Answer to Reviewers

We would like to thank the reviewers for the detailed and constructive reviews. We think that the review suggestions and the revisions as a consequence hereof have substantially improved sections of the discussion and results, as well as figures of the manuscript. We hope that the reviewers find the revised version of the manuscript more balanced in accordance with some of the critique points raised by reviewer#2.

Reviewer #1

This paper presents an original approach to disentangle rainfall effects to other factors such as the grazing on the vegetation dynamics, and particularly the greening trends of the Sahel. It aims to analyze if NDVI data are able to capture variations observed in in situ observations of vegetation caused by rainfall variability and differences in grazing regimes.

I noted that authors have taken into account most of the suggestions made during the first stage of the review process, so I have now just five comments:

1) For the definition of the SoS and EoS of the growing season, you us ed TIMESAT. You used the MODIS NDVI product, but it exists also the MODIS vegetation phenology product providing also estimates of the timing of vegetation phenology. So I wondered why you chosen TIMESAT rather than the existing product?

The MODIS SoS and EoS products are in 500 m resolution and created mainly from 8-day EVI. We want to keep to the 250 m resolution data as this is the only MODIS resolution that is comparable with the smaller ungrazed plots.

2) To found the best parameter for monitoring biomass, you test here each parameter separately. Why you don't test the combination of parameters?

This is a very valid point and multiple regression or PCA analysis is a natural next step. However we feel that this should be thoroughly treated in a separate study and perhaps include biomass sampling from more diverse locations and with less focus on grazing. For this study it is also a point of discussion to keep the NDVI metrics at level with the research gone into identifying the greening of the Sahel, i.e. using a single parameter.

3) You found for your site that the best parameter for monitoring biomass is the small integrated NDVI. Do you think that this will be the case for other Sahelian areas?

For annual herbaceous vegetation, yes, it is reasonable to assume that focusing on the growing season activity represented by the small integrated NDVI should be the best parameter.

4) P11, L26 change 15 and 30% by 15% and 30%

Corrected

5) Last comment, this paper benefits from an important database of field measurements, so it is quite "frustrating" that you used only 8 years of data. I understand the reasons why you don't use AVHRR data but however I wondered if you plan to test also

the possibility of using AVHRR dataset.

This is a good point. The time series from the AVHRR GIMMS3g pixel covering the test site are now included together with site averaged biomass and precipitation.The results of the GIMMS3g comparison with in situ measured biomass have been discussed in the text also, however pointing out that a strict comparison is inadequate due to the spatial scales mismatch.

Reviewer #2.

This paper addresses the impact of grazing intensity and exclosure on the relation between remote sensing data and standing biomass, considered a proxy of above groundnet primary productivity (ANPP). It is based on a very valuable long-term dataset, describedand analysed in Miehe et al 2010, and MODIS data. It proposes a new hypothesisconcerning the Sahelian NDVI trend.

Three main results are shown:

i) Differences are found between exclosures and grazed pastures in terms of biomass, plant species and species traits. It is shown that end-of-season standing biomass is higher for exclosures than for grazed plots, mostly foryears with cumulated rainfall larger than average.

ii) The best NDVI metric to correlate to end-of-season biomass, for both exclosure and grazed pasture, is the NDVI integrated over the growing season (iNDVI).

iii) It is shown that the higher end-of-season standing biomass of exclosures does not translate in a higher iNDVI.

The discussion then suggests that increasing grazing intensity in the Sahel over the last decades may have contributed to the 'regreening' trend observed by satellites. The paper reads well. References are up to date and relevant. Figures are clear (but see below, some figures should be added). It is well suited for Biogeosciences. This study addresses two very important points: first, the impact of free or managed grazing on biomass and productivity, second its impact on NDVI and the possible role of changing grazing intensity on the NDVI trend detected by satellites in the Sahel. It potentially provides an important contribution to the 'Sahel greening' debate and deserves publication. A number of issues have to be addressed before it can be published though.

We would like to take the opportunity to thank the reviewer for the insightful, detailed and constructive comments and suggestions for an improved and more balanced manuscript. We agree with reviewer on more or less all issues raised and believe that the revised version of the manus has largely benefitted from the comments and suggestions.

General comment:

The paper is based on a very valuable dataset that was already analysed in Miehe et al.2010. It is unnecessary to repeat what was done and found before. That should mostly go in the introduction, since it is known already (ex. difference in terms of biomass, effect of rainfall). The paper should focus on what is new: namely the link between field and remote sensing for exclosure and grazed land, and the possible differences. In the same vein, the different metrics have been compared before in the same area (M'Bow et al. 2013 among others). Again, the present paper should focus on what is new: the differences between exclosure and grazed land in terms of these metrics. Some trimming is necessary.

Thanks; the suggested trimming has been done as suggested. Most of the biomass/precipitation differences are now merely described under the site description with reference to Miehe 2010 and a few sentences is provided in the introduction as well. Reviewer 1 suggested that the AVHRR GIMMS pixel values are shown together with biomass and rainfall. While this is not strictly necessary for the grazing issue, it is a good suggestion and will satisfy some curiosity amongst the readers involved in validation of long term dataset. It is however pointed out that a strict comparison is inadequate due to the mismatch of spatial scales between

GIMMS pixel resolution and Widou ground observations. In summary, figure 2 has been kept and improved with the GIMMS3g iNDVI time series, while figure 3A & B are now left out.

The conclusion that changes in grazing intensity may play a role in the NDVI trend is largely unsubstantiated and largely extrapolated. This extrapolation ignores a number of interfering factors. I recommend to better substantiate the results and conclusions and to be more cautious before generalizing. Following are two issues to address so as to reach more solid conclusions.

Going through the manuscript again, we fully agree with this important comment and for that reason we have chosen to substantially change the way the linkage between grazing and the Sahel greening is presented in the discussion since this hypothesis was in fact not supported by the data presented; changes to the revised manus are explained further below.

1) Confusion between ANPP and end-of-season standing biomass. The measurements of end-of-season biomass is a proxy for ANPP. It is best suited for annual vegetation. However, as it is commented in other papers (by Miehe among many others), several factors impact the ANPP/end of season standing biomass: herbivory (grazing, insects etc ...), phenology and measurement dates and frequency. For most studies, these factors are considered negligible, since, for example, they do not change a lot between sites or years. In this study, the very objective is to address the impact of differences in grazing intensity and species composition, therefore these factors have to be discussed.

We thank the reviewer for this comment. We acknowledge that this is an important difference when the aim is to study differences in grazed and non-grazed biomass. We have chosen to use a consistent terminology throughout the manuscript by using the term "end of season standing biomass" (abbreviated as ESSB in the revised manus) since this reflects more accurately what has been measured at the site over the years studied. The difference between ANPP and ESSB has been explained more thoroughly in the "field data" section (ESSB being used as a proxy for ANNP) – furthermore the timing of ESSB sampling are discussed in the context of changes in species as pointed out by the reviewer (see below).

There are already some elements in the text (in the discussion section), which try to estimate ingestion by cattle. In my opinion, this deserves a full treament, with a description of methods, data and results. I acknowledge it is a difficult task. However, it needs to be addressed to support the conclusions on the impact of grazing on ANPP (note also that ingestion is not the only effect. Trampling also occurs). Some words on the consequence of changing leaf lifespan on the date of peak biomass may be needed also. If exclosure plants have higher lifespan, does that mean that late september biomass data are closer to ANPP than for exclosure than for grazed pastures? Is there 2-year old plant matter (e.g. litter, straws) that should be removed from ANPP. All over the text, there is a need to distinguish ANPP from end-of-season aboveground biomass (do not use productivity or production when end-of-season biomass is the variable or provide corrected estimates of ANPP).

Again, we acknowledge the reviewer comment on this. However, the full data required to address and adjust for the difference between "end of season standing biomass" and ANPP do not exist for this site. Unfortunately estimates of trampling and ingestion do not exist in more detail than already put into the discussion. We have chosen to include the information about livestock ingestion in the section of field data with a reference to the publication by Miehe et al 2010 including this information. This information is used to show that the ESSB sampled in grazing exclosures are orders of magnitude higher than the value expected to be ingested by livestock from the current stocking densities. We believe that this is as far as we can go based on the available data, but the point that the difference between ESSB for grazed and non-grazed areas by far exceed the quantity expected to be ingested by livestock has been made more clear in abstract and conclusion.

2) More important: The possible impact of changes in grazing intensities on the NDVI Sahel trend is not really substantiated. The results nicely show that NDVI / biomass relationship is different for exclosure compared to two different grazing systems. One can conclude that there is no significant differences betyween the grazed plots (communal versus controlled), despite different grazing intensities. Then, if the (un-cultivated) Sahel as a whole is considered a 'grazed' area over the last decades, as opposed to a large exclosure in 1984 becoming progressively grazed, we can draw the opposite conclusion: 'Changing grazing intensity is NOT responsible for NDVI trends in the Sahel'.

This is a crucial point and again we fully acknowledge the critique by reviewer that the conclusion was in fact not supported by empirical evidence. We have discussed this amongst authors and a large amount of text has been changed in the revised manuscript (in particular the abstract, discussion and conclusion) to make it more clear what can concluded from the Widou data presented and what is merely hypotheses that can/should be studied further with the availability of appropriate datasets.

I recommend to revise the discussion/conclusion of the paper, based on more substantiated findings, and I recommend to have a much more balanced conclusion.

We have done so and hope that reviewer agrees that the revised manuscript appears more balanced in the sense that we do not claim anymore that the data presented here supports that grazing will cause a greener Sahel. What can be concluded from the data presented is nicely summarized by reviewer in the beginning of the reviewer comments and the discussion of the impact on EO greening of Widou/Sahelian rangelands from changes in grazing, is kept as discussion items not claimed to be supported by the ground observations.

Minor comments:

1) The influence of grazing intensity on NPP estimates found by other authors is not always in line whith what is reported here (decrease of NPP du to grazing). For instance, see Hiernaux et al. 2009, J. Hydrology for similar ecosytems. Please moderate/change your statement.

Thank you for pointing this out. The statement has been modified to include points from this publication:
Hiernaux, P. Mougin, E., Diarra, L., Soumaguel, N., Lavenu, F., Tracol, Y. and Diawara, M., 2009, Sahelian rangeland response to changes in rainfall over two decades in the Gourma region, Mali: Journal of Hydrology, v. 375, p. 114-127.

2) Exclosure is a very atypical situation in the Sahel. The nature of such exclosures deserve some comments. In my opinion, a catlle-free Sahel would not look like (firefree) exclosures. The difference between communal and controlled grazing makes probably more sense.

This is of course a very valid point, and it should already have been mentioned in the text. It has been added to the discussion.

