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Does Vegetation Parameterization from EO NDVI Data Capture Grazing induced Variations in Species Composition and Biomass in Semi-Arid Grassland Savanna?

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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 measurement. 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 grazing on natural rangeland vegetation. This paper analyses time series of parameterized Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI data by comparison with data from the Widou Thiengoly test site in northern Senegal. Field data include grazing intensity, vegetation productivity, and species composition from sizeable areas suitable for comparison with moderate – coarse resolution satellite imagery. It is established that sampling plots excluded from grazing have higher Net Primary Production (NPP) and different species composition as compared to plots under controlled grazing or communal grazing. The seasonal small integrated NDVI, derived using absolute thresholds to estimate start and end of growing seasons, is identified as the parameter most strongly related to vegetation productivity for all grazing regimes. However plot-pixel comparisons demonstrates how the NDVI/biomass 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 in 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 $\mathrm{t\,ha^{-1}}$ 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

standing crop biomass and limited ability to turn additional water in wet years into biomass can cause neutral or even increasing NDVI trends over time. It is important to note that these findings are based on limited data and needs to be further verified, as it ultimately indicates that the greening of Sahel could partly be an indicator of increasingly intensified grazing.

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 such as composition, biomass and Sahelian vegetation resource availability (Seaquist et al., 2006; Olsson et al., 2005; Heumann et al., 2007; Herrmann et al., 2005; Fensholt and Proud, 2012; Fensholt and Rasmussen, 2011; Anyamba and Tucker, 2005; Tucker, 1978, 1979). Especially herbaceous vegetation dominated by annual plant species has been found to have strong relations between in situ measured biophysical parameters and commonly used vegetation sensitive indices such as the normalized difference vegetation index (NDVI) (Dardel et al., 2014; Prince, 1991b, a; Tucker et al., 1985). For an adequate interpretation of vegetation evolution, the heavy reliance 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 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, 1991b, a; Milich and Weiss, 2000; Rasmussen, 1998). 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 of vegetation structure (see e.g. Wessels et al., 2006; Prince and Goward, 1995, 1996; Prince et al., 1995; Goetz et al., 1999). 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. Precipitation / vegetation interaction has been studied using NDVI (Nicholson et al., 1990) and NDVI has also been used to investigate inter-annual carry-over effects (Philippon et al., 2007, 2009; Martiny et al., 2005; Camberlin et al., 2007) and for disentanglement of climate and human influence (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, and species composition (Breman and Cisse, 1977; 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 (Wezel and Schlecht, 2004; Hiernaux and Turner, 1996; Hiernaux, 1998; Miehe et al., 2010; Hiernaux et al., 1999; Elberse and Breman, 1989, 1990; Oba et al., 2000; Dardel et al., 2014), as well as remote sensing data (Olsson et al., 2005; Herrmann et al., 2005; Fuller, 1998; 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 (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 (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^{-1} 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 Widou Thiengoly test site in Northern Senegal. For this purpose the data from Widou Thiengoly are unique and offers the possibility for comparing plot measurements with pixel derived values from sensors at medium spatial resolution. We compared and analyzed the field measurements with the growing season vegetation parameters derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument.

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 micro-habitat, rainfall regime, grazing intensity and fire events. Pastoralism is the main land use.

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 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. All plots have been consistently sampled for above ground biomass at the end of growing seasons by clipping the herb layer on 25 subplots with 1 m^2 per plot (for details see Miehe et al., 2010). For the ungrazed areas biomass equals above ground net primary production (ANPP), while for plots subjected to grazing the standing crop represents ANPP reduced by grazing. 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 are interested in applying a 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, available from 2000 and onwards on 16 day temporal resolution, has a spatial resolution of 250 m. This is high enough for comparison with the 1 ha sampling plots, while still providing a temporal resolution sufficient for 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 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 (5.5–8 km) for comparison with the ungrazed areas at the Widou Thiengoly site (Tucker et al., 2005).

