Soil Carbon Dynamics in the Northern Rangelands Trust Member Conservancies, Kenya

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Executive Summary A key question in the management of pastoral systems in semi-arid grasslands is how grazing and other management affects soil carbon. Soil carbon may be a key mediator of soil fertility and the capture of available rainfall, but the influence of management on soil carbon is not well understood. In this study, we conducted a ground survey of vegetation and soils at 86 sites across 8 different conservancies within the Northern Rangelands Trust in Samburu and Isiolo Districts in northern Kenya. This phase of our sampling was designed to accomplish two objectives: 1) to establish a baseline for comparison of soil carbon over time, and 2) to test a predictive model that estimates the accrual rate of carbon based on a few soil and vegetation characteristics. To accomplish these objectives, sites were non-randomly selected to encompass a wide range of soil types across as many conservancies as possible, and to compare areas of different livestock grazing management: no to light livestock grazing (Core Areas), moderate livestock grazing (Buffer Areas), and heavy continuous livestock grazing (Village Areas). While all areas have the potential for wildlife grazing, this grazing pressure is not managed and therefore is not factored into our analysis at this stage. At each site, soil and vegetation were sampled together. Soil was sampled to 20 cm depth, and analyzed for total organic carbon, texture (percent sand, silt, and clay), and bulk density. Vegetation was sampled by clipping live, aboveground plant biomass, and analyzed for lignin and cellulose content. In addition, current and past grazing intensity were estimated for each site. These soil and vegetation parameters (i.e., soil texture, lignin and cellulose content, historic average grazing intensity) along with interpolated average annual rainfall, were entered into a predictive soil carbon dynamic model called SNAP. The SNAP model was used to predict current soil organic carbon (SOC) stocks based on the estimated history of grazing. The mean predicted SOC stocks were then compared with mean observed SOC stocks for each type of management, and predicted SOC stock at a particular site was compared against observed SOC at the same site. The results suggested that within the NRT Conservancies, the model predicted mean and individual site SOC values with more than 90% accuracy. The SNAP model results suggest that prolonged, heavy, continuous grazing in the NRT Conservancies over the past 30 years has greatly depleted SOC stocks, but that reduction in grazing intensity will lead to recovery of SOC at a potential rate of 0.3-0.5 tons C/ha/yr across a variety of soil types. Because of past degradation, there is a large capacity for recovering SOC stocks in the Conservancies. These results suggest that planned grazing management beginning in the NRT Conservancies should help restore SOC and productivity in these semi-arid grasslands, and could result in an economically viable carbon offset project. Further sampling planned in the coming months will help to validate the accuracy of these assessments across all Conservancies potentially participating in the grazing management program, and more precisely assess the progress of specific grazing management actions within a few selected conservancies.

Introduction

Sustainability of human livelihoods is a major goal of economic development efforts across much of semi-arid East Africa (Paavola 2008, Wren and Speranza 2010, Marshall 2011). A central goal of these efforts is to improve sustainable in productivity in pastoralist systems particularly as an adaptation to impending climate change (Brooks et al. 2009, Galvin 2009, Kratli and Schareika 2010, Dong et al. 2011). Over the past 30-40 years, incentives for pastoralists to settle permanently have led to heavy continuous grazing over large areas of grassland and savanna and accompanying soil and habitat degradation (Galvin 2009, Dong et al. 2011, Marshall 2011). One major way that degradation occurs is through the loss of soil organic carbon (SOC) from a lack of carbon inputs (no leaves to fix carbon) and losses due to erosion from overexposure of bare ground (Li et al. 2008, Maraseni et al. 2008, McClaran et al. 2008). Loss of SOC not only reduces the nutrient base for plant production, it also can affect the proportion of rainfall that infiltrates and is held by soil (Maraseni et al. 2008, Abdelkadir and Yimer 2011, Teague et al. 2011). Past losses of SOC may limit the current capacity of soil to support production that will meet the demands of pastoralist populations. Recovery of SOC in degraded pastoral lands therefore may be a key process in improving sustainable plant and animal production, enhancing biodiversity values, and in adapting or mitigating climate change.

Relatively little is known about whether and at what rate changing grazing management can restore carbon to soil. Most reviews suggest that a reduced stocking rate is necessary for SOC recovery, but a recent review ((McSherry and Ritchie submitted) suggests that, in tropical grasslands, grazing may enhance and even be necessary to restore SOC. A major missing tool in making the calculation is an accurate and reasonably precise model of soil carbon dynamics. Relatively few models of SOC dynamics are available, and the most popular ones are CENTURY (Carrera et al. 2007, Feng and Zhao 2011) and RothC models (Leifeld et al. 2009, Xu et al. 2011). Our analysis of their model structure suggests that they are not well-suited to predicting the impact of altered grazing regimes on SOC, both because 1) they require many parameters that are difficult to measure and 2) neither considers grazing much more than a vegetation removal process.

