no sign of cropping at least during the previous century) were mapped  
177 over the same area covered by historical aerial photo coverages of 1950 (IGN ) and 1975  
178 (IGNN). Land use mapping was also performed on low altitude aerial color slides taken in  
179 1994, 1995 and 1996. Finally, land use mapping was extended to high resolution multispectral  
180 satellite data (SPOT images) by supervised classification in 2007, 2008, 2009, and 2010.

181

### 182 1.3. *Monitoring woody plant and tussock grasses in field hedge samples*

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

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

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

$$200 \quad Ba = C^2/(4.\pi) \quad (1)$$

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

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

207 
$$F_m = \alpha \cdot C^\beta \quad (2)$$

208 
$$W_m = \gamma \cdot C^\delta \quad (3)$$

209 The species-specific coefficients  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\delta$  are provided in **Table SI 2** . Error associated  
210 with the use of allometric functions such as these is likely if the sizes of woody plants  
211 sampled fall outside the range of circumferences used to generate the function. Unfortunately,  
212 such ranges are not systematically documented for the allometric functions used but it is  
213 unlikely that the size distribution of woody plants sampled here are outside the ranges used to  
214 develop these functions.

215 The crown area ( $C_a$ , m<sup>2</sup>) is estimated as the area of the ellipsoid shape defined by the  
216 largest crown diameter ( $D$ , m) and the perpendicular diameter ( $d$ , m):

217 
$$C_a = \pi \cdot (D \cdot d) / 4 \quad (4)$$

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

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

#### 232 **1.4. Surveying land tenure and human population**

233 The land-use maps in 1994 to 1996 were used as background to survey and map land tenure,  
234 identifying the family managing each field and under which tenure status: primary rights to  
235 the land generally held by members of chieftaincy lineage and the few purchases of land, or  
236 secondary rights which characterizes the rights held by those outside of the chieftaincy  
237 lineage (Hiernaux and Ayantunde 2004). An additional survey was conducted in 1998 on the

238 history of each field, establishing the ancestor of the actual family head that had first cleared  
 239 the field for cropping, the year of that clearing and the list of the names of the successive  
 240 managers since clearing. The land tenure status of crop fields and land rights of families in  
 241 three major villages have been further studied and characterized recently (Turner and  
 242 Moumouni 2018a, b). The composition of families were surveyed in 1994, 1998 and 2013  
 243 (Zezza et al. 2016) that allows an assessment of demographic growth and changes in family  
 244 composition. These population surveys were compared with the more recent administrative  
 245 population census performed in 2008 and 2013 (INS-Niger 2013).