4 Methods

First, the relationship between precipitation and standing crop is examined to quantify the differences between dry, average, and wet years for the different grazing regimes. This is done by binning years based on 100 mm precipitation intervals and calculating the average standing crop for each bin. Measurements from individual plots, together with characteristics of species composition data, are then compared with growing season parameterization as derived from MODIS NDVI. Several different vegetation parameters are tested as proxies for ANPP, including amplitude, start, large integral, length, maximum, small integral, end, and annual sum. EO-based vegetation parameters 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, the most highly correlated parameter (small NDVI integral) is selected to examine how well differences in vegetation caused by grazing and inter-annual rainfall variability are captured.

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 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 is approximately 70 % of any given pixels area. Pixels which are not constituted by at least 70 % of the same grazing treatment 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 out the most heterogeneous pixels in terms of grazing. Taking these factors into account, we used 15 locations where sampling plots and MODIS pixels corresponds (Table 1). The MODIS data product time span from April 2000 to present, combined with a stop in vegetation sampling after the 2007 growing season, restrict temporal overlap to between 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.

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 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 growth after fructification (see Table A1 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):

$$\hat{w} = \left(\sum_{i=1}^{n} \frac{S_{\mathrm{f}1} \cdot V_1 + S_{\mathrm{f}2} \cdot V_2 \ldots + S_{\mathrm{f}j} \cdot V_j}{S_{\mathrm{f}1} + S_{\mathrm{f}2} \ldots + S_{\mathrm{f}j}} \right) \Big/ n \tag{1}$$

Where $S_{\mathrm{f}j}$ 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 Appendix A for variable values for the individual species.)

4.3 Satellite derived growing season parameters

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

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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.

5 Results

5.1 Precipitation and standing crop

Standing crop ($\mathrm{t\,ha^{-1}}$) averaged by grazing regime is shown together with annual precipitation in Fig. 2, and consistently higher productivity is seen for ungrazed plots from 1998, following several years with no drought. In Fig. 3a the distribution of annual precipitation is shown in bins of 100 mm. The two bins of highest frequency show that precipitation most commonly varies between 200 and 400 mm per year (22 years out of 27). Data from several more extreme years are also available, due to the long time series of observations. This includes 3 dry years (1983, 1984 and 1992) in the 100–200 mm bin, and 2 wet years in the 400–500 mm bin (1989 and 2005). The biomass measured for plots of different grazing regimes, averaged by the four precipitation intervals from Fig. 3a, are shown in Fig. 3b. The ungrazed plots appear to generally have more biomass than the communal grazed plots, whereas plots subjected to controlled grazing is in between.

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 parameters and field data

The seven EO-based vegetation parameters from both TIMESAT threshold setting methods, the annual sum of NDVI, and field data measurements of biomass (from plots listed in Table 1) have been compared using the Pearson product-moment correlation (Table 4a and b). Significant relations ($p < 0.5$) are indicated by ^{a} and highly significant relations ($p < 0.005$) are indicated by ^{b}.

For the parameters estimated using relative thresholds, the amplitude, maximum and small integral are all highly correlated to biomass 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 estimated using the absolute thresholds, the amplitude, end, maximum, large integrals and small integrals are all highly correlated with biomass 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 biomass for all grazing treatments, although less so than small integrals.