3) The differences in biomass / iNDVI for the different plots is really interesting. A figure with ANPP / iNDVI would be nice (in addition to endèof-season-biomass/iNDVI), whith estimates of grazing and phenology influences to correct ANPP as much as possible. I was wondering if the differences would still significant when such corrections are accounted for. Also, it seems that one year is largely driving the correlation for

exclosure (do the results still hold wihtout that year, in terms of different relationships between the plots, after correction for herbivory/trampling effects ?) Consider also including figures with average annual cycle of NDVI for the plots, as an illustration of the differences (or the absence of).

This is a valid point as well, but unfortunately apart from the estimation of ingestion already mentioned in the discussion, we have no solid data/methods available to convert standing crop into ANPP. Therefore the wording of the text has been changed to reflect this by writing "ESSB" instead.

4) Are there any data or literature results on the optical properties of the exclosure plots? That would feed a nice discussion. Differences in canopee architecture ?LAI ?leaf optical properties ? Nitrogen content?

Yes this is a very important point. Unfortunately we do not have detailed information on this and without this information there is no empirical support (in the Widou data presented) for the linkage between species composition and the impact on seasonally integrated NDVI. For this reason we have based a part of the discussion on the results reported by Mbow et al. (2013) where such data is available from the Dahra site.

5) A number of statements have to be down-toned or reformulated. For instance 'It is beyond doubts that the increasing population in Sahel and the widespread practice of pastoralism has caused a signifcant increase in livestock over the recent decades (Ickowicz et al. 2012)'. I would be much more cautious, as real figures for livestock are extremely local or often unaccurate, to say the least (except maybe in some places with sedentary cattle, like the Ferlo ?). Also, in agropastoral Sahel, increase in population is not always accompanied by increase in livestock, you may have less land available for grazing.
The last two sentences of the discussions are questionable also. In some places, NDVI trend has already been shown to correspond to herbaceous biomass and ANPP trends (long term field and satellite studies, papers by Dardel et al., among others for recent studies).

Yes agreed, the statements mentioned have been toned down or changed (see also answer to 2. major point of review). The study of Dardel 2014 was already included but has been additionally used in the text.

Beside, I don't see why the Olsen et al. paper is in line with the paper on trees in the Sahel. In region where tree cover is less than 5%, iNDVI has not been shown to depend on tree cover changes (neither chnages in magnitude, nor in specific composition), as far as I know. Please explain. The term 'improvement' needs to be defined in a scientific way, if to be used in a discussion like this (Biodiversity? Productivity?People income? Livestock ?).

Ok this part has now been removed from the paper, but as reviewer is aware (we believe☺) new research from Brandt et al. (some published – some in prep) is looking into these interesting issues in relation to the greening debate.

6) A technical question, of minor importance. There may be a pixel-size issue, when large view angle MODIS data are plotted against field data. The authors may want to consider only near-nadir data. That may event improve their results. Perhaps this has been looked at already.

Yes, this is a question that is/have being studied amongst the co-authors and reviewer is right that the angular effect is of importance when calculating seasonal metrics from MODIS index data in the Sahel. In this study we have chosen to be on the "safe side" by using fitting algorithms based on the MODIS standard product that does already to some degree incorporate selection of low view angles in the composting scheme (the one observation with the lowest view angle out of the two highest NDVI observations in a given *composite period is selected). The MODIS BRDF corrected product could as well have been selected for the current study – however it is expected that the curve-fitting performed when using the TIMESAT software for calculating the NDVI seasonal metrics does mitigate this issue of off-nadir measurements.*

For these reasons, I recommend 'major revisions' to the manuscript.

Does ~~Vegetation Parameterization from~~ EO NDVI ~~Data~~ Seasonal Metrics Capture Variations in Species Composition and Biomass due to Grazing in Semi-Arid Grassland Savanna?

Olsen, J.L.[1], Miehe, S.[2], Ceccato, P.[3], Fensholt, R.[1]

1: Department of Geosciences and Natural Resource Management, University of Copenhagen.
Rolighedsvej 23
1958 Frederiksberg C
Denmark
E-mails: jlo@ign.ku.dk (Olsen, J.L.), rf@ign.ku.dk (Fensholt, R.)

2: Faculty of Geography, Philipps-University.
Biegestraβe 10
D-35032 Marburg
Germany
E-mail: **Sabine.Miehe@gmx.net** (Miehe, S.)

3: The International Research Institute, Columbia University.
61 Route 9W
Palisades, NY 10964
USA
E-mail: **pceccato@iri.columbia.edu** (Ceccato, P.)

Abstract

Most regional scale studies of vegetation in the Sahel have been based on Earth Observation (EO) imagery, due to the limited number of sites providing continuous and long term *in situ* meteorological and vegetation measurements. From long time series of coarse resolution normalized difference vegetation index (NDVI) data a greening of the Sahel since the 1980s has been identified. ~~The greening appears highly related to a general increase in rainfall following the severe droughts of the 1970s and 80s. In the same time period the region has experienced a drastic population boom and a resulting increase in numbers of livestock.~~ However, it is poorly understood how commonly applied remote sensing techniques reflect the ~~extensive~~ influence of extensive grazing (and changes in grazing pressure) on natural rangeland vegetation. This paper analyses time series of ~~parameterized~~ Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI ~~data~~ metrics by comparison with data from the Widou Thiengoly test site in northern Senegal. Field data include grazing intensity, end of season standing biomass (ESSB)~~vegetation productivity,~~ and species composition from sizeable areas suitable for comparison with moderate - coarse resolution satellite imagery. It is ~~established~~ shown that sampling plots excluded from grazing have a ~~higher Net Primary Production (NPP) and~~ different species composition characterized by a longer growth cycle as compared to plots under controlled grazing or communal grazing. Also substantially higher ESSB is observed for grazing exclosures as compared to grazed areas, exceeding substantially the amount of biomass expected to be ingested by livestock for this area. The seasonal ~~small~~ integrated NDVI (NDVI small integral; capturing only the signal inherent to the growing season recurrent vegetation), derived using absolute thresholds to estimate start and end of growing seasons, is identified as the ~~parameter~~ metric most strongly related to ~~vegetation productivity~~ESSB for all grazing regimes. However plot-pixel comparisons demonstrate~~s~~ how the NDVI/~~biomass~~ ESSB relationship changes due to grazing induced variation in annual plant species composition and the NDVI values for grazed plots are only slightly lower than the values observed for the ungrazed plots. Hence, average ~~biomass~~ ESSB in ungrazed plots since 2000 was 0.93 tons/hectare, compared to 0.51 tons/hectare for plots subjected to controlled grazing and 0.49 tons/hectare for

communally grazed plots, but the average integrated NDVI values for the same period were 1.56, 1.49, and 1.45 for ungrazed, controlled and communal respectively, i.e. a much smaller difference. This indicates that a grazing induced development towards less ~~standing crop biomass~~ESSB and shorter cycled annual plants ~~and~~ with ~~limited~~ reduced ability to turn additional water in wet years into biomass is not adequately captured by seasonal NDVI metrics.

Keywords; biomass, ~~Senegal,~~ *in situ* measurements, MODIS, satellite data, Senegal,~~MODIS~~

1. *Introduction*

The need for long time series of data on a regional scale to monitor vegetation development in the semi-arid Sahel is crucial, since this region has been characterized by high variability in rainfall (Nicholson et al., 1990) combined with an increasing population (Ickowicz et al., 2012) over the last decades. Much research on resource availability and land degradation have been based on time series of medium and low spatial resolution Earth observation (EO) data spurred by the limited amount of ground based long-term data for this region. Long term EO datasets of vegetation indices (VI's) derived from satellite based optical sensors have been used over many years to estimate ground based vegetation ~~parameters~~ metrics such as composition, biomass and Sahelian vegetation resource availability (Tucker, 1978; Tucker, 1979; Anyamba and Tucker, 2005; Herrmann et al., 2005; Olsson et al., 2005; Seaquist et al., 2006; ~~Olsson et al., 2005;~~ Heumann et al., 2007; Fensholt and Rasmussen, 2011; ~~Herrmann et al., 2005;~~ Fensholt and Proud, 2012~~; Fensholt and Rasmussen, 2011; Anyamba and Tucker, 2005; Tucker, 1978; Tucker, 1979~~). Especially~~,~~, for herbaceous vegetation dominated by annual plant species, ~~has been found to have~~ a strong relation~~s~~ between *in situ* measured ~~biophysical parameters~~biomass (end of season standing biomass (ESSB) is often used as a proxy for aboveground net primary production (ANPP)) and commonly used vegetation sensitive indices such as the normalized difference vegetation index (NDVI) has been found (Tucker et al., 1985; Prince, 1991a; Prince, 1991b; Dardel et al., 2014~~; Prince, 1991b; Prince, 1991a; Tucker et al., 1985~~). For an adequate interpretation of vegetation ~~evolution~~change studies, the ~~heavy reliance~~dependency on remote sensing for large scale and long term studies makes it important to have a clear understanding of how vegetation properties are derived from the often coarse spatial resolution data and the potential implications of working with EO based proxies for vegetation productivity.

Numerous studies have used vegetation indices (in particular the NDVI) ~~integrated over the growing season ((Budde et al., 2004; Anyamba and Tucker, 2005; Fensholt et al., 2009)),~~ as a proxy for vegetation productivity in semi-arid environments ~~(~~(Tucker et al., 1986; Prince, 1991a; Prince, 1991b; Rasmussen, 1998; ~~Prince, 1991a;~~ Milich and Weiss, 2000; Anyamba and Tucker, 2005; ~~Rasmussen, 1998;~~Fensholt et al., 2009)~~)~~. Inter-comparison of NDVI trends in Sahel between products from AVHRR, MODIS terra, and SPOT VGT has been conducted (Fensholt et al., 2009). While it was found that trend patterns were not identical between sensors, annual average NDVI from all three products compared reasonably well to *in situ* NDVI measurements from the Dahra field site in northern Senegal from 2002 to 2007. Using MODIS NDVI as reference, the coarse resolution GIMMS AVHRR data was found to be well suited for long term vegetation studies in Sahel-Sudanian areas receiving less than 1000 mm/year of precipitation.

