



# 1 Impacts of the seasonal distribution of rainfall on vegetation productivity 2 across the Sahel

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7

8 **Abstract** Climate change in drylands has caused alterations in the seasonal distribution of rainfall including increased heavy  
9 rainfall events, longer dry spells, and a shifted timing of the wet season. Yet, the aboveground net primary productivity (ANPP)  
10 in drylands is usually explained by annual rainfall sums, disregarding the influence of the seasonal distribution of rainfall. This  
11 study tests the importance of seasonal rainfall metrics (onset and cessation of the wet season, number of rainy days, rainfall  
12 intensity, number of consecutive dry days and heavy rainfall events) on growing season ANPP. We focus on the Sahel and  
13 north-Sudanian region (100-800 mm year<sup>-1</sup>) and apply daily satellite based rainfall estimates (RFE-2.0) and growing season  
14 integrated NDVI (MODIS) as a proxy for ANPP over the study period 2001-2015. Growing season ANPP in the arid zone  
15 (100-300 mm year<sup>-1</sup>) was found to be rather insensitive to variations in the seasonal rainfall metrics, whereas vegetation in the  
16 semi-arid zone (300-700 mm year<sup>-1</sup>) was significantly impacted by most metrics, especially by the number of rainy days and  
17 timing (start and cessation) of the wet season. We analyzed critical breakpoints for all metrics, showing that growing season  
18 ANPP is particularly negatively impacted after >10 consecutive dry days and that a rainfall intensity of 7 mm day<sup>-1</sup> is detected  
19 for optimum growing season ANPP. We conclude that number of rainy days and the timing of the wet season are seasonal  
20 rainfall metrics being decisive for favorable vegetation growth in semi-arid Sahel which needs to be considered when  
21 modelling primary productivity from rainfall in the dryland's of Sahel and elsewhere.

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23

## 24 **Introduction**

25 Livihoods in most drylands depend heavily on aboveground net primary production (ANPP) in the form of  
26 rain-fed crops and fodder for livestock (Abdi et al., 2014; Leisinger, KM, Schmitt, 1995). Annual ANPP thus plays  
27 a decisive role in the context of livelihood strategies, food security and people's general wellbeing. ANPP in  
28 drylands is primarily controlled by water availability with annual rainfall typically being limited to a short and  
29 erratic wet season which can be highly variable between years. The current study focus on the sub-Saharan Sahel  
30 zone, being one of the largest dryland areas in the world, which has been referred to as the region showing the  
31 largest rainfall anomalies worldwide during the last century (Nicholson, 2000). Throughout the centuries, the  
32 Sahelian population has adapted to this high rainfall variability and thus great inter-annual differences in available  
33 ANPP can be balanced for example by a temporary abandonment of agriculture or seasonal livestock migration  
34 (Romankiewicz et al., 2016). However, 21st century climate change threatens established coping strategies not only  
35 by increasing inter-annual variability of rainfall regimes as a whole (Field, 2012; Kharin et al., 2007), but also by  
36 an increasingly unpredictable seasonality and an altered number of heavy rainfall and drought events (Fischer et  
37 al., 2013; Smith, 2011; Taylor et al., 2017). Improved knowledge on the vegetation response to the seasonal  
38 variability of rainfall is thus crucial to better interpret the consequences of climate predictions of an altered global  
39 hydrological cycle and to implement appropriate adaptation measures to climate change and food security in arid  
40 and semi-arid lands like the Sahel.

41 While it is well known that the productivity of dryland vegetation is highly prone to variations in the  
42 availability of water resources at the annual scale (Fensholt et al., 2013; Fensholt and Rasmussen, 2011; Herrmann  
43 et al., 2005; Huber et al., 2011), there is a current lack of understanding how the seasonal distribution of rainfall  
44 impacts on growing season ANPP (Rishmawi et al., 2016). Several studies have demonstrated the vegetation



45 sensitivity to the timing and magnitude of rainfall events based on individual plot data and model estimates (Bates  
46 et al., 2006; Fay et al., 2000; Guan et al., 2014; Thomey et al., 2011), but the impact of specific rainfall metrics  
47 (such as wet season length/timing, number of rainy days, rainfall intensity, number of consecutive dry days and  
48 extreme events) on dryland vegetation productivity has rarely been studied at the regional scale potentially  
49 including different biotic and abiotic controls. A few studies show that there is a strong dependency of Sahelian  
50 vegetation growth on the timing of the start of the wet season (Diouf et al., 2016) and the frequency and distribution  
51 of dry spells (Proud and Rasmussen, 2011), but currently no regional scale study assessing a variety of rainfall  
52 metrics exists systematically analyzing the importance of rainfall metrics on vegetation growth as a function of  
53 mean annual rainfall. Recent studies suggest that not only a shift in the timing of the wet season but also increasing  
54 extreme events occur in Sahel (Panthou et al., 2014; Sanogo et al., 2015; Taylor et al., 2017; Zhang et al., 2017),  
55 showing the need for a comprehensive understanding on how rainfall seasonality impacts on vegetation production.

56 The assessment of rainfall metrics capturing the seasonal variability and the associated impact on growing  
57 season ANPP requires daily rainfall records and a robust methodology being able to extract the timing (start and  
58 end) and duration of the wet season (Dunning et al., 2016; Liebmann et al., 2012). The availability and quality of  
59 such data, and uncertainties in methods to extract the rainfall seasonality (Fitzpatrick et al., 2015) have complicated  
60 regionally scaled studies on this topic. However, a new generation of high spatial resolution satellite based daily  
61 rainfall estimates blended with station data has recently opened up the possibility to fill the gap between plot and  
62 model based studies. Here our study aims at applying daily rainfall estimates to analyze and understand the impact  
63 of seasonal rainfall metrics on vegetation productivity for the entire Sahel.

64

## 65 **Materials and methods**

66 An empirical analysis is conducted based on gridded information of rainfall metrics based on daily satellite  
67 estimates and seasonally integrated NDVI (hereafter NDVI SIN) as a proxy for the growing season ANPP. The



68 period of analysis covers 2001-2015 which allows for a per-pixel analysis including state of the art Earth  
69 observation datasets of both African Rainfall Estimation (RFE-2.0) and Moderate Resolution Imaging  
70 Spectroradiometer (MODIS) vegetation. The rainfall metrics include: number of rainy days, daily intensity, heavy  
71 rainfall events, number of consecutive dry days and seasonal rainfall amount which were analyzed as explanatory  
72 variables for the observed spatial variability in seasonal vegetation productivity along the gradient of mean seasonal  
73 rainfall.