246

## 247 2. Results

### 248 2.1. Field hedge and land use mapping

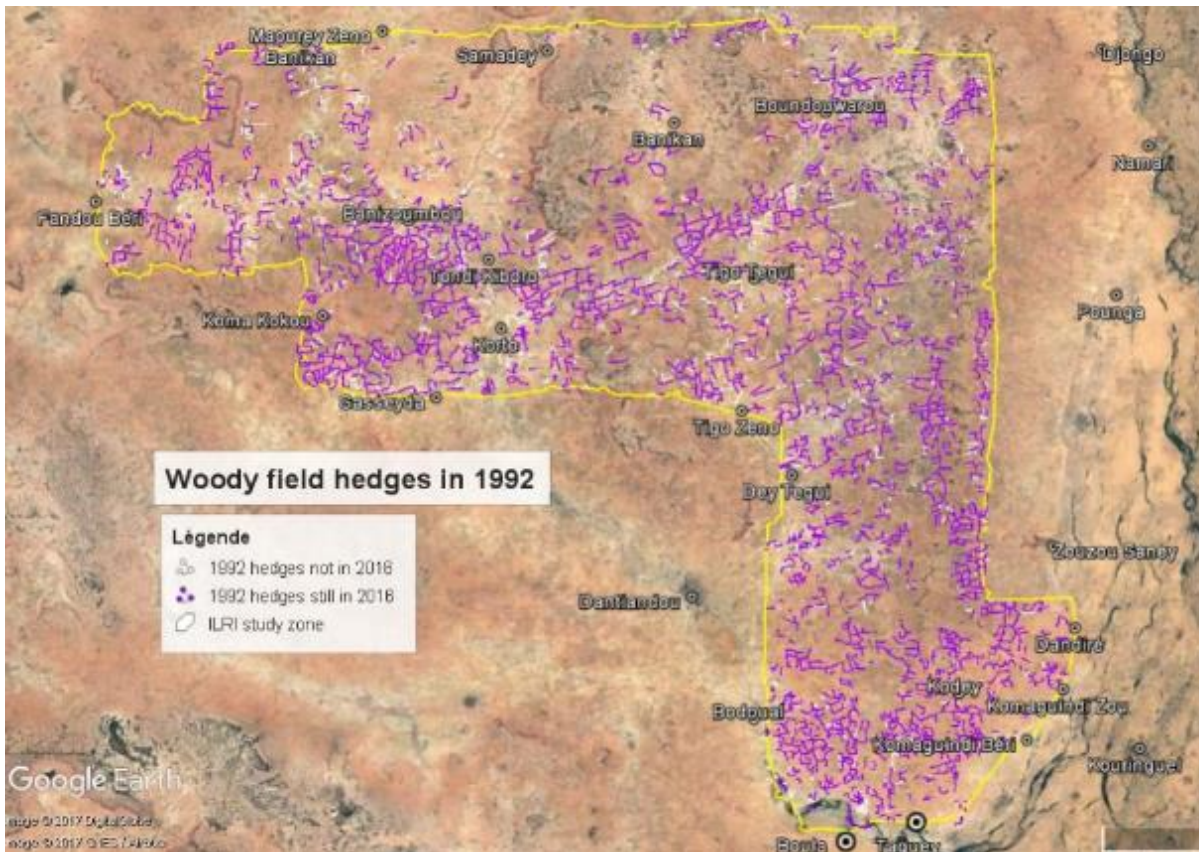
#### 249 *Field hedge mapping*

250 The total length of woody field hedges in the study area in 1992 equals 1006 km over 499  
 251 km<sup>2</sup> of land (equivalent to 2.02 km km<sup>-2</sup>) and over 435 km<sup>2</sup> of agricultural land (2.31 km km<sup>-2</sup>  
 252 ) when the unarable rangelands, without field hedges, are excluded (**Fig. 3, Table 1**). In 2016,  
 253 174.1km (17.5%) of these 1992 field hedges had disappeared, but 1591.3 km of new hedges  
 254 were observed so that the resulting density of woody field hedges per area of agricultural land  
 255 reached 5.56 km km<sup>-2</sup> (**Fig. 4**). Woody field hedges had thus increased by a factor 2.4  
 256 equivalent to a mean annual increase rate of 3.7% from 1992 to 2016.

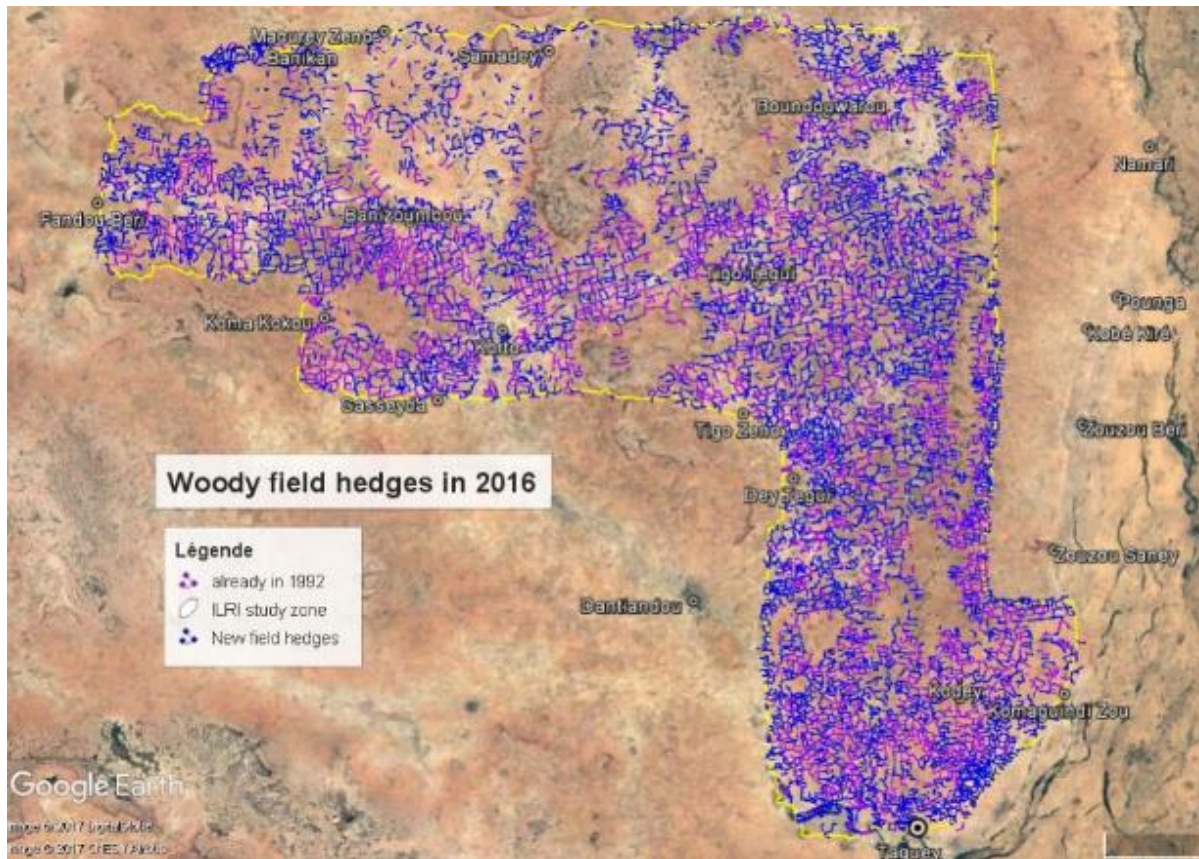
257 **Table 1.** Inventory of woody field hedges over the study area (499 km<sup>2</sup> out of which 435 km<sup>2</sup>  
 258 of agricultural lands) in 1992 and 2013-2016. The density of hedges is calculated at the full  
 259 landscape (499 km<sup>2</sup>) or at the agricultural land (435 km<sup>2</sup>) scale.