When inter-comparing the parameters calculated using the two threshold methods, some are highly correlated, with r values exceeding 0.9 and following the 1 : 1 line (Fig. 4), but the start, end and length parameters 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 biomass (Table 4a) and start appears unrelated. When calculated using absolute thresholds, end and length are positively correlated with biomass, while start is negatively but weakly correlated (Table 4b). However, the relation between length/end and biomass calculated using relative thresholds is only significant ($p < 0.05$) when compared with biomass of controlled plots, while relations between length and end, calculated using absolute thresholds, and biomass 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 is based on two reasons: first, it is the parameter of 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. Time lines in Fig. 5a–c show small integrated NDVI averaged for grazing treatment together with annual biomass. 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 biomass 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 more than three times the biomass was measured at excluded plots this year. In 2005 the relative difference in biomass 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. 5d–f the relations between individual measurements of plot biomass and small integrated NDVI for coinciding MODIS pixels are shown (see r values in Table 4b). The relations between biomass 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 received very little precipitation and can be categorized as drought years with low biomass (Fig. 2). After 1997 ungrazed plots appear to consistently produce a larger amount of biomass. 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 ungrazed plots, and of long-term degradation in the grazed areas.

Differences between grazed and non-grazed areas are particularly evident in the stronger increase of biomass production 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 on controlled and communally grazed plots being less than the actual NPP. With a daily consumption around 6 kg dry matter per day and the fixed and estimated stocking densities in the experimental area, it can be estimated that on average 0.05 $\mathrm{t\,ha^{-1}}$ biomass are consumed in the controlled paddock area and 0.1 t on the communal pasture during the three months of the rainy season. Figure 2 shows, however, that the difference in biomass between grazed and ungrazed plots constantly exceeds 0.1 $\mathrm{t\,ha^{-1}}$ 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 and can influence precipitation / NPP relationship for herbaceous savanna vegetation, despite plots being located close together and receiving near-identical precipitation.

MODIS NDVI growing season parameters 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 biomass. Which threshold method is suitable 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 produced depending on the choice of threshold method. The 16 days 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 (Fig. 4) it is shown how many parameters are only very slightly affected by this. Amongst these are the small NDVI integrals. Although the values do not conform strictly to the 1 : 1 line, as absolute thresholds result in slightly higher values, they are very highly correlated (Fig. 4f). 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 (Prince, 1991b, a; Tucker et al., 1985, 1986; Fensholt and Rasmussen, 2011; Olsson et al., 2005; Eklundh and Olsson, 2003; Fensholt et al., 2006).

The comparison of MODIS NDVI metrics with biomass show that several parameters are well correlated with the field data, but the small NDVI integral is the overall highest correlated across grazing treatments. This is in line with recent findings as reported in (Fensholt et al., 2013). The apparent lack of sensitivity of the small integral to threshold methods, together with the higher correlations, is a strong argument for using this as vegetation productivity proxy 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.

The values of 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 is large (Fig. 5) and despite the stronger cover degree and longer life span found when assessing species characteristics (Table 3). This can be interpreted as a decoupling of the biome specific NDVI relation to biomass in a case where the species composition found under heavy grazing results in higher NDVI per unit biomass, than the ungrazed but more productive conditions of ungrazed plots. The relationships in Table 4b between small integral and biomass 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. 5 it is clearly shown how NDVI cannot differentiate between the higher productivity of the ungrazed plots and lower productivity of grazed plots.

In Fig. 6 a conceptual illustration shows how linear relations between small integrated NDVI and biomass can change over time depending on ungrazed and grazed conditions. Of the two arrows shown in the figure, only the course represented by the downward 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 arrow).

The grazing induced changes in the NDVI/biomass ratio (Fig. 5d–f) puts into question the interpretation of NDVI trends as proxies for trends in ANPP. Instead it leads to the hypothesis that an increasing trend in NDVI, over e.g. a decade, does not necessarily relate to a positive trend in ANPP but can also represent a shift in herbaceous vegetation caused by increasingly intense grazing resulting in less biomass, changed species composition, and lower ability to turn surplus water in wet years into biomass. This finding potentially has large implications for how the greening of Sahel from positive trends in NDVI may be interpreted. 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. The interpretation of increasing (or neutral) NDVI trends indicated here 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.

It is beyond doubt that the increasing population in Sahel and the widespread practice of pastoralism has caused a significant 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. This is in line with a recent study in Senegal, south of Widou Thiengoly, where impoverishment of woody vegetation was found despite greening trends identified using AVHRR NDVI (Herrmann and Tappan, 2013).