74

### 75 ***Study area***

76 The Sahelian zone covers arid and semi-arid biomes and is one of the world's largest dryland areas bordering  
77 the Sahara Desert to the north (Fig. 1). The delineation of the Sahel is often done by using average annual rainfall  
78 isohyets, with the northern boundary at 100 mm year<sup>-1</sup> and the southern boundary defined by 700 mm year<sup>-1</sup> (Lebel  
79 and Ali, 2009). For this study we expanded the southern limit towards the Sudanian zone until 800 mm annual  
80 rainfall to include also the zone where rainfall as the primary climatic forcing variable on vegetation productivity  
81 is expected to level off (Fensholt et al., 2013; Huber et al., 2011; Kaspersen et al., 2011). The Sahel is characterized  
82 by a unimodal rainfall regime and the landscape is generally flat and consists of large plains interspersed with sand  
83 dunes and rocky formations. The large stretches of plains are mainly used for grazing and subsistence cultivation.  
84 The northern parts of the Sahel are dominated by open and sparse grass- and shrublands, while cropland, open  
85 woody vegetation and deciduous shrublands characterize the southern parts (Breman and Kessler, 1995).

86

### 87 ***RFE rainfall data***

88 RFE-2.0 is a gauge-satellite blended rainfall product developed by the NOAA Climate Prediction Center (CPC)  
89 (Herman et al., 1997) gridded at 11 × 11 km spatial resolution and widely used to explain changes in vegetation  
90 productivity (Fensholt and Rasmussen, 2011). RFE-2.0 uses additional techniques to better estimate precipitation



91 while continuing the use of cloud top temperature and station rainfall data, in all four input data sources are included:  
92 (1) daily Global Telecommunications System (GTS) rain-gauge data, (2) Advanced Microwave Sounding Unit  
93 (AMSU)-based rainfall estimates, (3) Special Sensor Microwave Imager (SSM/I)-based estimates, (4) the  
94 Geostationary Operational Environmental Satellite (GOES) precipitation index (GPI) calculated from cloud-top  
95 infrared (IR) temperatures on a half-hourly basis.

96

### 97 *Deriving rainfall seasonality metrics*

98 The method used to identify the onset and cessation of the wet season is referred to Liebmann et al. (2012)  
99 and applicable to multiple datasets for precipitation seasonality analysis across the African continent (Dunning et  
100 al., 2016). As is described in Liebmann et al. (2012), the climatology wet season is initially determined by the  
101 climatological cumulative daily rainfall anomaly,  $A(d)$ , calculated from the long-term (2001-2015) average  
102 rainfall ( $R_i$ ) for each day of the calendar year minus the long-term annual-mean daily average ( $\bar{R}$ ). The day with  
103 minimum value ( $d_s$ ) is defined as the start of the wet season and the maximum point ( $d_c$ ) marks the end of the wet  
104 season.

105 (1)

$$106 \quad A(d) = \sum_{i=1}^d R_i - \bar{R}$$

107 Subsequently, the onset and cessation were calculated individually for each year and each grid point. For each  
108 year the extraction of the seasonality of the wet season was based on equation (2). The daily cumulative rainfall  
109 anomaly  $A(D)$  on day ( $P_i$ ) was computed for each day in the range  $d_s - 50$  to  $d_c + 50$  for each year and the day with  
110 minimum value is considered as the onset of the wet season.

111 (2)



112

$$A(D) = \sum_{j=d_s-50}^D P_i - \bar{R}$$

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### ***Estimation of growing season ANPP***

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We used the NDVI SIN derived from the MODIS/Terra surface reflectance product (MOD09Q1 collection 6) as a proxy for the growing season ANPP. NDVI was calculated from the MODIS red and near-infra red bands (8 day composites) for the period 2001-2015. The NDVI SIN was derived using TIMESAT (Jönsson and Eklundh, 2004), a widely used tool to extract vegetation seasonal metrics. For this study, we applied the Savitzky-Golay filter and determined the start and end of season at 20% and 50% of the amplitude respectively. The method is well established and proven to be a reliable proxy for the growing season ANPP in Sahel (Fensholt et al., 2013; Olsson et al., 2005). NDVI data was aggregated to the resolution of RFE-2.0 (11×11 km) using a bilinear resampling method. Both Globeland30 and ESA CCI (2010) land cover maps were used to mask water bodies, irrigated and flooded areas.



## 132 *Statistical analyses*

133 The Pearson's correlation coefficient was used to measure the relationship between growing season ANPP  
134 and rainfall metrics. Additionally, Generalized Additive Models (GAMs) (Wood, 2017) implemented in the R  
135 computing environment (Team, 2014) were applied to derive smooth response curves with seasonal rainfall amount  
136 as the explanatory variable and the linear coefficients (averaged over 10 mm rainfall steps) as the response variable.  
137 The models were parameterized assuming normal error distributions. Furthermore, a random forest ensemble  
138 learning method (Breiman, 2001) was used to analyze the relative importance of individual rainfall variables on  
139 growing season ANPP as a function of the seasonal rainfall amount. This algorithm produces multiple decision  
140 trees based on bootstrapped samples and the nodes of each tree are built up by an iterative process of choosing and  
141 splitting nodes to achieve maximum variance reduction. Thus the variables with highest difference are considered  
142 as most important factors. All pixels based on 15-year averages of seasonal rainfall metrics and ANPP were used  
143 for this analysis. Additionally, a multiple regression analysis was applied to identify and map the spatial distribution  
144 of the relative importance of the three most important seasonal rainfall metrics (onset and end of the wet season  
145 and rainy days) explaining the growing season ANPP at the per-pixel level (based on a 15-year time series).

146 A piecewise regression was used to identify breakpoints (Muggeo, 2003), i.e. critical thresholds in the  
147 relationship between rainfall metrics and vegetation growth. A breakpoint is an indication that the vegetation  
148 response to changes in a given rainfall metric surpasses a threshold beyond which vegetation functioning is  
149 significantly altered. Such a threshold, at the level of individual rainfall seasonality metric, provides an indication  
150 of rainfall conditions beyond which vegetation does not tolerate further stress without a marked impact on the  
151 growing season ANPP. The 95th percentile of NDVI SIN was selected to represent the potential vegetation  
152 productivity attainable for a given rainfall amount (Donohue et al., 2013) and the breakpoint regression was applied  
153 to the potential vegetation productivity and corresponding rainfall seasonal metrics.

154



## 155 **Results**

### 156 *Spatial pattern of rainfall metrics*

157 A clear north-south gradient was observed for the onset, rainy days (RD), heavy rainfall events (R95p) and  
158 consecutive dry days (CDD) based on a 15-year (2001-2015) average value, with a later onset, more rainy days  
159 and less heavy rainfall events towards the south (Fig.3a,c,e). The cessation of the wet season (Fig.3b) shows some  
160 longitudinal differences with the latest dates found in the eastern Sahel, followed by the western Sahel and the  
161 central Sahel showing the earliest cessation dates. A considerable difference between southeastern and  
162 southwestern Sahel (Fig. 3d) was observed in the rainfall intensity (SDII). The relatively low rainfall intensity in  
163 the southeastern Sahel is mirrored by considerably higher numbers of rainy days.

