Responses to comments:

We thank the assocciate editor for these additional suggestions. As for the "However, I agree with anonymous referee 2 that the relationship presented in figure 4 is a non-linear relationship."
We have now removed the mentioning of linearity.

As for "Furthermore I suggest to present the "data availability" section not following "summary and conclusion", but in the method section."
We have moved that section accordingly.

M. Marshall Referee #1

Received and published: 29 September 2017

The manuscript titled, "Impacts of the seasonal distribution of rainfall on vegetation productivity across the Sahel" uses gridded climate and vegetation data to determine the impact of seasonal rainfall metrics (typically ignored over large areas) on NPP. The analysis is performed over the Sahel where NPP estimates are used extensively for food security analysis and other important areas of drylands research. The manuscript is generally well written and organized. The analysis is thorough and sufficiently addresses the objectives of the manuscript. The discussion and summary adequately capture the major findings. I believe the manuscript should be accepted by Biogeosciences after the authors address the few questions/comments below

We would like to thank Dr. Marshall for the supportive comments on the manuscript. We have implemented all of the suggestions and we believe that the revised version is now substantially improved. Below we respond to each of the comment individually.

1) Regarding grammar: the sentences in the introduction and discussion tend to be

long-winded, omit commas, and confuse “that” and “which.” Sections, subsections, etc. should be numbered 1., 1.1, 1.1.1. throughout the manuscript. Use past tense for tasks performed and present tense for general statements. There are other minor grammatical and spelling errors that should be addressed.

R1: Thanks. We have edited the introduction and have rephrased some overly convoluted sentences. We have carefully gone through the manuscript to remove additional minor errors and the subsections have been numbered as suggested.

2) The methods section would flow better if rainfall and NDVI were detailed in their own data subsection.

R2: In the revised version we have chosen to present the CHIRPS rainfall data in a separate subsection 2.2 (L91), whereas the use of the MODIS NDVI is now included as a part of the section describing the TIMESAT seasonal integration approach “2.4 Estimation of growing season ANPP” (L123).

3) RFE-2.0 is no longer a “state of the art” dataset and is not appropriate for daily rainfall estimation. RFE-2.0 is primarily used at 10-day intervals. The developers caution against using the daily product, because the estimates are statistically disaggregated from the 10-day data and therefore may or may not represent the physical reality. Why was the RFE successor CHIRPS not used for the analysis? It is higher resolution and I would suspect provides more realistic daily rainfall estimates: : :Why was daily data necessary if it was compared alongside 8-day MODIS?

R3: Thank you for suggesting the use of the CHIRPS data. We fully agree and the CHIRPS data was used to replace RFE in the revised MS.

4) Regarding MOD09Q1: : :the 8-day composites are quite noisy over the Sahel due to persistent cloud cover. Was any filtering done prior to S-G? Was the optimized MODIS S-G used? If so, please provide citation. Otherwise, how did you determine the smoothing terms? Certainly not a requirement for this manuscript, but the authors should consider using eMODIS in the future, since it is a 10-day product intended to be analyzed alongside RFE-2.0 or CHIRPS for food security applications.

R4: We thank the reviewer for this good suggestion. Here, we applied a Savitsky-Golay filter on the 8-day MODIS composites. On the one hand, Savitsky-Golay filtering has been reported to be robust against noise and missing data, while preventing over-smoothing. On the other hand, as the presence of clouds is one major error sources of EO data in the Sahel region during the rainy season, we routinely checked the quality of MODIS time series via TIMESAT GUI, where one can test how does Gaussian/ Double Logistic/ Savitsky-Golay filter smooth the data and cope with noise removal. For this study (and some other studies published recently), the Savitskey-Golay filter was chosen since it can filter out the noise and capture the temporal features for the time series, whereas the other two filters generally over-smooth the temporal curve. As described in the revised version of the MS, we have set a window size of 4 and seasonal parameter of 0.5 to fit one season per year, number of iterations for upper envelope adaptation of 2, and strength of the envelope adaptation of 2.

The eMODIS is indeed a product identified more cloud observations in some regions such as Canada and US. It will definitely be considered in the future analysis along also with initial tests that we have conducted based on the MODIS MAIAC processing chain.

We added in the text as: "*For this study, we applied the Savitzky-Golay filter implemented in TIMESAT with the following settings: A window size of 4 was applied and a seasonal parameter of 0.5 to fit one season per year. Both the number of iterations for upper envelope adaptation and strength of the envelope adaptation were set to 2 and the start and end of season were determined as 20% and 50% of the amplitude respectively.*" (L130-134)

5) The relationships in Figure 5 are non-linear. Why were they not fit with an exponential curve? How do you take into account the non-linearity of NDVI in highly productive grid cells?

R5: Yes, thanks - they are not exactly linear relationships for the most variables. We used exponential regression in the revised version to better represent the statistical relationship between variables.

Minor

Ln 54-57: Sentence beginning with "Recent studies: : :" is difficult to understand and should be reworded.

R6: Thanks, we have rephrased the sentence. (L55)

Ln 100: Typo "(R. Fensholt and Rasmussen, 2011)"

R7: Sorry for this. This part in this new version is deleted and other similar problems were checked throughout the manuscript.

Ln 117-130: Consider using a different nomenclature for climatological and dynamic rainfall anomalies.

R8: In order to keep consistent with the work by Liebmann et al., we have adopted their nomenclature.

Liebmann, B., Bladé, I., Kiladis, G. N., Carvalho, L. M. V, Senay, G. B., Allured, D., … Funk, C. (2012). Seasonality of African precipitation from 1996 to 2009. Journal of Climate, 25(12), 4304–4322. https://doi.org/10.1175/JCLI-D-11-00157.1

Font sizes in the figures are too small.

R9: Thanks, we have enlarged font size for the figures.

Anonymous Referee #2

Received and published: 16 October 2017

General comments

The well-written and well-structured manuscript presents an analysis about the impact of the seasonal rainfall distribution on ANPP in the Sahel zone during the period 2001-2015. The authors utilized a gridded dataset of daily precipitation to compute different seasonal rainfall metrics and related these to NDVI SIN (derived from a time series of MOD09Q1) as a proxy for ANPP. The objective of the manuscript is addressed with a sound methodology and the findings of the authors are supported by the results. Overall, the topic is very interesting and relevant, e.g. for the food security and climate change community, and I support the acceptance of the manuscript after minor revisions. In general, I would like the authors to address a few more issues in the discussion/conclusion. First, please discuss the quality of the utilized data products, especially the rainfall dataset, and if this could affect the obtained results. Second, please address the possibility of an adaptation of the vegetation (e.g. change in species composition) to a change in the seasonal rainfall distribution (related to the last paragraph in the summary and conclusion section). Furthermore, I would be interested if the authors tested if there is a relationship (correlation) between the different analysed seasonal rainfall metrics. But this does not need to be part of the paper (it is just curiosity). More specific comments are given below.

We would like to thank the reviewer for the supportive comments and suggestions, which have certainly helped us in improving the manuscript. We have implemented all of the suggestions and we believe that the revised version of the MS is now substantially improved. Below we respond to each of the comment individually.

General comments

First, please discuss the quality of the utilized data products, especially the rainfall dataset, and if this could affect the obtained results.

R1: Thanks. We have adopted reviwer1's suggestion and your comment (L90) and the CHIRPS data were used to replace RFE, We discuss data quality in the beginning of the discussion section of the revised version: (L267-278) " *Uncertainty in the rainfall data is inevitably to have an impact on the extraction of seasonal rainfall metrics which further impacts the relationship between seasonal rainfall metrics and ANPP. Based on improved climatologies systematic bias in the CHIRPS dataset has been removed and the data is considered state-of-the-art within quasi-global, high spatial resolution rainfall datasets (Funk et al., 2015). As this study does not address temporal changes in the seasonal rainfall metrics or ∑NDVI, but merely presents results on the general coupling* *between rainfall metrics and vegetation productivity, we consider the results to be statistically robust. We conducted a parallel set of analyses based on the RFE-2.0 rainfall product developed by the NOAA Climate Prediction Center (CPC) (Herman et al., 1997), which, like CHIRPS, is also a gauge-satellite blended and the outcome of these analyses yielded nearly similar results as what is presented here. At the same time ∑NDVI derived from MODIS will also be impacted from cloud cover during the growing season, but the use of the Savitzky-Golay filtering algorithm has proven to be an effective way of overcoming residual noise effects in the NDVI time-series (Fensholt et al., 2015).”*

Second, please address the possibility of an adaptation of the vegetation (e.g. change in species composition) to a change in the seasonal rainfall distribution (related to the last paragraph in the summary and conclusion section).

R2: This is an excellent point, which is on our to-do-list, however it would require long-term records of field observations of herbaceous species composition to study further – but that would certainly be interesting. We have added the following sentence to this section (L353-356).

“Inter-annual differences in the seasonal distribution of rainfall is known to have an impact on species composition in Sahel (Mbow et al., 2013) and it is likely the herbaceous vegetation is able to adapt to changes seasonal rainfall distribution expressed by a shift in the abundance of species favored by increased heavy rainfall events and longer dry spells.”

Furthermore, I would be interested if the authors tested if there is a relationship (correlation) between the different analysed seasonal rainfall metrics. But this does not need to be part of the paper (it is just curiosity).

R3: The non-parametric Spearman’s rank correlation coefficients between all seasonal rainfall metrics are showed in the below:

	R	Onset	Cessation	RD	SDII	R95sum	CDD
R	1						
Onset	-0.79	1					
Cessation	0.60	-0.45	1				
RD	0.92	-0.83	0.60	1			
SDII	0.69	-0.37	0.32	0.38	1		
R95sum	-0.91	0.82	-0.60	-0.99	-0.35	1	
CDD	-0.82	0.67	-0.33	-0.86	-0.41	0.84	1

Specific comments

Line 12: "number of rainy days, rainfall intensity, number of consecutive dry days and heavy rainfall events" -> please specify that these metrics refer to the rainy season

R4: We changed the text as 'This study tests the importance of rainfall metrics in the wet season (onset and cessation of the wet season, number of rainy days, rainfall intensity, number of consecutive dry days and heavy rainfall events) on growing season ANPP' . (L11)

Line 17: Please add a half sentence to shortly explain the meaning of "breakpoints" in this context

R5: Thanks, we have included the following sentence in the abstract: "We analyzed critical breakpoints for all metrics to test if vegetation response to changes in a given rainfall metric surpasses a threshold beyond which vegetation functioning is significantly altered." (L17-18)

Line 26: remove "KM" from the reference

R6: Sorry for this. It has been changed accordingly. (L28)

Line 29: "wet season which can be highly variable between years" -> the wet season is highly variable in time and space (please add the space component)

R7: Thanks. It has been changed accordingly. (L31)

Line 34: "21st century climate change" -> add "predicted"

R8: Thanks, we have changed it as suggested.

