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Does EO NDVI seasonal metrics capture variations in species composition and biomass due to grazing in semi-arid grassland savannas?

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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 a long time series of coarse resolution normalized difference vegetation index (NDVI) data a greening of the Sahel since the 1980s has been identified. However, it is poorly understood how commonly applied remote sensing techniques reflect the influence of extensive grazing (and changes in grazing pressure) on natural rangeland vegetation. This paper analyses the time series of Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI metrics by comparing it with data from the Widou Thiengoly test site in northern Senegal. Field data include grazing intensity, end of season standing biomass (ESSB) and species composition from sizeable areas suitable for comparison with moderate – coarse resolution satellite imagery. It is shown that sampling plots excluded from grazing have a 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, substantially exceeding the amount of biomass expected to be ingested by livestock for this area. The seasonal 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 metric most strongly related to ESSB for all grazing regimes. However plot-pixel comparisons demonstrate how the NDVI/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 ESSB in ungrazed plots since 2000 was 0.93 t ha^{-1}, compared to 0.51 t ha^{-1} for plots subjected to controlled grazing and 0.49 t ha^{-1} 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 ESSB and shorter-cycled annual plants with reduced ability to turn additional water in wet years into biomass is not adequately captured by seasonal NDVI metrics.

1 Introduction

The need for a 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 few decades. Much research on resource availability and land degradation has been based on time series of medium and low spatial resolution Earth observation (EO) data spurred

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by the limited amount of ground-based long-term data for this region. Long term EO data sets of vegetation indices (VI's) derived from satellite-based optical sensors have been used over many years to estimate ground-based vegetation metrics such as composition, biomass and Sahelian vegetation resource availability (Tucker, 1978, 1979; Anyamba and Tucker, 2005; Herrmann et al., 2005; Olsson et al., 2005; Seaquist et al., 2006; Heumann et al., 2007; Fensholt and Rasmussen, 2011; Fensholt and Proud, 2012). Especially for herbaceous vegetation dominated by annual plant species, a strong relation between in situ measured 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, 1991, b; Dardel et al., 2014). For an adequate interpretation of vegetation change studies, the 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) as a proxy for vegetation productivity in semi-arid environments (Tucker et al., 1986; Prince, 1991a, b; Rasmussen, 1998; Milich and Weiss, 2000; Anyamba and Tucker, 2005; 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^{-1} 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. 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). At the 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 (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).

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, 2009) and for the disentanglement of climate and human influence (Wessels et al., 2007; Seaquist et al., 2009). 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, ESSB, and species composition (Breman and Cisse, 1977; Hiernaux and Turner, 1996; Hiernaux, 1998; 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.

Much research has studied the influence of both climatic and anthropogenic factors on vegetation evolution in the Sahel. While this research includes studies based on field and experimental data (Elberse and Breman, 1989, 1990; Hiernaux and Turner, 1996; Hiernaux, 1998; Hiernaux et al., 1999; Oba et al., 2000; Wezel and Schlecht, 2004; Miehe et al., 2010; Dardel et al., 2014), as well as remote sensing data (Fuller, 1998; Anyamba et al., 2005; Herrmann et al., 2005; Olsson et al., 2005; Fensholt et al., 2009; Fensholt and Rasmussen, 2011), 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) has evoked questions as to what processes on the ground actually reflect these changes (Begue et al., 2011; Herrmann and Tappan, 2013).

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. For this purpose the data from Widou Thiengoly test site in Northern Senegal are unique