164

### 165 *General response of growing season ANPP to rainfall metrics*

166 The median growing season ANPP clearly follows the mean seasonal rainfall gradient (Fig.4) with a near  
167 linear relationship with other biotic and abiotic factors (e.g. soil texture, nutrients, species composition, fire regime  
168 and seasonal rainfall distribution) causing a wide range of values as indicated by the different quantile values.

169

170 The relationships between all the rainfall metrics and growing season ANPP were found to be significant  
171 ( $p < 0.001$ ) and the correlation coefficient ( $r$ ) varied between  $-0.78$  and  $0.82$  (Fig.5). For the region as a whole, the  
172 number of rainy days was identified as the most important metric impacting on the growing season ANPP ( $r = 0.82$ )  
173 (Fig.5c), closely followed by heavy rainfall events (R95p) ( $r = -0.78$ ) (Fig.5e), cessation ( $r = 0.69$ ) (Fig.5b) and onset  
174 ( $r = 0.61$ ) (Fig.5a) of the wet season. The impact of consecutive dry days (CDD) on growing season ANPP was also  
175 relatively strong ( $r = -0.60$ ) (Fig.5f), whereas a rather weak correlation was observed between growing season ANPP  
176 and rainfall intensity (SDII) ( $r = 0.28$ ) (Fig.5d). For all rainfall metrics except R95p and CCD, the plots show a



177 bimodal distribution of the points, which is caused by the differences in the east-west patterns of the spatial  
178 distribution of rainfall metrics (onset, cessation, RD and SDII) in Sahel as reported in Fig.3.

179

### 180 ***Response of growing season ANPP to rainfall metrics along the rainfall gradient***

181 Although the relationship between growing season ANPP and seasonal rainfall amount (Pt) obviously changes  
182 along the rainfall gradient (Fig. 4), variations in seasonal rainfall distribution can cause considerable changes in  
183 growing season ANPP under the same rainfall gradient (Fig. 5). The influence of seasonal rainfall distribution on  
184 growing season ANPP was thus analyzed under different mean annual rainfall values along the north (low rainfall)  
185 to south (high rainfall) gradient (Fig. 6). The dependency of growing season ANPP on rainfall metrics is clearly  
186 seen to be a function of the seasonal rainfall amount. Below  $\sim 300$  mm year<sup>-1</sup>, the vegetation seems to be stable and  
187 rather insensitive to variations of the rainfall metrics, however, above 300 mm year<sup>-1</sup>, the impacts can be clearly  
188 seen by a larger spread in growing season ANPP values for a given amount of seasonal rainfall (Fig. 6). For example,  
189 the growing season ANPP decreases strongly with a later onset, an earlier cessation of the wet season, a smaller  
190 number of rainy days, a higher rainfall intensity, more heavy rainfall events and longer dry spells. Above  $\sim 700$  mm  
191 year<sup>-1</sup>, the vegetation shows again a reduced sensitivity to variations of the wet season by a convergence of growing  
192 season ANPP values irrespective of the seasonal rainfall metric value.

193

194 The Pearson's correlation coefficient was used to quantify the strength of the impact of individual seasonal  
195 rainfall metrics on growing season ANPP as a function of seasonal rainfall (Fig. 7). In general, the impacts of  
196 rainfall metrics on vegetation are distinctive along the 100-800 mm year<sup>-1</sup> gradient with a peak in  $r$  values  
197 (respectively positive or negative dependent on the rainfall metric) for most metrics around 700 mm year<sup>-1</sup> followed  
198 by a sharp drop-off (Fig. 7b, c, d, e) (cessation of wet season, RD, SDII and R95p). It should be noted that modelling  
199 uncertainties increase for all rainfall metrics due to fewer observations in the lowermost seasonal rainfall total bins.



200 For the wet season the pattern of onset is reversed with a sharp increase in  $r$  values from 700-800 mm year<sup>-1</sup>. The  
201 number of consecutive dry days (CDD) shows moderate  $r$  values balancing around zero generally indicating less  
202 importance of the CDD variable on growing season ANPP along the rainfall gradient analyzed.

203

204

205 The relative importance of the individual rainfall metrics on growing season ANPP was assessed based on a  
206 random forest model (Fig. 8a). The explained variance of growing season ANPP explained by rainfall metrics (blue  
207 line in Fig. 8a) is increasing with mean annual rainfall up to 600-700 mm year<sup>-1</sup> from where the degree of explained  
208 variance decreases, which corresponds with the results presented in Fig. 4 (the widest belt of the quantile values is  
209 observed for rainfall of 600-700 mm year<sup>-1</sup>, suggesting that the seasonal rainfall metrics additional to the seasonal  
210 rainfall amount is increasingly important in this rainfall zone) and in Fig. 7. The cessation of the wet season was  
211 identified as the most important factor controlling growing season ANPP in semi-arid areas of Sahel (300-700 mm  
212 year<sup>-1</sup>), followed by the onset and number of rainy days. As measured by the relative importance, these three rainfall  
213 metrics together accounted for 60-70% of the variance explained by all rainfall metrics for all seasonal rainfall  
214 amounts. In arid areas (100-300 mm year<sup>-1</sup>) the number of rainy days was found to be the most important variable.

215

216 The spatial distribution of the relative importance of the onset and cessation of the wet season and number of  
217 rainy days on growing season ANPP was identified at the pixel-level for 2001 to 2015 (Fig. 8b). At Sahel scale,  
218 the number of rainy days (bluish colors) is observed to be the dominating factor, followed by the onset of the wet  
219 season (reddish colors) and cessation (greenish colors). There are no clear signs of a latitudinal or longitudinal  
220 dependency on which rainfall metric is dominating, but some clustering is evident with a predominance of rainy  
221 days influence in the Western Sahel with limited influence by the cessation date on the growing season ANPP.

