Validation of a remote sensing method of estimating grazing impacts in northern Kenya rangelands

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AFRICA BIODIVERSITY COLLABORATIVE GROUP

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Executive Summary

Remote sensing can be a powerful tool for monitoring changes in semi-arid rangelands and the effects of management, but methods are still lacking to be able to accurately monitor the movements and impacts of livestock that often dominate grazing in such rangelands. In this report, a new method of monitoring livestock based on time differences in satellite-based measurements of "greenness" (NDVI, Normalized Difference Vegetation Index) is validated with unprecedented intensive measurements of forage biomass on rangelands in Kalama and Westgate Conservancies in northern Kenya. Forage biomass was measured in July 2014 under very dry consitions in 60 small quadrats, 30 before grazing and 30 after herds of thirty or more cattle moved through each block, in each of thirty 250 x 250 m blocks that each corresponded with similar sized measurement units (pixels) of the MODIS satellite. Biomass was strongly correlated (R^2 = 0.58-0.60) with measurements of NDVI both before and after cattle passed through each block. More importantly, the amount of forage removed by cattle (difference in biomass between "Before" and "After" grazing) was significantly correlated (R^2 = 0.30) with a three-week difference in NDVI. This suggests that small differences in NDVI over short time periods can closely approximate grazing impacts and that uncertainty in NDVI-based measures of grazing found in previous studies are more likely limited by under-sampling in ground-based measurements rather than errors in satellite measurements. **Maps of changes in NDVI may therefore be used to identify areas of different past grazing use, provide feedback on compliance of herders with rotational grazing plans, monitor large-scale livestock movements, and anticipate future conflicts among different pastoralist groups in common rangelands.** This method also appears to be suitable for monitoring vegetation as required by carbon market standards, such as the Verified Carbon Standard, and may greatly reduce the cost and increase the efficacy of implementing projects with improved livestock management.

Introduction

Ecological and management changes on semi-arid rangelands are notoriously difficult to quantify and monitor repeatedly, due to the large scale of management jurisdictions and movements of animals, and their highly dynamic climate[1-3]. Opportunities to manage livestock in rangelands for the purpose of carbon sequestration in soils will require well-developed monitoring tools in order to show compliance with project activities that store carbon[4]. A major hurdle in such monitoring is tracking livestock movements and impacts on vegetation across large landscapes, such as those found in many developing countries with large pastoralist populations.

Satellite imagery has long been held out as a potential tool for monitoring livestock, but uncertainty as to which images and which vegetation characteristics should be tracked have slowed progress[3]. In addition, a favorite metric of vegetation production and "greenness, the normalized difference vegetation index, or NDVI [5,6], has yielded measurements with high uncertainty (> 50%) when ground-truthed with actual measurements of standing biomass or productivity[6,7]. Typically NDVI explains only about 30-40% of the variation in grass biomass, and while it can be useful in comparing broad areas under different livestock management and comparing patterns of variation in production over long time scales [5,6,8,9], its high uncertainty has left many skeptical of its use as a tool to track animal impacts[3].

A key reason for this uncertainty is that ground measurements typically occur at very small scales (< 2 m) because of the time-intensive nature of sampling biomass. Consequently, these measures do not capture much of the variability that is integrated in the record for a single measurement unit (pixel) of a satellite image (30 – 500 m). This leads to what can be called "scale mismatch error," or an error introduced by the failure of ground measurements to incorporate information across the spatial extent of satellite measurements. This is further exacerbated for NDVI, because its utility is best applied to data from MODIS satellites, which image virtually everywhere on earth every day, but at a cost of coarse resolution of measurements (pixels 250m in length and larger). Moreover, the timing of biomass measurements and events that affect it, such as the passing of livestock herds, are often poorly coupled. It is thus possible that NDVI provides a more accurate assessment of biomass and/or production than is thought, but this accuracy cannot be evaluated because of large scale mismatch errors.

Here, results are presented of some intensive sampling of biomass in a semi-arid northern Kenya rangeland and its association with NDVI. The study featured two unique aspects: first biomass was sampled in a very high number of small quadrats per MODIS pixel in order to reduce scale mismatch error, and measurements were made in the same area just prior to and just after grazing by large herds (> 30 head) of cattle, and carefully timed such that the first MODIS image would be taken pre-grazing, and a later (3 weeks) image would occur post-grazing. The measurements were made in the peak dry season (July) as a rigorous test of the power of NDVI to track vegetation, since NDVI is notoriously insensitive to changes in biomass under dry, unproductive conditions in landscapes with considerable bare ground[7,8,10]. The validity of NDVI was tested by correspondence between (1) NDVI and ground-measured biomass, (2) the difference in NDVI and the difference in ground-measured biomass before and after grazing, and (3) the relative difference in NDVI with a calculation of grazing intensity (1-biomass before/biomass after).