Year	Type of hedges	Number	Total length	Mean length	Density within study area	Density in study area's agricultural land
		#	Km	m	km/km <sup>2</sup>	km/km <sup>2</sup>
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

260



**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.

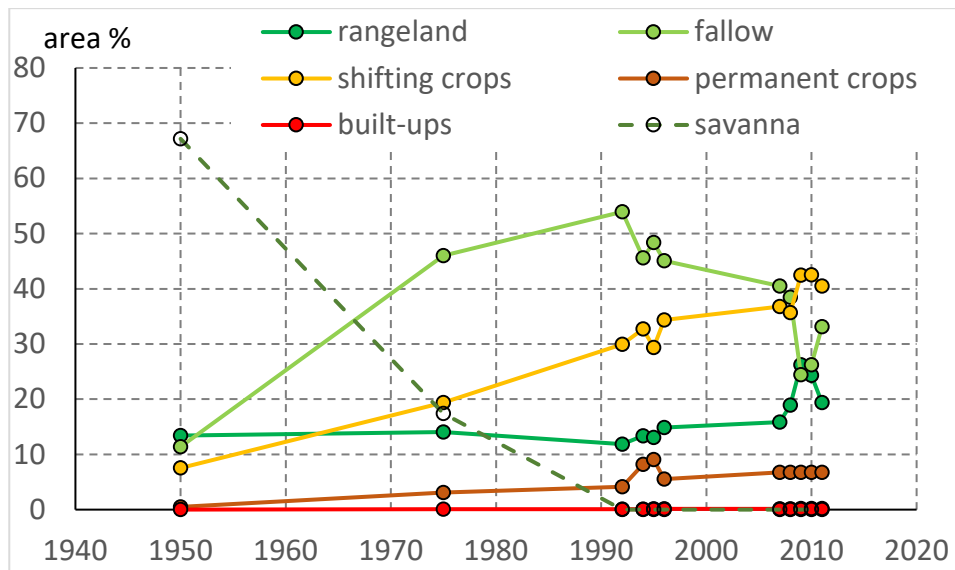


**Figure 4.** Map of the woody field hedges in 2013-16 from Google earth imagery of 11/11/2016 (70% East side), 31/01/2016 (10%, Mid-Center), or 28/09/2013 (20%, West). Hedges that were already present in 1992 (purple), new hedges (blue) are delineated with study area delineated in in yellow.