Line 89: Provide a reference/website where to access the RFE-2.0 data

R9: RFE-2 was replaced with CHIRPS, so this paragraph has been deleted. We added the website and reference for CHIRPS.

Line 90: Please provide an explanation why you opted for the RFE-2.0 dataset and not another daily precipitation dataset like CHIRPS (see also comment of M. Marshall)

R10: Since we fully agree that CHIRPS data will be a better choice than RFE, we have followed this suggestion and replaced all the analyses by CHIRPS data.

Line 109: "on day (Pi)" -> Is there something missing, e.g. "on a certain day"?

R11: Thanks. We rephrased this sentence to make it clearer.

Line 122: Provide a reference for the MOD09Q1 product and/or a website where to access the product

R12: Thanks. We have added a "Data availability" section following "Summary and conclusion". (L358)

Line 128: Please specify if you did the resampling of the NDVI data before or after applying TIMESAT

R13: Thanks. We have rephrased this part a bit to make it clearer. We first calculated the ∑NDVI and then the resampling was done. e.g., The derived small seasonal integral was used as the ∑NDVI. The method is well established and proven to be a reliable proxy for the growing season ANPP in Sahel (Olsson et al., 2005; Rasmus et al., 2013). The ∑NDVI data was then aggregated to the resolution of CHIRPS (0.05 °) using a bilinear resampling method. (L134)

Line 129: Provide a reference for both land cover maps; Specify how the masking was done (i.e., did you mask out water if both LC maps indicate water in a pixel or if at least one of the LC indicate water?)

R14: Thanks for your suggestion. It has now been specified that pixels with water were masked out if one or both of the land cover products indicated the presence of water in a pixel. (L136-137)

Line 133: Please explain why you chose the Pearson0s correlation coefficient and not for example the non-parametric Spearman‘s rank correlation coefficient

R15: We thank the reviewer for this comment. We have used the non-parametric Spearman’s rank correlation coefficient in the new version since it measures the monotonic relationship which is a better choice in this study. This has now been corrected in the text. (L141)

Line 134: Please provide the R package name for the GAMs

R16: Thanks. The MGCV package is provided.

Line 135: “Team, 2014” should be “R Team, 2014”

R17: Thanks. It has been corrected accordingly.

Line 138: “individual rainfall variables” -> please use terms consistently, e.g. use “individual seasonal rainfall metrics” here

R18: Thanks for your suggestion; it has been done accordingly throughout the MS.

Line 151f: “The 95th percentile of NDIV SIN [: : :] for a given rainfall amount” -> It is not fully clear how you calculated the potential vegetation productivity: Did you calculate it pixel-wise? Does the “given rainfall amount” represent the mean annual rainfall sum of a pixel? -> please clarify the description of your calculations

R19: Thanks, we have rephrased this sentence (L162-166). We added ‘*The 95th percentile of ∑NDVI was selected to represent the potential vegetation productivity attainable for a given seasonal rainfall metric (Donohue et al., 2013). Seasonal rainfall metrics were binned according to the dynamic range of the individual metrics and the average 95th percentile of ∑NDVI was calculated for each bin (for onset, cessation and RD bins with an interval* *of 1 were used; for SDII a bin of 0.3 was applied; for R95sum bin intervals were set to 0.02; finally we used bins 0.5 for CDD)’.*

Line 158: “with a later onset” -> should it not be “with an earlier onset”?

R20: Sorry for this mistake and it has been changed to ‘earlier’.

Line 166f: “with a near linear relationship” -> Fig. 4 does not look like a linear relationship

R21: Here we simply want to show the spread of ∑NDVI for each rainfall zone and when considering the different quantiles of the plot, we actually believe that it’s correct to present this Fig. 4 relationship as near-linear.

Line 182: “variations in seasonal rainfall distribution” -> Do you mean all seasonal rainfall metrics?

R22: Yes, the term seasonal rainfall distribution was used to indicate seasonal rainfall metrics. To make it clearer, we have now added a few examples “(e.g., onset and R95sum)”. (L198)

Line 239: “from where the rather low amount of vegetation loses sensitivity to even more extreme seasonal distribution” -> please reformulate as the phrase is not really clear

R23: Sorry for this. We have rephrased this sentence to: “from where the vegetation loses sensitivity to the impact from an increased frequency of heavy rainfall events” (L258-259)

Line 255: RESTREND approach -> please explain a bit more this approach

R24: Thanks, we have added this part a parenthesis explaining the approach: “regressing Σ NDVI from annual precipitation and subsequently calculating the residuals as the difference between observed Σ NDVI and Σ NDVI as predicted from annual precipitation)” (L285-289)

Line 367f: Some information like publisher are missing for this publication

R25: Sorry for this mistake. It was an IPCC report and we specified this in the L417.

Line 390f: Information about journal volume, issue and pages missing

R26: Sorry for this. The missing information was added. (L441)

Line 400: Some information like publisher are missing for this publication

R27: Added. (L451)

Line 432f: Should be “R Team” instead of “Team, R”; there is twice the year 2014

R28: Sorry for the mistake. Corrected. (L479)

Table 1: Definition of CDD: should it not include “during the wet season” or something Similar

R29: Thanks. We rephrased the sentence, which now reads: “Maximum number of consecutive days with rainfall <1 mm during wet season”

Figure 1: Here the study area is defined as the area between 100-700 mm annual rainfall. But in the description of the study area on page 4 you define your study area as the area between 100-800 mm annual rainfall -> Please choose one definition and use it consistently throughout the paper

R30: Sorry for this mistake. We used 100-800 mm yr^{-1} and it has been changed throughout the MS accordingly.

Figure 5: Please provide a parameter and a unit for the color scale in the sub-figures

R31: Thank, we have added ‘Density’ as the title for the color scale.

Figure 6: Maybe provide an r value for each sub-figure as in figure 5

R32: Since there are three variables shown in each sub-figure, we have decided to report the r values in a separate analysis (Figure 7).

Impacts of the seasonal distribution of rainfall on vegetation productivity across the Sahel

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

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Keywords: Drylands, Seasonal rainfall metrics, Aboveground net primary production, Remote sensing

1 Introduction

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

While it is well known that the productivity of dryland vegetation is highly prone to variations in the availability of water resources at the annual scale (Fensholt et al., 2013; Fensholt and Rasmussen, 2011; Herrmann et al., 2005; Huber et al., 2011), there is a current lack of understanding how the seasonal distribution of rainfall impacts on growing season ANPP (Rishmawi et al., 2016). Several studies have demonstrated the vegetation sensitivity to the timing and magnitude of rainfall events based on individual plot data and model estimates (Bates et al., 2006; Fay et al., 2000; Guan et al., 2014; Thomey et al., 2011), but the impact of specific rainfall metrics (such as wet season length/timing, number of rainy days, rainfall intensity, number of consecutive dry days and extreme events) on dryland vegetation productivity has rarely been studied at the regional scale, potentially including different biotic and abiotic controls. A few studies show that there is a strong dependency of Sahelian vegetation growth on the timing of ~~the start of~~ the wet season (Diouf et al., 2016) and the frequency and distribution of dry spells (Simon Richard and Rasmussen, 2011), but currently no regional scale study assessing a variety of rainfall metrics exists systematically analyzing the importance of rainfall metrics on vegetation growth as a function of mean annual rainfall. Further, there are evidences ~~Recent studies suggest~~showing that not only a shift in the timing of the wet season but also increasing extreme events occur in Sahel (Panthou et al., 2014; Sanogo et al., 2015; Taylor et al., 2017; Zhang et al., 2017), ~~showing~~ suggesting the need for a comprehensive understanding on how rainfall seasonality impacts on vegetation production.

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

2 Materials and methods

An empirical analysis is conducted based on gridded information of rainfall metrics based on daily satellite estimates and seasonally integrated NDVI (hereafter ∑NDVI~~ SIN~~) as a proxy for the growing season ANPP. The period of analysis covers 2001-2015 which allows for a per-pixel analysis including state of the art Earth observation datasets of both Climate Hazards Group InfraRed Precipitation with Station (CHIRPS version 2.0)~~African Rainfall Estimation (RFE-2.0)~~ and Moderate Resolution Imaging Spectroradiometer (MODIS) vegetation. The rainfall metrics include: number of rainy days, daily intensity, heavy rainfall events, number of consecutive dry days and seasonal rainfall amount which were analyzed as explanatory variables for the observed spatial variability in seasonal vegetation productivity along the gradient of mean seasonal rainfall.

2,1 Study area

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

2.2 Data sets

2.2.*1* ~~RFE~~ CHIRPS rainfall data

The CHIRPS data set uses TIR imager and gauge data, as well as monthly precipitation climatology, CHPClim, and atmospheric model rainfall fields from the NOAA Climate Forecast System, version 2 (CFSv2) and TRMM 3B42 (Funk et al., 2015). The CHIRPS grids at 0.05˚ and 0.25˚ spatial resolutions and extends from 1981 to present. In our study, the CHIRPS data at daily resolution were used to extract seasonal rainfall variables.

~~RFE-2.0 is a gauge-satellite blended rainfall product developed by the NOAA Climate Prediction Center (CPC) (Herman et al., 1997) gridded at 11 × 11 km spatial resolution and widely used to explain changes in vegetation productivity (Fensholt and Rasmussen, 2011). RFE-2.0 uses additional techniques to better estimate precipitation while continuing the use of cloud top temperature and station rainfall data, in all four input data sources are included: (1) daily Global Telecommunications System (GTS) rain-gauge data, (2) Advanced Microwave Sounding Unit (AMSU)-based rainfall estimates, (3) Special Sensor Microwave Imager (SSM/I)-based estimates, (4) the Geostationary Operational Environmental Satellite (GOES) precipitation index (GPI) calculated from cloud-top infrared (IR) temperatures on a half-hourly basis.~~

2.2.2 MODIS NDVI data

The newly released MODIS/Terra surface reflectance product (MOD09Q1 collection 6)- was used to derive an NDVI time series for the period 2001-2015. The NDVI was calculated from the MODIS red and near-infra red bands (8 day composites) and the growing season integrated NDVI was widely used to estimate vegetation productivity over Sahel (Fensholt and Proud, 2012).

