

1 **Woody plant decline in the Sahel of western Niger (1996-2017):**
2 **is it driven by climate or land use changes?**

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21 **Abstract**

22 Although a recovery of woody vegetation has been observed throughout the Sahel, western
23 Niger has not followed the overall satellite-derived greening trend. While satellite imagery can be
24 used to study overall patterns and trends, only field observations can provide insights in the
25 dynamics of woody plant populations. Here we used field data from 29 sites in the Dantiandou
26 district in Niger to study woody species composition, plant density, crown cover, basal area, foliage
27 and wood mass from 1996 to 2017. All sites show a decrease in woody plant parameters with a faster
28 decrease in rangeland than in agricultural land. Most of the decrease is due to the loss of shrubs,
29 while trees do not change significantly. When field observations were scaled up to the district level
30 using land use maps, shrub density decreased from 342 to 155 ha⁻¹ in agricultural land, and from
31 1567 to 250 ha⁻¹ in rangeland. Trends in annual rainfall and soil moisture during the study period
32 were not significant and cannot explain the decrease of woody vegetation. Instead, the expansion of

33 cropped areas, shortened crop-fallow cycles and the increasing pressure on wood resources to satisfy
34 demand for fuel and construction materials may have contributed to the decline.

35 **Keywords:** dryland vegetation; Sahel greening; agrarian parkland; fallow; shrub; field survey

36 **Introduction**

37 Despite its sparsity, dryland vegetation plays a major role in the inter-annual dynamics of the
38 global carbon cycle (Poulter et al 2014; Ahlström et al 2015). Analyses of remote sensing time series
39 starting in the 1980s show an overall greening trend of tropical dryland vegetation (Fensholt et al
40 2012; Andela et al. 2013). In the Sahel belt (about 3 million km²), which is situated south of the
41 Sahara desert, a greening trend has predominated since the 1980s (Tucker et al. 1991; Eklundh and
42 Olsson, 2003; Dardel et al. 2014; Brandt et al. 2019) following the largest and most severe drought
43 of the 20th century that hit the Sahel from 1968 to the mid-1990s (Ozer et al. 2017). The underlying
44 causes of the overall ‘greening trend’ cited in the literature include increasing temperature and CO₂
45 concentration (Buitenwerf et al. 2012), changes in rainfall amount and seasonal distribution (Brandt
46 et al. 2019), changes in runoff and water infiltration (Rockström et al 1998; Epule et al. 2014), as
47 well as changes in land use (Leroux et al. 2017), fire regimes, rangeland afforestation and “Farmer
48 Managed Natural Regeneration” (Reij et al 2005). There are, however, exceptions to the general
49 ‘greening trend’ among which the study area in western Niger is prominent (Dardel et al. 2014;
50 Leroux et al. 2017).

51 Woody vegetation was found to play a major role in the long-term vegetation trends
52 (Anchang et al. 2019; Brandt et al. 2019), while annual herbaceous vegetation, including crops,
53 explains the large seasonal and inter-annual variations in satellite observed vegetation (Diouf et al.
54 2015). Several studies attribute parts of the greening trend in the Sahel to woody plants (Tian et al
55 2017). For example, Brandt et al. (2016a) and Horion et al (2014) used dry season Normalised
56 Difference Vegetation Index (NDVI) to separate the signal of woody vegetation from that of
57 herbaceous vegetation. Using this method, the study area in south-west Niger shows a decrease in
58 woody cover between 2000 and 2014, while trends are generally increasing in most areas of the
59 Sahel (Brandt et al. 2016b). The general increase in woody cover and its local decrease in western
60 Niger was also confirmed by coarse scale passive microwave observations from 1992 to 2012 (Tian
61 2017; Brandt et al. 2019).

62 In the literature, annual rainfall and its seasonal distribution has been identified as the main
63 driver of vegetation changes in the Sahel (Gianini et al. 2008; Boulain et al. 2009; Gonzalez et
64 al.2012). When the effect of annual rainfall variations on herbaceous vegetation growth is assessed
65 by calculating the rain use efficiency (RUE), the trend of RUE residuals over the years has remained
66 generally positive in the Sahel since the 1980s (Prince et al. 1998; Fensholt and Rasmussen, 2011).
67 However, western Niger stands out, with insignificant or negative trends of the RUE residual over
68 time (Leroux et al. 2017; Anchang et al. 2019). Field validation of these remotely-sensed trends
69 remains a challenge because of the scarcity of long-term field observations at relevant spatial scales
70 (Dardel et al. 2014).

71 In African savannas, the maximum woody plant crown cover is also controlled by mean
72 annual rainfall at least between 100 and 600 mm y⁻¹ (Sankaran et al 2005). Yet, woody crown cover
73 is far below its maximum in the vast majority of areas. Deforestation and the loss of woody
74 vegetation has always been attributed a leading role in the desertification processes affecting the
75 Sahel (Benjaminsen and Hiernaux, 2019). Moreover, the reduction in woody plant density or crown
76 cover is therefore often the main criteria used to assess ecosystem degradation. Hence, planting trees
77 is considered the best solution to combat desertification, as for the iconic case of the Great Green
78 Wall project (Bellefontaine et al. 2011). Massive wood clearing has long been taking place since the
79 early colonial era, but it only started to become a major concern in the 1970s, when population
80 growth and rapid urbanization increased the demand for domestic fuel (Montagne and Housseini,
81 2000). The clearing of forests and savannas to crop new land and exploit wood as construction
82 material or fuel, has been consistently blamed for ecosystem degradation (Rochette, 1986). In
83 addition, tree pruning for fodder and the direct browsing of saplings, bushes and shrubs by livestock
84 are thought to impede the regeneration of woody plants (Gijbers et al. 1994). These assumptions
85 have recently been challenged by remote sensing-based studies showing a relatively high tree density
86 in managed areas (Brandt et al., 2020), and overall positive trends in tree cover (Brandt et al.2016b).
87 However, while satellite time series show woody plant patterns and vegetation trends that can be
88 interpreted as woody cover changes, they do not document the other attributes of woody plant
89 vegetation needed to understand the woody population dynamics: woody plant density, tree height,
90 crown area, basal area, and species composition can only be documented by field surveys and
91 monitoring.

92 The long-term field monitoring of woody vegetation in the Sahel has been limited to
93 conservation areas or rangelands under light grazing intensity (Hiernaux et al.2009b; Diouf et al.

94 2015). Otherwise, monitoring is typically carried out on a localized case-study basis (Miehe et al.
95 2010) and over timescales that are not long enough to assess any meaningful trends (Gijsbers et al.
96 1994). This study presents a dataset of long-term field observations of woody vegetation in the
97 agropastoral managed Sahel. It includes 29 field sites monitored from 1996 to 2017, with each site
98 selected to be representative of the main types of land use within each topographic and soil setting in
99 the district of Dantiandou in Western Niger (Hiernaux et al. 2009a). This dataset of field
100 measurements gives a unique opportunity to assess the direction and magnitude of woody population
101 changes in density, crown cover, basal area, foliage mass and wood mass, as well as woody plant-
102 form and species composition. Moreover, these assessments should contribute to better understand
103 the drivers and processes of the dynamics of woody population in an agropastoral context. The
104 objectives of this study are to:

- 105 (1) characterize the woody vegetation of each land use type.
- 106 (2) establish woody vegetation trends over the 1996-2017 period from field observations and
107 analyse the relative contribution of trees and shrubs and their species to these trends for each
108 land use type.
- 109 (3) check if the trend over time of the aggregated crown cover measured in the field is
110 consistent with trends observed by satellites.
- 111 (4) upscale the site observations to the study site using land use maps in order to compare
112 trends with regional variables such as climate variables.
- 113 (5) analyse the drivers of the trends observed in woody vegetation:
 - 114 • Are the trends in woody plant population attributes driven by trends in annual rainfall
115 or rainfall distribution variables?
 - 116 • Are they driven instead by the trends of evapotranspiration, soil moisture in topsoil
117 and in the root zone, considering the overall increase in atmosphere temperature?
 - 118 • Are they influenced locally by changes in runoff/run-on water balances?
 - 119 • Are they driven by the trend in land use particularly by the increase of the area
120 cropped following human demography?
 - 121 • Are they driven instead by the increased pressure on woody plant resources due to
122 increases in local population density, economy and the relative proximity of the town
123 of Niamey?