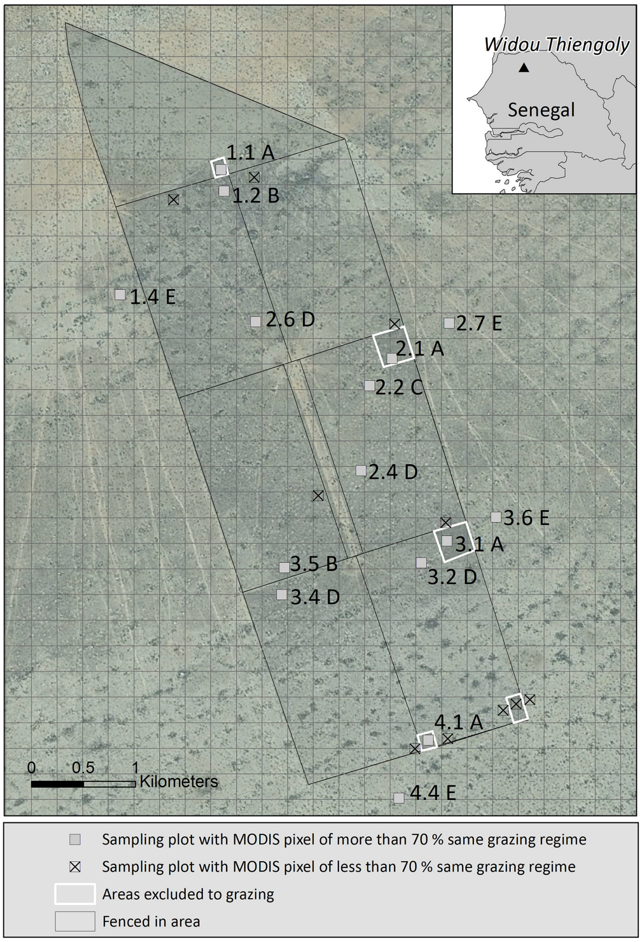

Figure 1. Site overview including sampling plots, rain gauges, and grid representing 250m MODIS pixels. Plot labels include plot numbers and grazing intensity (A = no grazing, B, C or D = controlled grazing, E = communal/free grazing). The high resolution background imagery was printed from Google Earth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

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 herbaceous ESSB and several years of species composition measurements from multiple sampling plots at Widou Thiengoly. We compared and analyzed the field measurements with the growing season vegetation 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 (Fig. 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 microhabitat, rainfall regime, grazing intensity and fire events. Pastoralism is the main land use. The relationship between precipitation and ESSB is examined in Miehe et al. (2010), and differences in ESSB for the grazing regimes were identified, despite the plots receiving similar precipitation. The ungrazed plots generally have more ESSB than the communal grazed plots, whereas plots subjected to controlled grazing is in between.

3 Data

3.1 Field data

Field data were collected in the framework of a grazing trial set up in 1981 by Senegal–Germany cooperation. Daily rainfall was measured at two to six rain gauges placed along the transect between the village and the southern end of the paddock area (Fig. 1). Twenty-five vegetation sampling plots of 1 ha 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^{-1} biomass are consumed on average in the controlled paddock area and 0.1 t on the communal pasture during the 3 months of the rainy season, assuming a consumption of 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 m^2 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 and Poissonet (1971). Every species touching a metal pin placed every meter along a SE-NW-oriented diagonal of 100 m 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 apply NDVI from the MODIS instrument (MOD13Q1 product), available from 2000 and onwards on 16-day temporal resolution and a spatial resolution of 250 m. The MOD13Q1 data product is commonly used for studies of vegetation changes and/or trends on larger scales and the spatial resolution allows for comparison with the 1 ha sampling plots, while still providing a temporal resolution sufficient for accurate inter and intra seasonal vegetation monitoring (Huete et al., 2002). Data from the National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR) instruments provide a much longer time series (starting in 1981) well aligned with the in situ data used here. However, available data sets (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 inadequate (5.5–8 km) for a direct comparison with the ungrazed areas at the Widou Thiengoly site. The NDVI time series from the GIMMS3g data set encompassing the test site (single pixel) is used here with these reservations in mind.

4 Methods

The 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 metrics as derived from MODIS NDVI. Several different vegetation metrics are tested as proxies for 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), small integral (capturing only the signal inherent to the growing season recurrent vegetation) and annual sum. EO-based vegetation metrics are extracted using the TIMESAT software (Jonsson and Eklundh, 2004). Two methods based on relative and absolute threshold settings for determining the 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 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 can be captured by EO metrics. The findings from the optimization of MODIS NDVI metrics are also applied when using the GIMMS3g NDVI data for the long-term comparison.

4.1 Overlap between sampling 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 extends 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 (chosen as 70 % of any given pixels area) meaning that pixels that include < 70 % area of 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 masking out the pixels characterized by most heterogeneous grazing treatments. Taking these factors into account, we used 15 locations where sampling plots and MODIS pixels correspond (Table 1). The MODIS data product covers from April 2000 to the present day and combined with a discontinuation of in situ vegetation sampling after the 2007 growing season, this restrict temporal overlap to cover 2000–2007. For 2000 and 2001 no suitable species inventory data were available. In 2006 biomass samples from only 2 of the 15 plots were collected.