2.3 Deriving rainfall seasonality metrics

The method used to identify the onset and cessation of the wet season is referred to Liebmann et al. (2012) and applicable to multiple datasets for precipitation seasonality analysis across the African continent (Dunning et al., 2016). As is described in Liebmann et al. (2012), the climatology wet season is initially determined by the climatological cumulative daily rainfall anomaly, $A(d)$, –calculated from the long-term (2001-2015) average rainfall (R_i) for each day of the calendar year minus the long-term annual-mean daily average ($\bar{R}$). The day with 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 season.

(1)

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

Subsequently, the onset and cessation were calculated individually for each year and each grid point. For each year the extraction of the seasonality of the wet season was based on equation (2). The daily cumulative rainfall anomaly $A(D)$ on a certain 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 minimum value is considered as the onset of the wet season.

(2)

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

Once the onset and cessation dates of the wet season for each year were found, the remaining variables were calculated (Table 1). Fig. 2a illustrates an example of daily rainfall for the grid point (13.5° N, 5.0° W) in 2001 and the corresponding cumulative daily anomaly curves are shown in Fig 2b. The blue and red lines signify $A(d)$ and $A(D)$, respectively. The range of minimum and maximum points in the blue line denotes the climatological wet season (Liebmann et al., 2012). The wet season of each individual year was then determined based on the daily precipitation observations covered by the climatological wet season. Areas where the annual minimum occurs after the 1st of October (desert areas) were excluded from further analysis (Diaconescu et al., 2015).

2.4 Estimation of growing season ANPP

The growing season integrated NDVI (∑NDVI)~~SIN~~ was used as a proxy for the growing season ANPP. The ∑NDVI 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 (Olsson et al., 2005; Rasmus et al., 2013). The ∑NDVI data was then aggregated to the resolution of CHIRPS~~RFE-2.0~~ (~~11×11 km~~0.05 °) using a bilinear resampling method. Both Globeland30 (Chen et al., 2014) and ESA CCI (2010) land cover maps (https://www.esa-landcover-cci.org/) were used to mask water bodies, irrigated and flooded areas if one of the both land cover products indicates the XX.

2.5 Statistical analyses

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

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

3 Results

3.1 Spatial pattern of rainfall metrics

A clear north-south gradient was observed for the onset, rainy days (RD), heavy rainfall events (~~R95p~~R95sum) and consecutive dry days (CDD) based on a 15-year (2001-2015) average value, with an ~~later ~~earlier onset, more rainy days and less heavy rainfall events towards the south (Fig.3a,c,e). The cessation of the wet season (Fig.3b) shows some longitudinal differences with the latest dates found in the eastern Sahel, followed by the western Sahel and the central Sahel showing the earliest cessation dates. A considerable difference between southeastern and southwestern Sahel (Fig. 3d) was observed in the rainfall intensity (SDII). The relatively low rainfall intensity in the southeastern Sahel is mirrored by considerably higher numbers of rainy days.

3.2 General response of growing season ANPP to rainfall metrics

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

The relationships between all the rainfall metrics and growing season ANPP were found to be significant ($p<0.001$) and the correlation coefficient (r) varied between -0.~~78~~ 79 and 0.~~82~~ 83 (Fig.5). For the region as a whole, the number of rainy days was identified as the most important metric impacting on the growing season ANPP (r=0.~~82~~83) (Fig.5c), closely followed by heavy rainfall events (~~R95p~~R95sum) (r=-0.~~78~~79) (Fig.5e), onset (r=-0.68) (Fig.5a) ~~cessation (r=0.69) (Fig.5b)~~ and cessation (r=0.66) (Fig.5b) of the wet season. The impact of consecutive dry days (CDD) on growing season ANPP was also relatively strong (r=-0.60) (Fig.5f), whereas a rather weak correlation was observed between growing season ANPP and rainfall intensity (SDII) (r=0.~~28~~48) (Fig.5d). For all rainfall metrics except RD, ~~R95p~~ R95sum and CCD, the plots show a bimodal distribution of the points, which is caused by the differences in the east-west patterns of the spatial distribution of rainfall metrics (onset, cessation~~,~~ ~~RD~~ and SDII) in Sahel as reported in Fig.3.

3.3 Response of growing season ANPP to rainfall metrics along the rainfall gradient

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

The non-parametric Spearman's rank ~~Pearson's~~ correlation coefficient was used to quantify the strength of the impact of individual seasonal rainfall metrics on growing season ANPP as a function of seasonal rainfall (Fig. 7). In general, the impacts of rainfall metrics on vegetation are distinctive along the 100-800 mm ~~year~~yr^{-1} gradient with a peak in *r* values (respectively positive or negative dependent on the rainfall metric) for most metrics around ~~700~~ 650 mm ~~year~~yr^{-1} followed by a sharp drop-off (Fig. 7)~~b, c, d, e) (cessation of wet season, RD, SDII and R95p)~~. It should be noted that modelling uncertainties increase for all rainfall metrics due to fewer observations in the lowermost seasonal rainfall total bins. For the wet season the pattern of ~~onset~~ RD, SDII, R95sum and CDD is ~~reversed~~ showed with a sharp ~~increase~~ decrease in *r* values from ~~700~~100-~~800~~ 300 mm y~~ea~~r^{-1}. The number of consecutive dry days (CDD) shows moderate *r* values balancing around zero generally indicating less importance of the CDD variable on growing season ANPP along the rainfall gradient analyzed.

The relative importance of the individual rainfall metrics on growing season ANPP was assessed based on a random forest model (Fig. 8a). The explained variance of growing season ANPP explained by rainfall metrics (blue line in Fig. 8a) is increasing with mean annual rainfall up to 600-700 mm y~~ea~~r^{-1} from where the degree of explained variance decreases, which corresponds with the results presented in Fig. 4 (the widest belt of the quantile values is observed for rainfall of 600-700 mm y~~ea~~r^{-1}, suggesting that the seasonal rainfall metrics additional to the seasonal rainfall amount is increasingly important in this rainfall zone) and in Fig. 7. The cessation of the wet season was identified as the most important factor controlling growing season ANPP in semi-arid areas of Sahel (~~300~~400-700 mm y~~ea~~r^{-1}), followed by the onset and number of rainy days. As measured by the relative importance, these three rainfall metrics together accounted for 60-70% of the variance explained by all rainfall metrics for all seasonal rainfall amounts. In arid areas (100-300 mm y~~ea~~r^{-1}) the number of rainy days was found to be the most important variable.

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

3.4 Critical points for growing season ANPP

A piecewise regression between growing season ANPP and seasonal rainfall metrics was applied to identify if critical breakpoints in the relationship between growing season ANPP and rainfall metrics exist (Fig. 9). We found that the most evident thresholds (average values for the Sahel zone) in relation to seasonal rainfall metrics influence on growing season ANPP relate to the onset of the wet season (Fig. 9a), the rainfall intensity (SDII) (Fig. 9d) and consecutive dry days (CDD) (Fig. 9f). If the onset of the wet season is later than day of year 1~~3~~40 this will have an increasingly negative effect on growing season ANPP as a function of the onset delay and contrastingly if the onset starts earlier than day of year 1~~3~~40 this will also have an increasingly adverse effect on growing season ANPP. Also, an optimum of rainfall intensity of ~~7~~ 13 mm day^{-1} was detected; if rainfall intensity exceeds ~~7~~ 13 mm day^{-1}, vegetation productivity starts to be negatively affected, whereas a lower intensity will also negatively impact on growing season ANPP. There was a pronounced decline in growing season ANPP as a function of number of consecutive dry days. However, when CDD exceeds ~~10~~ ~14 days a breakpoint in the curve is detected, as dry spells of this magnitude leads to a strong reduction in vegetation growth. The number of rainy days (Fig. 9c) was linearly related to growing season ANPP until ~~75~~ 69 days, beyond which RD becomes less decisive for the amount of growing season ANPP. Similarly, heavy rainfall events (fraction of annual rainfall events exceeding the 95th percentile) (Fig. 9e) were negatively related to growing season ANPP, until a certain threshold (larger than 0.~~83~~80), from where the ~~rather low amount of~~ vegetation loses sensitivity to ~~even more~~the stronger heavy rainfall events~~extreme seasonal distributions~~. Finally, the cessation date of the wet season (Fig. 9b) was shown to be nearly linearly related to growing season ANPP. A breakpoint is detected by the piecewise regression algorithm around day 285~~57~~, beyond which the delay in cessation date was slightly more favorable for higher growing season ANPP yields as compared to a cessation date before day 285~~7~~.

4 Discussion

This study presents first empirical evidence on the impact of rainfall seasonality on vegetation productivity at regional scale and the results provide a clear picture on the importance of six rainfall metrics on growing season ANPP under different rainfall conditions (i.e. mean annual rainfall). The Sahel zone is often defined from isohyets of annual rainfall as a common denominator of the hydrological conditions of the region. It was however shown here, that considerable east-west differences occur in several of the seasonal rainfall metrics analyzed with a much higher number of rainy days and corresponding lower rainfall intensity in the southeastern Sahel as compared to the southwestern part. These spatial patterns could be supported by CHIRPS and RFEv2 data sets (Fig.3 and Fig.S1).

Variability in the rainfall intensity is shown here to influence the growing season ANPP generated over a growing season (Fig. 9d) and hence spatio-temporal changes in rainfall intensity (but characterized by the same amount of seasonal rainfall) will impact vegetation productivity. This has important implications for the use of the rain use efficiency (RUE) (Houerou, 1984) or RESTREND approach (Evans and Geerken, 2004) which is derived from annually or seasonally summed rainfall and commonly used as an indicator for land degradation (Archer, 2004; Bai et al., 2008; Fensholt and Rasmussen, 2011; Prince et al., 1998; Wessels et al., 2007) as discussed in Ratzmann et al. (2016). Interestingly, a limited impact of rainfall seasonality on growing season ANPP was found in arid lands below 300 mm ~~year~~yr^{-1} rainfall, suggesting that the species composition is adapted to rainfall variation, and that the rather sparse vegetation cover is able to effectively utilize rainfall independent of the seasonal distribution. This is very different in the semi-arid and northern sub-humid zone (300-700 mm ~~year~~yr^{-1}), where variations in rainfall seasonality are found to be more closely linked with variations in growing season ANPP. This implies that a favorable distribution of rainfall may lead to increased productivity, as it was observed in Senegal between 2006 and 2011 (Brandt et al., 2017), but below average rainfall conditions with an unfavorable distribution lead to an immediate reduction in vegetation cover and growing season ANPP.