124 **Material and methods**

125 *The study site*

126 The study area extends over 499 km² in the district of Dantiandou, in south-west Niger,
127 located 80 km east of the capital town Niamey (**Fig. 1**), and includes three agropastoral territories
128 and twenty villages including Banizoumbou (Hiernaux and Turner, 2002). According to the last
129 national population survey in 2008 (INS-Niger 2015), the study area had 19,200 inhabitants
130 (38.5/km²). A demographic study of a subsample of 400 families between 2008 and 2013 calculated
131 a net annual growth rate of 2.6% (Hiernaux et al. 2016). Assuming this rate, the population would
132 have reached 24,000 inhabitants (48.5/km²) in 2017.

133 The climate is typical of the semi-arid monsoonal tropics with an average annual rainfall (\pm
134 standard deviation) of 486 \pm 101 mm at Banizoumbou (1990-2019), distributed from June to October
135 in 35 \pm 8 rainy days, among which 12 \pm 2.5 are above 15 mm provided by convective storms (Lebel
136 and Ali, 2009). Topography, soils and land-use history shape the landscape with a large difference
137 between rangelands and agricultural lands. Currently, rangelands are restricted to shallow soils on
138 plateaus and on small mid-slope hardpans, which together extend over 14% of the landscape (**Fig. 1;**
139 **SI PH 1-2**). They are also located in narrow low-lying areas under flood risk (1%). Rangeland
140 vegetation is patchy due to uneven rainwater redistribution caused by runoff/run-on over shallow soil
141 and depressions. It includes the iconic “tiger bush” (**SI PH 2**), in which bare impluvia alternate with
142 dense linear thickets set perpendicular to the very gentle slope of the plateau (d’Herbès et al. 2001).
143 The species composition of these thickets is very poor compared to other Sahelian “tiger bushes”
144 (Hiernaux and Gérard 1999), dominated by *Combretum micranthum*¹, *C. nigricans* and *Guiera*
145 *senegalensis*. Rangelands are grazed year-round under communal access but grazing also extends to
146 fallows, year-round or only in the dry season depending on accessibility, and to cropped fields after
147 the crop harvest (Turner et al. 2005). Agricultural lands extend to the deep, but infertile sandy soils
148 along the slopes and at the bottom of the valleys (Turner and Hiernaux 2015), they are composed of
149 crop fields and fallow fields. A small fraction of the crop fields (less than 10% of agricultural lands)
150 is cropped every year (**SI PH 3**), though permanent cropping is only feasible when manure is applied
151 to the soil, largely through corralling livestock on the fields during the dry season. Shifting crops
152 extend over 90% of the cropped lands (**SI PH 4-5**), characterized by the alternation of cropping
153 periods, typically lasting 5 years, and fallow periods, typically lasting 3 years (Hiernaux and Turner,
154 2002). Woody vegetation in agricultural lands is an open agrarian parkland (Boffa 1999) resulting
155 from the long history of selective clearing with two woody plant strata: scattered large trees of
156 selected species (*Faidherbia albida*, *Detarium microcarpum*, *C. glutinosum*, *Prosopis africana*,

¹ Plant species are named after the Flora of West Tropical Africa (Hutchinson and Dalziel 1954-1972)

157 *Piliostigma reticulatum*, *Neocarya macrophylla* and *Sclerocarya birrea*), and denser bushes annually
158 cut down in crop fields and left growing in fallows, mostly *G. senegalensis*, *C. glutinosum* and
159 *Annona senegalensis*. In addition, a web of woody hedges delimits the fields and tracks that radiate
160 from each village. The shrubs and the few trees in these hedges are not planted, but rather left after
161 clearing, and are dominated by *C. glutinosum*, *G. senegalensis*, and *P. reticulatum* (Hiernaux et al.
162 2019).

163

164 ***Rainfall, evapotranspiration, soil moisture and land use trends over the study period***

165 Trends in annual rainfall, as well as in seasonal distribution variables (number of rainy days
166 per category of daily rainfall amounts, date of first and last significant rain, and date of first and last
167 useful and unlimited soil moisture) were investigated using the Banizoumbou rain gauge (13.55°N;
168 2.66°E) data (AMMA-CATCH, African Monsoon Multidisciplinary Analysis-Couplage de
169 l'Atmosphère Tropicale et du Cycle éco-Hydrologique, database: <http://www.amma-catch.org>).
170 Trends in annual rainfall were also established for the region (13°-14°N; 20-3°E) from the AMMA-
171 CATCH data base (Kriged maps at 0.25° resolution aggregated by year) and from satellite
172 observations (CHIRPS, Climate Hazards group InfraRed Precipitation with Satellite data, annual
173 product at 0.25° resolution, <https://data.chc.ucsb.edu/products/CHIRPS-2.0/>). In addition, the daily
174 actual and potential evapotranspiration accumulated annually and the annual mean soil moisture in
175 the top 10 cm and of the root zone were extracted from the GLEAM, Global Land-surface
176 Evaporation: the Amsterdam Methodology, v3 data base in a window of 1°x1° so 16 pixels of a
177 quarter of degree square (Martens et al. 2017; Miralles et al. 2011). The Thornthwaite Moisture
178 Index (TMI) was calculated in two different ways:

$$179 \quad \text{TMI1} = 100 (P - E_p) / E_p \quad (1)$$

180 with P (mm) being the mean annual rainfall and E_p (mm) the mean annual potential
181 evapotranspiration from the 16 GLEAM pixels centered on the study site (Mather 1974),

$$182 \quad \text{TMI4} = 100 ((P - (E_r + E_w)) / E_p - 0.6 * 100 (E_p - E_r) / E_p) \quad (2)$$

183 with E_r (mm) being the annual actual evapotranspiration from vegetated and bare soils and E_w (mm)
184 the evaporation from open water in the pixels (Karunarathne et al. 2016). Trends of actual and
185 potential evapotranspiration, mean soil moisture in topsoil and in the root zone, TMI1 and TMI4
186 were assessed over the study period by linear regressions.

187

188 ***Land use trends in the study area***

189 Trends in land use were established by mapping the main land use categories over the study
190 area either by the interpretation of aerial photos (1996), or by supervised classification of

191 multispectral high resolution SPOT, Satellite Pour l'Observation de la Terre, (2004, 2012) or
192 Sentinel-2 images (2017). Trends were established by plotting the area extent of each land use type
193 over time: rangeland, young and old fallow, shifting crop and manured crop field, villages and
194 camps.

195 In addition, the duration of the crop and fallow cycles have been assessed in 1996, 2004,
196 2012 and 2017 for 59 shifting crop sites monitored in Dantiandou since 1994 (Hiernaux et al. 2009a).
197 At the onset of the monitoring, in 1994, the recent land use history of these sites was documented by
198 interviewing farmers. Then, the changes in land use were recorded annually to actualize the duration
199 of fallow and crop periods. The duration of the completed and uncompleted periods were averaged
200 every year.

201

202 ***Woody plant site sampling***

203 The woody population of a set of 29 2-hectare sites sampled in the district of Dantiandou
204 (Niger) between 13° 20' - 13° 35' latitude North and 2° 35' -2° 52' longitude East has been described
205 and monitored since 1996. The 29 sites represent a range of topographic and soil types within
206 rangelands, fallows, and crop fields (**Fig. 1**). In addition, 12 samples of field hedges were selected in
207 proximity to these sites to assess and monitor their woody plants, as their linear pattern requires
208 specific survey methods (Hiernaux et al. 2019a). To avoid double counting, any trees and shrubs
209 growing in field hedges were not included in the 29 site surveys.