It is well documented that the relationship between integrated NDVI and herbaceous Aboveground Net Primary Production (ANPP) is empirically based and varies as a function vegetation structure (see e.g. (~~Wessels et al., 2006;~~ Prince and Goward, 1995; Prince et al., 1995; Prince and Goward, 1996; Goetz et al., 1999; Wessels et al., 2006)). For instance early studies by ~~(~~Tucker et al. ~~,~~(1985) and ~~(~~Prince ~~,~~(1991a) found a moderate linear relationship between the satellite observations of VI's and the seasonal primary production based on NOAA AVHRR data for vegetation monitoring in the Sahel. For areas of pronounced seasonality, like the semi-arid Sahel, it is generally accepted that the most accurate EO-based estimates of annual ANPP is obtained if the satellite signal derived from the dry season is omitted and preferably information derived only from the growing season is considered (Mbow et al., 2013). However, this can be done in multiple ways and several studies focusing on the Sahelian region have extracted and used different EO-based characterisations of the annual vegetation growth (Eklundh and Olsson, 2003; Olsson et al., 2005; Heumann et al., 2007; Fensholt and Proud, 2012; Fensholt et al., 2013~~; Heumann et al., 2007; Olsson et al., 2005~~). At current state there is no consensus about which NDVI metric should be used as a proxy for annual ANPP, and vegetation metrics related to NDVI amplitude, length of growing season, or different ways of calculating the growing season integral, have all been suggested ~~-~~(~~de Jong et al. 2011;~~ Eklundh and Olsson, 2003; Olsson et al., 2005; Heumann et al., 2007; de Jong et al., 2011; Fensholt and Proud, 2012; Fensholt et al., 2013~~; Heumann et al. 2007; Olsson et al. 2005~~).

~~Inter-comparison of NDVI trends in Sahel between products from AVHRR, MODIS terra, and SPOT VGT has been conducted (Fensholt et al., 2009). While it was found that trend patterns were not identical between sensors, annual average NDVI from all three products compared reasonably well to in situ NDVI measurements from the Dahra field site in northern Senegal from 2002 to 2007. Using MODIS NDVI as reference, the coarse resolution GIMMS AVHRR data was found to be well suited for long term vegetation studies in Sahel-Sudanian areas receiving less than 1000 mm/year of precipitation.~~

~~For areas of pronounced seasonality, like the semi-arid Sahel, it is generally accepted that the most accurate EO-based estimates of annual ANPP is obtained if the satellite signal derived from the dry season is omitted and preferably information derived only from the growing season is considered (Mbow et al., 2013). Several studies focusing on the Sahelian region have extracted and used different EO-based characterisations of the annual vegetation growth (Eklundh and Olsson, 2003; Fensholt and Proud, 2012; Fensholt et al., 2013; Heumann et al., 2007; Olsson et al., 2005). The type of time series parameterization functioning as the best proxy for annual ANPP is however not agreed upon and vegetation measurements related to NDVI amplitude, length of growing season, or different ways of calculating the growing season integral, have all~~

~~been suggested.~~Precipitation/vegetation interaction has been studied using NDVI (Nicholson et al., 1990; Herrmann et al., 2005; Huber et al., 2011) and NDVI has also been used to investigate inter-annual carry-over effects (Martiny et al., 2005; Camberlin et al., 2007; Philippon et al., 2007; Philippon et al., 2009~~;~~ ~~Martiny et al., 2005; Camberlin et al., 2007~~) and for disentanglement of climate and human influence (Wessels et al., 2007; Seaquist et al., 2009~~; Wessels et al., 2007~~). Although water is the primary limiting factor for vegetation growth in the Sahel (Eagleson, 1982) and precipitation amounts and patterns have been found to influence both NPP and species composition of grasslands (Knapp et al., 2002; Wezel and Schlecht, 2004), the effects of grazing are also acknowledged to have large impacts on herbaceous vegetation in terms of both NPP, ~~standing crop~~ESSB, and species composition (Breman and Cisse, 1977; Hiernaux and Turner, 1996; Hiernaux, 1998;~~ Hiernaux and Turner, 1996;~~ Miehe et al., 2010). Recent research based on *in situ* measurements of NDVI suggests that inter-annual variation of species composition may have a large influence on the relationship between NPP and NDVI (Mbow et al., 2013). As managed grazing and pastoralism is the dominant livelihood strategy in the Sahel and in drylands in general (Asner et al., 2004), it is important to analyze and understand the impact from grazing on EO-based vegetation indices. ~~This could lead to an improved basis for interpretations of vegetation trends as reported in the recent greening of the Sahel (Olsson et al., 2005; Herrmann et al., 2005; Fuller, 1998; Fensholt and Rasmussen, 2011).~~

Much research has studied the influence of both climatic and anthropogenic factors on vegetation evolution in the Sahel. While this research includes ~~vegetation~~ studies based on field and experimental data (Elberse and Breman, 1989; Elberse and Breman, 1990; Hiernaux and Turner, 1996; Hiernaux, 1998; Hiernaux et al., 1999; Oba et al., 2000; Wezel and Schlecht, 2004; ~~Hiernaux and Turner, 1996; Hiernaux, 1998;~~ Miehe et al., 2010; ~~Hiernaux et al., 1999; Elberse and Breman, 1989; Elberse and Breman, 1990; Oba et al., 2000;~~ Dardel et al., 2014), as well as remote sensing data (Fuller, 1998; Anyamba et al., 2005; Herrmann et al., 2005; Olsson et al., 2005; ~~Herrmann et al., 2005; Fuller, 1998;~~ Fensholt et al., 2009; Fensholt and Rasmussen, 2011~~; Anyamba et al., 2005; Fensholt et al., 2009~~), the recent greening of the Sahel found from statistically significant trends in time series of AVHRR GIMMS data (Eklundh and Olsson, 2003; Herrmann et al., 2005; Olsson et al., 2005~~; Eklundh and Olsson, 2003~~) has evoked questions as to what processes on the ground actually reflects these changes (Begue et al., 2011; Herrmann and Tappan, 2013~~; Begue et al., 2011~~). Inter-comparison of NDVI trends in Sahel between products from AVHRR, MODIS terra, and SPOT VGT has been conducted (Fensholt et al., 2009). While it was found that trend patterns were not identical between sensors, annual average NDVI from all three products compared reasonably well to in situ NDVI measurements from the Dahra field site in northern Senegal from 2002 to 2007. Using MODIS NDVI as reference, the coarse resolution GIMMS AVHRR data was found to be well suited for long term vegetation studies in Sahel-Sudanian areas receiving less than 1000 mm/year of precipitation.

For areas of pronounced seasonality, like the semi-arid Sahel, it is generally accepted that the most accurate EO-based estimates of annual ANPP is obtained if the satellite signal derived from the dry season is omitted and preferably information derived only from the growing season is considered (Mbow et al., 2013). Several studies focusing on the Sahelian region have extracted and used different EO-based characterisations of the annual vegetation growth (Eklundh and Olsson, 2003; Fensholt and Proud, 2012; Fensholt et al., 2013; Heumann et al., 2007; Olsson et al., 2005). The type of time series parameterization functioning as the best proxy for annual ANPP is however not agreed upon and vegetation measurements related to NDVI amplitude, length of growing season, or different ways of calculating the growing season integral, have all been suggested.

The objective of this study is to examine whether appropriate time series parameterization of the EO-based vegetation index NDVI can adequately capture variations in *in situ* measured vegetation abundance and species composition, caused by inter-annual rainfall variability and differences in grazing regimes under identical soil and meteorological conditions.

In general there is a scarcity of *in situ* measurements suitable for comparison with remote sensing images in the semi-arid grassland savanna. Data gathered under controlled stocking conditions, over long time spans, and covering large enough areas to effectively measure the effects of different grazing intensities are scarce. We accessed and examined 27 years of standing herbaceous biomass and several years of species composition measurements from multiple sampling plots at the WidouThiengoly test site in Northern Senegal. For this purpose the data from Widou Thiengoly test site in Northern Senegal are unique and offers the possibility for comparing plot measurements with pixel derived values from sensors at medium spatial resolution. We accessed and examined 27 years of ~~standing~~ herbaceous ~~biomass~~ESSB and several years of species composition measurements from multiple sampling plots at ~~the~~ Widou Thiengoly ~~test site in Northern Senegal~~. We compared and analyzed the field measurements with the growing season vegetation ~~parameters~~ metrics derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument.

The specific objective of this study is to examine whether appropriate time series parameterization of the EO-based vegetation index NDVI can adequately capture variations in *in situ* measured vegetation abundance and species composition, caused by inter-annual rainfall variability and differences in grazing regimes under identical soil and meteorological conditions.

2. *Site*

The Widou Thiengoly test site, also described in (Miehe et al., 2010), is located in the Ferlo region in northern Senegal (15°59’N, 15°19’W). The fenced paddock area measures 7.6 km from its northernmost to southernmost point and is 2.1 km wide (Figure 1). The site is located south of the Widou Thiengoly deep well, with the northern tip just a few hundred meters from the well and village areas. The soil is Cambic Arenosol according to FAO soil map (FAO IUSS Working Group WRB, 2006; FAO, 2009) and the average annual precipitation in the study period of 1981 to 2007 was 277 mm (*in situ* gauge data), with 1983 being the driest (105 mm) and 2005 the wettest year (478 mm) (rainfall variability of 28%). The vegetation consists of tree and shrub savannas dominated by *Sclerocarya birrea*, *Balanites aegyptiaca*, *Acacia* spp. and

Boscia senegalensis, with the woody strata covering on average <5%. The herbaceous layer is almost exclusively constituted by annuals and usually dominated by grasses, with strongly varying proportions of forbs, depending on micro-habitat, rainfall regime, grazing intensity and fire events. Pastoralism is the main land use. The relationship between precipitation and ~~standing crop biomass~~ESSB is examined in ~~(~~Miehe et al. (2010), and differences in ~~standing crop~~ESSB for the grazing regimes ~~was~~ were identified, despite the plots receiving similar precipitation. The ungrazed plots generally have more ~~standing crop~~ESSB than the communal grazed plots, whereas plots subjected to controlled grazing is in between.

Figure 1: Site overview including sampling plots, rain gauges, and grid representing 250m MODIS pixels. Plot labels include plot numbers and grazing intensity (A = no grazing, B, C or D = controlled grazing, E = communal/free grazing). The high resolution background imagery was printed from Google Earth (@2014 Google - Cnes/Spot Image, Digital Globe).

3. ***Data***

3.1 *Field data*

Field data were collected in the framework of a grazing trial set up in 1981 by Senegalo-German cooperation. Daily rainfall was measured ~~in~~ at two to six rain gauges placed along the transect between the village and the southern end of the paddock area (Figure 1). Twenty-five vegetation sampling plots of 1 hectare were subjected to three different grazing regimes. Grazing exclosure (no grazing) is represented by 5 plots (labeled A), controlled grazing by 14 plots (subdivided into B, C and D according to local gradients of grazing intensity – see ~~(~~Miehe et al.~~,~~ (2010)), and the free communal pasture by 5 plots outside the paddock area (labeled E). Communal use is considered to represent the heaviest grazing intensity. From stocking densities in the experimental area, it has been estimated that 0.05 t/ha biomass are consumed on average in the controlled paddock area and 0,1 t on the communal pasture during the three months of the rainy season, assuming a consumption around 6 kg dry matter per day per livestock unit (Miehe et al., 2010).