Not surprisingly, the number of rainy days showed the highest positive correlation with growing season ANPP (Fig. 5c), with increasing productivity along with increasing rainy days, up to ~~75~~ 69 days, where the relation weakens (Fig. 9c). The importance of this metric is closely followed by the heavy rainfall events, which were negatively correlated with growing season ANPP (Fig. 5e), and decreases the productivity until heavy rainfall events reach a share of 80%, which leads to a constant level of low vegetation productivity (Fig. 9e). The importance of the timing of the wet season, i.e. the start and cessation, increases rapidly along the rainfall gradient, having the highest impact on growing season ANPP in the semi-arid zone (300-700 mm ~~year~~yr^{-1}). The reason for the importance of the timing of the onset of the growing season on the growing season ANPP (Fig. 9a) with an almost linear decrease in growing season ANPP as a function of onset delay should be found in the predominance of annual grasses which are photoperiodic (Vries and Djitèye, 1982). The end of season is thus controlled by day length and do therefore not compensate for a delay in the onset. Also a too early onset was found to decrease growing season ANPP, which is likely to be associated with so-called “false starts” of the growing season. Often, an early start of the growing season is accompanied by a significant number of dry-days occurring shortly after the start of the rainy season with a detrimental impact upon plant growth (Simon Richard and Rasmussen, 2011). Finally, we found that the general impact of consecutive dry days is difficult to quantify (Fig.7f). However, a rather clear critical threshold of ~~10~~ 14 consecutive days without rainfall was found to have an increased adverse impact on the growing season ANPP. This threshold of ~~10~~ 14 days as an average for Sahel is related to the depletion time of the upper layer soil water and the root depth of the herbaceous stratum (primarily annual grasses) but will vary spatially with different soil and vegetation types (Vries and Djitèye, 1982).

Several studies have reported a tendency towards an earlier start of the wet season (Sanogo et al., 2015; Zhang et al., 2017), but projections predict a delay of the wet season in the later 21th century (Biasutti and Sobel, 2009; Guan et al., 2015). Moreover, an increase in heavy rainfall events and prolonged dry spells are observed and projected for the future (Sanogo et al., 2015; Taylor et al., 2017; Zhang et al., 2017). Our results show that the semi-arid zone will be most prone to these projected changes, and an increase in heavy rainfall events, a delay in the start of the wet season and dry spells exceeding ~~10~~ 14 days will cause a significant reduction in vegetation productivity, although the annual rainfall amount may be constant or even increasing. Disregarding the importance and impact of varying rainfall distribution on vegetation productivity leads to a bias in any ANPP prediction, and this knowledge should be implemented in any prediction and estimation of ANPP, both for ecosystem models and remote sensing based analyses, especially in the context of food security. Although this study did not include a temporal change component of the metrics analyzed, the length of high quality time series data of both vegetation productivity and rainfall with a daily temporal resolution does provide the possibility for adding a temporal dimension which will be pursued in a future study.

5 Summary and conclusion

In this study we analyzed the impact of seasonal rainfall distribution (represented by onset and cessation of the wet season, number of rainy days, rainfall intensity, number of consecutive dry days and heavy rainfall events) on growing season ANPP for the Sahelian zone. Overall, a clear north-south gradient was observed for the onset, rainy days, heavy rainfall events and consecutive dry days, but also considerable differences in cessation date, number of rainy days and the rainfall intensity were observed between Eastern and Western Sahel. We found the strongest relationship between growing season ANPP and the number of rainy days (r=0.~~82~~83), closely followed by a negative correlation between growing season ANPP and heavy rainfall events (r=-0.~~78~~79). Growing season ANPP in the arid zone (100-300 mm ~~year~~yr^{-1}) was rather insensitive to variations in the rainfall metrics, whereas vegetation in the semi-arid zone (300-700 mm ~~year~~yr^{-1}) was significantly impacted by most metrics, especially by the number of rainy days and timing (start and cessation) of the wet season. Finally, the critical breakpoints analysis between growing season ANPP and all rainfall metrics show that the growing season ANPP are particularly negatively impacted after >~~10~~ 14 consecutive dry days and that a rainfall intensity of ~~7~~ 13 mm day^{-1} is detected for optimum growing season ANPP. Overall, it can be concluded that seasonal rainfall distribution significantly influence ANPP and the effect of different rainfall metrics is observed to vary along the north-south rainfall gradient. These findings have important implications for the sheer amount of dryland studies in which annually or seasonally summed rainfall and ANPP are used to derive indicators of land degradation or anthropogenic influence (e.g. the use of RUE and RESTREND). When studying subtle changes in dryland vegetation productivity based on time series of satellite data, as caused by both climate and anthropogenic forcing, it is essential also to consider the potential effect from changes in the rainfall regime as expressed in the seasonal rainfall metrics studied here.

Data availability. The CHIRPS data are available at http://chg.geog.ucsb.edu/data/chirps/. The MODIS surface Reflectance product (MOD09Q1) can be downloaded at https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table. The global land cover 30 is available at http://www.globeland30.org/ and ESA CCI land cover is accessed from https://www.esa-landcover-cci.org/.

Competing interests. The authors declare that they have no conflict of interest.

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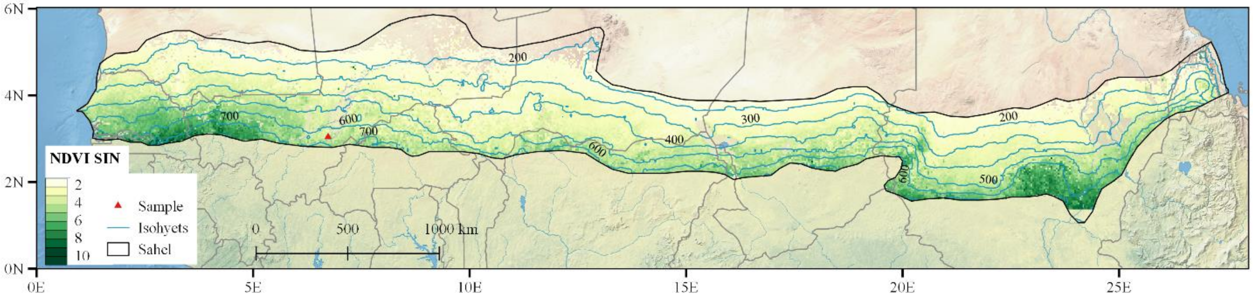
Table 1 Rainfall metrics describing the seasonality and extreme events

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 >=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 ≥1 mm	mm day^{-1}
Heavy rainfall events (~~R95p~~R95sum):	Fraction of annual rainfall events exceeding the (2001–2015) 95th percentile	%
Consecutive dry days (CDD):	Maximum number of consecutive days with rainfall <1 mm during wet season	days
Seasonal rainfall amount (R~~Pt~~)	Rainfall amount during the wet season	mm ~~year~~yr^{-1}



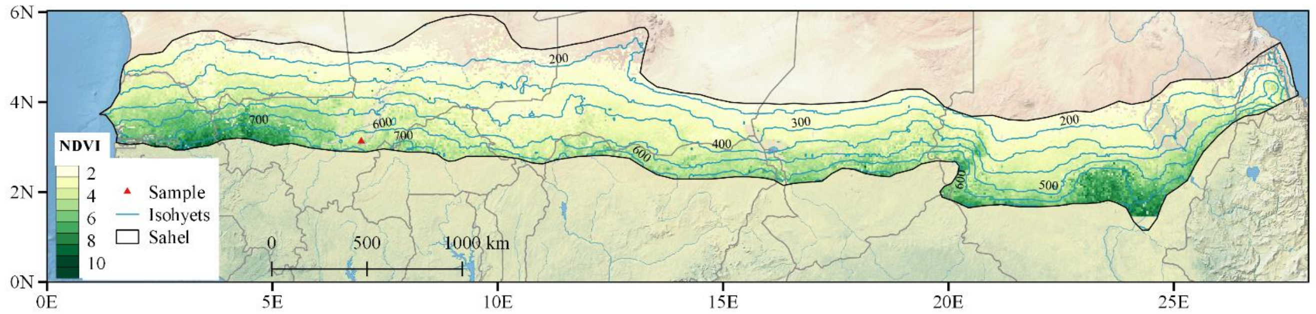


Fig 1. Study area outlining the Sahelian region (black color; 100-~~700~~ 800 mm~~-~~ yr^{-1}~~annual rainfall~~). ∑NDVI ~~SIN~~ (seasonal integral) is based on a 15-year (2001-2015) average using MODIS data; the red grid point (13.5˚ N, 5.0˚ W) is used to illustrate the extractions of onset and cessation of the wet season shown in Fig. 2. Isohyets are based on a 15-year (2001-2015) average of the seasonal rainfall amount (RFE-2.0).