Methods

The study was conducted during July 2014 in the Kalama and Westgate Conservancies in northern Kenya (35.5 °E, 0.7 °N). The area was semi-arid rangeland dominated by annual grasses and herbaceous dicots (forbs) and trees of the genus *Acacia* and *Commiphora*, a very typical habitat type in East Africa. These conservancies receive 400-450 mm annual rainfall on average, and mostly in November and March-May. However, rainfall for the study site was well below average as suggested by the USDA- USDA FEWS early warning dataset for northern Kenya. Consequently much of the herbaceous vegetation occurred at low biomass and was largely senesced during the study.

These conservancies were also selected because they feature zones that receive either controlled dry season grazing (July-October) (Buffer areas) or only very rare grazing in times of extreme drought (Core areas). This ensured that at least some herbaceous vegetation would be standing prior to use by cattle. The livestock employed in the study were zebu cattle typical of East Africa[7] that were maintained by their owners (local members of each conservancy) in loose groups of at least 30 and herded through sampling blocks in a normal fashion. Seven different herds were used during the grazing period of the study.

Biomass

Biomass was measured by 60 clipping small 25 x 25 (0.0825 m^2) quadrats in each "block" of quadrats. Pre-grazing blocks were clipped July 18-23, and post-grazing blocks were clipped after July 25, 2014. This represents a dramatic increase in sampling effort over most previous ground-truthing studies. Thirty quadrats were clipped prior to cattle grazing and thirty were clipped one week following grazing. Each block measured 250 m on each side, and blocks were separated by at least 100 m. Block locations within the conservancy were strongly constrained by the location of cattle herds, which were not under investigator control, and so the majority of blocks occurred within the Kalama conservancy (Fig. 1). Quadrat locations within each block were selected at random and marked so that post-grazing samples would not overlap pre-grazing ones. Plots with no vegetation were counted and considered to have zero biomass. Clipped plant material was mostly already dry, but if not was placed in paper bags and dried in the sun for two days to a constant weight. Plant samples were weighed with Pesola spring scales to the nearest 0.5 g.