261

262 ***Land use mapping.***

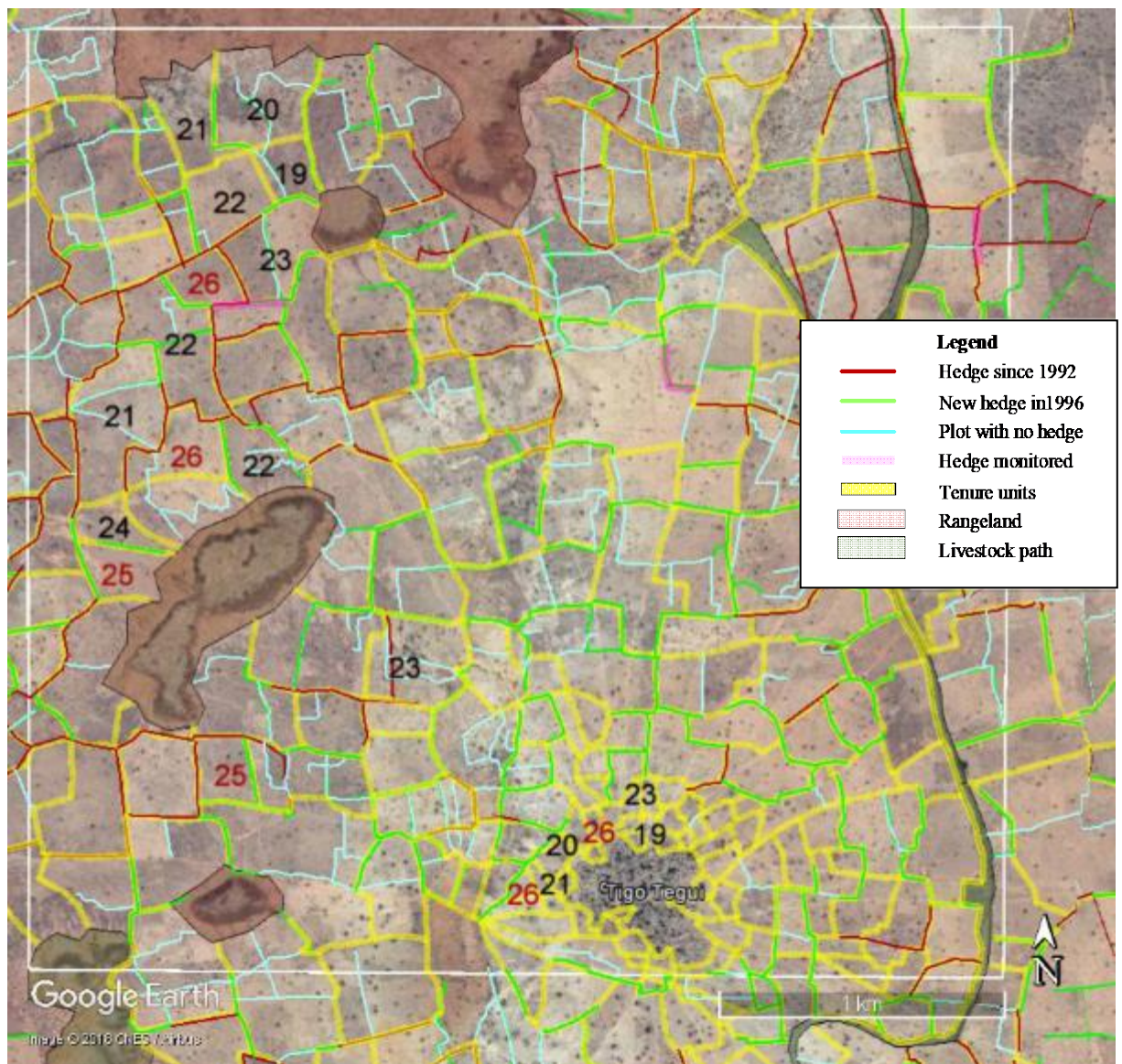
263 There were significant changes in land use within the 499km<sup>2</sup> study area since 1950. There  
 264 has been a rapid extension of the cropped area from 1950-1975 with the disappearance of  
 265 ‘pristine’ savannas (**Fig. 5**). Since 1992, cropped area continued to increase to the detriment  
 266 of fallows with interannual variations due to farmers adjusting their sowing and weeding  
 267 practices to observed rainfall received by individual fields (**Fig. 2**). The land use dynamics  
 268 from 1950 to 2018 is also illustrated by series of aerial views centered over the northern  
 269 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 (499km<sup>2</sup>). 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.