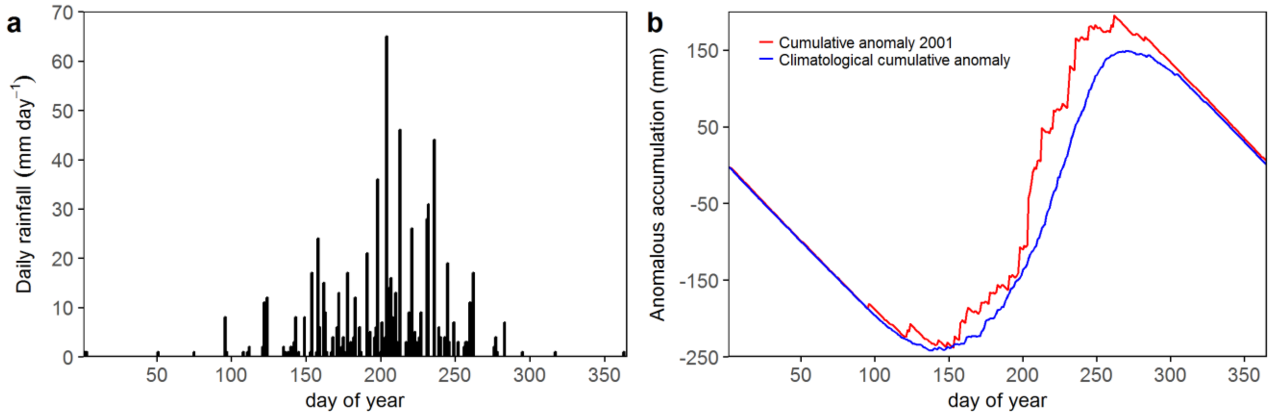
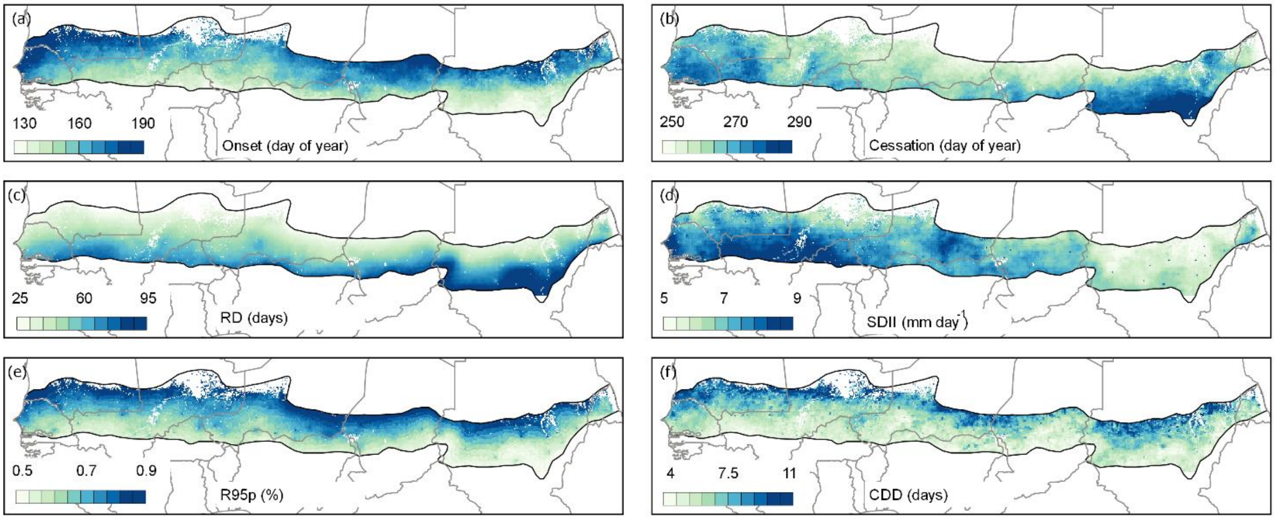


Fig.2. (a) Daily rainfall distribution and (b) anomalous accumulative curve for the grid point 13.5˚ N, 5.0˚ W (shown in Fig. 1) for the year of 2001. The blue line (accumulated anomaly) is computed from a 15-year (2001-2015) average of daily rainfall.



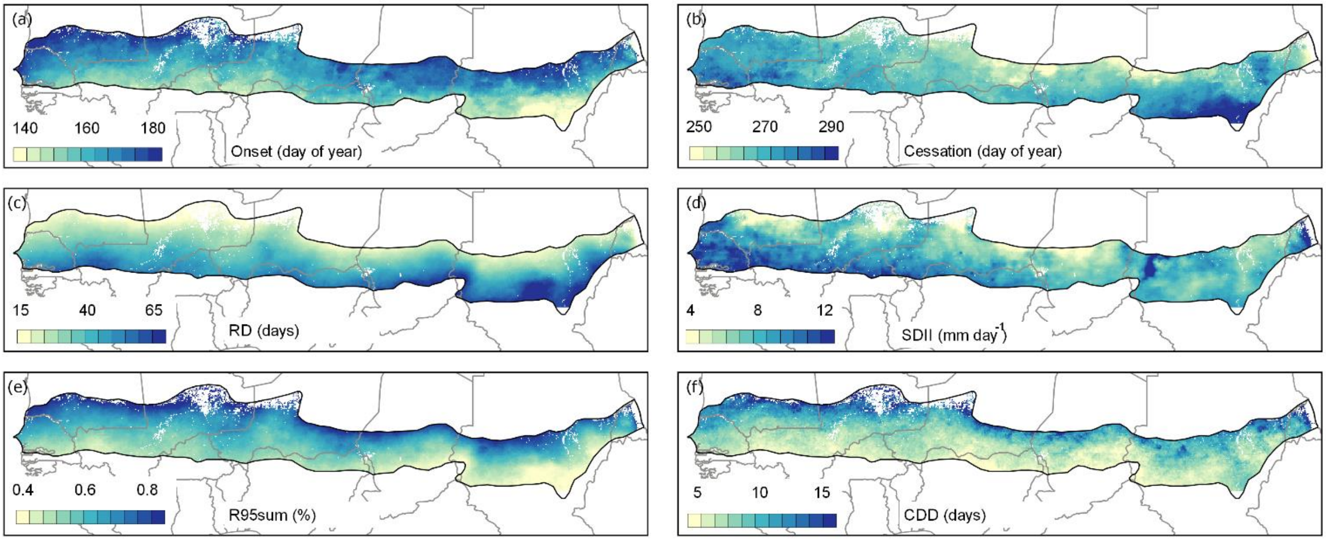
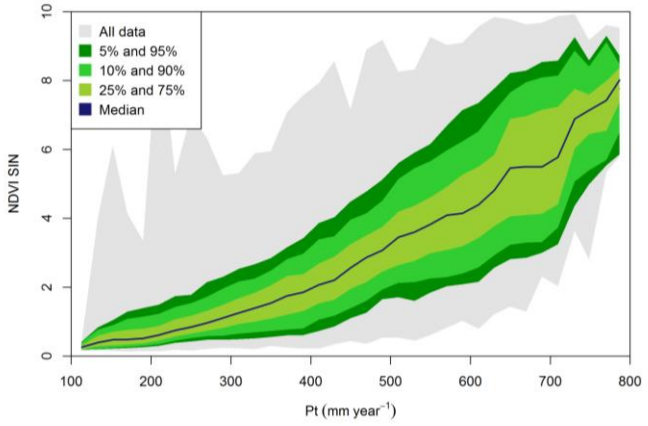


Fig.3. Spatial distribution of average seasonal rainfall metrics a) onset of wet season (day of year); b) cessation of wet season (day of year); c) rainy days (days); d) daily intensity (mm day^{-1}); e) heavy rainfall events (%); f) consecutive dry days (days) based on 15-year averages (2001-2015).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



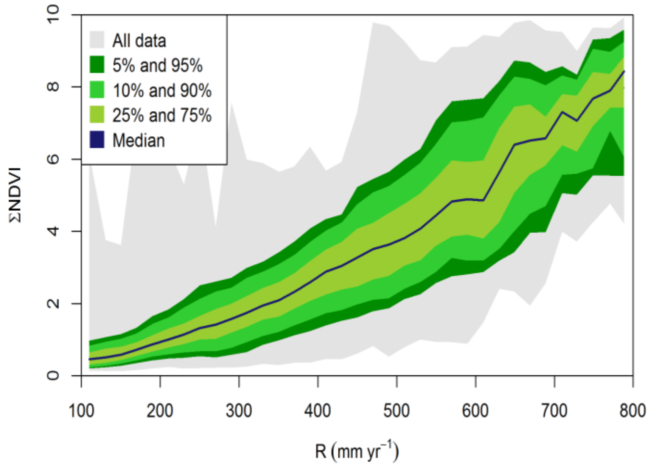
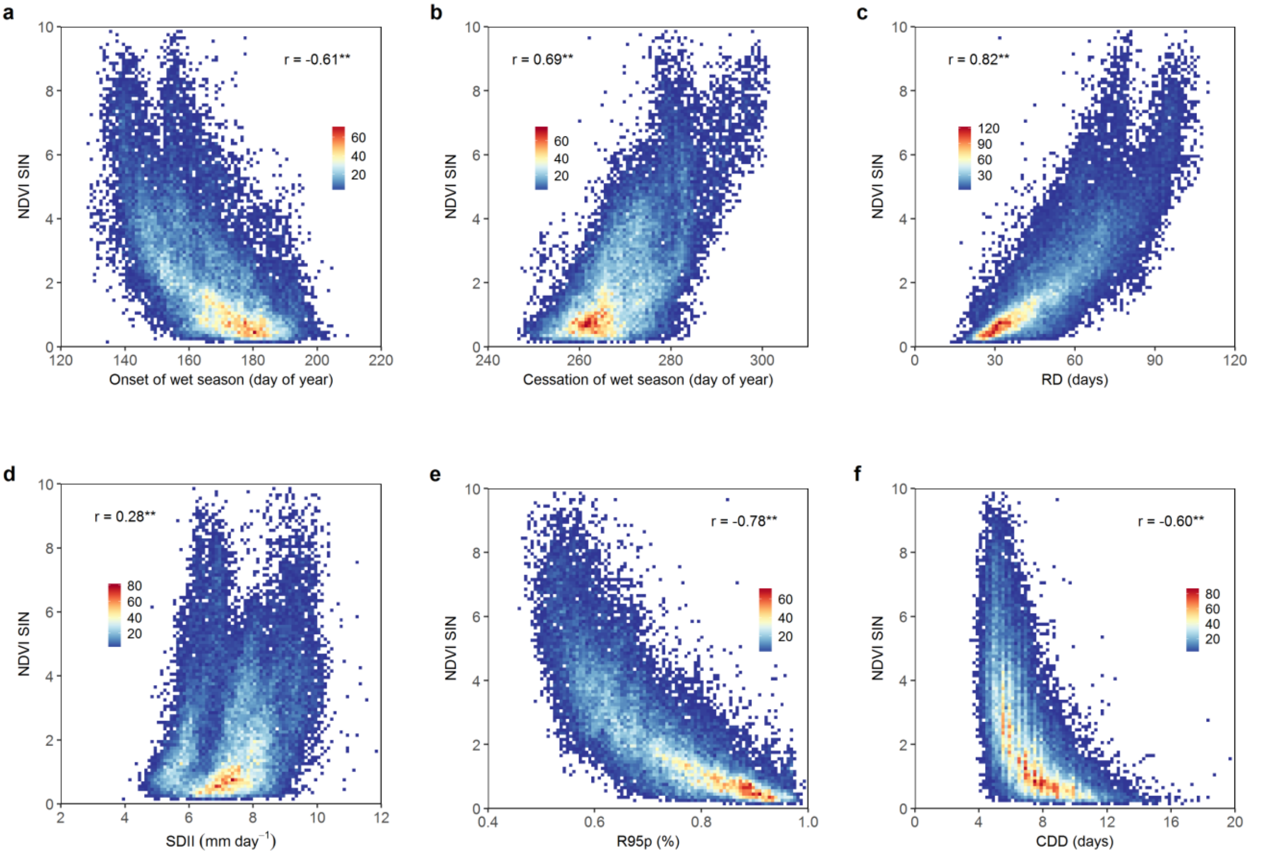