222



### 223 ***Critical points for growing season ANPP***

224 A piecewise regression between growing season ANPP and seasonal rainfall metrics was applied to identify  
225 if critical breakpoints in the relationship between growing season ANPP and rainfall metrics exist (Fig. 9). We  
226 found that the most evident thresholds (average values for the Sahel zone) in relation to seasonal rainfall metrics  
227 influence on growing season ANPP relate to the onset of the wet season (Fig. 9a), the rainfall intensity (SDII) (Fig.  
228 9d) and consecutive dry days (CDD) (Fig. 9f). If the onset of the wet season is later than day of year 134 this will  
229 have an increasingly negative effect on growing season ANPP as a function of the onset delay and contrastingly if  
230 the onset starts earlier than day of year 134 this will also have an increasingly adverse effect on growing season  
231 ANPP. Also, an optimum of rainfall intensity of  $7 \text{ mm day}^{-1}$  was detected; if rainfall intensity exceeds  $7 \text{ mm day}^{-1}$ ,  
232 vegetation productivity starts to be negatively affected, whereas a lower intensity will also negatively impact on  
233 growing season ANPP. There was a pronounced decline in growing season ANPP as a function of number of  
234 consecutive dry days. However, when CDD exceeds 10 days a breakpoint in the curve is detected, as dry spells of  
235 this magnitude leads to a strong reduction in vegetation growth. The number of rainy days (Fig. 9c) was linearly  
236 related to growing season ANPP until 75 days, beyond which RD becomes less decisive for the amount of growing  
237 season ANPP. Similarly, heavy rainfall events (fraction of annual rainfall events exceeding the 95th percentile)  
238 (Fig. 9e) were negatively related to growing season ANPP, until a certain threshold (larger than 0.83), from where  
239 the rather low amount of vegetation loses sensitivity to even more extreme seasonal distributions. Finally, the  
240 cessation date of the wet season (Fig. 9b) was shown to be nearly linearly related to growing season ANPP. A  
241 breakpoint is detected by the piecewise regression algorithm around day 257, beyond which the delay in cessation  
242 date was slightly more favorable for higher growing season ANPP yields as compared to a cessation date before  
243 day 257.

244



## 245 Discussion

246 This study presents first empirical evidence on the impact of rainfall seasonality on vegetation productivity at  
247 regional scale and the results provide a clear picture on the importance of six rainfall metrics on growing season  
248 ANPP under different rainfall conditions (i.e. mean annual rainfall). The Sahel zone is often defined from isohyets  
249 of annual rainfall as a common denominator of the hydrological conditions of the region. It was however shown  
250 here, that considerable east-west differences occur in several of the seasonal rainfall metrics analyzed with a much  
251 higher number of rainy days and corresponding lower rainfall intensity in the southeastern Sahel as compared to  
252 the southwestern part. Variability in the rainfall intensity is shown here to influence the growing season ANPP  
253 generated over a growing season (Fig. 9d) and hence spatio-temporal changes in rainfall intensity (but characterized  
254 by the same amount of seasonal rainfall) will impact vegetation productivity. This has important implications for  
255 the use of the rain use efficiency (RUE) (Houerou, 1984) or RESTREND approach (Evans and Geerken, 2004)  
256 which is derived from annually or seasonally summed rainfall and commonly used as an indicator for land  
257 degradation (Archer, 2004; Bai et al., 2008; Fensholt and Rasmussen, 2011; Prince et al., 1998; Wessels et al.,  
258 2007) as discussed in Ratzmann et al. (2016). Interestingly, a limited impact of rainfall seasonality on growing  
259 season ANPP was found in arid lands below 300 mm year<sup>-1</sup> rainfall, suggesting that the species composition is  
260 adapted to rainfall variation, and that the rather sparse vegetation cover is able to effectively utilize rainfall  
261 independent of the seasonal distribution. This is very different in the semi-arid and northern sub-humid zone (300-  
262 700 mm year<sup>-1</sup>), where variations in rainfall seasonality are found to be more closely linked with variations in  
263 growing season ANPP. This implies that a favorable distribution of rainfall may lead to increased productivity, as  
264 it was observed in Senegal between 2006 and 2011 (Brandt et al., 2017), but below average rainfall conditions with  
265 an unfavorable distribution lead to an immediate reduction in vegetation cover and growing season ANPP.

266 Not surprisingly, the number of rainy days showed the highest positive correlation with growing season ANPP  
267 (Fig. 5c), with increasing productivity along with increasing rainy days, up to 75 days, where the relation weakens



268 (Fig. 9c). The importance of this metric is closely followed by the heavy rainfall events, which were negatively  
269 correlated with growing season ANPP (Fig. 5e), and decreases the productivity until heavy rainfall events reach a  
270 share of 80%, which leads to a constant level of low vegetation productivity (Fig. 9e). The importance of the timing  
271 of the wet season, i.e. the start and cessation, increases rapidly along the rainfall gradient, having the highest impact  
272 on growing season ANPP in the semi-arid zone (300-700 mm year<sup>-1</sup>). The reason for the importance of the timing  
273 of the onset of the growing season on the growing season ANPP (Fig. 9a) with an almost linear decrease in growing  
274 season ANPP as a function of onset delay should be found in the predominance of annual grasses which are  
275 photoperiodic (Vries and Djitéye, 1982). The end of season is thus controlled by day length and do therefore not  
276 compensate for a delay in the onset. Also a too early onset was found to decrease growing season ANPP, which is  
277 likely to be associated with so-called “false starts” of the growing season. Often, an early start of the growing  
278 season is accompanied by a significant number of dry-days occurring shortly after the start of the rainy season with  
279 a detrimental impact upon plant growth (Proud and Rasmussen, 2011). Finally, we found that the general impact  
280 of consecutive dry days is difficult to quantify (Fig.7f). However, a rather clear critical threshold of 10 consecutive  
281 days without rainfall was found to have an increased adverse impact on the growing season ANPP. This threshold  
282 of 10 days as an average for Sahel is related to the depletion time of the upper layer soil water and the root depth  
283 of the herbaceous stratum (primarily annual grasses) but will vary spatially with different soil and vegetation types  
284 (Vries and Djitéye, 1982).

285 Several studies have reported a tendency towards an earlier start of the wet season (Sanogo et al., 2015; Zhang  
286 et al., 2017), but projections predict a delay of the wet season in the later 21th century (Biasutti and Sobel, 2009;  
287 Guan et al., 2015). Moreover, an increase in heavy rainfall events and prolonged dry spells are observed and  
288 projected for the future (Sanogo et al., 2015; Taylor et al., 2017; Zhang et al., 2017). Our results show that the  
289 semi-arid zone will be most prone to these projected changes, and an increase in heavy rainfall events, a delay in  
290 the start of the wet season and dry spells exceeding 10 days will cause a significant reduction in vegetation



291 productivity, although the annual rainfall amount may be constant or even increasing. Disregarding the importance  
292 and impact of varying rainfall distribution on vegetation productivity leads to a bias in any ANPP prediction, and  
293 this knowledge should be implemented in any prediction and estimation of ANPP, both for ecosystem models and  
294 remote sensing based analyses, especially in the context of food security. Although this study did not include a  
295 temporal change component of the metrics analyzed, the length of high quality time series data of both vegetation  
296 productivity and rainfall with a daily temporal resolution does provide the possibility for adding a temporal  
297 dimension which will be pursued in a future study.