All plots have been consistently sampled for above ground biomass at the end of growing seasons (ESSB) by clipping the herb layer on 25 subplots with 1 m² per plot (for details see ~~(~~Miehe et al.~~,~~ (2010)). Annual plant species composition has been registered for all plots since 1992 by line transect sampling according to (Daget & Poissonet, 1971). Every species touching a metal pin placed every meter along a SE-NW-oriented diagonal of 100 meters across the plots was counted once. The number of touches of each species across all 100 collection points was taken as a measure of the relative frequency of the species.

3.2 *Satellite data*

For this study we ~~are interested in~~ apply ~~inga data product commonly used for studies of vegetation evolution on larger scales and over time, more specifically the Normalized Difference Vegetation Index (~~NDVI ~~). NDVI data (MOD13Q1 product)~~from the MODIS instrument (MOD13Q1 product), available from 2000 and onwards on 16-day temporal resolution~~, has~~ and a spatial resolution of 250 meters.The MOD13Q1 data product is commonly used for studies of vegetation changes/trends on larger scales and the spatial resolution allows ~~This is high enough~~for comparison with the 1 Ha sampling plots, while still providing a temporal resolution sufficient for accurate inter and intra seasonal vegetation monitoring ~~growing season evolution~~(Huete et al., 2002). Data from the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) instruments provides a much longer time series (starting in 1981) well aligned with the ***in situ*** data used here. However, available datasets (e.g. the GIMMS3g NDVI (Tucker et al., 2005) and LTDR (Pedelty et al., 2007)) are produced from reduced resolution Global Area Coverage (GAC) AVHRR data rendering the spatial resolution ~~too coarse~~inadequate (5.5-8 km) for a direct comparison with the ungrazed areas at the Widou Thiengoly site~~(Tucker et al., 2005)~~. **The** NDVI

~~NDVI~~ **time series from** the ~~single~~ **GIMM~~s~~**S3g dataset ~~pixel covering~~encompassing **the test site** (single pixel) **is used** here with these reservations in mind.~~to provide a long term context with full time series of *biomass* measurements.The site constitutes 25 % of the pixel area, and as such the communally grazed plots are the most representative for comparison (include with precipitation and biomass figure).~~

4. ***Methods***

The ~~**standing crop measurements**~~ESSB **and precipitation are compared with AVHRR GIMMs NDVI data** only **to provide long term context for the site.** The site covers approximately 25 % of the GIMMS3g pixel area, and as such the communally grazed plots are the most representative for a direct comparison with the coarse resolution EO data. Measurements from individual plots, together with characteristics of species composition data, are compared with vegetation growing season ~~parameterization~~ metrics as derived from MODIS NDVI. Several different vegetation ~~parameters~~ metrics are tested as proxies for ~~standing crop~~ESSB, including maximum values, amplitude (difference between maximum and minimum NDVI), start of season, end of season, length of season, large integral (capturing the signal inherent to the growing season recurrent and persistent vegetation), ~~length, maximum,~~ small integral ~~,~~(capturing only the signal inherent to the growing season recurrent vegetation) ~~end,~~ and annual sum. EO-based vegetation ~~parameters~~ metrics are extracted using the TIMESAT software (Jonsson and Eklundh, 2004). Two methods based on relative and absolute threshold settings for determining start and end of seasons are tested. Relative thresholds determine the start and end of the growing season from chosen percentages of the annual time series amplitude, while absolute thresholds determine the start and end from fixed NDVI values. Both methods have been used and reported in the scientific literature, but without testing the implications of the methodological choice. From ~~these~~ comparisons with *in situ* measured ESSB, the most highly correlated parameter (small NDVI integral) is selected to examine how well differences in vegetation composition and abundance caused by different grazing regimes ~~and inter-annual rainfall variability are~~can be captured by EO metrics. **The findings from** ~~parameterization~~ the optimization of~~of~~ **MODIS NDVI** metrics **are also** ~~implemented~~ applied **when** using the ~~parameterizing GIMMs~~ GIMMS3g **NDVI data** for the long term comparison**.**

4.1 *Overlap betweensampling plots and pixels*

The biomass and species composition sampling plots of approximately one hectare do not all fit well within a single MODIS pixel. This is partly due to many plots located close to fences surrounding the areas of different grazing treatments.This set up was originally meant to make sampling comparison easier between plots under different grazing regimes. Therefore the combination of a MODIS pixel covering an area subjected to a single grazing treatment, and in which a sampling plot also fits well, makes several plots/pixels combinations unsuitable for per-pixel comparisons. If a sampling plot is extending into more than one MODIS pixel, the pixel within which the sampling plot center is located is used. To avoid using MODIS data covering heterogeneous grazing treatments a threshold is set~~. For this study the threshold~~(chosen ~~isapproximately~~as 70 % of any given pixels area)~~.~~ meaning that ~~P~~pixels ~~which~~ that ~~are not constituted by~~include ~~at least~~< 70 % ~~of~~ area of ~~the same~~a dedicated grazing treatment experiment area are not used for per-pixel analysis. This value is meant to balance the need to include as much data as possible from the smaller ungrazed plots, while still ~~sorting~~ masking out the ~~most~~ pixels characterized by most heterogeneous ~~pixels in terms of~~ grazing treatments. Taking these factors into account, we used 15 locations where sampling plots and MODIS pixels correspond~~s~~ (Table 1). The MODIS data product ~~time-span~~covers from April 2000 to present and~~,~~ combined with a ~~stop~~discontinuation of ~~in~~ *in situ* vegetation sampling after the 2007 growing season, this restrict temporal overlap to ~~between~~ cover 2000 ~~and~~ 2007. For 2000 and 2001 no suitable species inventory data were available. In 2006 biomass samples from only 2 of the 15 plots were collected.

Table 1: Sampling plot characteristics and percentage coverage of differently grazed areas of coinciding MODIS pixels. Grazing: A = excluded (ungrazed), BCD = controlled, E = communal.

4.2 *Characteristics of annual species in suitable plots*

To provide an assessment of the general annual species properties for the three grazing regimes, each species has been assigned semi-quantitative values (ranging from 1-3) for characteristics which may influence the signal as observed from satellite time series. This includes cover degree, biomass, and life span (table 2). These values are not biophysical units, but relative between species. For cover degree, a value of 1 represents poor cover of small or filiform leaves, upright growth and mainly erectophile structure, leaving much visible soil surface when seen vertically. A value of 3 is a strong cover degree given to plants with large/broad or numerous horizontally arranged leaves (planophile) and dense tufts (grasses), where little soil visible when seen vertically. A value of 2 is in between. For biomass a value of 1 is given to small, tender plants of little biomass, 2 is given to plants of medium biomass, and 3 is given to tall, spreading or compact plants of high biomass. For life span a value of 1 represents short cycle plants, which are often already vanished or dried up at biomass harvest time (end of September). 2 is given to annual plants of medium length life span, and 3 is given to plants with optimum development at the end of the rainy season with plant parts able to continue growth after fructification (see supplementary material for the specific values assigned to each species).

Table 2: Variables and ranges used to characterize herbaceous species.

The numbers of different species present in plots and their frequency varies inter-annually (see ranges in Table 2). Assessments of general species characteristics for each grazing regime are calculated as the multi-year means of frequency weighted averages for each of the three variables of cover degree, biomass, and life span (eq. 1):

Where is the mean frequency of species j for all plots of similar grazing treatment in one year, is the variable value (1-3) for a given species characteristic (e.g. cover degree) and *n* is the number of years. (See appendix A for variable values for the individual species).

4.3 *Satellite derived growing season ~~parameters~~metrics*

Eight different ~~parameters~~ metrics are derived from NDVI metrics, seven of them by using the TIMESAT software.TIMESAT fits smoothed curves to time series and extract seasonal ~~parameters~~ metrics (Jonsson and Eklundh, 2004), including: amplitude, start of growing season, large integral, length, maximum, small integral, and end of growing season. In addition to these, the annual sum was calculated. When using TIMESAT the start and end of seasons can be defined, either by setting a relative threshold on the amplitude of a given year, or by using absolute values. Minimum NDVI can differ depending on surface properties, such as soil, topography and litter. Therefore defining start and end using specified percentages of the amplitude (relative threshold) can be seen as a way to insure the flexibility that is needed to analyze larger areas. Otherwise the risk exists of setting a threshold below min or above max NDVI for a given pixel and missing a growing season entirely. On the other hand, relative thresholds risk introducing a bias in start of season and end of season as a function of the amplitude, as larger amplitudes will require higher NDVI values before a threshold is reached. For a smaller and relatively homogenous area with similar minimum NDVI, better accuracy may be achieved by setting absolute thresholds (fixed NDVI values), as they are not dependent on variation in amplitude. Both methods were applied here to investigate if either absolute or relative thresholds produce ~~parameters~~ metrics that are more highly correlated to field data. An inter-comparison between the two sets of results is also performed to examine if any of the seven TIMESAT derived ~~parameters~~ metrics are particularly sensitive to choice of threshold method. The annual sum is naturally not dependent on estimates of either start or end.

The relative thresholds determining the start and end of growing season is set to 15 % and 30 % respectively. The start of growing season is set according to base (non-growing season) NDVI which did not exceed 15 % of the annual amplitude for any pixels examined. The higher percentage applied to determine the end of growing season is necessary to leave out the initial wilting period after the chlorophyll activity has dropped off, but where NDVI is not yet down to pre-growing season level. The values set for absolute thresholds are 0.22 and 0.25 for the start and end of growing season respectively (values found by carefully studying time series from pixels within the area). The other settings in TIMESAT where identical for both runs: Savitzky-Golay fitting function with a window size of 3, and 2 iterations with no spike method used (see ~~(~~Jonsson and Eklundh, (2004) for details on TIMESAT). These settings, especially the small window size of the Savitzky-Golay filter, produced a curve fit respecting the NDVI observations of the MODIS product. **For GIMMs NDVI the same settings are used, except for the absolute thresholds, which are 0.~~17~~23 for start of season and 0.2~~1~~6 for end of season.**

5. Results

5.1 *Precipitation, ~~and standing crop~~ ESSB and Long-term coarse resolution NDVI*

~~Standing crop~~ESSB (tons/ha) averaged by grazing regime is shown together with annual precipitation **and GIMMS small integrated NDVI values** for the period 1981-2007 ~~in~~ (Figure 2), and consistently higher productivity is seen for ungrazed plots from 1998, following several years with favorable rainfall conditions (no drought conditions detected for the site since 1992). The correlation (r) between GIMM~~s~~S3g iNDVI and ESSB for communally grazed plots (representing more than 75% of the pixel) is 0.61. Calculating an average ~~standing crop~~ESSB value, including plots under controlled grazing regime and exclosures weighted by their percentage of the GIMM~~s~~S3g pixel, do not change the *r* value.