210 Two sampling methods were used to record quantitative data for woody plant populations at
211 the 29 sites. In 1996, 2004, and 2012, the woody vegetation at each study site was described within
212 four replicate circular plots placed systematically along a 200 m central axis (Hiernaux et al. 2009b).
213 The diameter of these plots was set in 1996 to ensure a minimum of ten individuals within each plot
214 (**Fig. SI 1a**). The plot size was kept unchanged in 2004 and 2012. Since the density of trees is much
215 lower than that of shrubs, plot areas used for trees were larger (most often 3,927 m²) than plot areas
216 used for shrubs (1,277 m²). When one or two shrub species largely dominated the population in
217 number, they were recorded separately in smaller plots (314 m²) (plot size details in **Table SI 2**). In
218 2017, woody vegetation was recorded following the Point-Centered Quarter, PCQ, method (Cottam
219 and Curtis 1956). Here, the woody plant density is assessed based on the distance of the closest
220 individual to sampling points set at regular intervals along a 200-m sampling line (every 25 meters
221 for shrubs and every 50 or 100 meters for trees, depending on tree density) within each of four
222 quadrants. Each quadrant is defined by the sampling line and the perpendicular line at the sampling
223 point (**Fig. SI 1b**). The mean density (*md*) and the standard deviation (*sd*) were calculated with the
224 algorithm proposed by Pollard (1971):

225
$$md = 10000 * 4 * (4n - 1) / (\pi \sum_{i=1}^{n,4} dist_{i,k}^2) \quad (1)$$

226
$$sd = \sqrt[2]{(md^2 / (4n - 2))} \quad (2)$$

227 with *dist* (in meters) equal to the distance measured between individuals ($k= 1$ to 4) and sampling
 228 points ($i= 1$ to n), and n equal to the number of sampling points ($n=9$ for shrubs; $n=5$ or 3 for trees);
 229 *md* and *sd* are expressed in number of plants per hectare. The change in survey method was justified
 230 by higher performance and robustness of the PCQ method providing unbiased estimates of woody
 231 plant density (Picard et al. 2005). The output of the two methods applied the same year on a range of
 232 site have been compared, showing no significant difference in population density estimates
 233 (Hiernaux et al., 2009b) authorizing the change in method for the last survey of the monitoring
 234 studied here.

235

236 **Woody plant measurements**

237 Considering the extremely wide range of individual woody plant sizes and population
 238 densities, trees and shrubs were surveyed separately. In African savannas, the conventional height
 239 threshold between trees and shrubs ranges between 3 and 5 meters (Di Gregorio and Jansen 1998). In
 240 this study, individuals with heights greater than or equal to 4 meters were considered as “trees” while
 241 individuals with heights lower than 4 meters were considered as “shrubs” including bushes (height
 242 below 2 meters) but excluding one year old saplings. The species name, the height H (in meters), the
 243 largest crown diameter D (in meters), the crown diameter perpendicular to the largest crown diameter
 244 d (in meters), and the circumference C (in centimeters) of each stem at 30 cm above ground or above
 245 the basal stem swallowing if any, were systematically recorded for all woody plants. The crown area,
 246 Ca (m^2), was estimated by the area of an ellipse defined by the largest crown diameter, D (m), and
 247 the perpendicular diameter, d (m), as:

248
$$Ca = \pi (D * d) / 4 \quad (3)$$

249 The basal area, ba (cm^2), of each stem was calculated from its circumference, C (cm) using the
 250 formula:

251
$$ba = C^2 / (4 \pi) \quad (4)$$

252 The basal area, Ba (cm^2) of each woody plant was calculated by summing the basal area of each
 253 stem, ba (from 1 to n), calculated by the formula:

254
$$Ba = \sum_1^n ba = \sum_1^n (C^2 / (4 \pi)) \quad (5)$$

255 Foliage (Fm) and wood (Wm) dry mass (kg DM) were estimated for all recorded individuals based
 256 on allometric models established for each species by destructive sampling. Individuals were selected
 257 at the peak of foliation over a wide range of sizes and an allometric model was fit between the base

258 circumference of each individual trunk (from 1 to n) and the dry mass of leaves or the wood volume.
259 Wood dry mass was then estimated by multiplying wood volume (cm³) by the specific volume
260 density, dw (g DM/cm³) (Nygard and Elfving 2000; Weber et al. 2017).

$$261 \quad Fm = 10^{-3} \sum_1^n \alpha C^\beta \quad (6)$$

$$262 \quad Wm = 10^{-3} dw \sum_1^n \gamma C^\delta \quad (7)$$

263 The species-specific coefficients α , β , γ and δ and volume densities are provided in **Table SI 1** for C
264 in centimeters, dw in g dry mass per cubic centimeter.

265

266 *Comparing woody populations between land use types.*

267 Annual site means were calculated for woody plant density, aggregated crown areas (further
268 referred to as crown cover), aggregated basal area, foliage mass and wood mass. Variables were
269 recorded separately for trees and shrubs, and then, for all woody plants together. All variable means
270 were also calculated per plant species in order to assess the species contribution to density, cover,
271 basal area, etc. A variance analysis using the General Linear Model (GLM procedure from SAS
272 software version 9.4) approach was conducted to test the significance of differences between land
273 use types. Mean differences between land use types were tested and ranked using the Student-
274 Newman-Keuls test ($p < 0.05$). Another variance analysis using GLM was conducted for the variable
275 means of all recorded trees and shrubs per land use type to assess the contribution of the size of
276 individual trees and shrubs to the differences in woody vegetation between land use types. Finally,
277 the effect of land use on the woody vegetation changes over time was assessed with a GLM variance
278 analysis of the woody plant variable means per land use types and per year. Significant differences
279 between annual means were then tested and ranked using a Student-Newman-Keuls test at $p < 0.05$.

280

281 *Comparing field and remote sensing data for woody plant cover*

282 Woody plant cover was assessed annually using remote sensing from 2000 to 2014 for 29
283 polygons (33 ha on average) delineated around the 29 monitored field sites (**Fig SI 2**). Estimates
284 were extracted from woody cover maps of the whole Sahelian region established in a previous work
285 (Brandt et al. 2016b). These annual woody cover estimates were based on annual mean dry season
286 NDVI calculated using MCD43A4 8-day composites for red and near-infrared bands of MODIS
287 imagery at 500-meter resolution. For details on the methodology, we refer to Brandt et al. (2016a). A
288 regression was performed on mean estimates by land use type over time to assess the trends for the
289 2000-2014 period. Mean woody vegetation cover assessed by satellite and their trends over years are

290 compared with the mean aggregated crown cover measured on the 29 sites and their trends over the
291 study period.

292

293 *Upscaling trends to the landscape scale*

294 The trends observed at the 29 sites were upscaled to the 499 km² area by weighting the means
295 of the woody plant attributes per land use type and per year by the relative area occupied by each
296 land-use type for a given year. In addition, woody plants from field hedges that were previously
297 excluded from the site woody plant inventories were added by multiplying the mean values of the 12
298 field hedge samples by the length of the network of field hedges at a given date (**Table SI 3**). The
299 woody plants of the 12 field hedge samples and the changes in the network of field hedges were
300 assessed in 1996 and again in 2016. The data was analyzed in a separate paper (Hiernaux et al.
301 2019).

302 To assess the contribution to changes of only the change in land-use, the means of woody
303 plant attributes observed in 1996 were weighed by the relative areas of each land use in the study
304 area as they change over the study period in 2004, 2012 and finally in 2017. These results were then
305 compared with the observed changes which include the change in land-use and the change of the
306 woody vegetation attributes within land use type.

307

308 **Relationship between vegetation dynamics and climate and soil moisture trends.**

309 The woody vegetation trends from 1996 to 2017 upscaled to the level of the study region
310 were compared to the rainfall and rainfall distribution trends over the same period. They were also
311 compared to the trends over the same period of the actual and potential evapotranspiration, of the
312 mean soil moisture in topsoil and in the root zone, and of the Thornthwaite Moisture indices (TMI1
313 and TMI4).

314

315 **Results**

316

317 *Trends in rainfall, evapotranspiration and soil moisture*

318 Rainfall data from Banizoumbou, Niamey, and over the study area showed variability
319 between years, with a series of wetter and dryer periods (**Fig. 7; Fig SI 7-9**). However, there is no
320 significant ($p>0.05$) trend in annual rainfall over the study period. None of the variables of the
321 rainfall distribution such as the dates of first and the last rain of the rainy season, the frequency of
322 large rain events (>30 mm) follow significant trends over the study period (**Fig SI 8**).

323 The marginal increases of the potential and actual evapotranspiration accumulated annually
324 over the region are not significant either (**Fig. 7a**) and there is no trend in transpiration. The slight
325 increase over years of the annual means of the moisture in the top (10 cm) of soil and in the root zone
326 are not significant ($p>0.05$), nor is the decrease of both Thornthwaite Moisture Indices (**Fig. 7b**).