298

## 299 **Summary and conclusion**

300 In this study we analyzed the impact of seasonal rainfall distribution (represented by onset and cessation of the  
301 wet season, number of rainy days, rainfall intensity, number of consecutive dry days and heavy rainfall events) on  
302 growing season ANPP for the Sahelian zone. Overall, a clear north-south gradient was observed for the onset, rainy  
303 days, heavy rainfall events and consecutive dry days, but also considerable differences in cessation date, number  
304 of rainy days and the rainfall intensity were observed between Eastern and Western Sahel. We found the strongest  
305 relationship between growing season ANPP and the number of rainy days ( $r=0.82$ ), closely followed by a negative  
306 correlation between growing season ANPP and heavy rainfall events ( $r=-0.78$ ). Growing season ANPP in the arid  
307 zone ( $100-300 \text{ mm year}^{-1}$ ) was rather insensitive to variations in the rainfall metrics, whereas vegetation in the  
308 semi-arid zone ( $300-700 \text{ mm year}^{-1}$ ) was significantly impacted by most metrics, especially by the number of rainy  
309 days and timing (start and cessation) of the wet season. Finally, the critical breakpoints analysis between growing  
310 season ANPP and all rainfall metrics show that the growing season ANPP are particularly negatively impacted  
311 after  $>10$  consecutive dry days and that a rainfall intensity of  $7 \text{ mm day}^{-1}$  is detected for optimum growing season  
312 ANPP. Overall, it can be concluded that seasonal rainfall distribution significantly influence ANPP and the effect  
313 of different rainfall metrics is observed to vary along the north-south rainfall gradient. These findings have



314 important implications for the sheer amount of dryland studies in which annually or seasonally summed rainfall  
315 and ANPP are used to derive indicators of land degradation or anthropogenic influence (e.g. the use of RUE and  
316 RESTREND). When studying subtle changes in dryland vegetation productivity based on time series of satellite  
317 data, as caused by both climate and anthropogenic forcing, it is essential also to consider the potential effect from  
318 changes in the rainfall regime as expressed in the seasonal rainfall metrics studied here.

319

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**Table 1** Rainfall metrics describing the seasonality and extreme events

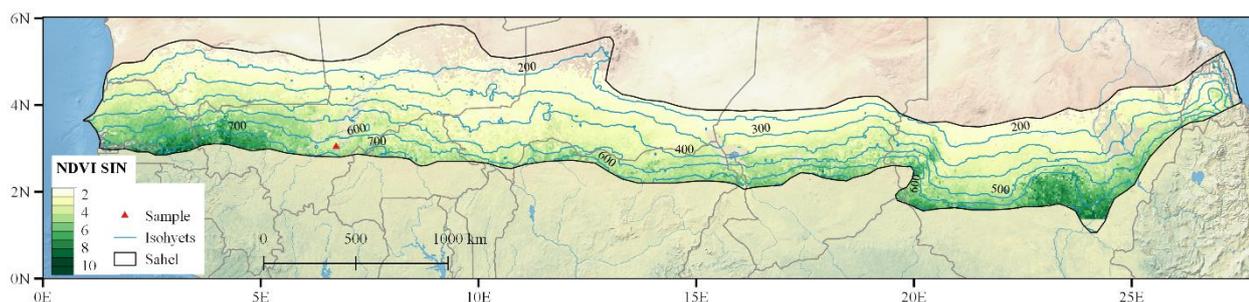
Index name	Definitions	Units
Onset of wet season (Onset)	The minimum value in the accumulative anomaly of daily rainfall	day of year
Cessation of wet season (Cessation)	The maximum value of the accumulative anomaly of daily rainfall	day of year
Rainy days (RD)	Number of days with rainfall $\geq 1$ mm between the onset and the cessation of the wet season	days
Rainfall intensity (SDII)	Ratio of annual total rainfall and number of rainy days $\geq 1$ mm	mm day <sup>-1</sup>
Heavy rainfall events (R95p):	Fraction of annual rainfall events exceeding the (2001–2015) 95th percentile	%
Consecutive dry days (CDD):	Maximum number of consecutive days with rainfall $< 1$ mm	days
Seasonal rainfall amount (Pt)	Rainfall amount during the wet season	mm year <sup>-1</sup>

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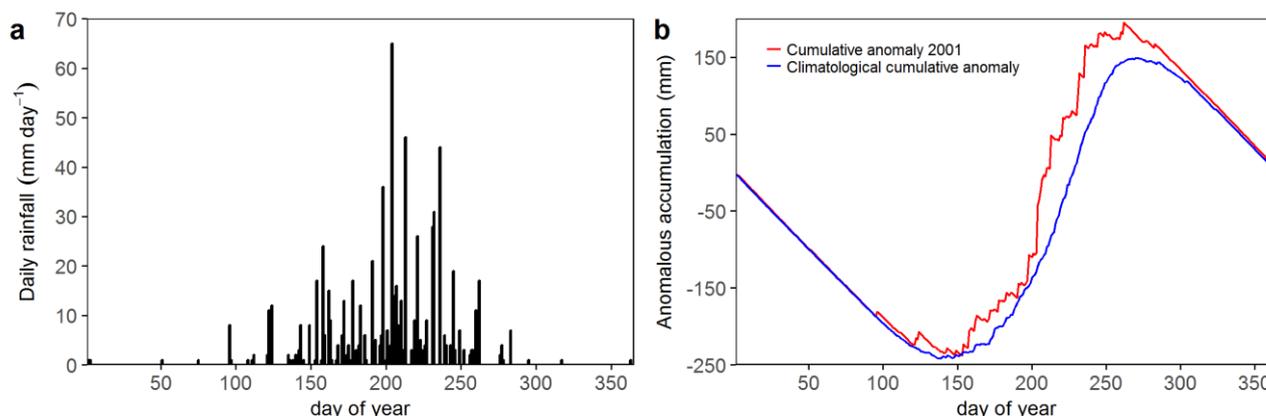
458 Fig 1. Study area outlining the Sahelian region (black color; 100-700 mm annual rainfall). NDVI SIN (seasonal integral) is

459 based on a 15-year (2001-2015) average using MODIS data; the red grid point (13.5° N, 5.0° W) is used to illustrate the

460 extractions of onset and cessation of the wet season shown in Fig. 2. Isohyets are based on a 15-year (2001-2015) average of

461 the seasonal rainfall amount (RFE-2.0).