Fig.4. Growing season ANPP (∑NDVI~~ SIN~~) as a function of mean seasonal rainfall amount (~~Pt~~R) plotted as quantiles for the Sahel-Sudanian zone (pixel averages for 2001-2015).


a
r = -0.61**
NDVI SIN
Onset of wet season (day of year)
60
40
20
b
r = 0.69**
NDVI SIN
Cessation of wet season (day of year)
60
40
20
c
r = 0.82**
NDVI SIN
RD (days)
120
90
60
30
d
r = 0.28**
NDVI SIN
SDII (mm day^{-1})
80
60
40
20
e
r = -0.78**
NDVI SIN
R95p (%)
60
40
20
f
r = -0.60**
NDVI SIN
CDD (days)
80
60
40
20

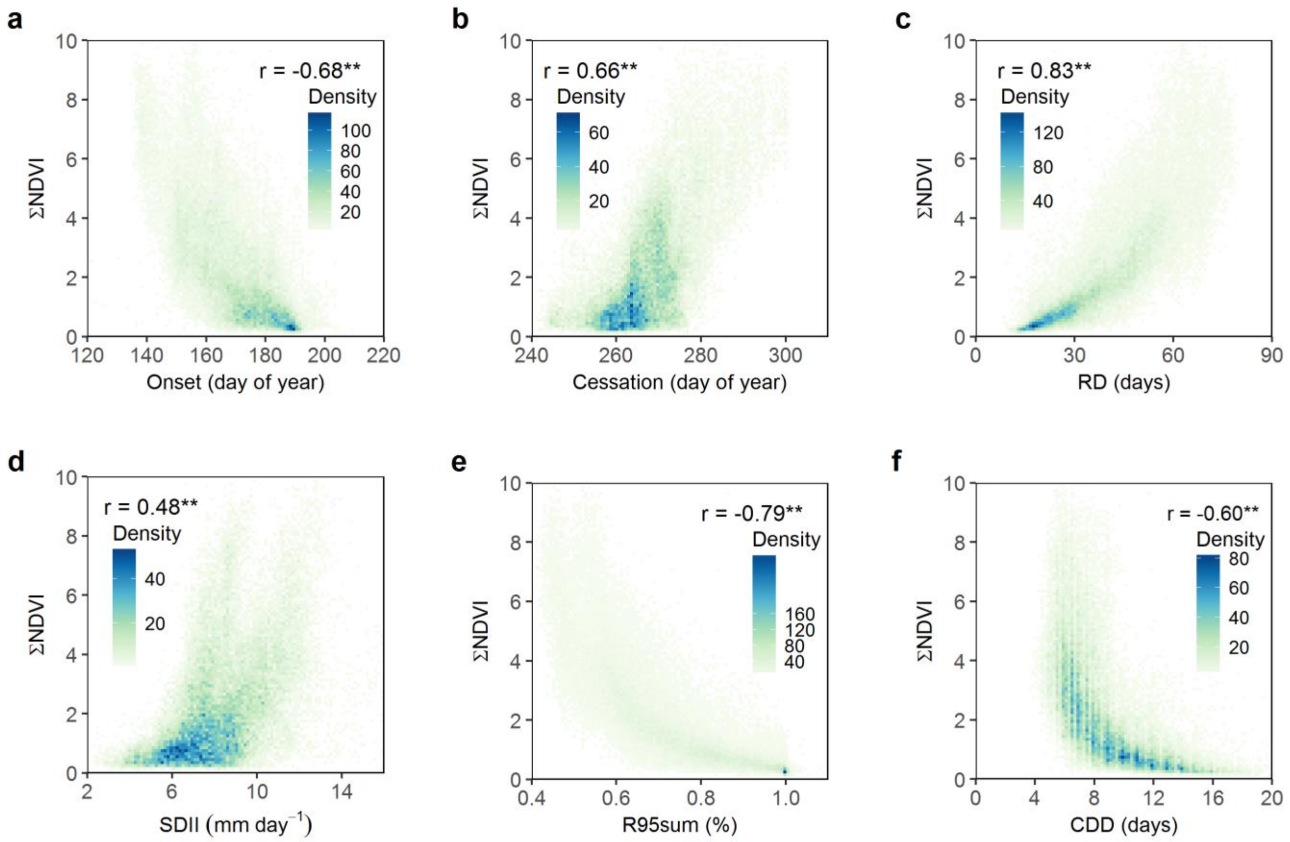
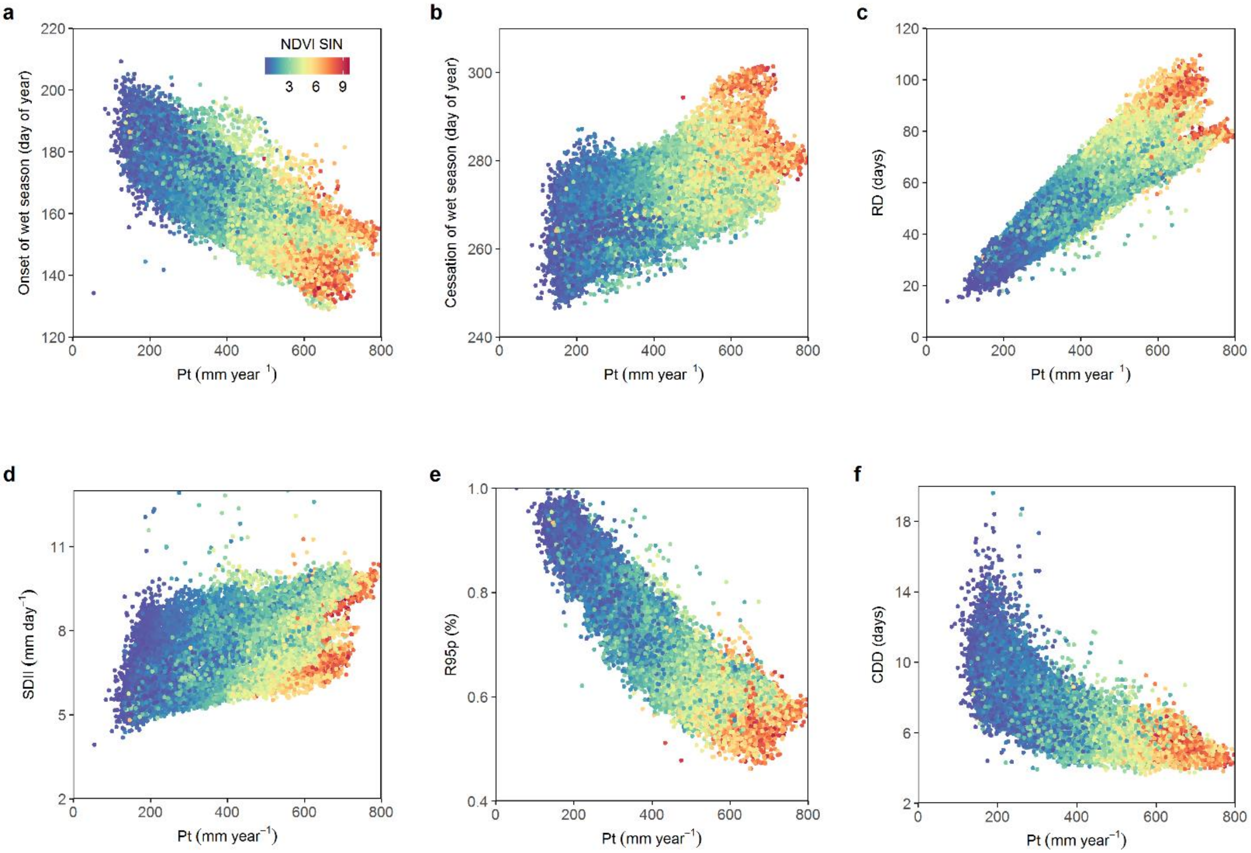


Fig.5. Density scatterplot showing the relationships between rainfall metrics and growing season ANPP (∑NDVI~~ SIN~~). All analyses are based on 15-year averages (2001-2015). ** denotes $p< 0.001$. All points (n=30862) are located between 100 and 800 mm annual rainfall.


a
NDVI SIN
3 6 9
Onset of wet season (day of year)
120 140 160 180 200 220
Pt (mm year⁻¹)
0 200 400 600 800
b
Cessation of wet season (day of year)
240 260 280 300
Pt (mm year⁻¹)
0 200 400 600 800
c
RD (days)
0 20 40 60 80 100 120
Pt (mm year⁻¹)
0 200 400 600 800
d
SDII (mm day⁻¹)
2 5 8 11
Pt (mm year⁻¹)
0 200 400 600 800
e
R95p (%)
0.4 0.6 0.8 1.0
Pt (mm year⁻¹)
0 200 400 600 800
f
CDD (days)
2 6 10 14 18
Pt (mm year⁻¹)
0 200 400 600 800