7 Conclusions

In this study we evaluated the ability of the 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.

From the extensive field observations at the Widou Thiengoly site it is established that plots excluded from grazing have higher net primary production (NPP) as compared to plots under controlled grazing or communal grazing (highest intensity).

Vegetation in ungrazed plots was also better able to increase NPP 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 shown.

An inter-comparison between NDVI growing seasons parameters derived using different threshold methods implemented in the TIMSAT software was performed. The results suggest that absolute threshold method is advantageous for local scale analysis. The best suited single parameter for monitoring biomass (NPP – grazing consumption) 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 ($r \geq 0.78$, $p < 0.005$) with biomass measurements 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 is large. The average standing crop in 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 $0.49\,\mathrm{t\,ha^{-1}}$ 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 clear variations observed in the NDVI / biomass productivity relationship as a function of grazing intensity. This indicates that a grazing induced development towards less standing crop, 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, can cause neutral or even increasing NDVI trends over time. It is important to note that these findings are based on limited data and needs to be further verified, as it ultimately indicates that the greening of Sahel could partly be an indicator of increasingly intensified grazing.

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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

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 4a. Correlation coefficients between in situ measurements of biomass and satellite based growing season parameters derived from MODIS NDVI product with *relative* amplitude dependent thresholds.

	Excluded ($n = 28$)	Controlled ($n = 49$)	Communal ($n = 28$)
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

Coefficients marked with ^{a} represent significant relations ($p < 0.05$) and coefficients marked with ^{b} represent highly statistically significant relations ($p < 0.005$).

Table 4b. Correlation coefficients between in situ measurements of biomass and satellite based growing season parameters derived from MODIS NDVI product with thresholds set to *absolute* values.

	Excluded ($n = 28$)	Controlled ($n = 49$)	Communal ($n = 28$)
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.

Table A1. Semi-quantitative values describing annual plant species properties, including cover degree, biomass, and life span.

Species name	Cover degree	Biomass	Life span
Abutilon pannosum	3	3	3
Acalypha ciliata	2	2	3
Acacia (juv)	1	1	3
Achyranthes argentea	3	2	2
Aerva javanica	3	3	3
Aeschynomene indica	3	3	3
Alternanthera nodiflora	2	2	3
Alysicarpus ovalifolius	2	2	3
Amaranthus viridis	3	3	3
Andropogon gayanus	3	3	3
Aristida funiculata	1	1	2
Aristida longiflora	3	2	3
Aristida stipoides	1	2	2
Aristida mutabilis and *adscensionis*	1	1	1
Blainvillea gayana	3	3	3
Boerhavia erecta and spp.	1	2	3
Boscia senegalensis (juv.)	2	1	3
Brachiaria xantholeuca and *orthostachys*	3	2	3
Brachiaria lata and spp.	3	2	3
Brachiaria deflexa and *ramosa*	2	2	3
Bulbostylis barbata and *Fimbristylis hispidula*	1	1	2
Calotropis procera juv.	2	2	3
Cardiospermum halicacabum	3	2	3
Cassia italica	2	2	3
Cassia mimosoides	1	1	3
Cassia obtusifolia	3	3	3
Cassia occidentalis	2	2	3
Cenchrus biflorus	3	2	3
Cenchrus prieurii	3	2	3
Ceratotheca sesamoides	2	2	3
Chloris pilosa	2	2	2
Chloris prieurii	2	2	2
Citrullus colocynthis	2	2	3
Cleome monophylla	1	1	2
Cleome tenella	1	1	1
Cleome viscosa	2	1	3

Table A1. Continued.