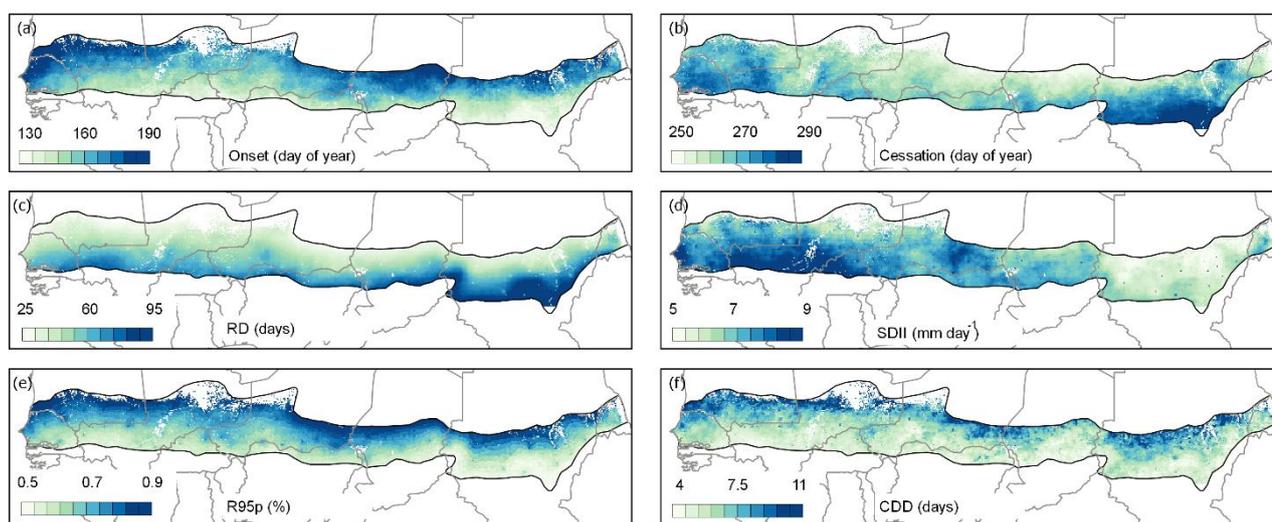
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464 Fig.2. (a) Daily rainfall distribution and (b) anomalous accumulative curve for the grid point 13.5° N, 5.0° W (shown in Fig.  
 465 1) for the year of 2001. The blue line (accumulated anomaly) is computed from a 15-year (2001-2015) average of daily rainfall.

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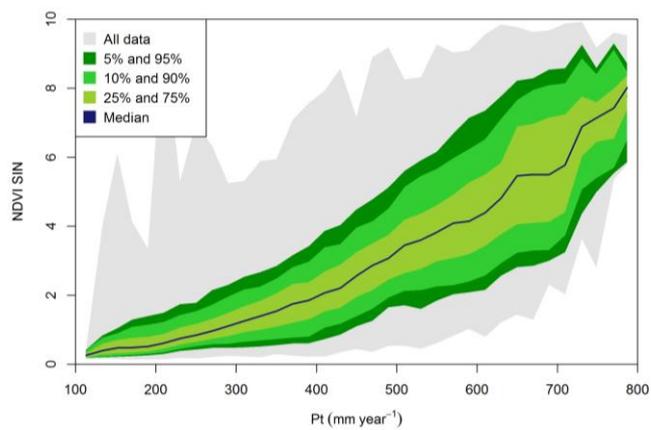


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468 Fig.3. Spatial distribution of average seasonal rainfall metrics a) onset of wet season (day of year); b) cessation of wet season  
 469 (day of year); c) rainy days (days); d) daily intensity (mm day<sup>-1</sup>); e) heavy rainfall events (%); f) consecutive dry days (days)  
 470 based on 15-year averages (2001-2015). Pixels within the study area are masked (white color) in accordance with the  
 471 description in the methods section.

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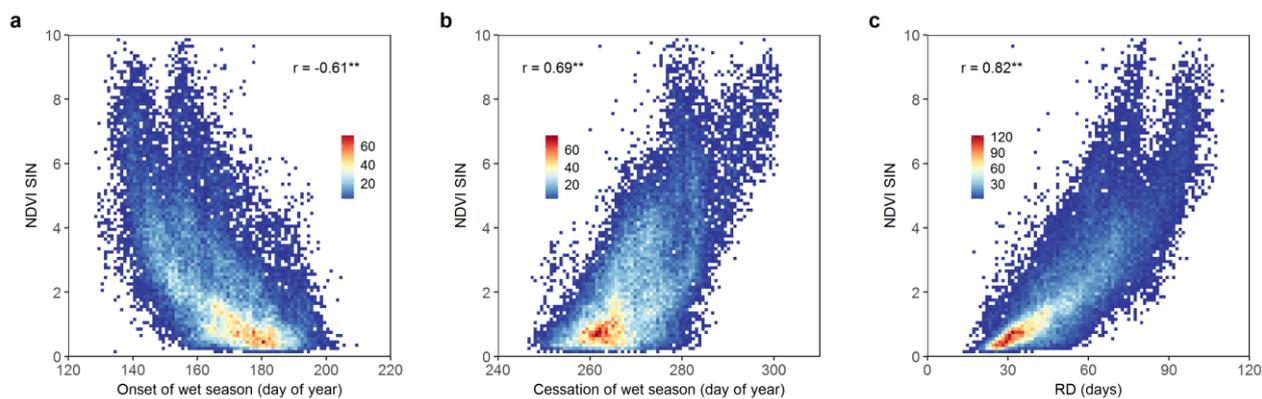


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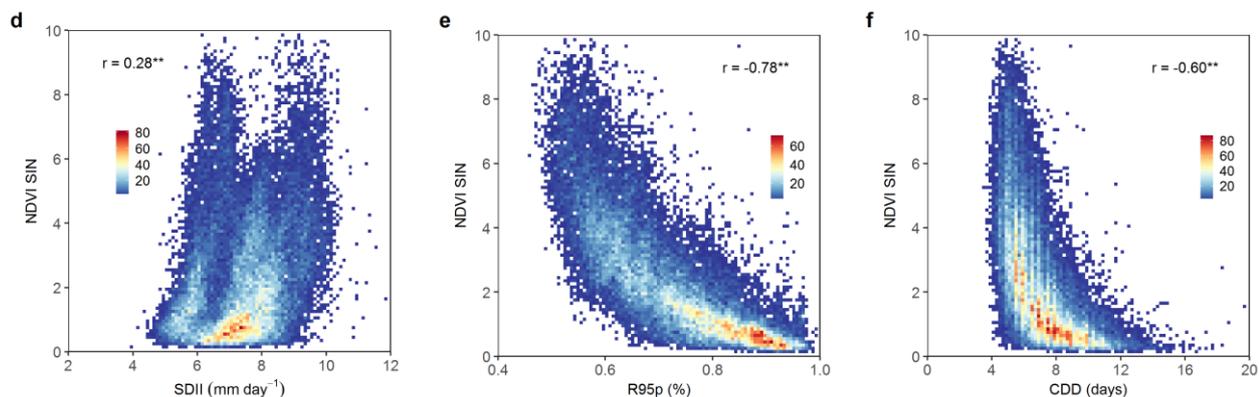
475 Fig.4. Growing season ANPP (NDVI SIN) as a function of mean seasonal rainfall amount (Pt) plotted as quantiles for the  
476 Sahel-Sudanian zone (pixel averages for 2001-2015).