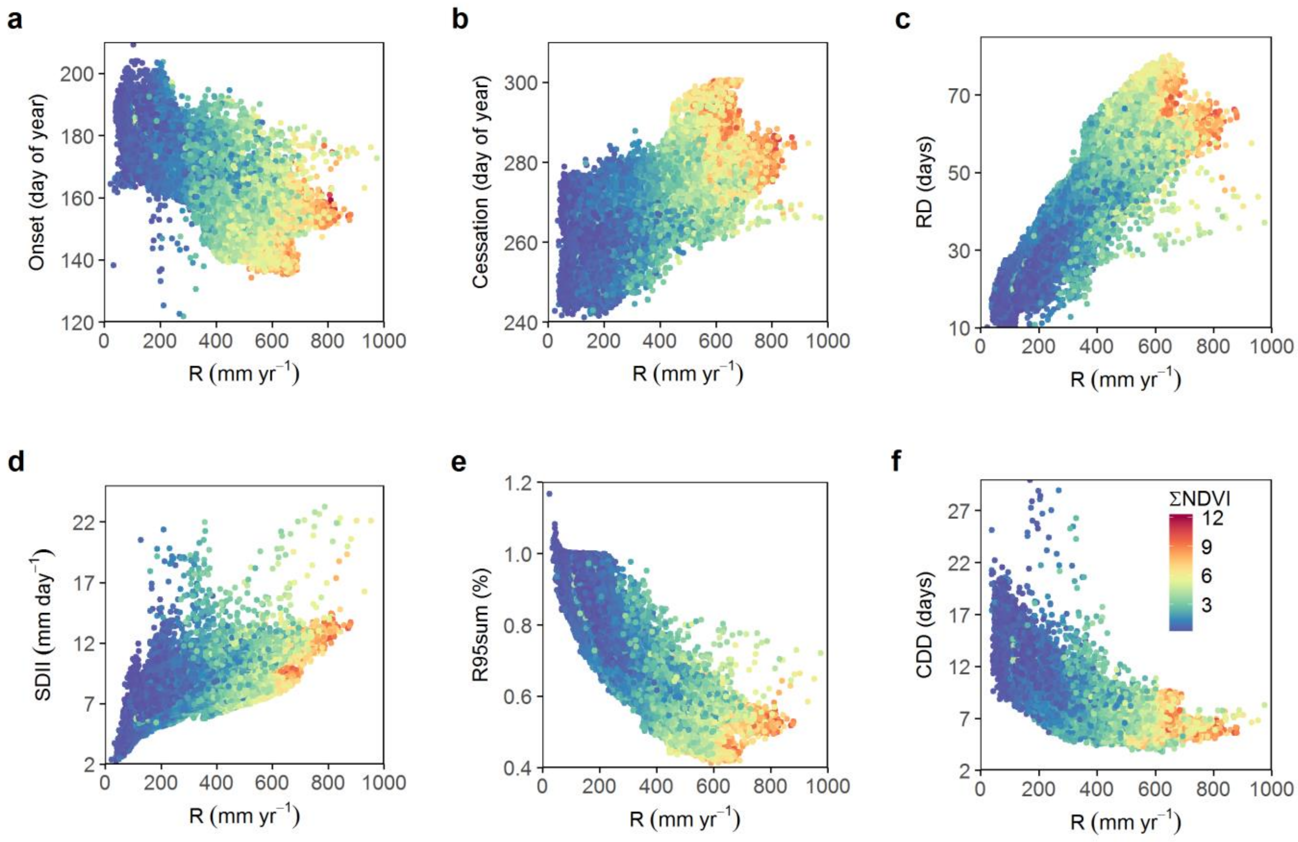
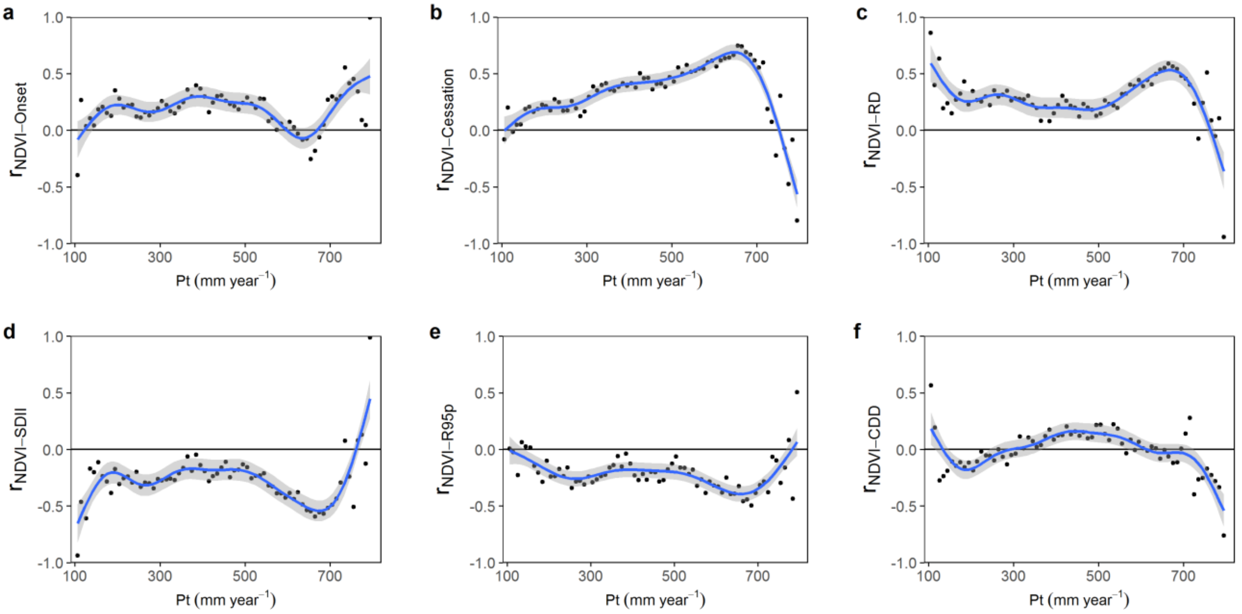


Fig. 6. Relationships between seasonal rainfall metrics and growing season ANPP as a function of seasonal rainfall amount based on 15-year averages (2001-2015).



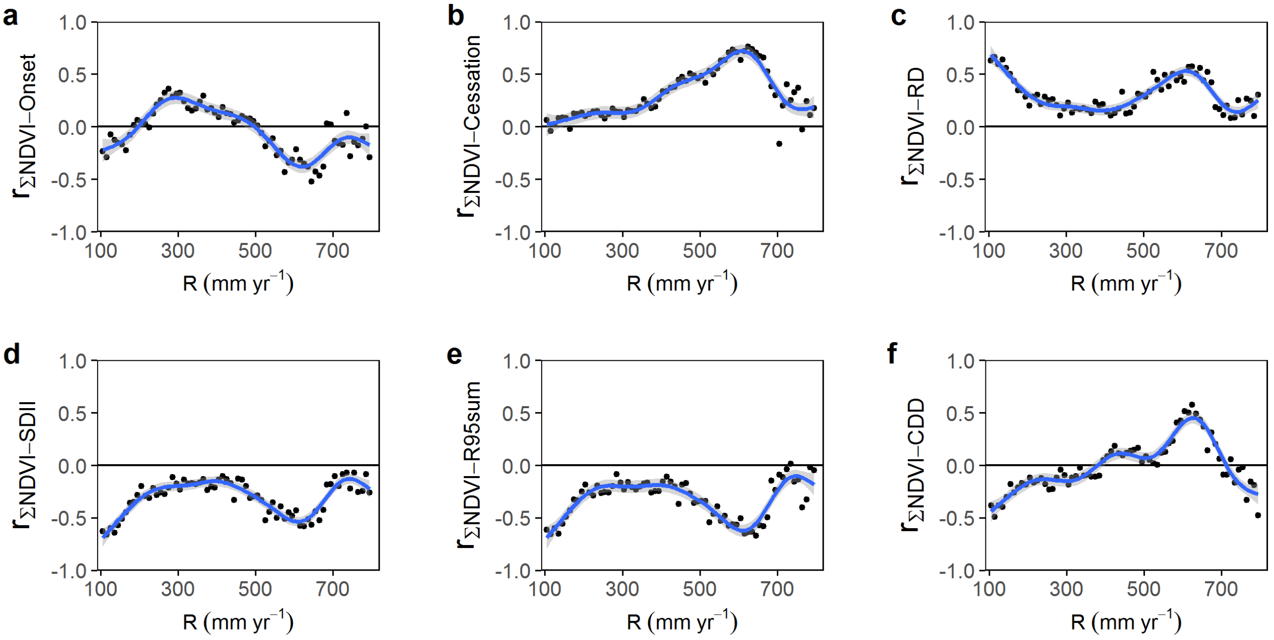
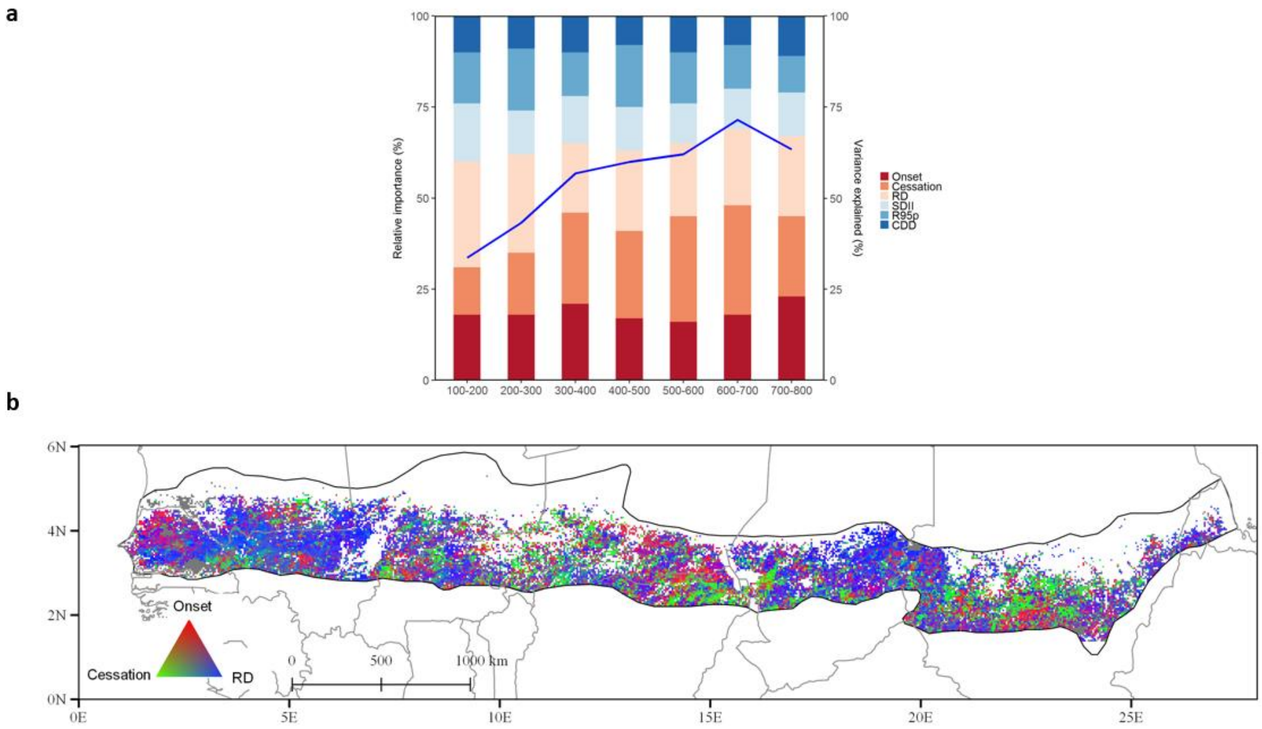