270 ***Land tenure mapping and recording field management history***

271 Using the 1994 land-use map, interviews of farmers produced a land tenure map as described  
 272 above. **Figure 6** shows a portion of the land tenure map, overlaid on the map of the woody  
 273 field hedges for an area lying northwest of a village in the center of the study area (see inset of  
 274 **Figure 1** for this figure's location within study area). The process of agricultural land splitting  
 275 through intergenerational inheritance is illustrated by a few fields identified on this portion of  
 276 the land tenure map (with fields attached to certain families designated by family codes 19 to  
 277 26 described more fully in **Fig SI 9**). In 1998 these fields were separately managed by eight  
 278 families (seven brothers and one of their sons) -- all descendants from a common ancestor,  
 279 Boulymane K., grandson of Koutoubi H. who founded the village in 1906 (Turner and  
 280 Moumouni 2018a). Boulymane K.'s only son, Moussa B., had seven sons who shared his  
 281 rights to the land he inherited (**Fig. SI 9**). The next generation currently in charge of field  
 282 management is composed of 26 family heads, associated with further splits of the land parcels  
 283 by a factor 3.7 on average. Some of these plot partitions generate new field hedges, either  
 284 already established in 2016 (in light green in **Fig. 6**) or just outlined (in light blue). Indeed,  
 285 the split of fields between brothers is sometimes initiated before the father's death ( $8.1 \pm 4.7$   
 286 years before, on average) but more commonly, after the father's death ( $13.4 \pm 16.6$  years after,  
 287 on average) (Turner and Moumouni, 2018b).



289

**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.

290

## 291 **2.2. Field hedge monitoring**

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

293 Mean woody plant density of surveyed hedges varies little between 15.9 in 1996, 20.7 in 2010  
 294 and 16.6 per 100m of hedge in 2015 (**Table 2; Fig. SI 4a**). In other words, woody plants, on  
 295 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 (m <sup>2</sup> )	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 ( m <sup>2</sup> )	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

296  
 297 **Table 2** shows that across the years 1996, 2010, 2015, basal area and leaf mass of all woody  
 298 plants first increased and then decreased as plant density while wood mass increases  
 299 throughout the monitoring period. The opposite trend is seen for cumulative crown cover  
 300 which first declines and then partially recovers over the same time period . This observation  
 301 likely results from the bias in crown diameter measurements in 2010 described above and  
 302 should be thus disregarded.

303 Among sites, contrasting trends were observed throughout the period. Woody plant  
 304 density decreased at two sites, remained relatively stable at four sites and increased from 1996  
 305 to 2010 and then slightly decreased in 2015 at the other four sites (**Fig. SI 5a**). Similarly, the  
 306 mean decrease in basal area hides an increase at five sites and a decrease at the other seven  
 307 (**Fig. SI 5c**). Cumulative crown cover, leaf mass, and wood mass display much less inter-site  
 308 variation with only one site in each case showing contrasting trends (**Figures S1 5d and S1**  
 309 **5e**).