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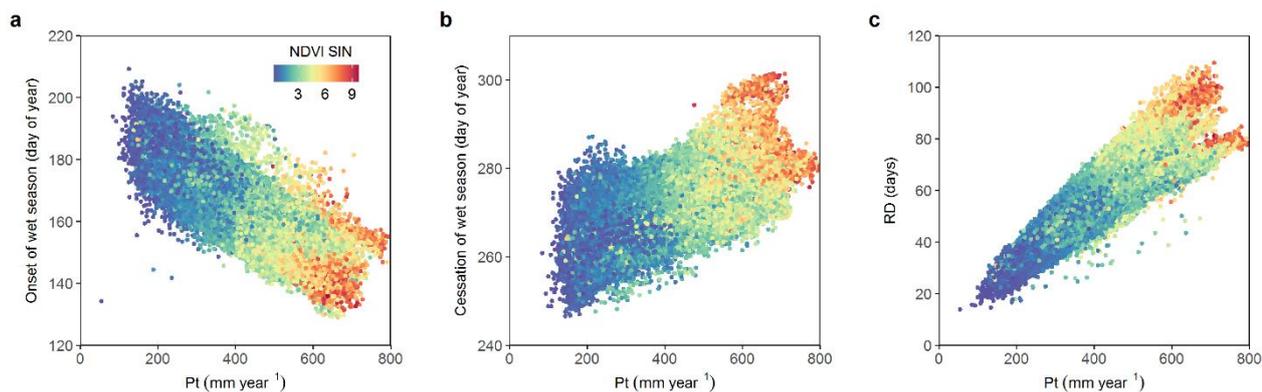


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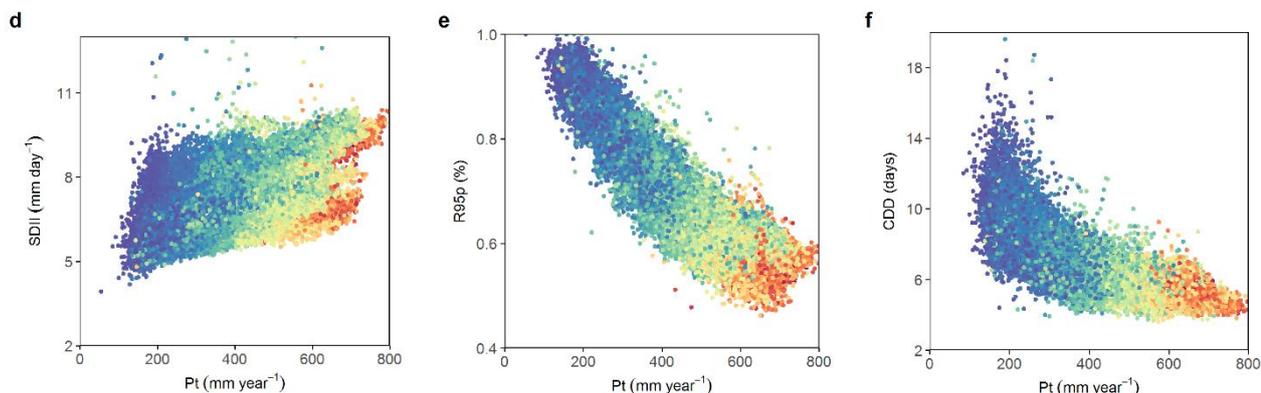
481 Fig.5. Density scatterplot showing the relationships between rainfall metrics and growing season ANPP (NDVI SIN). All  
 482 analyses are based on 15-year averages (2001-2015). \*\* denotes  $p < 0.001$ . All points ( $n=30862$ ) are located between 100 and  
 483 800 mm annual rainfall.

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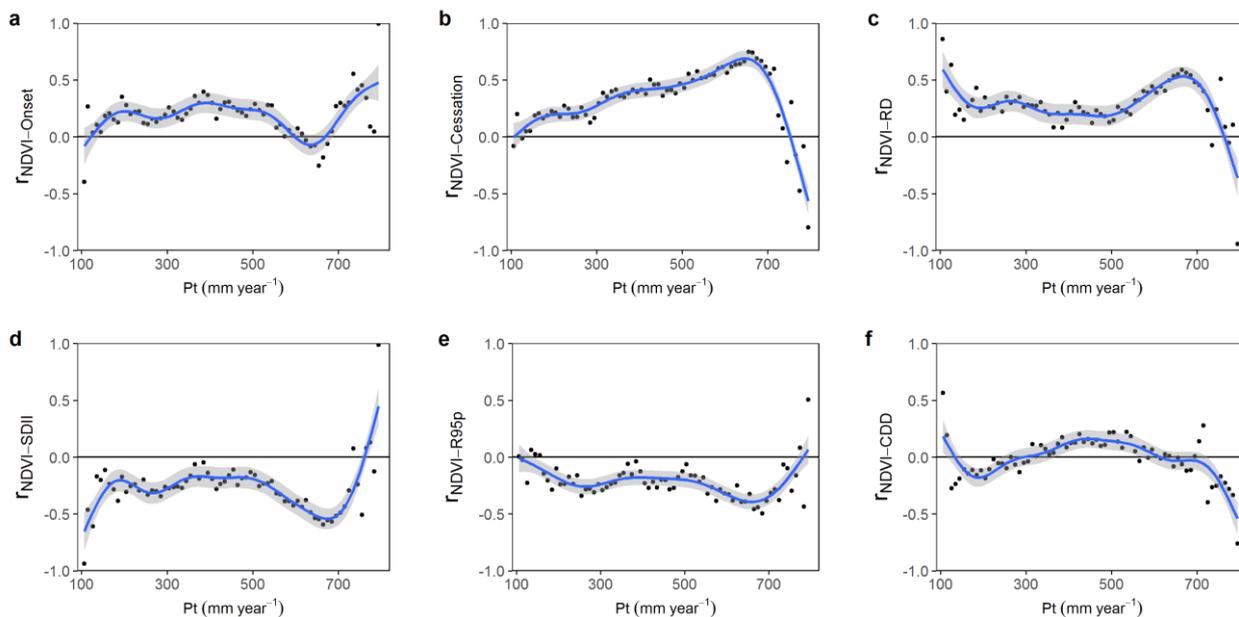


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488 Fig. 6. Relationships between seasonal rainfall metrics and growing season ANPP as a function of seasonal rainfall amount  
 489 based on 15-year averages (2001-2015).