Species name	Cover degree	Biomass	Life span
Combretum aculeatum (juv.)	2	1	3
Commelina benghalensis	3	1	3
Commelina forskalei	3	1	3
Corallocarpus epigaeus	2	2	3
Corchorus olitorius	2	2	3
Corchorus tridens	2	2	3
Crotalaria podocarpa	2	3	3
Chrozophora senegalensis	2	3	3
Ctenolepis cerasiformis	1	2	3
Cucumis melo	3	2	3
Cyperus rotundus	2	1	3
Dactyloctenium aegyptiacum	3	2	2
Digitaria horizontalis	2	2	2
Echinochloa colona	3	2	3
Eragrostis ciliaris	1	1	2
Eragrostis diplachnoides	2	2	3
Eragrostis lingulata and *cilianensis*	1	1	2
Eragrostis pilosa	1	1	2
Eragrostis tremula and *aspera*	1	1	2
Euphorbia aegyptiaca	3	1	2
Gisekia pharnaceoides	2	1	2
Grewia bicolor (juv.)	2	1	3
Gynandropsis gynandra	2	2	3
Hackelochloa granularis	1	1	2
Heliotropium bacciferum	3	3	3
Heliotropium strigosum	1	1	2
Hibiscus asper	3	3	3
Hibiscus sabdariffa	3	3	3
Hibiscus sidaeformis	3	2	3
Indigofera astragalina	3	3	3
Indigofera colutea	2	2	3
Indigofera diphylla	3	2	3
Indigofera pilosa	2	1	2
Indigofera secundiflora	3	3	3
Indigofera senegalensis and *aspera*	3	2	3

Table A1. Continued.

Species name	Cover degree	Biomass	Life span
Ipomoea coptica	2	1	3
Ipomoea dichroa	2	2	3
Ipomoea kotschyana	2	1	3
Ipomoea pes-tigridis	3	2	3
Ipomoea eriocarpa	2	1	3
Ipomoea triloba	3	2	3
Ipomoea vagans	2	1	3
Kohautia grandiflora and *senegalensis*	1	1	2
Leptadenia hastata	2	2	3
Leptothrium senegalense	3	2	3
Limeum diffusum	1	1	2
Limeum pterocarpum	1	1	2
Limeum viscosum	2	1	2
Maerua angolensis (juv.)	2	1	3
Merremia aegyptiaca	3	1	3
Merremia pinnata	1	1	3
Merremia sp.	2	1	3
Merremia tridentata	3	2	3
Mollugo nudicaulis and *cerviana*	1	1	2
Momordica balsamina	2	1	3
Monsonia senegalensis	3	1	2
Panicum laetum	2	2	1
Pancratium trianthum	2	2	3
Pennisetum pedicellatum	2	2	2
Pennisetum typhoides	2	3	3
Peristrophe bicalyculata and *Dicliptera verticillata*	2	2	3
Pergularia daemia	3	2	3
Phyllanthus niruri and *pentandrus*	1	1	2
Polygala erioptera	1	2	2
Polycarpaea linearifolia	2	2	2
Portulaca foliosa	2	1	1
Portulaca oleracea	2	1	2
Pupalia lappacea	2	2	3
Rogeria adenophylla	3	3	3

Table A1. Continued.

Species name	Cover degree	Biomass	Life span
Schoenefeldia gracilis	2	2	2
Sclerocarya birrea (juv.)	1	1	3
Sesamum alatum	1	1	3
Sesuvium hydaspicum and *portulacastrum*	2	1	2
Sesbania rostrata	3	3	3
Sorghum bicolor	2	3	3
Spermacoce chaetocephala and *radiata*	2	1	3
Sphenoclea zeylanica	2	1	3
Stylochiton hypogaeus	3	2	3
Tephrosia purpurea	3	3	3
Tephrosia uniflora	3	3	3
Tetrapogon cenchriformis	2	2	2
Tinospora bakis	2	2	3
Tragus berteronianus	2	1	2
Trichoneura mollis	2	2	3
Tribulus terrestris	3	2	3
Urginea indica and *Dipcadi tacazzeanum*	1	1	3
Waltheria indica	3	3	3
Zornia glochidiata	3	1	3