Figure 2: Light grey columns: Annual precipitation recorded at Widou Thiengoly test site. Values calculated as average from 2-6 gauges. Solid lines: ESSB measured for different grazing regimes, A: Excluded from grazing, BCD: Controlled grazing, E: Communal grazing. **Dashe**d line: GIMM~~s~~S3g **small integrated NDVI** (absolute thresholds applied).

5.2 *Species composition*

Around 120 different annual and perennial plant species have been registered since sampling started. The number of annual species registered per plot varies between 7 and 26. Changes through time in species composition have been observed between plots under different grazing treatments. Commonly found species for all grazing regimes are *Aristida mutabilis & adscensionis, Schoenefeldia gracilis, Indigofera senegalensis & aspera, Cenchrus biflorus, Gisekia pharnaceoides, Zornia glochidiata, Dactyloctenium aegyptiacum, Tragus berteronianus, Alysicarpus ovalifolius,* and *Eragrostis ciliaris*. Some species are common in areas with controlled or communal grazing, including *Chloris prieurii* and *Eragrostis tremula & aspera* but not common in ungrazed plots. In ungrazed plots *Monsonia senegalensis, Commelina forskalei,* and *Tetrapogon cenchriformis* are common, while they are not found in grazed areas. The general plant species characteristics for each grazing regime, calculated as frequency weighted averages (eq. 1), show species in ungrazed plots to have stronger cover degree (2.34 vs 1.65 or 1.63) and longer life span (2.30 vs 1.67 or 1.70), as compared to plots under controlled or communal grazing (Table 3). The controlled and communally grazed plots show little difference in characteristics as species favored by grazing are common for both.

Table 3: General plant species characteristics for each grazing regime, calculated as species frequency weighted averages for the period of 2002 to 2005.

5.3 *Relation between EO-based vegetation ~~parameters~~ metrics and field data*

The seven EO-based vegetation ~~parameters~~ metrics from both TIMESAT threshold setting methods, the annual sum of NDVI, and field data measurements of ESSB (from plots listed in Table 1) have been compared using the Pearson product-moment correlation (Table 4A and Table 4B). Significant relations ($p < 0.05$) are indicated by * and highly significant relations ($p < 0.005$) are indicated by **.

For the ~~parameters~~ metrics estimated using relative thresholds, the amplitude, maximum and small integral are all highly correlated to ~~standing crop~~ESSB across grazing regimes, although r values from comparison with plots excluded from grazing are lower for amplitude and maximum, than for small integral. For ~~parameters~~ metrics estimated using the absolute thresholds, the amplitude, end, maximum, large integrals and small integrals are all highly correlated with ESSB of the controlled and communal grazing regimes. However, only end ($r = 0.72$), large integral ($r = 0.76$) and small integral ($r = 0.80$) have high correlation with measurements from grazing excluded plots. The ~~simple~~ annual sums are also highly correlated to ESSB for all grazing treatments, although less so than small integrals.

Table 4: Correlation coefficients between *in situ* measurements of ESSB and satellite based growing season ~~parameters~~ metrics derived from MODIS NDVI product with: A) Thresholds relative to the seasonal NDVI

~~relative~~amplitude.~~dependent thresholds.~~ B) Thresholds set to an **absolute** NDVI value~~s~~. Coefficients marked with * represent significant relations ($p < 0.05$) and coefficients marked with ** represent highly statistically significant relations ($p < 0.005$).

When inter-comparing the ~~parameters~~ metrics calculated using the two threshold methods, some are highly correlated, with r values exceeding 0.9 and following the 1:1 line (Figure ~~4~~3), but the start, end and length ~~parameters~~ metrics are observed to be very different with low r values (0.46, 0.48 and 0.52 respectively). The length and end of growing season calculated using relative thresholds are negatively correlated with ESSB (Table 4A) and start appears unrelated. When calculated using absolute thresholds, end and length are positively correlated with ~~biomass~~ESSB, while start is negatively but weakly correlated (Table 4B). However, the relation between length/end and ESSB calculated using relative thresholds is only significant ($p < 0.05$) when compared with ESSB of controlled plots, while relations between length and end, calculated using absolute thresholds, and ESSB are significant on $p < 0.05$ for all grazing regimes.

Figure ~~4~~3: Relationship between growing season ~~parameters~~ metrics calculated by using relative thresholds (x-axis) and absolute thresholds (y-axis) in TIMESAT.

The small integrated NDVI derived using absolute threshold values is used for examining whether the differences found in field data are also captured in the NDVI metrics. This choice is based on the following two reasons: first, ~~it is the parameter~~ this seasonal NDVI metric ~~of~~ shows highest consistent correlation with field data across grazing treatment, and second, the absolute thresholds appear to be the more robust method for this small area of analysis. Time lines in Figure ~~5~~4A-C show small integrated NDVI averaged for grazing treatment together with ESSB. The small integrated NDVI for excluded plots are on average slightly higher than those of the controlled and communal pastures. Comparing with Figure 2 higher NDVI for excluded plots would be expected in most years, and especially for 2003 and 2005, where the differences in ESSB are large. For 2003 the small integrated NDVI is higher for excluded plots (values of 1.6 vs 1.3 for controlled and 1.4 for communal) but the difference is not of the same magnitude as for the ground observations~~, as~~ where more than three times the ~~biomass~~ ESSB was measured at excluded plots this year. In 2005 the relative difference in ~~biomass~~ ESSB was also large, but no difference in NDVI between excluded and controlled plots are found, while communal plot small integrated NDVI was only slightly lower. In Figure ~~5~~4D-F the relations between individual measurements of plot ESSB and small integrated NDVI for coinciding MODIS pixels are shown (see *r* values in Table 4B). The slope of the relations between ~~biomass~~ ESSB and NDVI are observed to be steeper for controlled and communally grazed areas, than for excluded areas.

Figure ~~5~~4: A, B and C: Black lines showing annual values of MODIS NDVI small integrals for pixels covering vegetation sampling plots, averaged for each grazing regime. Grey bars showing ~~standing crop biomass~~ESSB averaged by grazing regime. D, E and F show relations between individual measurements of plot ~~biomass~~ ESSB and MODIS NDVI small integrals.

6. **Discussion**

The years 1983, 1984 and 1992 ~~received~~ are characterized by ~~very little~~limited precipitation and can be categorized as drought years with low biomass (Figure 2). After 1997 ungrazed plots appear to consistently have more ~~standing crop~~ESSB as compared to grazed areas (both controlled and communal grazing). In ~~(~~Miehe et al. ~~,~~(2010) this is attributed to precipitation variability, which before this point was higher and therefore masked the grazing influence. It was also concluded that there is evidence of a gradual change in species composition ~~on~~for ungrazed plots, and of long-term degradation in the grazed areas with increase of grasses and species of low fodder quality.

Differences between grazed and non-grazed areas are particularly evident in the stronger increase of ESSB on exclosure plots when precipitation is above average. Findings from clipping experiments showed clipping simulating grazing to reduce NPP (Hiernaux and Turner, 1996).This is consistent with ~~biomass~~ ESSB on controlled and communally grazed plots being less than the ~~actual NPP~~ESSB measured for grazing exclosures. **However,** ~~it also noted in (~~**Hiernaux et al.** (**2009)** reports **that intense grazing can** on the one hand **promote long cycled annual** herbaceous vegetation of relatively high biomass (**refused by livestock), such as *Sida cordifolia,* thereby maintaining or increasing production, or** on the other hand **grazing may** also **favor short cycle annuals of high fodder quality** but relatively lower biomass**, such as *Zornia Glochidiata*~~, which lessens production~~.** Data from Miehe et al. (2010) are used here to assess the potential impact on ESSB from livestock ingestion: With a daily consumption around 6 kg dry matter per day per livestock unit and ~~the~~ fixed ~~and estimated~~ stocking densities in the experimental area, it can be estimated that on average 0.05 t/ha biomass are consumed in the controlled paddock area and 0,1 t on the communal pasture during the three months of the rainy season.**While trampling may affect soil and vegetation (Hiernaux et al. 1999), no assessment of trampling effect on the herbaceous vegetation are available** for Widou Thiengoly. Figure 2 shows, however, that the difference in biomass between grazed and ungrazed plots constantly exceeds 0.1 t/ha by several orders of magnitude after 1997, which supports true differences in productivity. This is further supported by the clear difference in general plant species characteristics between ungrazed and grazed plots (Table 3). The grazing intensity and the effects it has on species composition therefore clearly affect the ~~biomass production~~ESSB and can influence precipitation/productivity relationship for herbaceous savanna vegetation, despite plots being co-located ~~close together~~ and receiving near-identical precipitation. It should be noted that the altered species composition towards longer cycled annuals for grazing exclosures is inevitably going to cause some uncertainty in the assumption about measuring ESSB as a proxy for ANPP. This is because annual herbaceous vegetation types of different cycle lengths are likely to peak with a different timing and selecting a uniform end of season date for the sampling will have to be a compromise between securing that limited biomass has disappeared from decay processes (short cycled annuals) and that vegetation growth has reached the seasonal maximum (longer cycled annuals).

MODIS NDVI growing season ~~parameters~~ metrics were calculated for comparison with the field data, to analyze which parameterization output from the NDVI time series generated the highest correlation with *in situ* measured ESSB. Which threshold method is the most suitable when estimating seasonal integrals and timing was investigated by applying both a relative and absolute threshold on NDVI to define start and end of growing season.It was observed that differences in estimated start, end, and length of growing seasons ~~was~~ were produced depending on the choice of threshold method. The 16-day~~s~~ temporal resolution of the MODIS NDVI product and short growing seasons are likely part of the explanation, and in future studies it could be interesting to investigate if an NDVI product of higher temporal resolution, from e.g. the geostationary MSG SEVIRI instrument, would reduce this difference. However, through inter-comparison (Figure ~~4~~3) it is shown ~~how~~ that many ~~parameters~~ metrics are only ~~very~~ slightly affected by this. Amongst these are the small NDVI integrals~~. Although~~ and even though the values do not conform strictly to the 1:1 line ~~,~~(as absolute thresholds ~~result~~ yields ~~in~~ slightly higher values~~,~~) the~~y~~ two approaches are very highly correlated (Figure ~~5~~3F). The large NDVI integrals are found to be more sensitive to the choice of threshold method. This is interesting as much research is based on the relation between seasonal sums of NDVI (equal to large integral) and ANPP in the Sahel (Tucker et al., 1985; Tucker et al., 1986; Prince, 1991a; Prince, 1991b; Eklundh and Olsson, 2003;~~Prince, 1991a; Tucker et al., 1985; Fensholt and Rasmussen, 2011;~~ Olsson et al., 2005; ~~Eklundh and Olsson, 2003;~~ Fensholt et al., 2006; Fensholt and Rasmussen, 2011~~; Tucker et al., 1986~~).