310



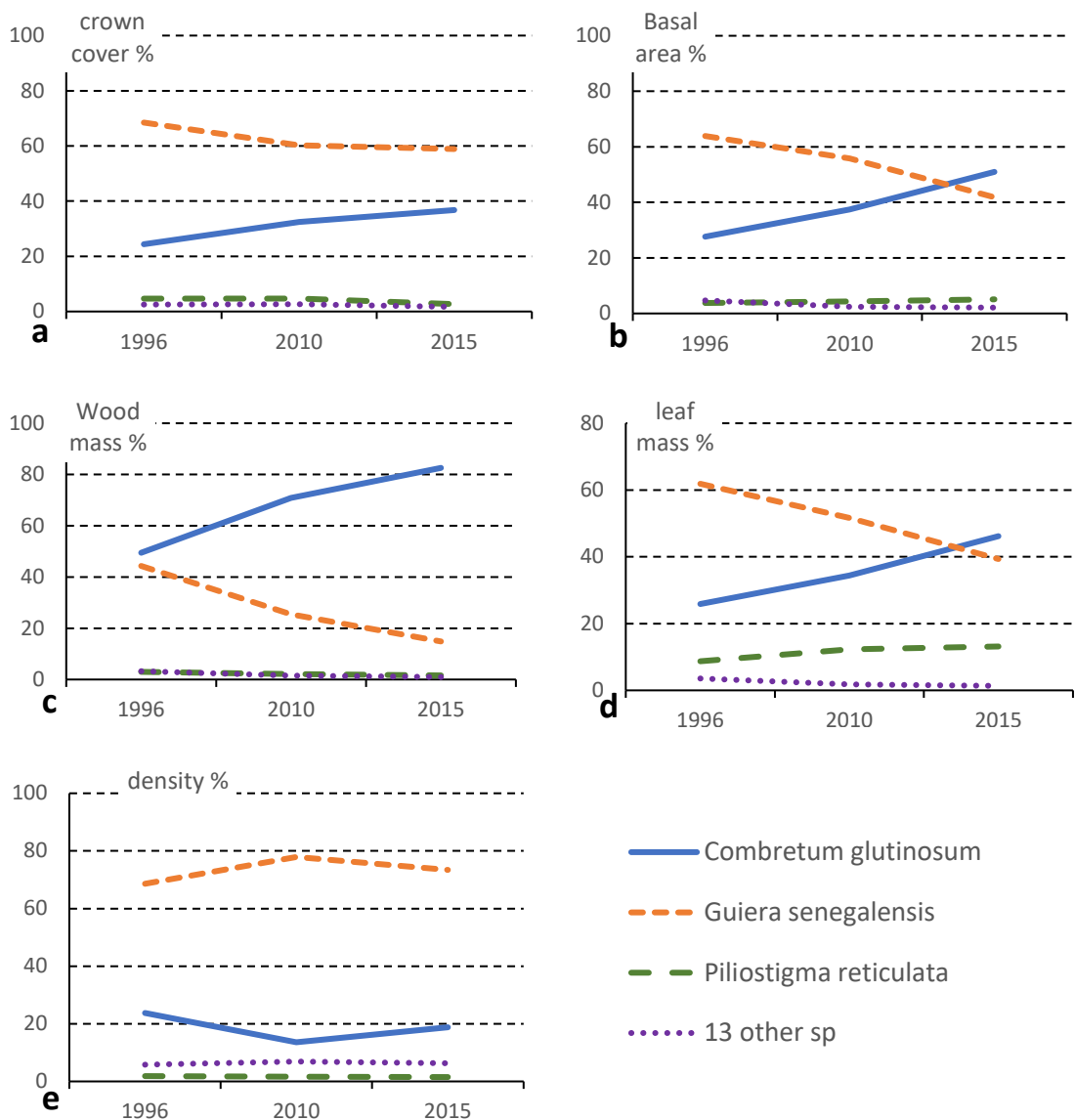
311 ***Tree and shrub contributions***

312 Crown cover, basal area, leaf mass, and wood mass show the same general trends for trees  
313 and shrubs across the monitored period. However, different trends in plant density were  
314 observed. The slight increase in woody plant density hides a decrease in the mean density of  
315 trees while shrub density strongly increased between 1996 and 2010, and then declined (**Fig**  
316 **SI 4a**). However, looking at each hedge, the overall decrease in tree density does not apply to  
317 sites K23, TT16 and BZ29 where tree density and aggregated basal area increased between  
318 2010 and 2015 probably because some of the shrubs passed the threshold of 4m in height and  
319 were counted as trees (**Fig SI 6 a,c**). For the other hedges, the decrease in tree density, basal  
320 area, with associated decreases in tree wood and leaf masses could be due to selective  
321 logging, especially at B24, K16, KZ7 and ND2 (**Fig 6 a,c 7a,c**). Shrub coppicing, such as that  
322 experienced at hedges B24, TT16 and TT17 between 2010 and 2015 did not affect shrub  
323 density but reduced basal areas, wood and leaf masses. In contrast, the KA5 and ND2 hedges  
324 that were not coppiced during the same period, show opposite trends (**Fig 6 b,d 7b,d**).

325 ***Botanical composition of field hedge woody populations.***

326 The number of woody plant species recorded in the 12 monitored hedges (**Table SI 3**) varied  
327 between 9 in 1996, 14 in 2010 and 12 in 2015 among which, three species largely dominate,  
328 together representing 93-98% of the total value depending on the parameter considered (**Fig.**  
329 **8**): *Guiera senegalensis*, *Combretum glutinosum* and *Piliostigma reticulata*. As a shrub, *G.*  
330 *senegalensis* ranks first in density and crown cover. *C. glutinosum*, which may grow as a tree,  
331 ranks first in wood mass. *P. reticulata*, a small tree which is often coppiced, always ranks  
332 third. Although plant density did not change much over time, *C. glutinosum* increased in  
333 crown cover and basal area leading to increases in leaf and wood masses. On the contrary *G.*  
334 *senegalensis* decreased in both crown cover and basal area leading to decreases in leaf and  
335 wood masses from 1996 to 2015.