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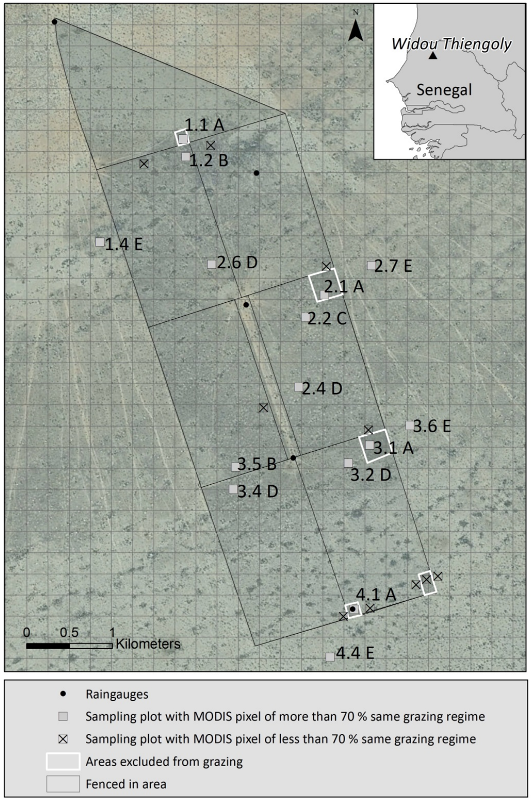

Figure 1. Site overview including sampling plots, rain gauges, and grid representing 250 m MODIS pixels. Plot labels include plot numbers and grazing intensity (A = no grazing, B, C or D = controlled grazing, E = communal/free grazing). The high resolution background imagery was printed from Google Earth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

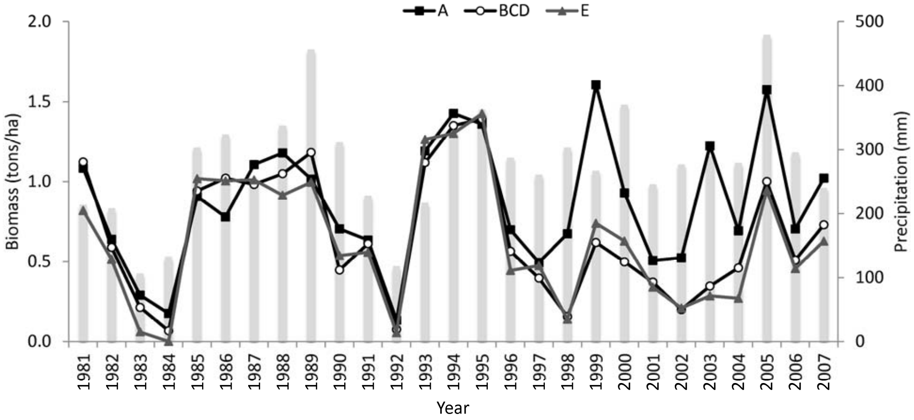

Figure 2. Light grey columns: annual precipitation recorded at Widou Thiengoly test site. Values calculated as average from 2 to 6 gauges. Lines: biomass measured for different grazing regimes, A: excluded from grazing, BCD: controlled grazing, E: communal grazing.