Fig.7. Effects of rainfall metrics on growing season ANPP as a function of seasonal rainfall amount. The Pearson's correlation between growing season ANPP and rainfall metrics are shown for each 10 mm interval. The lines are GAM fitting curves and shading represents the 95% confidence intervals of the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


a
100
75
50
25
0
Relative importance (%)
100-200
200-300
300-400
400-500
500-600
600-700
700-800
100
75
50
25
0
Variance explained (%)
Onset
Cessation
RD
SDII
R95p
CDD
b
6N
4N
2N
0N
0E
5E
10E
15E
20E
25E
Onset
Cessation
RD
0
500
1000 km

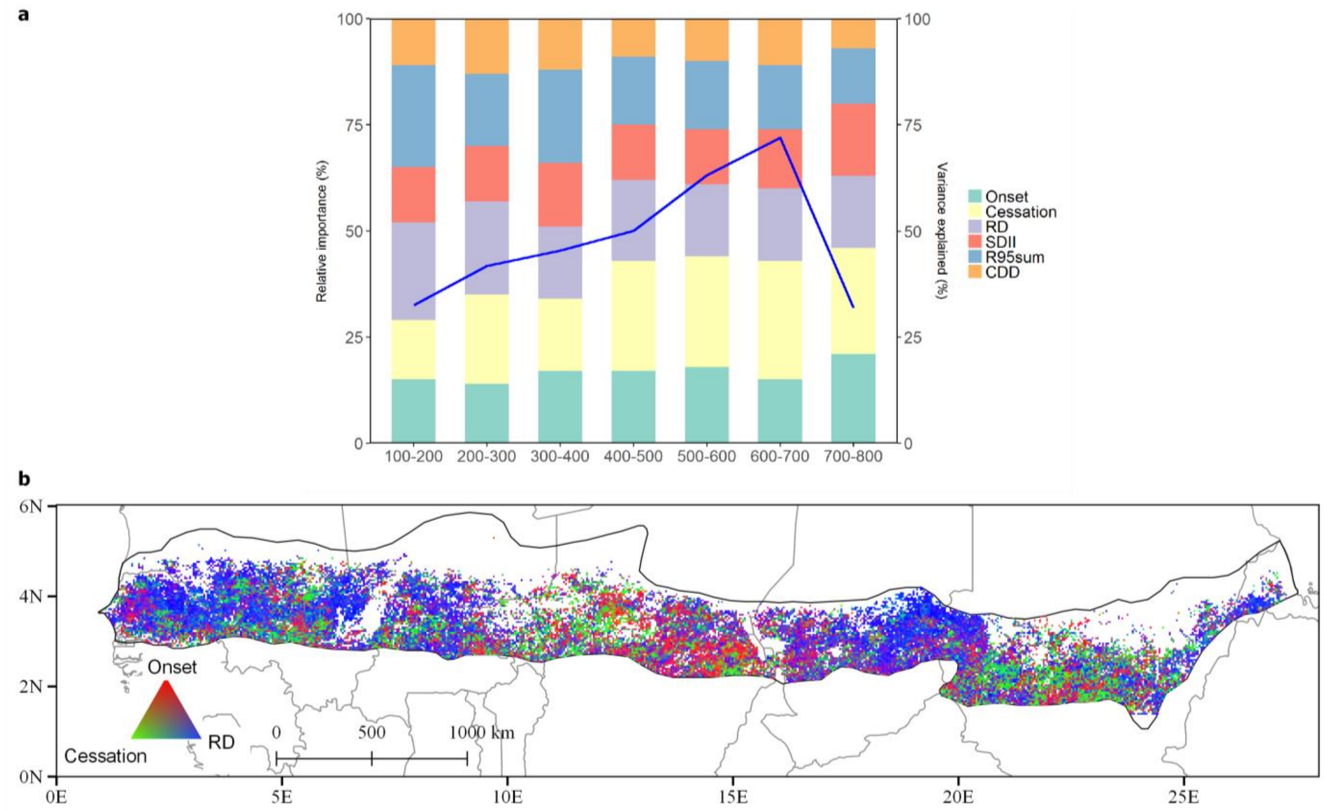
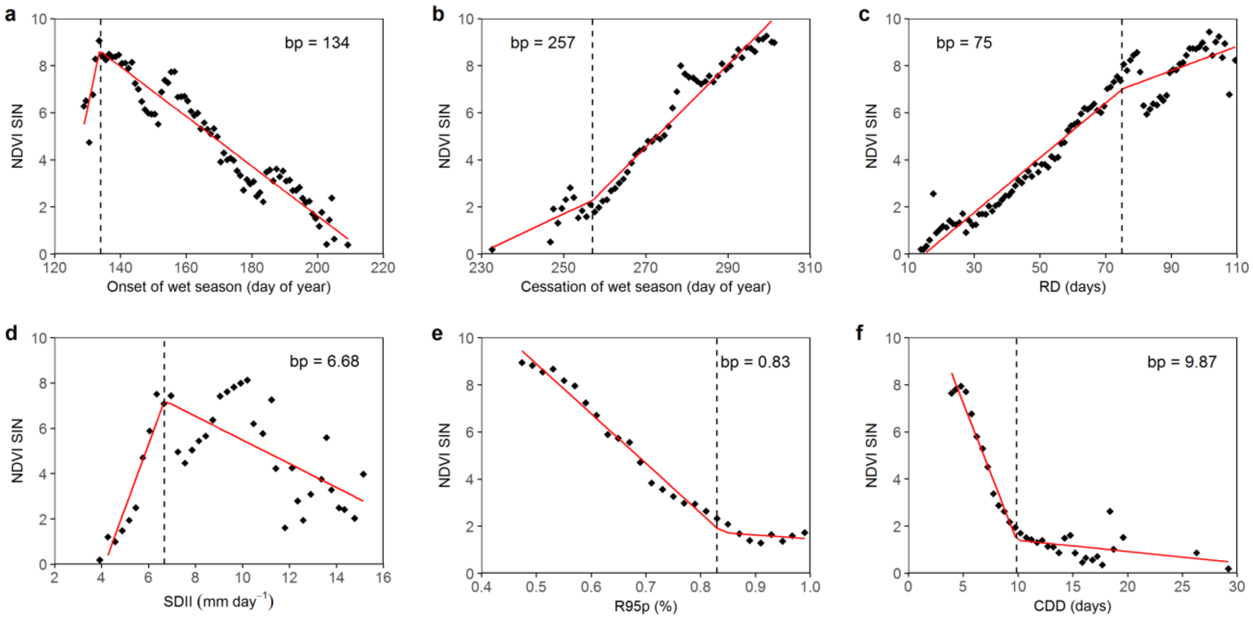


Fig.8. a) Generalized relationships between growing season ANPP and Onset, Cessation, RD, SDII, ~~R95p~~R95sum, CDD as a function of seasonal rainfall amount (100 mm intervals) based on 15-year average values (relative importance in %). The blue line shows the overall variance of growing season ANPP explained by the rainfall metrics per 100 mm seasonal rainfall amount based on the random forest method. b) Spatial distribution of the relative importance of onset, cessation of wet season and rainy days to growing season ANPP for 2001-2015 based on a multiple regression. Pixels within the study area are masked (white color) in accordance with the description in the methods section.



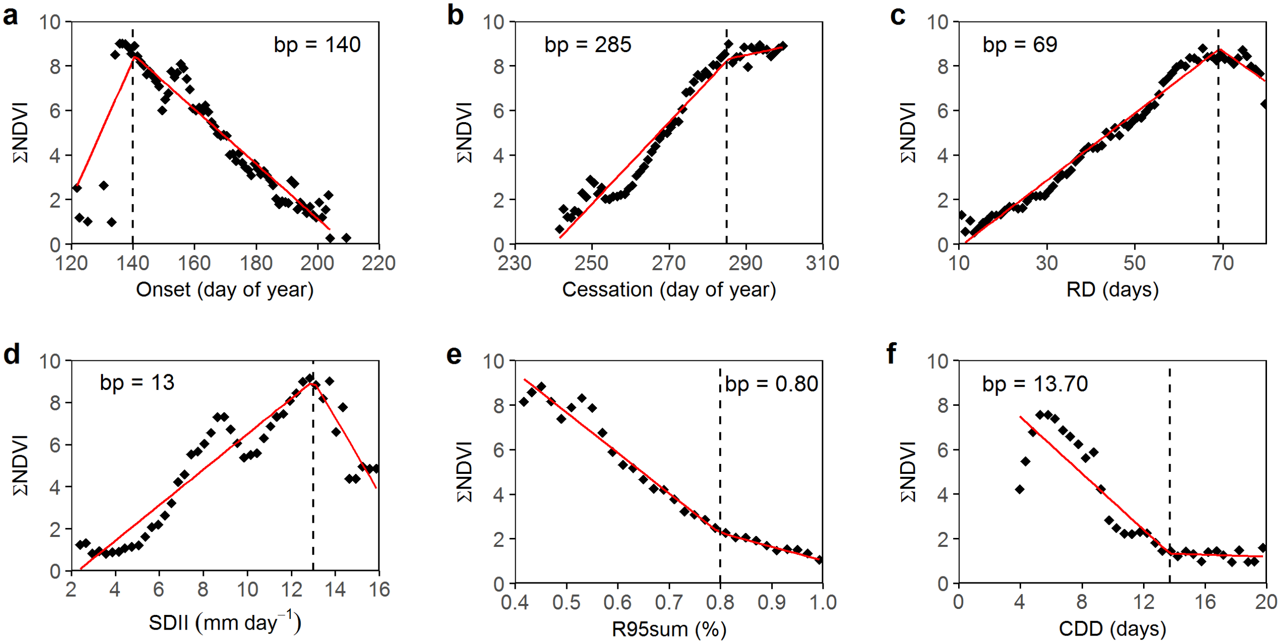


Fig. 9. Growing season ANPP (individual points represent 95th percentile of ∑NDVI~~-SIN~~ value for each rainfall metric bins) plotted against rainfall metrics. Solid red lines denote piecewise regression between growing season ANPP and rainfall metrics and dashed lines indicate the breakpoint (bp) for rainfall individual variables.