The comparison of MODIS NDVI metrics with ~~biomass~~ ESSB shows that several ~~parameters~~ metrics are well correlated with the ~~field data~~ground observations, but the small NDVI integral is the overall highest correlated across grazing treatments. This is in line with recent findings as reported in Mbow et al. (2013) and ~~(~~Fensholt et al.~~,~~ (2013). The ~~apparent lack of~~reduced sensitivity of the small integral to threshold methods, together with the higher correlations, is a strong argument for using this as vegetation productivity proxy for ecosystems dominated by herbaceous vegetation instead of the more commonly used large integral. This is further underlined if large NDVI integrals are calculated using relative thresholds, as the results are not as highly correlated with biomass data as many other ~~parameters~~metrics. ~~While t~~**The** long time series of **GIMM**~~s~~S3g **NDVI data** from the AVHRR instruments fits well with the vegetation sampling conducted in Widou Thiengoly, but **is** ~~mainly~~ **showed** mainly **for context**ual comparison~~,~~ **as** ~~its~~ the ~~long time series fits well with the vegetation sampling,~~ spatial scales of EO data and ground observations, respectively, does not allow for a direct comparison. However, also ~~it is worth noting that quite low correlation between GIMMs NDVI and standing crop is found. F~~f**or the GIMM**~~s~~S3g **NDVI the small integrated** ~~parameter~~ metric **was** ~~also~~ **found to have the highest correlation with** ~~standing crop~~ESSB (r = 0.61). ~~. In contrast~~This is a bit lower than ~~(~~**Dardel et al.** (**2014)** who **found** ~~much higher~~strong **correlations between herbaceous biomass and GIMM**S3g~~s~~ **NDVI, but this may be explained by** the differences in spatial coverage of ground observations used (**spatial averaging performed for** ~~a larger~~multiple **area**s of ground observations by Dardel et al. (2014)~~;~~, **while this study** ~~only uses~~is based on **a single pixel**).

The values of MODIS small integrated NDVI for controlled and communally grazed plots are only slightly lower than the values observed for the ungrazed plots. This is even true in years where the difference in ~~standing crop~~ESSB is large (Figure ~~5~~4) and despite the stronger cover degree and longer life span found when assessing species characteristics (Table 3). The relationships in Table 4B between small integral and ESSB may appear quite robust for all grazing regimes. There are high correlation coefficients and 49 sets of compatible field data/satellite data observations for controlled grazing, and 28 sets of observations for no grazing and communal grazing. However, in Figure ~~5~~4 it is clearly shown how NDVI cannot differentiate between the higher ESSB of the ungrazed plots and lower ESSB of grazed plots.

In Figure ~~6~~5 a conceptual illustration shows ~~how~~ two different linear relations between small integrated NDVI (or any other seasonal NDVI integration) and biomass ~~can change~~~~are~~ presented ~~over time depending~~as a function of the grazing pressure (~~on~~ ungrazed and grazed conditions). Of the two horizontal arrows (black lines) shown in the figure, only the course represented by the ~~downward~~ right- arrow going from grazed to ungrazed is actually represented in data, as the Widou Thiengoly site was all grazed prior to fencing in 1981. Assuming that the process is reversible, implementing intense grazing on currently excluded areas will, in time, result in species compositions similar to currently grazed plots (the change indicated by the ~~upward~~ left- arrow). The results presented here suggest that EO based NDVI metrics are in fact only to a limited degree able to capture the grazing induced variations in *in situ* measured ESSB and species composition.

It should be noted that the ungrazed plots at Widou Thiengoly does not generally ~~represen~~represent ~~tsan unusual~~the **situation in the Sahel**~~.The ungrazed plots represent~~ but rather **an extreme case** ~~in opposition~~that is different **to** ~~long term~~communal ~~intensely~~ **grazed areas** as being the normal conditions for Sahelian rangelands**.** However, if assuming an overall increase in livestock density in Sahel during recent decades (Ickowicz et al., 2012) driven by the rapid growth in human population, grazing induc~~z~~ed changes in species composition and ESSB add an interesting perspective to the interpretation of the observed greening due to the altered NDVI/ESSB relationship (Figure 4 D-F) as a function of grazing pressure. ~~If the Sahel has become gradually more intensely grazed, then a gradual decrease of the commonness of species found in the ungrazed plots, and an increase of the species found in grazed plots, is possible.~~It is clear that differences in ESSB does not translate into a uniform NDVI metric response and therefore the reverse interpretation that an increase in greening as observed in the Sahel equals an increase in ESSB does not necessarily hold true. Hypothetically,~~;~~

~~The grazing induced changes in the NDVI/biomass ratio (Figure 5 D-F) add an interesting perspective to the remote sensing based greening trends for Sahel. However, g~~**gradual changes in species composition in increasingly grazed areas of the Sahel can be one of the reasons why few studies have identified the greening trends in field data, with the recent study ~~(~~by Dardel et al. (2014) as an ~~exception~~exception.**

Changing NDVI/biomass relationship as a function of species composition was as also reported by Mbow et al. (2013) using *in situ* NDVI measurements, exemplified by a year with heavy presence of *Zornia glochidiata* (a short cycled annual species with low biomass and high greenness due to a planophile leaf orientation) common in grazed areas. Such a change in the NDVI/biomass relationship caused by a change in species towards annuals characterized by a higher g~~G~~reenness/biomass ratio can be illustrated by the vertical set of arrows in Figure 5 (dashed lines). The presented data from Widoy Thengoly does not allow for a detailed analysis of the relationship between species composition and NDVI, but it would be interesting to study further if the apparent lack of NDVI to monitor the *in situ* observed decrease in ESSB for grazed areas could be influenced by the presence of species like *Zornia glochidiata* which is known to generate high NDVI per unit of biomass. We do not here attempt to suggest that this is a major factor in the observed greening. But we do suggest that grazing induced changes in species composition may pose an important challenge in the attempt to reconcile NDVI trends with field measurements.

It is important to stress that the results presented here are based on limited observations and are therefore inconclusive on larger scales. However, the Widou Thiengoly dataset presented here is rather unique and~~.~~ t~~T~~he standard interpretation of increasing NDVI trends as increased biomass productivity ideally needs to be further tested by 1: Monitoring of long term ungrazed areas, with existing record of species composition, subjected to increasingly intense grazing and over an area large enough for comparison with at least medium resolution satellite observations. 2: Confirmation of findings in other Sahelian locations geographically distant from Widou Thiengoly by excluding more areas to grazing. EO observed greening should not be indiscriminately interpreted as an improvement in livelihood before this greening trend has been interpreted into biophysically meaningful processes.

Figure ~~6~~5: Conceptual figure illustrating the potential effect of grazing on the relationship between small integrated NDVI and ~~standing crop biomass~~ESSB.

~~The increasing population in Sahel and the widespread practice of pastoralism has caused an increase in livestock over the recent decades (Ickowicz et al., 2012) and thereby also increasing grazing intensity. In the light of the findings presented here the EO-based greening of Sahel (documented from coarse resolution imagery) should probably not be indiscriminately interpreted as an improvement before this observed greening has been interpreted into biophysically meaningful processes.~~

7. **Conclusions**

In this study we evaluated the ability of the MODIS 250m ~~Normalized Difference Vegetation Index (~~NDVI~~)~~ to reflect changes in vegetation properties induced by different grazing regimes under identical (or close to) soil and meteorological conditions for a semi-arid environment in the West African Sahel.

From the extensive field observations at the Widou Thiengoly site in Senegal it is ~~established~~ shown that plots excluded from grazing have substantially ~~more~~ higher values of ~~standing crop~~ESSB as compared to plots under controlled grazing or communal grazing (highest intensity), even when taking livestock ingestion into account. Vegetation in ungrazed plots was also better able to increase standing crop during wet years, where precipitation exceeds the long term average. Furthermore, annual plant species characteristics were assessed based on semi-quantitative evaluations of cover degree, biomass, and life span. By calculating species frequency weighted averages for each grazing regime, overall lower cover degrees and shorter life spans of species in grazed plots ~~are~~ were~~shown~~ found.

An inter-comparison between NDVI growing season ~~sparameters~~ metrics derived using different threshold methods implemented in the TIMESAT software ~~was performed. The results~~ suggests that an approach applying absolute NDVI threshold ~~method~~ values is advantageous for local scale analysis as conducted here. The most well ~~best~~ suited metric ~~single parameter~~ for monitoring ESSB in this semi-arid grassland area is identified as small integrated NDVI, due to low sensitivity to choice of threshold, as well as consistently strong relations (r >= 0.78, p < 0.005) with ~~standing crop~~ESSB for all grazing regimes.

However, the values of small integrated NDVI for controlled and communally grazed plots are only slightly lower than the values observed for the ungrazed plots, even in years where the difference in ~~standing crop~~ESSB is large. The average ~~standing crop~~ESSB ~~in~~ for ungrazed plots since 2000 was 0.93 tons/hectare, compared to 0.51 tons/hectare for plots subjected to controlled grazing and 0.49 tons/hectare for communally grazed plots, while average small integrated NDVI values for the same period were 1.56, 1.49, and 1.45 for ungrazed, controlled and communal respectively.

~~There are c~~Clear ~~variations~~ differences in the observed ~~in the~~ NDVI/~~biomass productivity~~ESSB relationship as a function of grazing intensity are found in this study. This indicates that slow and ~~a~~gradual grazing induced ~~development~~ changes towards less ~~standing crop~~ESSB, species with lower cover degree and shorter life span, and limited ability to turn additional water in wet years into biomass ~~due to heavy grazing~~, will not necessarily be reflected in NDVI ~~trends over time~~metrics and therefore an increase in NDVI over time cannot unambiguously be concluded to represent an increase in herbaceous biomass in the semi-arid Sahel.

8. Acknowledgements

This research is part of the project entitled Earth Observation based Vegetation productivity and Land Degradation Trends in Global Drylands. The project is funded by the Danish Council for Independent Research (DFF) Sapere Aude programme.

References Cited

Anyamba, A. and Tucker, C.J., 2005, Analysis of Sahelian vegetation dynamics using NOAA-AVHRR NDVI data from 1981-2003: Journal of Arid Environments, v. 63, p. 596-614.

Anyamba, A., Tucker, C.J., Huete, A.R., and Boken, V.K., 2005, Monitoring Drought Using Coarse-Resolution Polar-Orbiting Satellite Data, *in* Boken, V.K., Cracknell, A.P., and Heathcote, R.L., eds., Monitoring and Predicting Agricultural Drought: A Global Study: New York, Oxford Univerisity Press.

Asner, G.P., Elmore, A.J., Olander, L.P., Martin, R.E., and Harris, A.T., 2004, Grazing systems, ecosystem responses, and global change: Annual Review of Environment and Resources, v. 29, p. 261-299.

Begue, A., Vintrou, E., Ruelland, D., Claden, M., and Dessay, N., 2011, Can a 25-year trend in Soudano-Sahelian vegetation dynamics be interpreted in terms of land use change? A remote sensing approach: Global Environmental Change-Human and Policy Dimensions, v. 21, p. 413-420.