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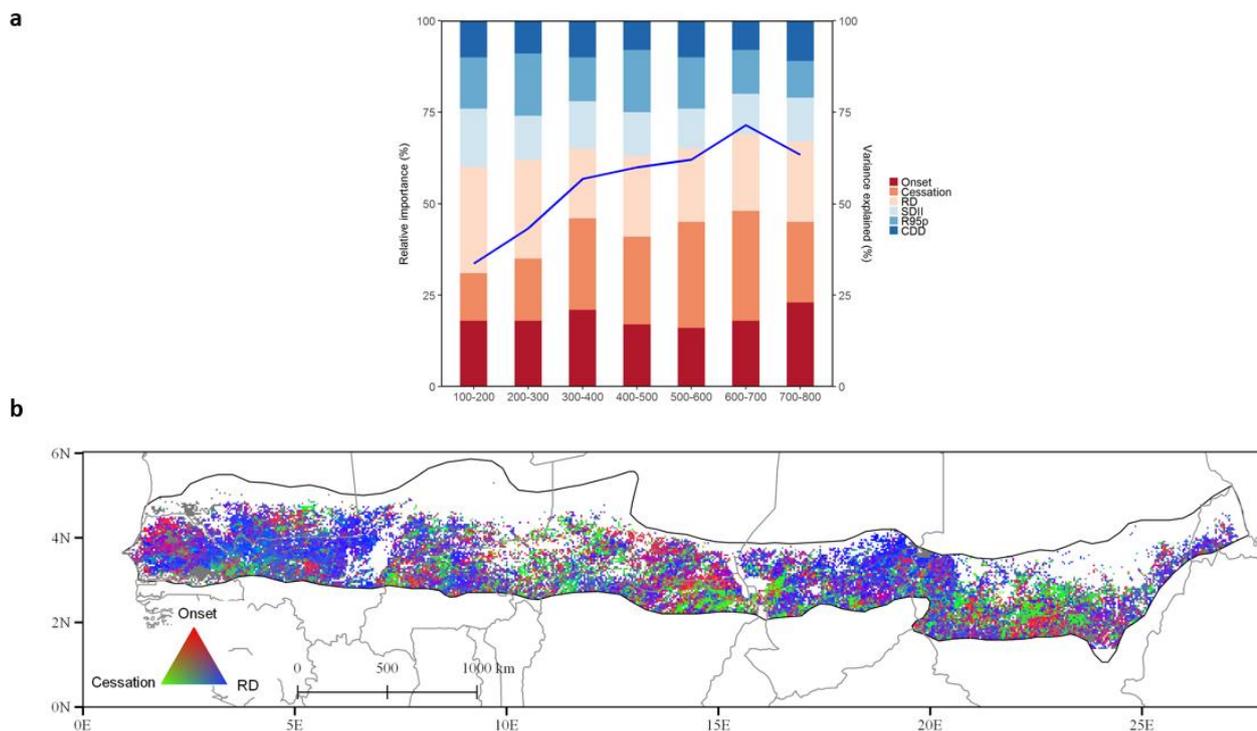


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493 Fig.7. Effects of rainfall metrics on growing season ANPP as a function of seasonal rainfall amount. The Pearson's correlation  
 494 between growing season ANPP and rainfall metrics are shown for each 10 mm interval. The lines are GAM fitting curves and  
 495 shading represents the 95% confidence intervals of the fitting.



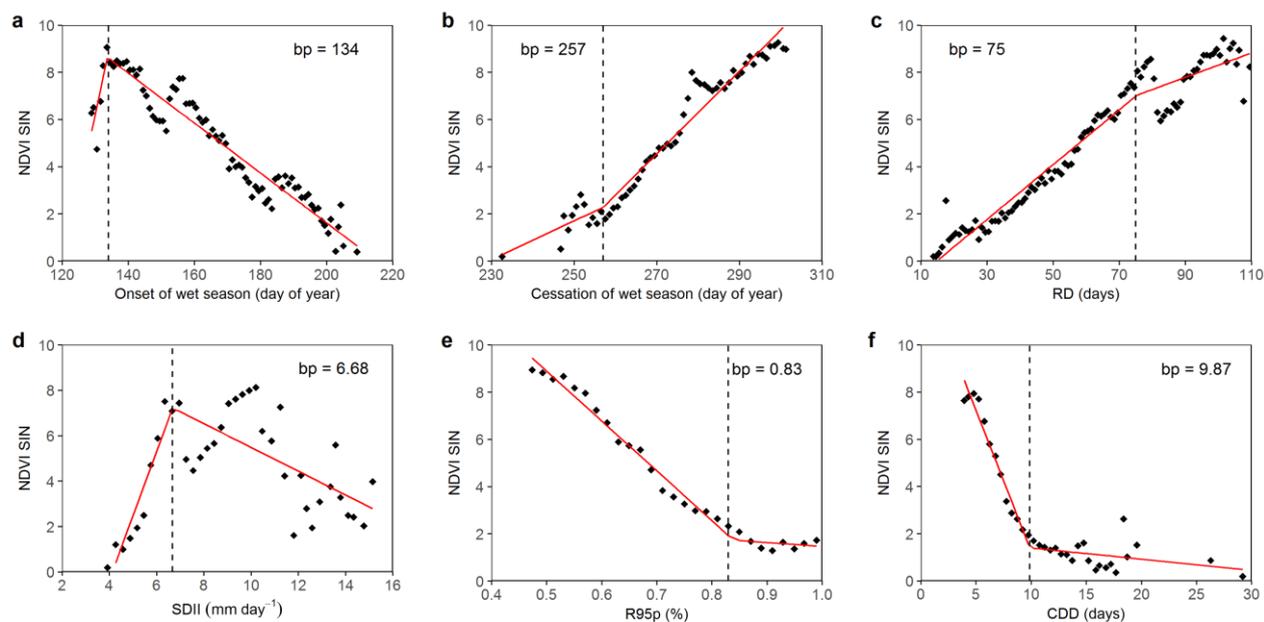
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498 Fig.8. a) Generalized relationships between growing season ANPP and Onset, Cessation, RD, SDII, R95p, CDD as a function  
499 of seasonal rainfall amount (100 mm intervals) based on 15-year average values (relative importance in %). The blue line  
500 shows the overall variance of growing season ANPP explained by the rainfall metrics per 100 mm seasonal rainfall amount  
501 based on the random forest method. b) Spatial distribution of the relative importance of onset, cessation of wet season and rainy  
502 days to growing season ANPP for 2001-2015 based on a multiple regression. Pixels within the study area are masked (white  
503 color) in accordance with the description in the methods section.

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Fig. 9. Growing season ANPP (individual points represent 95th percentile of NDVI SIN value for each rainfall metric bins)

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plotted against rainfall metrics. Solid red lines denote piecewise regression between growing season ANPP and rainfall metrics

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and dashed lines indicate the breakpoint (bp) for rainfall individual variables.

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