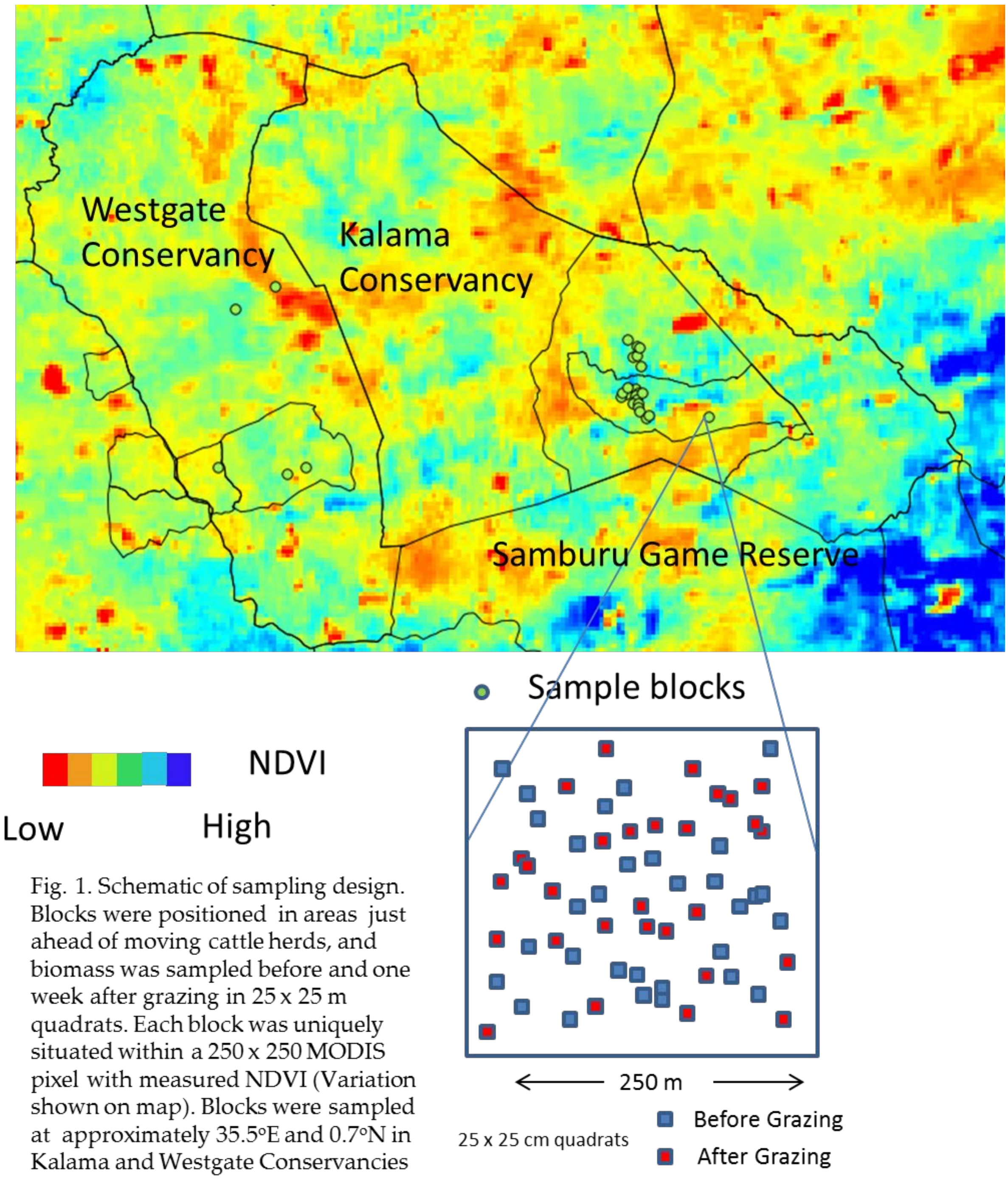

Fig. 1. Schematic of sampling design. Blocks were positioned in areas just ahead of moving cattle herds, and biomass was sampled before and one week after grazing in 25 x 25 m quadrats. Each block was uniquely situated within a 250 x 250 MODIS pixel with measured NDVI (Variation shown on map). Blocks were sampled at approximately 35.5°E and 0.7°N in Kalama and Westgate Conservancies (thin black borders) near Samburu Game Reserve in northern Kenya.

Satellite images

MODIS Aqua MYDAQ1) provided the highest resolution imagery available (250 m). Two raster images that contained the study area were downloaded from the NASA Earth Explorer site: MYD13Q1.A2014073.h21v08.005.2014092110204. hdf (July 23) and

MYD13Q1.A2014097.h21v08.005.2014114093452.hdf (August 10) Files were converted to GeoTiff files with the HEG tool (NASA), and laid under a vector layer of block locations. NDVI values for the MODIS pixel on each date were matched with corresponding block numbers.

Statistics

Associations between NDVI and measured biomass and all derivative calculations were performed with linear regression using IBM SPSS version 21. Grazing intensity was calculated as 1-Biomass After/Biomass Before, while relative change in NDVI was calculated as 1- NDVI After/NDVI Before.

Results

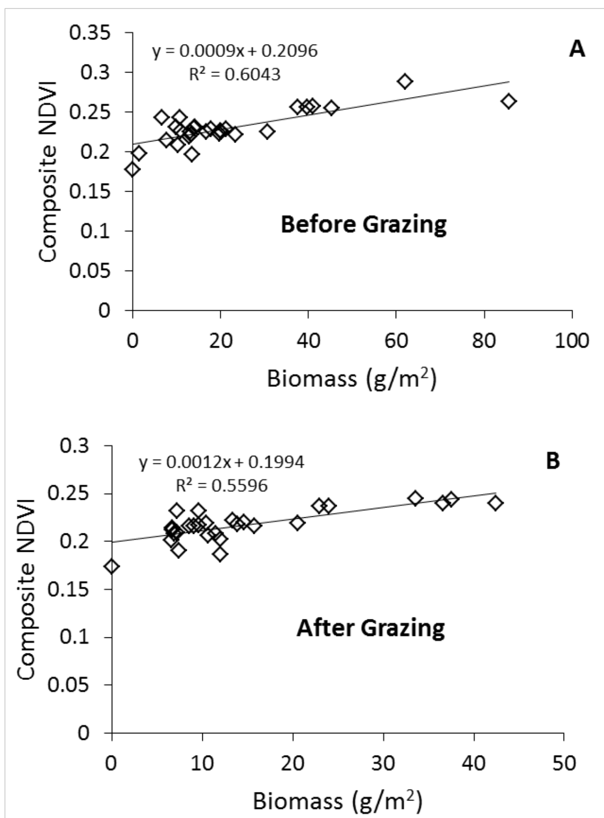

Fig. 2. Regressions between ground measured Biomass (g/m²) and calculated NDVI from MODIS composite images for Kalama and Westgate Conservancies in northern Kenya rangelands.