327 *Land use change in the study site*

328 From 1996 to 2017, the area covered by cropped fields, C, has increased from 40% to 51.3% over the
329 study site area, and from 47% to 64% of the arable lands in the study site due to the loss fallows. The
330 annual increase rate of the area cropped, x, is calculated as $(1+x)^{21} = C_{2017}/C_{1996} = 51.3/40.0 =$
331 1.0187, so that $x \approx 1.9\%$. Rangelands have also expanded by 1.4% annually as a result of abandoned
332 eroded agricultural lands (**Fig. 2a**). As a result of the expansion of both cropped and rangeland areas,
333 fallow areas decreased by 2.3% annually. Furthermore, the mean duration of the cropped period in
334 shifting cultivation was 4.3 years in 1996. It peaked at 5.7 years in 2004 and decreased at 3.2 years in
335 2017 (**Fig. 2b**). At the same time, the mean duration of the fallowing period in shifting cropland
336 decreased from 4.1 years in 1996 to 2.8 in 2012 but rose again to 3.8 years in 2017.

337

338 *Woody plant populations differ between land use types and topography.*

339 Stem density, crown cover, basal area, foliage and wood mass, all differ significantly
340 ($p<0.001$) between croplands, fallows, and rangelands for shrubs and all woody plants combined,
341 while for trees they do not differ, or differ only marginally ($p<0.05$) (**Table 1**). Trees and shrubs are
342 markedly denser in rangelands (71 and 1,023 ha^{-1}) than in fallows (4 and 213 ha^{-1}) and croplands (5
343 and 290 ha^{-1}). Trees have also larger cover, basal areas, foliage mass and wood mass in rangelands
344 compared to fallows and cropped fields. This is due to higher plant density in rangelands, in spite of
345 the lower mean height, crown area, and basal area of individual trees and shrubs in rangelands (**Fig.**
346 **SI 3**). Density, cover, basal area, foliage mass and wood mass of both trees and shrubs do not differ
347 significantly between cropped and fallowed fields (**Table 1**). However, shrub crown cover and
348 foliage mass are systematically higher in fallowed than in cropped fields (**Table 1**), mostly because
349 of significantly larger values of height, crown area and basal areas (**Fig. SI 3**).

350 The woody vegetation of the rangeland sites located downslope have a higher density, cover,
351 basal area, foliage mass and wood mass compared to rangeland sites located upslope (**Fig. SI 4**).
352 Conversely, the woody vegetation of fallows and cropped fields does not differ between upslope and
353 downslope locations, apart from a higher woody plant density upslope in cropped fields.

354 The woody species composition is similar between cropped fields and fallows (**Fig. 3**), while
355 different in rangelands. This is mostly due to the larger proportion of *Combretum micranthum* and

356 *Combretum nigricans* on rangelands, both more common on finer textured soils, and the absence of
357 *Detarium microcarpum* and *Prosopis africana* (**Fig. SI 5**).

358

359 ***Trends of woody vegetation over two decades (1996-2017)***

360 For all land use types, woody plant density, cover, basal area, foliage mass and wood mass
361 decreased over the 21-year period. This decrease is however only significant ($p < 0.05$) for plant
362 density in rangelands and fallows, for cover, foliage mass and wood mass in rangelands, and for
363 wood mass in croplands (**Fig. 4**). The significant decrease of all shrub-related variables is driving the
364 overall decrease in woody vegetation, while changes in tree-related variables are slight or not
365 significant (**Table 1; Fig. SI 6**).

366 Plant density decreases regardless of land use type or topographic position (**Fig. SI 4a,c**).
367 Basal area also decreases markedly downslope for all land-uses, while upslope it increases slightly
368 from 1996 to 2004, followed by a rapid decrease (**Fig. SI 4b,d**). The decrease is more significant for
369 the denser woody vegetation downslope than upslope.

370 In croplands, *Guiera senegalensis* consistently dominates woody plant density, but its
371 contribution to basal area, crown cover, foliage mass and wood mass slightly decreased over time
372 while the contribution of *Combretum glutinosum*, *Piliostigma reticulatum* and *Faidherbia albida*
373 increased (**Fig. 5**). In rangelands, the decrease of woody vegetation density and crown cover was
374 accompanied by a loss in less common tree species such as *Pterocarpus erinaceus*, and *Lannea*
375 *microcarpa*, and shrub species such as *Boscia angustifolia* and *Grewia bicolor*.

376

377 ***Woody plant cover trends assessed by satellite remote sensing***

378 Annual woody plant cover estimates assessed using satellite image polygon encompassing the
379 field sites show a decrease from 2000 to 2014 for all land use types (**Fig. 6**). The decrease becomes
380 more significant starting in 2003 onwards and is more significant for the rangeland sites, which has a
381 more negative slope of -4% per year, compared to -2.2% for fallows and -2.0% for croplands.

382

383 ***Upscaling woody vegetation trends to the landscape scale***

384 Upscaling the woody plant data of crop and fallow field sites to the study area indicated a
385 decrease in all shrub vegetation parameters over the two decades (**Table SI 6**). This remains true
386 despite the addition of the field hedges (**Table SI 3**), which moderately increased over time as a
387 result of the densification of the hedge network (Hiernaux et al. 2019). Adding the rangeland
388 component exacerbates the decrease for all shrub vegetation parameters (**Table 2**). Trees, however,
389 only decreased in crown cover and basal area, increased very little in density, and increased slightly

390 more in foliage mass and wood mass. Together, trees and shrubs decreased during the two decades of
391 the study period by about 63% in density, 58% in cover, 34% in basal area, 22% in foliage mass, and
392 only by 14% in wood mass.

393 Land use change's contribution to the woody vegetation change assessed by only changing
394 the proportion of cropped versus fallowed fields while the vegetation characteristics per land use
395 type are kept unchanged, only caused a decrease of the crown cover of trees, shrubs and all woody
396 plant combined, while it marginally decreased trees density and basal area (**Table SI 7**).

397 The trend of the species contribution varies depending on the variable considered: the species
398 contribution to plant density changed slightly (**Fig. 5a**) while basal and crown areas of the main
399 shrubs, *Guiera senegalensis* and *Combretum micranthum*, decreased in favor of the dominant trees
400 *Combretum glutinosum*, *Piliostigma reticulatum*, and *Faidherbia albida* (**Fig. 5b**) and these trends
401 are stronger for foliage mass and even more so for wood mass (**Fig. 5c**).

402

403

404 **Discussion**

405

406 ***What are the edaphic determinants of woody vegetation in the study site?***

407 Two woody vegetation ecosystems characterized by plant density, cover, basal area, and to a
408 lesser extent by species composition are found in western Niger: **1**) the highly patterned woody
409 vegetation of rangelands mostly found on the hard pan that tops the sandstone plateau and mid-slope
410 flats, **2**) the scattered two layered vegetation of the agricultural lands found on the deep sandy soils
411 along the slopes and at the bottom of the valleys. Paradoxically, there is a higher plant density, cover,
412 and basal area in rangelands despite shallow soils and active run-off (Galle et al. 1999), compared to
413 the deep sandy soil and high infiltration rates found in agricultural lands (Boulain et al. 2009).

414 However, the higher woody plant density is distributed patchily in “tiger bush”, which are dense
415 thickets alternating with bare soil impluvia (**SI PH 1-2**). The alternating impluvia provide run-off
416 water and nutrients to the thickets (Ludwig and Tongway 1995). Similar patterns and densities have
417 been found on shallow soils with gentle slopes throughout the Sahel (D’Herbès et al. 2001). In
418 comparison to the “tiger bush” in other regions, the species composition of the “tiger bush” found in
419 western Niger is extremely poor, largely dominated by a few *Combretaceae* species. This may be
420 related to the soil acidity and poor organic matter and mineral contents (Hiernaux and Gérard 1999).

421 The few trees and numerous shrubs found in agricultural lands are scattered except for the
422 man-made network of field hedges, where trees and shrubs are not planted but protected from cutting
423 as a marker of land tenure (Hiernaux et al. 2019). The tree density, basal area, cover, foliage mass

424 and wood mass do not differ significantly between cropped and fallowed fields. However, because
425 shrubs in fallows are left to grow during the fallowing period, fallows have significantly higher shrub
426 crown cover and foliage mass than cropped fields where shrubs are cut down annually. The species
427 diversity of the woody vegetation in agricultural lands in the study area is poor, dominated by
428 Combretaceae species, compared to woody populations growing elsewhere in the Sahel on sandy
429 soils with a similar climate. This is most likely due to the very poor soil fertility (Turner and
430 Hiernaux 2015). In the regularly manured crop fields close to villages and camps, the species
431 diversity of scattered trees tends to increase with species such as *Faidherbia albida*, *Detarium*
432 *microcarpum*, *Prosopis africana*, *Ziziphus mauritiana*, *Sclerocarya birrea*, *Hyphaene thebaica* and
433 *Adansonia digitata*.