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 rep-

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-silty interdunes	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-silty interdunes	3 %	97 %	
D	2.6	Sandy upper and middle slopes		100 %	
D	3.4	Sandy upper and middle slopes		100 %	
D	2.4	Sandy-silty interdunes		95 % (5 % corridor)	
D	3.2	Sandy upper and middle slopes	3 %	97 %	
E	1.4	Clayey interdunes			100 %
E	2.7	Sandy-silty interdunes			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

resents 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 is 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 growing after fructification (see Supplement for the specific values assigned to each 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):

$$\hat{w} = \left(\sum_{i=1}^{n} \frac{S_{f1} \times V_1 + S_{f2} \times V_2 \ldots + S_{fj} * V_j}{S_{f1} + S_{f2} \ldots + S_{fj}} \right) / n, \qquad (1)$$

where S_{fj} is the mean frequency of species j for all plots of similar grazing treatment in one year, V_j is the variable value (1–3) for a given species characteristic (e.g. cover degree) and n is the number of years. (See Supplement for variable values for the individual species).

4.3 Satellite-derived growing season metrics

Eight different metrics are derived from NDVI metrics, seven of them by using the TIMESAT software. TIMESAT fits smoothed curves to time series and extract seasonal 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

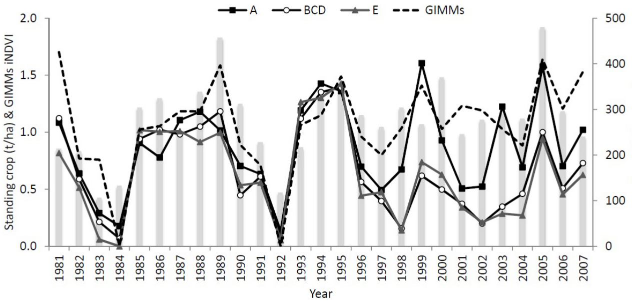

Figure 2. Light grey columns: Annual precipitation recorded at Widou Thiengoly test site. Values calculated as average from 2–6 gauges. Solid lines: ESSB measured for different grazing regimes, A: excluded from grazing, BCD: controlled grazing, E: communal grazing. Dashed line: GIMMS3g small integrated NDVI (absolute thresholds applied).

if either absolute or relative thresholds produce 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 metrics are particularly sensitive to the 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 the growing season, respectively (values found by carefully studying time series from pixels within the area). The other settings in TIMESAT were 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 0.23 for start of season and 0.26 for end of season.

5 Results

5.1 Precipitation, ESSB and long-term coarse resolution NDVI

ESSB (ton ha^{-1}) averaged by grazing regime is shown together with the annual precipitation and GIMMS small integrated NDVI values for the period 1981–2007 (Fig. 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 GIMMS3g iNDVI and ESSB for communally grazed plots (representing more than 75 % of the pixel) is 0.61. Calculating an average ESSB value, including plots under controlled grazing regime and exclosures weighted by their percentage of the GIMMS3g pixel, does not change the r value.

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

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* and *adscensionis*, *Schoenefeldia gracilis*, *Indigofera senegalensis* and *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* and *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.

5.3 Relation between EO-based vegetation metrics and field data

The seven EO-based vegetation 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 b). Significant relations ($p < 0.05$) are indicated by [a] and highly significant relations ($p < 0.005$) are indicated by [b].

For the metrics estimated using relative thresholds, the amplitude, maximum and small integral are all highly correlated to 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 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 annual sums are also highly correlated to ESSB for all grazing treatments, although less so than small integrals.

When inter-comparing the metrics calculated using the two threshold methods, some are highly correlated, with r values exceeding 0.9 and following the 1 : 1 line (Fig. 3), but the start, end and length 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 the start appears unrelated. When calculated using absolute thresholds, the end and length are positively correlated with ESSB, while the 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.

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, this seasonal NDVI metric 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 Fig. 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 Fig. 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 where more than three times the ESSB was measured at excluded plots this year. In 2005 the relative difference in 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 Fig. 4d–f the relations between individual measurements of plot ESSB and small integrated NDVI for coinciding MODIS

Table 4. Correlation coefficients between in situ measurements of biomass and satellite-based growing season metrics derived from MODIS NDVI product with: **(a)** relative amplitude dependent thresholds. **(b)** Thresholds set to absolute values.