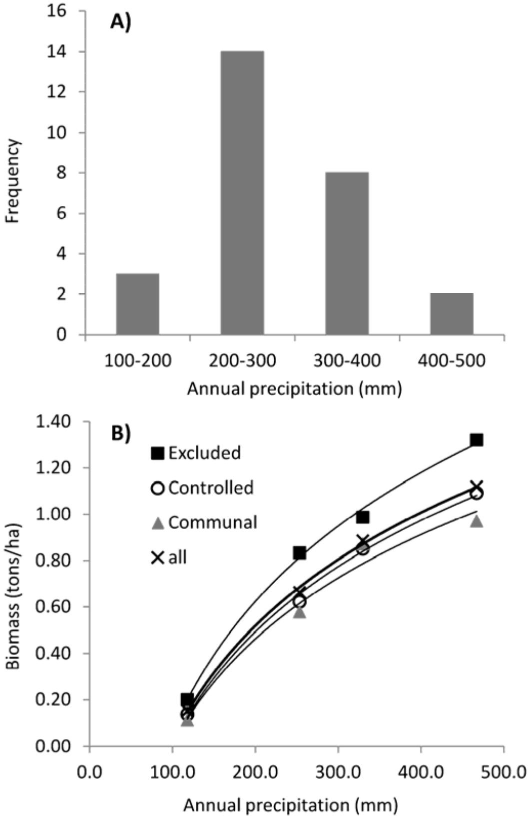

Figure 3. (A) Frequency of annual precipitation binned by intervals of 100 mm. **(B)** Average biomass production in tons per hectare for each 100 mm interval of annual precipitation (average precipitation bin value shown). All 25 sampling plots are used and divided by grazing regime, including the 10 plots not suitable for comparison with MODIS data.

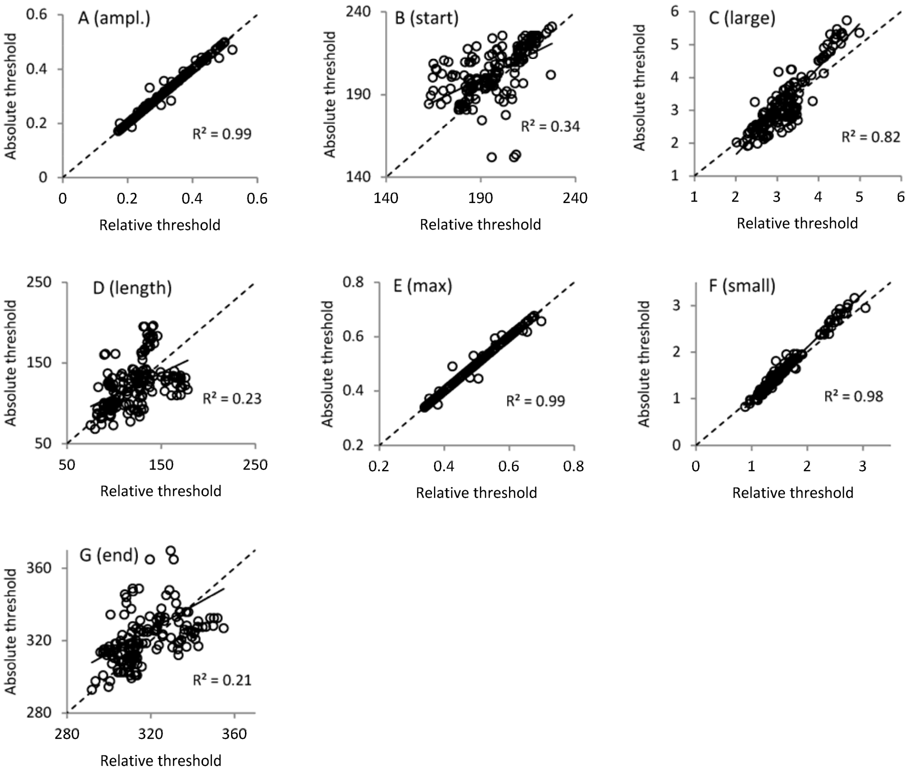

Figure 4. Relationship between growing season parameters calculated by using relative thresholds (*x* axis) and absolute thresholds (*y* axis) in TIMESAT.