434

435 ***What are the woody vegetation trends from 1996 to 2017 at the 29 field sites?***

436 Woody vegetation trends differ depending on land use and the considered vegetation attribute
437 (**Fig. 4**). Total woody plant density decreased progressively over the study period (**Fig. 4a**), while
438 basal area, foliage mass and wood mass first slightly increased from 1996 to 2004, and then started to
439 steadily decrease after 2004 (**Fig. 4bde**). On the contrary, crown cover first decreased markedly and
440 then continued to decrease less rapidly (**Fig. 4c**). The divergent trends of crown cover during the first
441 period (1996 to 2004) are explained by the 20% reduction of the mean tree and shrub crown size
442 (**Table SI 4**). This reduction is likely due to a slight difference methodology to measure crown
443 diameters. The method used in 1996, 2012 and 2017 took into account the protruding branches,
444 while the method used in 2004 rounded the crown to an oval shape. The rapid decrease of crown
445 cover between 1996 and 2004 should therefore be disregarded. Despite the exclusion of this time
446 period, crown cover still experiences a decrease over the course of the study period.

447 The overall decrease in woody vegetation is largely driven by a decrease in shrubs (**Table 2**,
448 **Fig. SI 6**). The loss of some rare species remains marginal, therefore showing neither a major loss in
449 species diversity (Gonzalez et al. 2012), nor a shift towards a more drought-adapted species
450 composition as reported from other parts of the Sahel (Hänke et al. 2016).

451

452 ***How do the trends in woody plant cover assessed by remote sensing compare with woody*** 453 ***vegetation trends measured in the 29 field sites?***

454 The woody plant cover assessed by remote sensing is often less than the crown cover
455 measured in the field, especially in rangelands (**Fig. 4c, Fig 6**). Part of the discrepancy comes from
456 the difference in site size, from 2 ha in field observations to 33 ha on average for satellite data (**Fig.**
457 **SI 2**), but the main reason for the difference is that field measured ‘crown cover’ is calculated by

458 summing the crown areas regardless of possible overlapping crowns, while the ‘vegetation cover’
459 assessed from space does not separate overlaps. These overlaps are not frequent in the scattered
460 woody plant pattern that dominates on the sandy soils of agricultural lands, but they are very
461 common in patchy patterns such as in the “tiger bush” thickets. As a result of this difference in
462 methodology, woody plant cover in rangelands is lower than in croplands and fallows when assessed
463 by satellite remote sensing (**Fig. 6**), while the sum of crown areas measured in the field in rangeland
464 sites is higher than in fallow and cropland sites (**Fig. SI 6c**). Nevertheless, woody plant cover
465 decreased progressively according to the satellite images from 2000 to 2014 regardless of land-use
466 type, and more markedly so in rangeland sites, which is in line with field observations. The analysis
467 of woody cover estimates over areas of known land use thus confirms that western Niger remains an
468 exception to the Sahel woody plant “greening” trend (Brandt et al. 2016b; Kaptué et al. 2015, Brandt
469 et al. 2019; Anchang et al. 2019).

470

471 *How the aggregation at landscape scale modulates overall woody vegetation trends?*

472 Weighted by the relative area occupied by croplands and fallows at the start and at the end of
473 the monitoring period, and then completed by the addition of the woody plants in field hedges,
474 woody vegetation in agricultural land shows a prominent decrease in shrub density and all other
475 variables (**Table SI 7**). As shrub density decreases, tree density marginally increases, leading to a
476 slight rise in woody plant foliage mass and wood mass. This slight increase can be explained by the
477 tree growth and the relative increase of *Combretum glutinosum* and *Piliostigma reticulatum* species
478 in fallows and shifting crop fields, and of *Faidherbia albida* in manured fields (**Fig. 5, Fig. SI 5**).
479 However, when the rangeland woody plants are aggregated at the whole landscape scale, total woody
480 plant vegetation density decreased by 63% and crown cover by 58% over the two decades studied,
481 mostly due to shrub loss (**Table 2**). Because trees were less affected, and those trees that survived
482 grew in size, the aggregated rates of decrease for tree basal area, foliage mass and wood mass were
483 limited.

484

485 *Are changes in climate driving the decrease in woody vegetation ?*

486 The overall decrease in woody vegetation seems to have accelerated since 2004, especially
487 for shrubs (**Fig 4, Fig. SI 6**). However, this trend is not consistent with the trend in annual rainfall
488 (**Fig. 7, Fig SI 7, 9**), nor with trends in rainfall distribution (**Fig. SI 8**). After the dry period from
489 1968 to 1997, annual rainfall recovered, although the mean remained below the mean of the wet
490 period from 1950-1967 (Ozer et al. 2017). Woody vegetation, at least in rangeland sites, would be
491 expected to regenerate with the increased rainfall starting in the mid 1990’s (Lebel and Ali 2009), as

492 observed elsewhere in the Sahel (Hiernaux et al. 2009b; Diouf et al. 2015). If a few consecutive
493 dryer years (2004-2005; 2009-2011) in the study area could have slowed down the regeneration
494 between 2004 and 2011, the six successive wetter years from 2012 onwards should have facilitated
495 the recovery. Instead, the loss of woody vegetation accelerated at the 29 monitored sites.

496 In addition to the increased rainfall since 1990, there are more frequent large rain events
497 (Panthou et al. 2014), and woody plants are more likely to benefit from larger rain events than annual
498 herbaceous plants because of their deeper root systems and longer growing season. It could be
499 argued that the increase in air temperature mollifies the increase in rainfall, since the annual potential
500 and actual evapotranspiration slightly increased over the study period (**Fig. 7a**). However, annual
501 means of soil moisture in the top 10 cm and in the root zone is found to increase (**Fig. 7b**). Changes
502 in rainfall, evapotranspiration and soil moisture therefore do not explain the overall decrease in
503 woody vegetation as they are in opposite direction.

504 When the changes in woody cover assessed by remote sensing are compared to changes in
505 rainfall using a rain use efficiency (RUE) approach, the study region showed either insignificant or
506 negative correlations between woody vegetation cover and rainfall (Kaptué et al. 2015, Brandt et al.
507 2019; Anchang et al. 2019). Compared to other areas in the Sahel, woody cover is lower and its
508 response to increased rainfall is weaker, despite equivalent rainfall (Kaptué et al. 2015). Low woody
509 crown cover and a weak response to rainfall in the study area could be related to the poor soil fertility
510 of the dominant sandy soils (Turner and Hiernaux 2015). The minimal species diversity of the woody
511 population (**Fig.SI 5; Table SI 5**) and the dominance of a few evergreen or long cycle deciduous
512 species such as *Guiera senegalensis* and *Combretum glutinosum* (**Fig. 5**) also reflects the poor soil
513 fertility further reduced by the extensive cropping system without the use of fertilizers.

514

515 ***Are changes in runoff/run-on balance affecting the woody plant decrease?***

516 When run-off increases, the woody vegetation located downslope is expected to increase, or
517 at least decrease less than woody vegetation located upslope, as has been observed elsewhere in the
518 Sahel (Couteron 1997; Dendoncker and Vincke 2019). In the study area, runoff had already
519 increased during the dry period of 1968-1989, further increasing with the recovery of rainfall in the
520 1990s (Amogu et al. 2015). More frequent large rain events resulted in more run-on downslope
521 (Leblanc et al. 2008), helping to recharge aquifers (Favreau et al. 2009). In rangelands, the
522 contrasting water balances regimes (Boulain et al. 2009) are most likely the reason for the
523 significantly higher ($p < 0.01$) downslope woody plant density and basal area compared to upslope

524 (Fig. SI 4). This pattern does not apply to cropped fields, where woody plant density is significantly
525 greater in slightly more fertile upslope fields (Fig. SI 4a,c). However, there is no difference in the
526 trends observed over the study period in relation to topographic position; woody plant density and
527 basal area decrease both upslope and downslope regardless of land use type. Rates of decrease are
528 even slightly greater for the denser woody populations downslope. Hydrological changes based on
529 topographic position thus do not explain changes in woody vegetation dynamics.