	Excluded ($n = 28$)	Controlled ($n = 49$)	Communal ($n = 28$)
(a)			
Amplitude	0.71[b]	0.77[b]	0.79[b]
End	−0.29	−0.55[b]	−0.45[a]
Large int.	0.56[b]	0.40[b]	0.53[b]
Length	−0.17	−0.36[a]	−0.29
Max	0.72[b]	0.78[b]	0.80[b]
Small int.	0.79[b]	0.76[b]	0.81[b]
Start	0.03	0.12	0.10
(b)			
Amplitude	0.61[b]	0.77[b]	0.79[b]
End	0.72[b]	0.42[b]	0.41[b]
Large	0.76[b]	0.68[b]	0.69[b]
Length	0.63[b]	0.39[b]	0.41[a]
Max	0.61[b]	0.78[b]	0.80[b]
Small	0.80[b]	0.78[b]	0.81[b]
Start	−0.32[a]	−0.29[a]	−0.25
Sum[c]	0.67[b]	0.72[b]	0.77[b]

Coefficients marked with [a] represent significant relations ($p < 0.05$) and coefficients marked with [b] represent highly statistically significant relations ($p < 0.005$). [c] Thresholds not relevant.

pixels are shown (see r values in Table 4b). The slope of the relations between ESSB and NDVI are observed to be steeper for controlled and communally grazed areas than for excluded areas.

6 Discussion

The years 1983, 1984 and 1992 are characterized by limited precipitation and can be categorized as drought years with low biomass (Fig. 2). After 1997 ungrazed plots appear to consistently have more ESSB 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 for ungrazed plots, and of long-term degradation in the grazed areas with an increase in 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 ESSB on controlled and communally grazed plots being less than the ESSB measured for grazing exclosures.

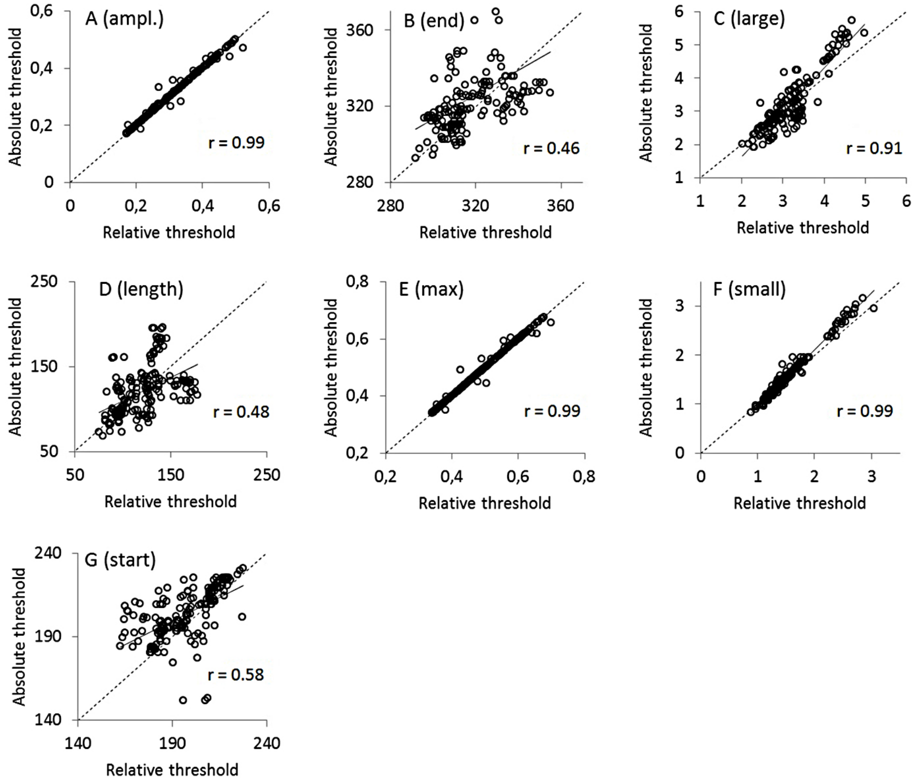

Figure 3. Relationship between growing season metrics calculated by using relative thresholds (x axis) and absolute thresholds (y axis) in TIMESAT.