336



**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.

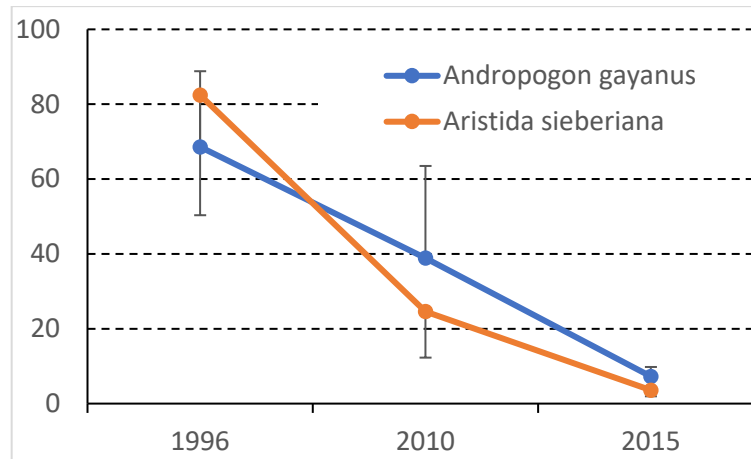
337

### 338 *Two perennial tussock grasses in the field hedges*

339 Two perennial grass species are common in some of the field hedges, growing between  
 340 woody plants. *Andropogon gayanus*, a 2-3m tall tussock grass, is protected by farmers in  
 341 fields and particularly in the hedges because of its multiple uses (woven mats, thatch, chicken  
 342 coops, beehives...) and the good fodder value of its dry season regrowth. *Aristida sieberiana*  
 343 is not protected but its seed dispersion and germination is favored by soil disturbance  
 344 associated with cropping. Both species' densities decreased during the study period with a  
 345 faster reduction of *A. sieberiana* than *A. gayanus* (**Fig. 9**). The large standard deviation of

346 density reflects quite different values among sites, the perennial grasses being more frequent  
347 either in more silty sands at the top of slopes or in depressions (**Fig. SI 8**). However a  
348 decrease in perennial grasses occurred in all sites.

349



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

350

### 351 *2.3. Contribution of field hedges to woody plant populations at the landscape scale*

352 Relating the woody plants described for 200m of field hedge to a band of land of 10m wide  
353 provides an estimate of the field hedge contribution to woody plant density, basal area, cover,  
354 leaf and wood masses per unit land. These contributions expressed per hectare are calculated  
355 by multiplying by 10 from the statistics expressed per 100 m of hedge (**Table 2**). Expressing  
356 hedge contributions in this way allows one to compare these values with those estimated  
357 within cropped or fallowed fields of the study area. The woody plant populations of the field  
358 hedges are much denser than that of cropped and fallowed fields (San Emeterio Cabañes et al.  
359 2013; Brandt et al. 2016), with densities and cover closer to that of Sahelian open woodlands  
360 (Hiernaux et al. 2009).

361 Alternatively, multiplying the hedge statistics from field observations in 1995 (**Table**  
362 **2**) by the density of hedges mapped in 1992 (**Table 1**) provides estimates of contribution of  
363 hedges over the study area's agricultural land in 1992-95 (**Table 3**). Similarly 2015 field  
364 statistics and 2013-2016 hedge map allows one to estimate the woody hedge contributions in  
365 2013-16. Estimates of the parameter contributions of woody plants found within hedges  
366 across the study area all increased over the 24 years with mean annual growth rates varying

367 between 3.9% for density, 5.4% for basal area, 2,7% for crown cover, resulting in annual  
 368 increases by 6.1% in foliage mass and 8.8% wood mass. Shrubs are driving the increases in  
 369 density, crown cover and foliage mass, while trees dominate the increase of basal area and  
 370 wood mass.

371 **Table 3.** Mean and standard deviation of the contribution of the field hedges to the density (ha<sup>-1</sup>)  
 372 <sup>1</sup>), basal area (m<sup>2</sup> ha<sup>-1</sup>), cover (%)), foliage and wood masses (kg ha<sup>-1</sup>) of woody plant  
 373 population on agricultural land within the study area in 1992-2005 and 2013-2016.

Parameter	Interval	Trees		Shrubs		All Woody	
		mean	Stdev	mean	Stdev	mean	stdev
Density ha <sup>-1</sup>	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 m <sup>2</sup> ha <sup>-1</sup>	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 <sup>-1</sup>	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 <sup>-1</sup>	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

374

375

### 376 3. Discussion

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

389 disregard is the inability of standard survey methods to assess linear vegetation patterns. Yet,  
390 as demonstrated by this research, woody plants found within field hedges contribute  
391 significantly to the woody populations of agricultural landscapes.