530

531 *Are changes in land use driving the woody vegetation decrease ?*

532 The cutting of shrubs once or twice a year on cropped fields causes a significant decrease in
533 shrub cover, basal area, foliage mass and wood mass, while shrub density is not affected and remains
534 similar to that of fallowed fields. The expansion of cropped fields from 47% to 64% of the
535 agricultural lands in the study area between 1996 and 2017 (Fig. 2a) is in part responsible for the
536 reduced shrub and tree cover, as well as for the reduced tree density, basal area and foliage mass
537 (Table SI 6). However, the decreasing trend of shrub density, basal area, and crown cover observed
538 over the study period in both cropped and fallowed fields (Fig. SI6) also contributes to the loss.
539 Though there was an increase in hedge shrubs (Table SI 3), mostly due to the creation of new hedges
540 to further partition croplands (Hiernaux et al. 2019), it is not sufficient to balance out the overall
541 decrease. The decreasing trend of shrub density and size in cropped and fallowed fields could in part
542 be a result of the shortened mean fallow periods from a maximum of 4.1 years in 1996 to 3.8 years in
543 2017 (Fig. 2b), and the continued soil degradation by successive cropping without the application of
544 fertilizers or manure. Nevertheless, encouraging the practice of sparing at least one stem when
545 cutting down shrubs during field clearing, known as “Farmer Managed Natural Regeneration”
546 (FMNR), could potentially attenuate losses. If maintained in the long run, it could help to increase
547 tree densities in agricultural lands (Reij et al. 2005). However, FMNR was introduced two decades
548 ago in the study area, and at present it has been adopted only by a minority of the farmers (Haglund
549 et al. 2011).

550

551 *Is the increased pressure on woody resources driving the woody vegetation decrease?*

552 The decrease in woody vegetation could also reflect the increasing pressure on shrub
553 resources that are exploited to provide fuel wood and construction material (house roofs, granaries,
554 fences) for the growing local rural population. Until the 1950s, the study area was sparsely
555 populated, in part because year-round water access was dependent on the digging of deep wells.
556 Though the density of the rural population (48.5 per km²) remains low compared to other regions
557 with similar rainfall patterns in the Sahel, such as the groundnut belt in Senegal (350 per km² in the

558 district of Diourbel). It is possible that the present population density is disproportionate to the poor
559 carrying capacity of the land. The proximity of Niamey (80 km) further contributes to the pressure on
560 resources, especially for firewood and charcoal (Montagne and Housseini, 2000). The rate of
561 decrease of woody vegetation is indeed higher in rangelands (**Fig. 4**), clearly visible in the satellite
562 data time series (**Fig. 6**). This reflects the increasing pressure on wood resources, facilitated by the
563 loose communal rights that govern rangeland forestry resources. In addition, some of the “tiger bush”
564 thickets, as well as the thickets on downslope hard pans and riverine thickets, are recently being
565 cleared for cropping by settlers who do not have easy access rights to farmland (Turner and
566 Moumouni 2018). For example, three of the six rangeland sites monitored were partially cleared,
567 allegedly for cropping (**SI PH1**). It came to light however that the main purpose was for wood
568 collection to be sold as firewood in Niamey. The plots were only cropped one year and with little
569 success, after which irreversible soil erosion started to take place (Trichon et al. 2018). In recent
570 years, tree planting and anti-erosive devices to control runoff from the plateau rangelands have
571 multiplied in Western Niger, serving as high labor-intensive activities funded by United Nation
572 bodies and nongovernmental organizations. The impact of these plantations on the woody population
573 remains minimal so far. In conclusion, land use change in conjunction with increasing pressure on
574 resources due the growing human population are the main drivers of the observed loss in woody
575 vegetation.

576

577 **Conclusion**

578 The analysis of the woody vegetation field surveys repeated four times between 1996 and
579 2017 at 29 sites representative of the western Niger landscape confirms the satellite observed
580 decrease of woody cover, allowing to analyze further the decrease and discuss its drivers. Indeed,
581 field data further reveals a decrease in woody population density, cover, basal area, foliage mass and
582 wood mass. This decrease affects all land use types but is prominent in rangelands. The decline is
583 driven by a decrease in shrub vegetation, while trees are less affected. Because trees are less affected
584 than shrubs, the decrease over two decades is mostly visible through plant density (declining by -
585 63% at the landscape scale) and crown cover (-58%), than basal area (-34%), foliage mass (-22%)
586 and wood mass (-14%). The relative contributions of individual species to plant density does not
587 change significantly over the study period, and species diversity remains low. Changes in rainfall
588 distribution and redistribution by runoff influenced by topography do not explain the decrease in
589 woody vegetation. The main cause of decrease in woody vegetation is the expansion of cropped
590 areas and the shortening of fallow periods (Hiernaux et al. 2019) especially in the context of poor
591 soil fertility and the lack of agriculture intensification, unlike in other Sahelian areas (Mortimore and

592 Turner 2005). In rangelands, the main cause of woody vegetation decrease is the increasing pressure
593 on wood resources to satisfy the demand for fuel and construction wood, not only from the local
594 rural population, but also from the rapidly growing urban population of Niamey only 80 km away.
595 The communal status of rangelands makes it difficult to control wood exploitation. National and
596 local management policies are currently addressing the decrease in woody vegetation and related soil
597 erosion by encouraging more sustainable practices such as tree planting on marginal land or the
598 adoption of FMNR. However, these policies have not yet reached the momentum needed to attenuate
599 the growing exploitation of woody vegetation in western Niger, impeding the occurrence of the
600 climate-driven woody vegetation increase observed elsewhere in the Sahel (Brandt et al. 2017).

601

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611

612 **References**

- 613 Ahlstrom A, Raupach MR, Schurgers G, [Smith B.](#), Arneth A., Jung M., Reichstein M., Canadell J.G.,
614 Friedlingstein P., Jain A.K., Kato E., Poulter B., Sitch S., Stocker B.D., Viovy N., Wang Y.P.,
615 Wiltshire A., Zaehle S., Zeng N., 2015. The dominant role of semi-arid ecosystems in the trend and
616 variability of the land CO₂ sink. *Science*,348: 895-899.
- 617 Amogu O., Esteves M., Vandervaere J.-P., Malam Abdou M., Panthou G., Rajot J.-L., Souley Yéro K.,
618 Boubkraoui S., Lapetite J.-M., Dessay N., Zin I., Bachir A., Bouzou Moussa I., Faran Maïga O., Gautier
619 E., Mamadou I., Descroix L., 2015. Runoff evolution due to land use change in a small Sahelian
620 catchment. *Hydrolog. Sc. J.* 60,1:78-95. DOI: 10.1080/02626667.2014.885654
- 621 Anchang J., Prihodko L., Kaptué A.T., Ross C.W., Ji W., Kumar S.S., Lind B., Sarr M.A., Diouf A.A., Hanan N
622 P., 2019. Trends in woody and herbaceous vegetation in the savannas of west Africa. *Remote Sens.* 11,
623 576. doi: 10.3390/rs11050576
- 624 Andela N., Liu Y.Y., Van Dijk A.I.J., De Jeu R.A.M., McVicar, T.R., 2013. Global changes in dryland
625 vegetation dynamics (1988-2008) assessed by satellite remote sensing: Comparing a new passive
626 microwave vegetation density record with reflective greenness data. *Biogeosc.* 10: 6657-6676.
627 doi:10.5194/bg-10-6657-2013
- 628 Bellefontaine R., Bernoux M., Bonnet B., Cornet A., Cudennec C., D'Aquino P., Droy I., Jauffret S., Leroy M.,
629 Mainguet M., Malagnoux M., Requier-Desjardins M., 2011. Le projet africain de Grande Muraille Verte:
630 quels conseils les scientifiques peuvent-ils apporter ? Une synthèse des résultats publiés. Agropolis
631 Prod., Montpellier, CSFD, dossier d'actualité, 41p.