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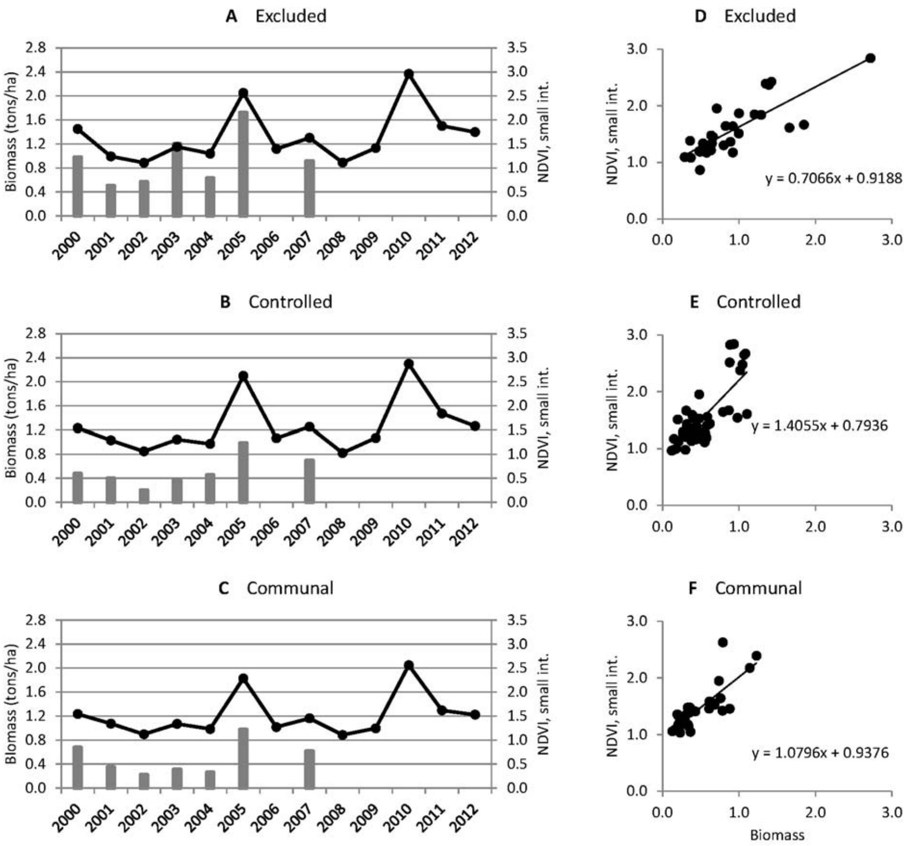

Figure 5. (A), **(B)** and **(C)**: black lines showing annual values of MODIS NDVI small integrals for pixels covering vegetation sampling plots, averaged for each grazing regime. Grey bars showing standing crop biomass averaged by grazing regime. **(D)**, **(E)** and **(F)** show relations between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

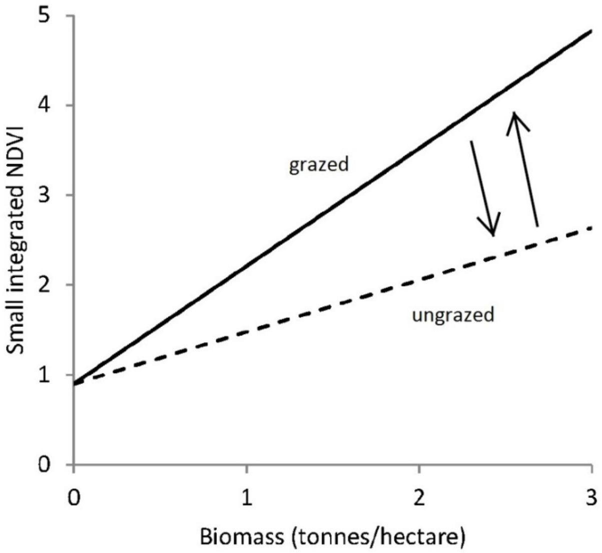

Figure 6. Conceptual figure illustrating the potential effect of grazing on the relationship between small integrated NDVI and standing crop biomass.