Breman, H. and Cisse, A.M., 1977, Dynamics of Sahelian Pastures in Relation to Drought and Grazing: Oecologia, v. 28, p. 301-315.

Budde, M.E., Tappan, G., Rowland, J., Lewis, J., and Tieszen, L.L., 2004, Assessing land cover performance in Senegal, West Africa using 1-km integrated NDVI and local variance analysis: Journal of Arid Environments, v. 59, p. 481-498.

Camberlin, P., Martiny, N., Philippon, N., and Richard, Y., 2007, Determinants of the interannual relationships between remote sensed photosynthetic activity and rainfall in tropical Africa: Remote Sensing of Environment, v. 106, p. 199-216.

Daget, P. and Poisonnet, J., 1971, Une méthode d'analyse phytologique des praires – Critères d'application: Annales Agronomique, v. 22, p. 5-41.

Dardel, C., Kergoat, L., Hiernaux, P., Mougin, E., Grippa, M., and Tucker, C.J., 2014, Re-greening Sahel: 30 years of remote sensing data and field observations (Mali, Niger): Remote Sensing of Environment, v. 140, p. 350-364.

de Jong, R., de Bruin, S., de Wit, A., Schaepman, M.E., & Dent, D.L.,2011, Analysis of monotonic greening and browning trends from global NDVI time-series. Remote Sensing of Environment, 115, 692-702.

Eagleson, P.S., 1982, Ecological Optimality in Water-Limited Natural Soil-Vegetation Systems .1. Theory and Hypothesis: Water Resources Research, v. 18, p. 325-340.

Eklundh, L. and Olsson, L., 2003, Vegetation index trends for the African Sahel 1982-1999: Geophysical Research Letters, v. 30.

Elberse, W.T. and Breman, H., 1989, Germination and Establishment of Sahelian Rangeland Species .1. Seed Properties: Oecologia, v. 80, p. 477-484.

Elberse, W.T. and Breman, H., 1990, Germination and Establishment of Sahelian rangeland species II. Effects of water availability: Oecologia, v. 85, p. 32-40.

FAO, 2009, Harmonized World Soil Database (version 1.1).

FAO IUSS Working Group WRB, 2006, World reference base for soil resources 2006. A framework for international classification, correlation and communication, *in* Michéli, E., Schad, P., and Spaargaren, O., eds., Rome, Food and Agriculture Organization of the United Nations.

Fensholt, R. and Proud, S.R., 2012, Evaluation of Earth Observation based global long term vegetation trends - Comparing GIMMS and MODIS global NDVI time series: Remote Sensing of Environment, v. 119, p. 131-147.

Fensholt, R. and Rasmussen, K., 2011, Analysis of trends in the Sahelian 'rain-use efficiency' using GIMMS NDVI, RFE and GPCP rainfall data: Remote Sensing of Environment, v. 115, p. 438-451.

Fensholt, R., Rasmussen, K., Kaspersen, P., Huber, S., Horion, S., and Swinnen, E., 2013, Assessing Land Degradation/Recovery in the African Sahel from Long-Term Earth Observation Based Primary Productivity and Precipitation Relationships: Remote Sensing, v. 5, p. 664-686.

Fensholt, R., Rasmussen, K., Nielsen, T.T., and Mbow, C., 2009, Evaluation of earth observation based long term vegetation trends - Intercomparing NDVI time series trend analysis consistency of Sahel from AVHRR GIMMS, Terra MODIS and SPOT VGT data: Remote Sensing of Environment, v. 113, p. 1886-1898.

Fensholt, R., Sandholt, I., Rasmussen, M.S., Stisen, S., and Diouf, A., 2006, Evaluation of satellite based primary production modelling in the semi-arid Sahel: Remote Sensing of Environment, v. 105, p. 173-188.

Fuller, D.O., 1998, Trends in NDVI time series and their relation to rangeland and crop production in Senegal, 1987-1993: International Journal of Remote Sensing, v. 19, p. 2013-2018.

Goetz, S.J., Prince, S.D., Goward, S.N., Thawley, M.M., and Small, J., 1999, Satellite remote sensing of primary production: an improved production efficiency modeling approach: Ecological Modelling, v. 122, p. 239-255.

Herrmann, S.M., Anyamba, A., and Tucker, C.J., 2005, Recent trends in vegetation dynamics in the African Sahel and their relationship to climate: Global Environmental Change-Human and Policy Dimensions, v. 15, p. 394-404.

Herrmann, S.M. and Tappan, G.G., 2013, Vegetation impoverishment despite greening: A case study from central Senegal: Journal of Arid Environments, v. 90, p. 55-66.

Heumann, B.W., Seaquist, J.W., Eklundh, L., and Jonsson, P., 2007, AVHRR derived phenological change in the Sahel and Soudan, Africa, 1982-2005: Remote Sensing of Environment, v. 108, p. 385-392.

Hiernaux, P., 1998, Effects of grazing on plant species composition and spatial distribution in rangelands of the Sahel: Plant Ecology, v. 138, p. 191-202.

Hiernaux, P., Bielders, C.L., Valentin, C., Bationo, A., and Fernandez-Rivera, S., 1999, Effects of livestock grazing on physical and chemical properties of sandy soils in Sahelian rangelands: Journal of Arid Environments, v. 41, p. 231-245.

Hiernaux, P. and Turner, M.D., 1996, The effect of clipping on growth and nutrient uptake of Sahelian annual rangelands: Journal of Applied Ecology, v. 33, p. 387-399.

Hiernaux, P. Mougin, E., Diarra, L., Soumaguel, N., Lavenu, F., Tracol, Y. and Diawara, M., 2009, Sahelian rangeland response to changes in rainfall over two decades in the Gourma region, Mali: Journal of Hydrology, v. 375, p. 114-127.

Huber, S., Fensholt, R. and Rasmussen, K. 2011, Water availability as the driver of vegetation dynamics in the African Sahel from 1982 to 2007. Global Planet Change 76, 186-195.

Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., and Ferreira, L.G., 2002, Overview of the radiometric and biophysical performance of the MODIS vegetation indices: Remote Sensing of Environment, v. 83, p. 195-213.

Ickowicz, A., Ancey, V., Corniaux, C., Duteurtre, G., Poccard-Cappuis, R., Touré, I., Vall, E., and Wane, A., 2012, Crop-livestock production systems in the Sahel - increasing resilience for adaptation to climate change and preserving food security, *in* Meybeck, A., Lankoski, J., Redfern, S., Azzu, N., and Gitz, V., eds., Building resilience for adaptation to climate change in agriculture sector. Proc. Joint FAO-OECD workshop, Roma.: FAO, p. 243-276.

Jonsson, P. and Eklundh, L., 2004, TIMESAT - a program for analyzing time-series of satellite sensor data: Computers & Geosciences, v. 30, p. 833-845.

Knapp, A.K., Fay, P.A., Blair, J.M., Collins, S.L., Smith, M.D., Carlisle, J.D., Harper, C.W., Danner, B.T., Lett, M.S., and McCarron, J.K., 2002, Rainfall variability, carbon cycling, and plant species diversity in a mesic grassland: Science, v. 298, p. 2202-2205.

Martiny, N., Richard, Y., and Camberlin, P., 2005, Interannual persistence effects in vegetation dynamics of semi-arid Africa: Geophysical Research Letters, v. 32.

Mbow, C., Fensholt, R., Rasmussen, K., and Diop, D., 2013, Can vegetation productivity be derived from greenness in a semi-arid environment? Evidence from ground based measurements: Journal of Arid Environments, v. 97, p. 55-65.

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

Milich, L. and Weiss, E., 2000, GAC NDVI interannual coefficient of variation (CoV) images: ground truth sampling of the Sahel along north-south transects: International Journal of Remote Sensing, v. 21, p. 235-260.

Nicholson, S.E., Davenport, M.L., and Malo, A.R., 1990, A Comparison of the Vegetation Response to Rainfall in the Sahel and East-Africa, Using Normalized Difference Vegetation Index from Noaa Avhrr: Climatic Change, v. 17, p. 209-241.

Oba, G., Stenseth, N.C., and Lusigi, W.J., 2000, New perspectives on substainable grazing management in arid zones of sub-Saharan Africa: Bioscience, v. 50, p. 35-51.

Olsson, L., Eklundh, L., and Ardo, J., 2005, A recent greening of the Sahel - Trends, patterns and potential causes: Journal of Arid Environments, v. 63, p. 556-566.

Pedelty, J., Devadiga, S., Masuoka, E., Brown, M., Pinzon, J., Tucker, C., Roy, D., Ju, J., Vermote, E., Prince, S., Nagol, J., Justice, C., Schaaf, C., Liu, J., Privette, J., and Pinheiro, A., 2007, Generating a Long-term Land Data Record from the AVHRR and MODIS Instruments. Geoscience and Remote Sensing Symposium, IGARSS 2007, p. 1021-1025.

Philippon, N., Jarlan, L., Martiny, N., Camberlin, P., and Mougin, E., 2007, Characterization of the interannual and intraseasonal variability of West African vegetation between 1982 and 2002 by means of NOAA AVHRR NDVI data: Journal of Climate, v. 20, p. 1202-1218.

Philippon, N., Martiny, N., and Camberlin, P., 2009, Forecasting the vegetation photosynthetic activity over the Sahel: a Model Output Statistics approach: International Journal of Climatology, v. 29, p. 1463-1477.

Prince, S.D., 1991a, A Model of Regional Primary Production for Use with Coarse Resolution Satellite Data: International Journal of Remote Sensing, v. 12, p. 1313-1330.

Prince, S.D., 1991b, Satellite Remote-Sensing of Primary Production - Comparison of Results for Sahelian Grasslands 1981-1988: International Journal of Remote Sensing, v. 12, p. 1301-1311.

Prince, S.D., Goetz, S.J., and Goward, S.N., 1995, Monitoring Primary Production from Earth Observing Satellites: Water Air and Soil Pollution, v. 82, p. 509-522.

Prince, S.D. and Goward, S.N., 1995, Global primary production: A remote sensing approach: Journal of Biogeography, v. 22, p. 815-835.

Prince, S.D. and Goward, S.N., 1996, Evaluation of the NOAA/NASA Pathfinder AVHRR Land Data Set for global primary production modelling: International Journal of Remote Sensing, v. 17, p. 217-221.

Rasmussen, M.S., 1998, Developing simple, operational, consistent NDVI-vegetation models by applying environmental and climatic information: Part I. Assessment of net primary production: International Journal of Remote Sensing, v. 19, p. 97-117.

Seaquist, J.W., Hickler, T., Eklundh, L., Ardo, J., and Heumann, B.W., 2009, Disentangling the effects of climate and people on Sahel vegetation dynamics: Biogeosciences, v. 6, p. 469-477.