- 632 Benjaminsen T.A., Hiernaux P., 2019. From desiccation to global climate change: a history of desertification
633 narrative in the West African Sahel, 1900-2018. *Global Envir.* 12: 206-236. Doi:
634 10.3197/ge.2019.120109
- 635 Boffa J.M., 1999. Agroforestry Parkland Systems in Sub-Saharan Africa: FAO Conservation Guide 34, Roma.
- 636 Boulain, N., Cappelaere, B., Séguis, L., Favreau, G., Gignoux, J., 2009. Water balance and vegetation change in
637 the Sahel : A case study at the watershed scale with an eco-hydrological model. *J. of Arid Envir.* 73, 12:
638 1125–1135.
- 639 Brandt M, Hiernaux P., Tagesson T., Verger A., Rasmussen K., Diouf A.A., Mbow C., Mougin E., Fensholt R.,
640 2016a. Woody plant cover estimation in drylands from Earth Observation based seasonal metrics.
641 *Remote Sensing of Envir.* 172: 28-38.
- 642 Brandt M, Hiernaux P., Rasmussen K., Mbow C., Kergoat L., Tagesson T., Ibrahim Y. Z., Wélé A., Tucker J.C.,
643 Fensholt R., 2016b. Assessing woody vegetation trends in Sahelian drylands using MODIS based
644 seasonal metrics. *Remote Sensing of Envir.*, 183: 215-225.
- 645 Brandt M., Hiernaux P., Rasmussen K., Tucker C. J., Wigneron J.-P., Diouf A. A., Herrmann S. M., Zhang W.,
646 Kergoat L., Mbow C., Abel C., Auda Y., Fensholt R., 2019. Changes in rainfall distribution promote
647 woody foliage production in the Sahel. *Com. Biol.* 13, 2, 1. Doi: 10.1038/s42003-019-0383-9
- 648 Brandt M. S., Rasmussen, K., Peñuelas, J., Tian, F., Schurgers, G., Verger, A., Fensholt, R., 2017. Human
649 population growth offsets climate-driven increase in woody vegetation in sub-Saharan Africa. *Nature*
650 *Ecology & Evolution*, 1, [0081]. DOI: 10.1038/s41559-017-0081
- 651 Brandt M., Tucker C.J., Kariryaa A., Rasmussen K., Abel C., Small J., Chave J., Vang Rasmussen L, Hiernaux
652 P., Diouf A.A., Kergoat L., Mertz O., Igel C., Gieseke F., SchöningJ., Li S., Melocik K., Meyer J., Sinno
653 S., Romero E., Glennie E., Montagu A., Dendoncker M., Fensholt R., 2020. An unexpectedly large count
654 of trees in the West African Sahara and Sahel. *Nature*. <https://doi.org/10.1038/s41586-020-2824-5>
- 655 Buitenwerf R., Bond W.J., Stevens N., Trollope W.S.W., 2012. Increased tree densities in South African
656 Savannas: >50 years of data suggests CO₂ as a driver. *Global Change Biol.*, 18: 675–684. doi:
657 10.1111/j.1365-2486.2011.02561.x
- 658 Cottam, G., Curtis, J.T., 1956. The use of distance measures in phytosociological sampling. *Ecology*, 37: 451-
659 460.
- 660 Couteron P., 1997. Contractions du couvert végétal et sécheresse. Exemples au nord-ouest du Burkina-Faso. In
661 d’Herbès, J.M., Ambouta J.M.K., Peltier R (eds): *Fonctionnement et gestion des écosystèmes forestiers*
662 *contractés sahéliens*. John Libbey Eurotext, Paris : 69-79.
- 663 Dardel C., Kergoat L., Mougin E., Hiernaux P., Grippa M., Tucker C. J., 2014. Re-greening Sahel: 30 years of
664 remote sensing data and field observations (Mali, Niger). *Remote Sensing of Envir.* 140, 350–364.
- 665 Dendoncker M., Vincke C., 2019, Low topographic positions enhance woody vegetation stability in the Ferlo
666 (Senegalese Sahel). *J. of Arid Envir.* 175, 104087. doi:10.1016/j.jaridenv.2019.104087
- 667 Di Gregorio A., Jansen L.J.M., 1998. A new concept for land cover classification system. *The Land* 2, 1: 55-65.
- 668 Diouf A.A., Brandt M., Verger A., Jarroudi M.E., Djaby B., Fensholt R., Ndione J.A., Tychon B, 2015. Fodder
669 biomass monitoring in Sahelian rangelands using phenological metrics from FAPAR time series. *Remote*
670 *Sens.* 7: 9122–9148.
- 671 D’Herbès J.M., Valentin C., Tongway D., Leprun J.C., 2001. Banded vegetation patterns and related structures.
672 In Tongway D, Valentin C. and Seghieri J. (eds): *Banded vegetation patterning in arid and semiarid*
673 *environments*. Springer, Ecological studies 149: 1-19.
- 674 Eklundh L., Olsson L., 2003. Vegetation index trends for the African Sahel 1982-1999. *Geophys. Res. Let.* 30:
675 1430–1433.
- 676 Epule, E. T., Peng, C., Lepage, L., & Chen, Z. (2014). The causes, effects, and challenges of Sahelian droughts: a
677 critical review. *Regional envir. change*, 14,1: 145-156.
- 678 Favreau, G., Cappelaere B., Massuel S., Leblanc M., Boucher M., Boulain N., Leduc C., 2009. Land clearing,
679 climate variability, and water resources increase in semiarid southwest Niger: A review. *Water*
680 *Resources Res.*, 45,7. doi:10.1029/2007wr006785.
- 681 Fensholt R., Langanke T., Rasmussen K., Reenberg A., Prince S.D., Tucker C.J., Scholes R.J., Le Q.B., Bondeau
682 A., Eastman R., Epstein H., Gaughan A.E., Hellden U., Mbow C., Olsson L., Paruelo J., Schweitzer C.,
683 Seaquist J., Wessels K., 2012. Greenness in semi-arid areas across the globe 1981-2007 - an Earth
684 Observing Satellite based analysis of trends and drivers. *Remote Sens. Environ.* 121, 144–158.
685 doi:10.1016/j.rse.2012.01.017

686 Fensholt R., Rasmussen K., 2011. Analysis of trends in the Sahelian ‘rain-use efficiency’ using GIMMS NDVI,
687 RFE and GPCP rainfall data. *Remote Sens. Environ.* 115: 438–451.

688 Galle S., Ehrmann M., Peugeot C., 1999. Water balance in a banded vegetation pattern : a case study of tiger
689 bush in Western Niger. In : Valentin C., Poesen J. (eds) *The significance of soil, water and landscape*
690 *processes in banded vegetation patterning. Catena* 37, 1-2: 197-216. ISSN 0341-8162

691 Giannini, A., Biasutti, M., & Verstraete, M. M. (2008). A climate model-based review of drought in the Sahel:
692 desertification, the re-greening and climate change. *Global and planetary Change* 64, 3-4:119-128.

693 Gijssbers, H.J.M., Kessler, J.J., Knevel, M.K., 1994. Dynamics and natural regeneration of woody species in
694 farmed parklands in the Sahel region (Province of Passore, Burkina Faso). *Forest Ecol. and Manag.* 64,
695 1:1-12.

696 Gonzalez P., Tucker C. J., Sy H., 2012. Tree density and species decline in the African Sahel attributable to
697 climate. *Journal of Arid Environments*, 78: 55–64.

698 Haglund E., Ndjeunga J., Snook J., Pasternak D., 2011. Dry land tree management for improved household
699 livelihoods: farmer managed natural regeneration in Niger. *J. of Envir. Manag.* 92, 7: 1696-1705.

700 Hänke H., Börjeson L., Hylander K., Enfors-Kausky E., 2016. Drought tolerant species dominate as rainfall and
701 tree cover returns in the West African Sahel. *Land Use Policy*, 59: 111-120.

702 Hiernaux P., Adamou K., Moumouni O., Turner M.D., Tong X., Savadogo P., Tong X., Mougin E., Malam Issa
703 O., 2019. Expanding networks of field hedges in densely populated landscapes in the Sahel. *For. Ecol.*
704 *Manag.* 440: 178-188. doi: 10.1016/j.foreco.2019.03.016

705 Hiernaux P., Adamou K., Zezza A., Ayantunde A.A., Federighi G., 2016. Milk offtake of cows in
706 smallholder farms of semiarid Sahel: low yields with high value! *Rev. Elev. Med. Vet. Pays*
707 *Trop.* 69, 4: 143-153. doi: 10.19182/remvt.31199

708 Hiernaux P., Ayantunde A., Kalilou A., Mougin E., Gérard B., Baup F., Grippa M., Djaby B., 2009a. Trends in
709 productivity of crops, fallow and rangelands in Southwest Niger: Impact of land-use, management and
710 variable rainfall. *J. of Hydrol.* 375: 65–77.

711 Hiernaux P., Diarra L., Trichon V., Mougin E., Soumaguel N., Baup F., 2009b. Woody plant population
712 dynamics in response to climate changes from 1984 to 2006 in Sahel (Gourma, Mali). *J. of Hydrol.* 375:
713 103–113.