NDVI in the two satellite images varied from 0.1776 to 0.2877, a typical range for low biomass dry season vegetation. Clipped biomass, averaged for each block, ranged from 0 to 86 g/m², but most contained less than 25 g/m². Ground biomass was very strongly correlated (R^2 >0.55) with NDVI both before and after grazing (Fig. 2). More importantly, the difference in NDVI between across weeks was significantly explained ($R^2 = 0.28$, $P < 0.001$)by the difference in measured biomass within that pixel (Fig. 3A). In contrast, the relative difference in NDVI was not significantly explained by grazing intensity (Fig. 3B).

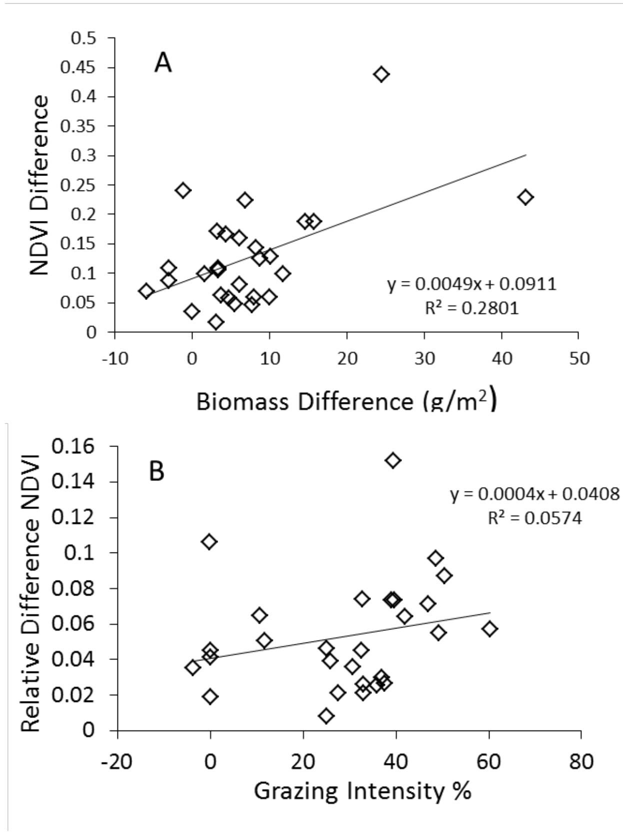

Fig. 3. Regressions of (A) the absolute difference in NDVI versus the absolute difference in biomass, and (B) the relative difference in NDVI (1 – (NDVI After/NDVI Before)) versus grazing intensity as defined by the relative difference in biomass (1- (Biomass After/Biomass Before Grazing)).

Discussion

The results clearly indicate that rangeland forage density may be reasonably accurately detected with NDVI (Fig. 2), and that grazing impacts can be detected by relatively small differences in NDVI of less than 10% (Fig. 3A). This result was likely achieved because of the intense sampling effort to obtain many biomass samples across a much greater extent of area within a MODIS measurement unit (pixel) than in previous studies. NDVI may thus be a much more powerful indicator of biomass and production than is currently thought, to the extent that it may be a strong monitoring tool for relatively low impact but ecologically important processes such as grazing. It is noteworthy that these results were obtained even during the dry season under very low (< 80 g/m^2) forage biomass, senesced vegetation conditions, when NDVI is purported to be very insensitive to vegetation changes[7,10].

All of these interpretations suggest that uncertainties in NDVI measurements are likely not due to satellite errors from atmospheric interference or multiple influences on spectral readings by different landscape components such as soil and trees. Instead the uncertainty has more likely arisen from under-sampling in ground measurements. This is understandable due to the time and expense of ground measurements, but these results suggest that an even stronger ground sampling effort in semi-arid rangelands across multiple months and environmental (rainfall) conditions could dramatically improve confidence in NDVI as a metric of productivity and green biomass. The critical role of these in a broad array of ecosystem processes, livestock production, wildlife conservation, and in monitoring global change, suggests that the intense sampling might be well worth the effort.