### 392 **3.1.Heterogenous structures and homogeneous species composition**

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

403 The species composition of the field hedges of the study area is relatively poor by  
404 comparison with other woody populations in Niger (Mahamane et al. 2009; Idrissa et al.  
405 2017) with only 16 species registered across the 12 sites over the three years of observation  
406 (**Table SI 3**). This poverty is reinforced by the fact that three species: *G. senegalensis*, *C.*  
407 *glutinosum* and *P. reticulata* together represent 93-94% of plant density, 96-97% of basal  
408 area, 97-98% of crown cover, wood and foliage masses. In Western Niger, the trees and  
409 shrubs of these field hedges are not planted, nor sown, but result from selective sparing of  
410 woody plants at field clearing. They are just the most common species found on the infertile  
411 acidic sandy soils in the southern Sahel (Hiernaux and Le Houérou, 2006)

412

### 413 **3.2. Weak trends in hedge woody plant and perennial grasses densities, cover and** 414 **production over last two decades.**

415 There is no significant consistent trend between 1996 and 2015 in hedge woody plant  
416 density, basal area, crown cover, wood and foliage masses across the 12 hedges monitored.  
417 Moreover, the weak trends found for total woody plant population in the hedges result from  
418 different trends between trees and shrubs (**Fig. SI 4, 6, 7**) and between hedges (**Fig. SI 6, 7,**  
419 **8**). The weakness of the overall trends, the contradictory trends among sites; between trees  
420 and shrubs, and between the two main species all argue in favor of a woody population  
421 dynamics more linked to site-specific management by selective shrub coppicing and tree

422 cutting than to long term climate changes. Given that the prime objective of the woody hedge  
423 establishment is to delineate field boundaries, one would expect a greater level of  
424 conservation of hedge plants than within the field (Burel 1996; Louppe and Yossi 2000). Yet,  
425 the decreases in tree density and basal area over the last two decades may reflect an  
426 intensification of woody plant exploitation (Lericollais 1990). The trends observed in shrub  
427 density confirm population stability, but again the slight downward trend in density that  
428 occurred in the last decade and the progressive decrease in shrub basal area is consistent with  
429 an increase in coppicing and exploitation pressure in spite of reported adoption by local  
430 farmers of “Assisted Natural Regeneration” (RNA) management practices (Botoni et al.  
431 2010). The density reduction of the two perennial herbaceous species, *A. gayanus* and *A.*  
432 *sieberiana*, is also consistent with an increase in exploitation pressure, by cutting the haulms  
433 of *A. gayanus* as construction material and grazing the dry season regrowth of both grasses.  
434 Indeed, these declines in perennial density over the last decade is inconsistent with the trend  
435 toward more frequent large rainfall events (Panthou et al. 2014) that should favor perennials  
436 to the detriment of annual herbaceous species.

437

### 438 3.3.A denser web of field hedges resulting from land tenure fragmentation.

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

455

#### 4563.4. **The increased contribution of field hedges to agricultural land woody plant population.**

457 The increased contribution of the hedges to the woody plants population at the landscape  
458 scale mainly comes from the densification of the web of hedges with their total length  
459 increasing by a factor of 2.4 in 24 years but is also influenced by the small changes in woody  
460 population structure as assessed on the sample of twelve hedge monitored from 1996 to 2015.  
461 The resulting contribution of hedges to woody plant density increased by 2.5, from 4.6 in  
462 1995 to 9.2 plant ha<sup>-1</sup> in 2016, mostly due to increasing shrub numbers with crown cover only  
463 increasing by a factor of 1.9 (**Table 3**). The hedge contribution to woody plant basal area  
464 tripled, so that leaf mass multiplied by 4.1 and wood mass multiplied by 12.7. Whether these  
465 increased contributions of field hedges to woody plant population compensate or not the  
466 reduction of trees and shrubs within fields and fallows still needs to be assessed. And if  
467 hedges do compensate for the losses within fields and fallows, would they further  
468 compensate, at the landscape scale, the decimation of the woody plants of the patterned  
469 vegetation of the plateau rangelands (Bouzou Moussa et al 2009; Abdourhamane Touré et al.  
470 2010)?

471

#### 472 **4. Conclusions**

473

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

490

## 491 **Acknowledgements**

492 The field work was first carried out under an ILRI (International Livestock Research Institute,  
493 Nairobi, Kenya) research project, more recent observations were funded by the AMMA-  
494 CATCH observatory (<http://www.amma-catch.org>). The authors are very grateful to the rural  
495 people of the Dantiandou district for their hospitality and for their patience with our endless  
496 inquiries. They are also grateful to Laurent Kergoat and two anonymous reviewers for their  
497 careful and inspirational review of the manuscript.

498

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