714 Hiernaux P., Gérard B., 1999. The influence of vegetation pattern on the productivity, diversity and stability of
715 vegetation: the case of the ‘brousse tigrée’ in the Sahel. *Acta Oecologica*, 20, 3: 147-158.

716 Hiernaux P., Turner M. D., 2002. The influence of farmer and pastoralist management practices on
717 desertification processes in the Sahel. In Reynolds J.F., Smith, M.S (eds): *Global Desertification. Do*
718 *Humans cause deserts.* Dahlem Univ. Press, Berlin: 135–148.

719 Horion S, Fensholt R, Tagesson T, Ehammer A., 2014. Using earth observation-based dry season NDVI trends
720 for assessment of changes in tree cover in the Sahel. *Intern. J. of Remote Sens.* 35: 2493-2515.

721 Hutchinson, J., Dalziel, J.M., 1954–1972. Flora of West Tropical Africa, second ed. In: Keay, R.W.J., Hepper,
722 F.N. (Eds.), Crown Agents for Overseas Gov. and Admin., London, vol. 1–3, 828, 544, 574 p.

723 INS-Niger, 2015. Recensement général de la population et de l’habitat 2012. Institut National de la Statistique,
724 Niamey, Niger, 54p.

725 Kaptué A.T., Prihodko L., Hanan N.P. , 2015. On regreening and degradation in Sahelian watersheds. *Proc. Nat.*
726 *Acad. Sci.* 112: 12133–12138.

727 Karunarathne, A.M.A.N., Gad, E.F., Disfani, M.M., Sivanerupan, S., Wilson, J.L., 2016. Review of
728 calculation procedures of Thornthwaite Moisture Index and its impact on footing design.
729 *Australian Geomechanics* 51, 1: 85-95.

730 Lebel T., Ali A., 2009. Recent trends in the Central and Western Sahel rainfall regime (1990–2007). *J. of Hydrol.*
731 375, 1-2: 52–64.

732 Leblanc M., Favreau G., Massuel S., Tweed S., Loireau M., Cappelaere B., 2008. Land clearance and
733 hydrological change in the Sahel: SW Niger. *Glob. and Planet. Change* 61, 3–4: 135–150.

734 Leroux L., Bégue A., Lo Seen D., Jolivot A., Kayitakire F., 2017. Driving forces of recent vegetation changes in
735 the Sahel: lessons learned from regional and local level analyses. *Remote Sens. of Envir.*, 191: 38-54.
736 Doi: 10.1016/j.rse.2017.01.014f

737 Ludwig JA, Tongway DJ, 1995. Spatial organisations of landscapes and its function in semi-arid woodlands,
738 Australia. *Landscape Ecology* 10, 51-63.

739 Martens, B., Miralles, D.G., Lievens, H., van der Schalie, R., de Jeu, R.A.M., Fernández-Prieto, D., Beck, H.E.,
740 Dorigo, W.A., Verhoest, N.E.C., 2017. GLEAM v3: satellite-based land evaporation and root-zone soil
741 moisture. *Geosc. Model Develop.* 10: 1903–1925. doi: 10.5194/gmd-10-1903-2017.

742 Mather J.R., 1974. *Climatology: fundamentals and applications*. McGraw-Hills, USA.

743 Miralles, D.G., Holmes, T.R.H., De Jeu, R.A.M., Gash, J.H., Meesters, A.G.C.A., Dolman, A.J., 2011. Global land-
744 surface evaporation estimated from satellite-based observations, *Hydrol. and Earth Syst. Sc.* 15, 453–
745 469. doi: 10.5194/hess-15-453-2011, 2011.

746 Miehe S., Kluge J., von Wehrden, H., Retzer V., 2010. Long-term degradation of Sahelian rangeland detected by
747 27 years of field study in Senegal. *Journal of Applied Ecology* 47:692-700.

748 Montagne P., Housseini M., 2000. Les jachères dans le bassin d’approvisionnement en bois de la ville de
749 Niamey. *Bois et Forêts des Tropiques* 266, 4: 55-59.

750 Mortimore M., Turner B., 2005. Does the Sahelian smallholder’s management of woodland, farm trees,
751 rangeland support the hypothesis of human-induced desertification? *J. of Arid Envir.* 63: 567-595.

752 Nygard R., Elfving B., 2000. Stem basic density and bark proportion in 45 woody species in young savanna
753 coppice forests in Burkina Faso. *Am. For. Sci.* 57: 143-153.

754 Ozer P., Laminou Manzo O., Tidjani A.D., Djaby B., de Longueville F., 2017 Evolution récente des extrêmes
755 pluviométriques au Niger (1950-2014) *Geo-Eco-Trop* 41, 3: 375-384.

756 Panthou G., Vischel T., Lebel T., 2014 : Recent trends in the regime of extreme rainfall in the Central Sahel.
757 *Internat. J. of Climat.* 34: 3998-4006.

758 Picard N., Kouyate A. M., Dessard H., 2005. Tree density estimations using a distance method in Mali Savanna.
759 *Forest Sc.* 51, 1: 7–18.

760 Pollard J. F., 1971. On distance estimators of density in randomly distributed forests. *Biometrics* 27: 991-1009.

761 Poulter B, Frank D, Ciais P *et al.*, 2014. Contribution of semi-arid ecosystems to interannual variability of the
762 global carbon cycle. *Nature*, 509: 600-603.

763 Prince S. D., De Colstoun E. B., Kravitz L. L., 1998. Evidence from rain-use efficiencies does not indicate
764 extensive Sahelian desertification. *Global Change Biology* 4: 359–374.

765 Reij C., Tappan G., Belemvire B., 2005. Changing land management practices and vegetation in the Central
766 Plateau of Burkina Faso (1968–2002). *J. of Arid Envir.* 63, 3: 642–659.

767 Rochette R., 1986. Déforestation et désertification a Sahel. *Aménagement et Nature*, 81 : 3-6.

768 Rockström J., Jansson P.E., Barron J., 1998. Seasonal rainfall partitioning under runoff and runoff conditions on
769 sandy soil in Niger. On-farm measurements and water balance modelling. *J. of Hydrol.* 210, 1-4: 68-92.

770 Sankaran M., N. P. Hanan, R. J. Scholes, J. Ratnam, D. J. Augustine, B. S. Cade, J. Gignoux, S. I. Higgins, X. Le
771 Roux, F. Ludwig, J. Ardo, F. Banyikwa, A. Bronn, G. Bucini, K. K. Caylor, M. B. Coughenour, A.
772 Diouf, W. Ekaya, C. J. Feral, E. C. February, P. G. H. Frost, P. Hiernaux, H. Hrabar, K. L. Metzger, H.
773 H. T. Prins, S. Ringrose, W. Sea, Jörg Tews, J. Worden and N. Zambatis, 2005. Determinants of woody
774 cover in African savannas. *Nature* 438/8: 846-849.

775 Tian F., Brandt M. S., Liu Y. Y., Rasmussen K., Fensholt R., 2017. Mapping gains and losses in woody
776 vegetation across global tropical drylands. *Global Change Biology*, 23,4: 1748-1760.
777 <https://doi.org/10.1111/gcb.13464>

778 Trichon V., Hiernaux P., Walcker R., Mougin E., 2018. The persistent decline of patterned woody vegetation:
779 The tiger bush in the context of the regional Sahel greening trend. *Glob Change Biol.* 00:1–16.
780 doi:10.1111/gcb.14059

781 Tucker C. J., Dregne H. E., Newcomb W. W., 1991. Expansion and Contraction of the Sahara Desert from 1980
782 to 1990. *Science* 253: 299–301.

783 Turner M. D., Hiernaux P., 2015. The effects of management history and landscape position on inter-field
784 variation in soil fertility and millet yields in southwestern Niger. *Agr., Ecos. and Envir.* 211: 73-83.

785 Turner M.D., Hiernaux P., Schlecht E., 2005. The distribution of grazing pressure in relation to vegetation
786 resources in semi-arid West-Africa: the role of herding. *Ecosystems* 8, 6: 668-681.

787 Turner M.D., Moumouni O., 2018. The dividing of fields in Sudano-Sahelian West Africa: the roles of soil
788 fertility variation and legal doctrine. *Land Use Policy* 77: 362-374.

789 Weber J.C., Sotelo Montes C., Abasse T., Sanquetta C.R., Silva D.A., Mayer S., Muñoz G.I.B., Garcia R.A.,
790 2017. Variation in growth, wood density and carbon concentration in five tree and shrub species in
791 Niger. *New Forest*, 17.