Seaquist, J.W., Olsson, L., Ardo, J., and Eklundh, L., 2006, Broad-scale increase in NPP quantified for the African Sahel, 1982-1999: International Journal of Remote Sensing, v. 27, p. 5115-5122.

Tucker, C.J., 1978, Comparison of Satellite Sensor Bands for Vegetation Monitoring: Photogrammetric Engineering and Remote Sensing, v. 44, p. 1369-1380.

Tucker, C.J., 1979, Red and Photographic Infrared Linear Combinations for Monitoring Vegetation: Remote Sensing of Environment, v. 8, p. 127-150.

Tucker, C.J., Justice, C.O., and Prince, S.D., 1986, Monitoring the Grasslands of the Sahel 1984-1985: International Journal of Remote Sensing, v. 7, p. 1571-1581.

Tucker, C.J., Pinzon, J.E., Brown, M.E., Slayback, D.A., Pak, E.W., Mahoney, R., Vermote, E.F., and El Saleous, N., 2005, An extended AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data: International Journal of Remote Sensing, v. 26, p. 4485-4498.

Tucker, C.J., Vanpraet, C.L., Sharman, M.J., and Vanittersum, G., 1985, Satellite Remote-Sensing of Total Herbaceous Biomass Production in the Senegalese Sahel - 1980-1984: Remote Sensing of Environment, v. 17, p. 233-249.

Wessels, K.J., Prince, S.D., Malherbe, J., Small, J., Frost, P.E., and VanZyl, D., 2007, Can human-induced land degradation be distinguished from the effects of rainfall variability? A case study in South Africa: Journal of Arid Environments, v. 68, p. 271-297.

Wessels, K.J., Prince, S.D., Zambatis, N., Macfadyen, S., Frost, P.E., and van Zyl, D., 2006, Relationship between herbaceous biomass and 1-km(2) Advanced Very High Resolution Radiometer (AVHRR) NDVI in Kruger National Park, South Africa: International Journal of Remote Sensing, v. 27, p. 951-973.

Wezel, A. and Schlecht, E., 2004, Inter-annual variation of species composition of fallow vegetation in semi-arid Niger: Journal of Arid Environments, v. 56, p. 265-282.

Appendix A - Supplementarymaterial

Species name	cover degree	biomass	life span
Abutilonpannosum	3	3	3
Acalyphaciliata	2	2	3
Acacia (juv)	1	1	3
Achyranthesargentea	3	2	2
Aervajavanica	3	3	3
Aeschynomeneindica	3	3	3
Alternantheranodiflora	2	2	3
Alysicarpusovalifolius	2	2	3
Amaranthus viridis	3	3	3
Andropogon gayanus	3	3	3
Aristidafuniculata	1	1	2
Aristidalongiflora	3	2	3
Aristidastipoides	1	2	2
Aristidamutabilis&adscensionis	1	1	1
Blainvilleagayana	3	3	3
Boerhaviaerecta&spp.	1	2	3
Bosciasenegalensis (juv.)	2	1	3
Brachiariaxantholeuca&orthostachys	3	2	3
Brachiarialata&spp.	3	2	3
Brachiariadeflexa&ramosa	2	2	3
Bulbostylisbarbata&Fimbristylishispidula	1	1	2
Calotropisprocerajuv.	2	2	3
Cardiospermumhalicacabum	3	2	3
Cassiaitalica	2	2	3
Cassiamimosoides	1	1	3
Cassiaobtusifolia	3	3	3
Cassiaoccidentalis	2	2	3
Cenchrusbiflorus	3	2	3
Cenchrusprieurii	3	2	3
Ceratothecasesamoides	2	2	3
Chlorispilosa	2	2	2
Chlorisprieurii	2	2	2
Citrulluscolocynthis	2	2	3
Cleomemonophylla	1	1	2
Cleometenella	1	1	1
Cleomeviscosa	2	1	3
Combretumaculeatum (juv.)	2	1	3
Commelinabenghalensis	3	1	3
Commelinaforskalei	3	1	3
Corallocarpusepigaeus	2	2	3

Corchorusolitorius	2	2	3
Corchorustridens	2	2	3
Crotalariapodocarpa	2	3	3
Chrozophorasenegalensis	2	3	3
Ctenolepiscerasiformis	1	2	3
Cucumismelo	3	2	3
Cyperusrotundus	2	1	3
Dactylocteniumaegyptiacum	3	2	2
Digitariahorizontalis	2	2	2
Echinochloacolona	3	2	3
Eragrostis ciliaris	1	1	2
Eragrostisdiplachnoides	2	2	3
Eragrostislingulata&cilianensis	1	1	2
Eragrostispilosa	1	1	2
Eragrostistremula&aspera	1	1	2
Euphorbiaaegyptiaca	3	1	2
Gisekiapharnaceoides	2	1	2
Grewiabicolor (juv.)	2	1	3
Gynandropsisgynandra	2	2	3
Hackelochloagranularis	1	1	2
Heliotropiumbacciferum	3	3	3
Heliotropiumstrigosum	1	1	2
Hibiscus asper	3	3	3
Hibiscus sabdariffa	3	3	3
Hibiscus sidaeformis	3	2	3
Indigoferaastragalina	3	3	3
Indigoferacolutea	2	2	3
Indigoferadiphylla	3	2	3
Indigoferapilosa	2	1	2
Indigoferasecundiflora	3	3	3
Indigoferasenegalensis&aspera	3	2	3
Ipomoeacoptica	2	1	3
Ipomoeadichroa	2	2	3
Ipomoeakotschyana	2	1	3
Ipomoeapes-tigridis	3	2	3
Ipomoeaeriocarpa	2	1	3
Ipomoeatriloba	3	2	3
Ipomoeavagans	2	1	3
Kohautiagrandiflora&senegalensis	1	1	2
Leptadeniahastata	2	2	3
Leptothriumsenegalense	3	2	3
Limeumdiffusum	1	1	2
Limeumpterocarpum	1	1	2
Limeumviscosum	2	1	2

Maeruaangolensis (juv.)	2	1	3
Merremiaaegyptiaca	3	1	3
Merremiapinnata	1	1	3
Merremiasp.	2	1	3
Merremiatridentata	3	2	3
Mollugonudicaulis&cerviana	1	1	2
Momordicabalsamina	2	1	3
Monsoniasenegalensis	3	1	2
Panicumlaetum	2	2	1
Pancratiumtrianthum	2	2	3
Pennisetumpedicellatum	2	2	2
Pennisetumtyphoides	2	3	3
Peristrophebicalyculata&Diclipteraverticillata	2	2	3
Pergulariadaemia	3	2	3
Phyllanthusniruri&pentandrus	1	1	2
Polygalaerioptera	1	2	2
Polycarpaealinearifolia	2	2	2
Portulacafoliosa	2	1	1
Portulacaoleracea	2	1	2
Pupalialappacea	2	2	3
Rogeriaadenophylla	3	3	3
Schoenefeldiagracilis	2	2	2
Sclerocaryabirrea (juv.)	1	1	3
Sesamumalatum	1	1	3
Sesuviumhydaspicum&portulacastrum	2	1	2
Sesbaniarostrata	3	3	3
Sorghum bicolor	2	3	3
Spermacocechaetocephala&radiata	2	1	3
Sphenocleazeylanica	2	1	3
Stylochitonhypogaeus	3	2	3
Tephrosiapurpurea	3	3	3
Tephrosia uniflora	3	3	3
Tetrapogoncenchriformis	2	2	2
Tinosporabakis	2	2	3
Tragusberteronianus	2	1	2
Trichoneuramollis	2	2	3
Tribulusterrestris	3	2	3
Urgineaindica&Dipcaditacazzeanum	1	1	3
Waltheriaindica	3	3	3
Zorniaglochidiata	3	1	3

Tables

Table 1: Sampling plot characteristics and percentage coverage of differently grazed areas of coinciding MODIS pixels. Grazing: A = excluded (ungrazed), BCD = controlled, E = communal.

Grazing	Plot	Topography	No grazing	Controlled	Communal
A	1.1	Clayey interdunes	64 %	36 %	
A	2.1	Sandy-siltyinterdunes	78 %	6 %	16 %
A	3.1	Sandy mid and lower slopes	77 %	21 %	2 %
A	4.1	Sandy mid and lower slopes	97 % (39 %)	0 % (58 %)	3 %
B	1.2	Clayey interdunes		100 %	
B	3.5	Sandy upper and middle slopes		100 %	
C	2.2	Sandy-siltyinterdunes	3 %	97 %	
D	2.6	Sandy upper and middle slopes		100 %	
D	3.4	Sandy upper and middle slopes		100 %	
D	2.4	Sandy-siltyinterdunes		95 % (5 % corridor)	
D	3.2	Sandy upper and middle slopes	3 %	97 %	
E	1.4	Clayey interdunes			100 %
E	2.7	Sandy-siltyinterdunes			100 %
E	3.6	Sandy mid and lower slopes			100 %
E	4.4	Sandy mid and lower slopes			100 %

Table 2: Variables and ranges used to characterize herbaceous species.

Variable	Range
Species frequency	1 – 100
Number of species in plot	7 – 26
Cover degree	1 – 3
Biomass	1 – 3
Life span	1 – 3

Table 3: General plant species characteristics for each grazing regime, calculated as species frequency weighted averages for the period of 2002 to 2005.

	Cover degree	Biomass	Life span
Ungrazed	2.34	1.51	2.30
Controlled	1.65	1.41	1.67
Communal	1.63	1.39	1.70

Table 4: Correlation coefficients between *in situ* measurements of biomass and satellite based growing season ~~parameters~~ metricsderived from MODIS NDVI product with: A) relative amplitude dependent thresholds. B) Thresholds set to absolute values. Coefficients marked with * represent significant relations ($p < 0.05$) and coefficients marked with ** represent highly statistically significant relations ($p < 0.005$).

A)	Excluded (n = 28)	Controlled (n = 49)	Communal (n = 28)
Amplitude	0.71**	0.77**	0.79**
End	-0.29	-0.55**	-0.45*
Large int.	0.56**	0.40**	0.53**
Length	-0.17	-0.36*	-0.29
Max	0.72**	0.78**	0.80**
Small int.	0.79**	0.76**	0.81**
Start	0.03	0.12	0.10

B)	Excluded (n = 28)	Controlled (n = 49)	Communal (n = 28)
Amplitude	0.61**	0.77**	0.79**
End	0.72**	0.42**	0.41**
Large	0.76**	0.68**	0.69**
Length	0.63**	0.39**	0.41*
Max	0.61**	0.78**	0.80**
Small	0.80**	0.78**	0.81**
Start	-0.32*	-0.29*	-0.25
Sum^{+}	0.67**	0.72**	0.77**

$^{+}$: Thresholds not relevant