However, 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*. Data from Miehe et al. (2010) are used here to assess the potential impact on ESSB from livestock ingestion: with a daily consumption of around 6 kg dry matter per day per livestock unit and fixed stocking densities in the experimental area, it can be estimated that on average 0.05 t ha^{-1} biomass are consumed in the controlled paddock area and 0.1 t on the communal pasture during the 3 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^{-1} 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 ESSB and can influence precipitation/productivity relationship for herbaceous savanna vegetation, despite plots being co-located 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 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 were produced depending on the choice of threshold method. The 16-day temporal resolution of the MODIS NDVI product and short growing seasons are likely part of the explanation, and

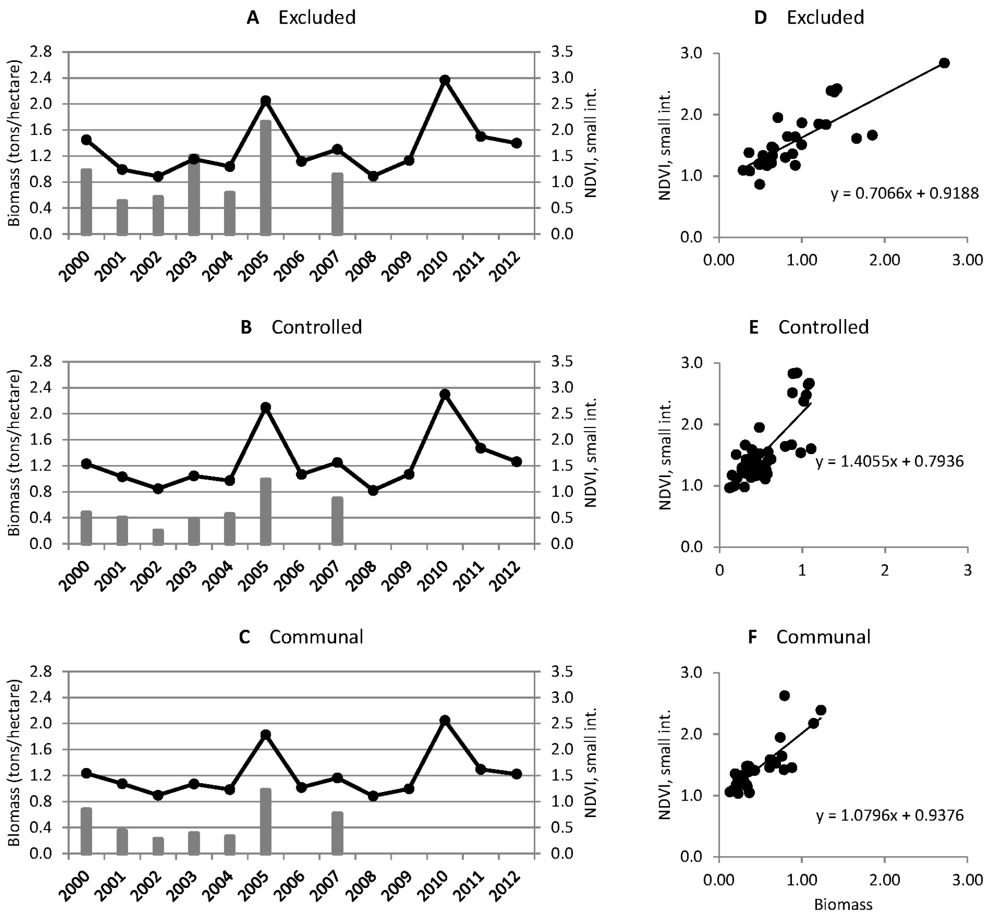

Figure 4. (a), **(b)** and **(c)**: black lines showing annual values of MODIS NDVI small integrals for pixels covering vegetation sampling plots, averaged for each grazing regime. Grey bars showing ESSB averaged by grazing regime. **(d)**, **(e)** and **(f)** show relations between individual measurements of plot ESSB and MODIS NDVI small integrals.