Despite the improvement in the relationship between NDVI and ground-measured biomass revealed in this study (Fig. 2), considerable uncertainty exists in further calculations of grazing impacts with NDVI. While highly significant, the absolute difference measured biomass before and after grazing explained only 28% of the variance in the absolute difference in NDVI before and after grazing (Fig. 3A), and grazing intensity explained less than 6% of the variance in relative difference in NDVI (Fig. 3B). Some part of this uncertainty is the compounding of error that results from summing or dividing two parameters that are each measured with error. Likely an additional source of error is variation among sites in the influence of other factors, such as tree cover and soil reflectance, that contribute to NDVI calculations[10]. For example, when forage (herbaceous) biomass approached zero, NDVI measures averaged around 0.2, suggesting some additional source of greenness on the landscape that would increase NDVI above zero. Very likely this was caused by trees. Rigorously, the influence of tree cover would be included as an additional variable in a multiple regression. However, as tree cover across the sampled MODIS pixels was not measured, the influence of trees speculatively can be factored out by assuming that forage biomass increases NDVI by some incremental amount above that driven by soil and trees, which in these data would appear to be approximately 0.2. Recalculating the relative difference in NDVI (RelΔNDVI) due to changes in herbaceous biomass, which would be a much closer measure of grazing intensity, reveals

$$\mathrm{Rel\Delta NDVI} = 1 - (\mathrm{NDVI}_{after} - 2000)/(\mathrm{NDVI}_{before} - 2000) \quad (1),$$

where NDVI_{before} and NDVI_{after} are NDVI before and after cattle grazing, respectively. Regression of RelΔNDVI versus grazing intensity based on ground biomass is significant ($R^2 = 0.19$, $N = 30$, $P = 0.008$) (Fig. 4), which suggests that relative difference in NDVI may indeed reflect grazing intensity once the influence of other contributing factors to NDVI are factored out.

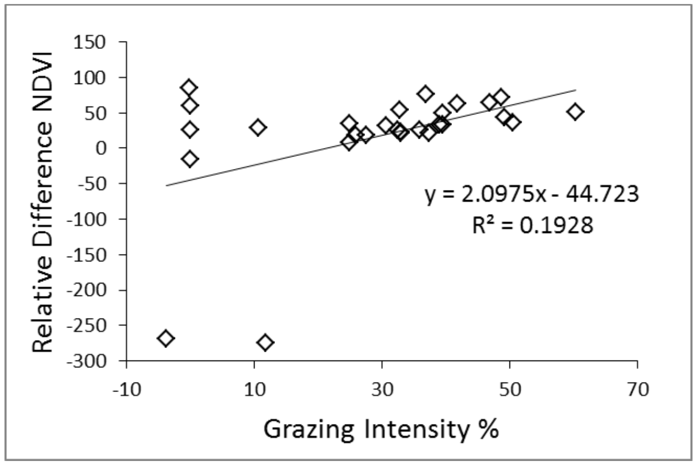

Figure 4. Relationship between grazing intensity based on measurement of ground biomass before and after cattle grazing and a corrected relative difference in NDVI corrected for the average influence of trees or other factors (equation 1).

Conclusion

The results offer the potential for NDVI to be a more precise monitoring tool than previously thought that can assess the impact of processes that produce relatively small changes in biomass or production even under dry low biomass conditions when NDVI is often insensitive to changes in biomass. This was true in this study, as the typical differences in biomass produced by grazing were mostly less than 25 g/m^2 and resulted in absolute changes of NDVI mostly less than 5%. Nevertheless these differences in NDVI were consistent across the sampling blocks, which suggests that, across many thousands of pixels in a remotely-sensed semi-arid rangeland, small changes in NDVI may offer a meaningful assessment of changes in productivity and biomass. Maps of such impacts can be used to identify areas of different intensity of prior use, provide feedback on compliance of herders with rotational grazing plans, monitor large-scale livestock movements, and anticipate future conflicts among different pastoralist groups in common rangelands.

The opportunities for confidently applying small magnitude changes in NDVI to ecological, management and conservation questions is immense, and NDVI may prove to be a powerful tool in monitoring ecosystem services and the influences of land use on these, such as carbon sequestration and soil-building[11] An NDVI-based calculation method appears to be suitable for monitoring changes in vegetation conditions as required carbon market standards, such as the Verified Carbon Standard, and may greatly reduce the cost and increase the efficacy of implementing projects with improved livestock management.

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