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 (Fig. 3) it is shown that many metrics are only slightly affected by this. Amongst these are the small NDVI integrals and even though the values do not conform strictly to the 1 : 1 line (as absolute thresholds yields slightly higher values) the two approaches are very highly correlated (Fig. 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; Olsson et al., 2005; Fensholt et al., 2006; Fensholt and Rasmussen, 2011).

The comparison of MODIS NDVI metrics with ESSB shows that several metrics are well correlated with the 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 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 metrics. The long time series of GIMMS3g NDVI data from the AVHRR instruments fits well with the vegetation sampling conducted in Widou Thiengoly, but is showed mainly for contextual comparison as the spatial scales of EO data and ground observations, respectively, does not allow for a direct comparison. However, also for the GIMMS3g NDVI the small integrated metric was found to have the highest correlation with ESSB ($r = 0.61$). This is a bit lower than Dardel et al. (2014) who found strong correlations between herbaceous biomass and GIMMS3g NDVI, but this may be explained by the differences in spatial coverage of ground observations used (spa-

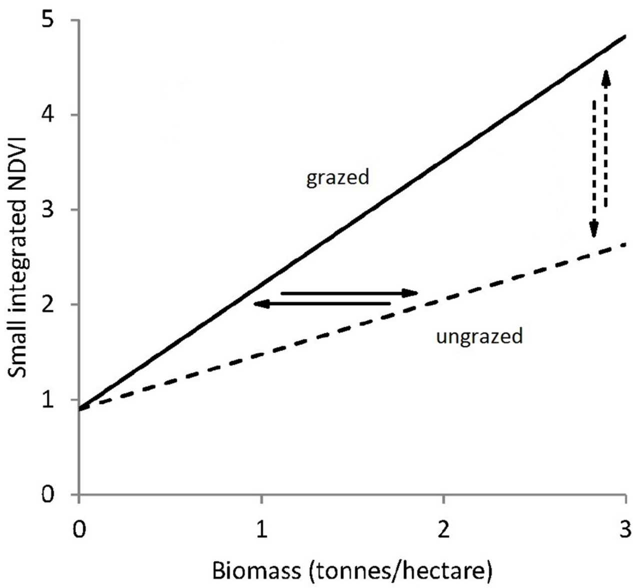

Figure 5. Conceptual figure illustrating the potential effect of grazing on the relationship between small integrated NDVI and ESSB.

tial averaging performed for multiple areas of ground observations by Dardel et al. (2014), while this study 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 ESSB is large (Fig. 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 Fig. 4 it is clearly shown how NDVI cannot differentiate between the higher ESSB of the ungrazed plots and lower ESSB of grazed plots.

In Fig. 5a conceptual illustration shows two different linear relations between small integrated NDVI (or any other seasonal NDVI integration) and biomass presented as a function of the grazing pressure (ungrazed and grazed conditions). Of the two horizontal arrows (black lines) shown in the figure, only the course represented by the 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 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 represent the situation in the Sahel but rather an extreme case that is different to communal 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-induced changes in species composition and ESSB add an interesting perspective to the interpretation of the observed greening due to the altered NDVI/ESSB relationship (Fig. 4d–f) as a function of grazing pressure. It is clear that differences in ESSB do 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, 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.

Changing NDVI/biomass relationship as a function of species composition was 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 greenness/biomass ratio can be illustrated by the vertical set of arrows in Fig. 5 (dashed lines). The presented data from Widoy Thengoly do 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 data set presented here is rather unique and the 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.

7 Conclusions

In this study we evaluated the ability of the MODIS 250 m 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 shown that plots excluded from grazing have substantially higher values of 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 were found.

An inter-comparison between NDVI growing season metrics derived using different threshold methods implemented in the TIMESAT software suggests that an approach applying absolute NDVI threshold values is advantageous for local scale analysis as conducted here. The most well-suited metric 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 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 ESSB is large. The average ESSB for ungrazed plots since 2000 was $0.93\,\mathrm{t\,ha^{-1}}$, compared to $0.51\,\mathrm{t\,ha^{-1}}$ 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.

Clear differences in the observed NDVI/ESSB relationship as a function of grazing intensity are found in this study. This indicates that slow and gradual grazing induced changes towards less ESSB, species with lower cover degree and shorter life span, and limited ability to turn additional water in wet years into biomass, will not necessarily be reflected in NDVI 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.

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