A recent soil carbon model developed for grasslands and savannas in Serengeti National Park (Ritchie submitted) and called SNAP (Serengeti National Park), places grazing and the more complex responses of ecosystems to grazing as a centerpiece in the calculation of changes in SOC[1]. These features make the model more distinct in its predictions compared to other available models and possibly more applicable to African savanna grasslands. The SNAP model has performed very well in predicting current soil carbon stocks in response to long-term grazing management at the Mbirikani Group Ranch in southern Kenya (Ritchie submitted).

The Northern Rangelands Trust Conservancies are currently a focus of development for pastoralist communities in the Lower Ewaso Nyiro River watershed region north of Mount Kenya. A recent drought in 2009-2010, which led to < 50% loss of livestock has emphasized to community leaders the need for restoring productivity. In response, communities have conducted pilot planned grazing activities to reduce the local grazing intensity. Several small-scale range restoration projects also have been initiated to restore perennial grasses and vegetation cover. The new grazing practices and restoration activities have the potential to rebuild soil carbon stocks, but considerable uncertainty exists over how quickly SOC can be restored and how intensive management input must be to achieve gains in SOC.

The objective of this study was to conduct a soil and vegetation survey in the NRT Conservancies across a large number of sites to (a) determine measureable differences in SOC and vegetation characteristics across areas that have been managed in different ways, and (b) measure parameters for the SNAP model in order to test the validity of the model for explaining how SOC would change in response to planned grazing management. The large number of sites sampled will explore the full range of available soil types, annual rainfall, vegetation species composition, and grazing intensities that are known to affect SOC and are key inputs into the SNAP model. Predicted values from the SNAP model were compared against observed SOC using regression and ANOVA statistics to determine accuracy and bias of SNAP in predicting soil carbon stocks following long-term management and predicting changes in SOC in response to changed management.

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[1] The model features compensatory responses of plants to increased grazing intensity, positive feedbacks between SOC and available moisture and between shoot and root growth at high grazing intensity. Its most striking component is a pathway of fixed carbon to soil carbon through grazer consumption, deposition as dung, and enhanced incorporation of carbon into soil by invertebrate detritivores such as dung beetles and termites.

Results

Conservancies were dominated by sandy loam soils that were surprisingly uniform in texture regardless of color. Except in black cotton soils on eroded lava plateaus or riparian areas, soil was 84-88% sand, < 5% silt and < 10% clay. Black cotton soils held 30-45% clay, 5% silt and < 65% sand. Consequently, percent sand within a soil class did not vary significantly among sites (sandy loam vs clay loam "black cotton") (P > 0.76). Based on these results for soil type, we altered the effect of soil type on the statistical analysis from a stand-alone dependent variable and included it in subsequent analyses as a covariate.

Effects of grazing management

Statistical Comparisons

Different management types were associated, as expected, with different current grazing intensities (Fig. 5). Village areas had the highest mean estimated grazing intensity of more than 70% standing biomass removed, while buffer and core areas had similar grazing intensities of 30-40% standing biomass removed (see Methods below). Grazing in treatment areas that removed Acacia reficiens, employed moveable bomas, and/or added seed was virtually undetectable, as grazing intensity was less than 10%. This result showed that livestock were effectively managed in these restoration areas to allow maximum recovery of existing vegetation and establishment of seedings.

These current grazing intensities were different from estimated historical grazing intensity. Virtually all sites were judged to have been grazed with greater than 90% intensity because of their extensive bare ground and lack of perennial herbaceous plant species. However, management types did differ in their historical grazing intensity (see Methods below) as buffer areas had significantly less grazing impact than other types (92%), which averaged 96-98% (Fig. 6). Lignin and cellulose content varied from 12% - 40% across sites and exhibited considerable variation even within a management type. Nevertheless, lignin + cellulose differed significantly among management types (F = 8.122, df=3,69, P < 0.001, Fig. 9).

From these site and treatment differences, we found that, after controlling for the influence of soil texture and historical grazing intensity, the Conservancies did not differ significantly in soil carbon density (Table 1). Likewise, management types differed significantly in SOC density (F=3.05, df=3,54, P=0.036, Fig. 8). However, in an ANCOVA that controlled for the significant influence of soil texture and historical grazing intensity, management types did not differ in SOC density (Table 2).

A major finding of this analysis (i.e., the ANCOVA's coupled with the comparison of means in Fig. 8) clearly show that any influence of management type or conservancy is associated with three primary drivers: 1) the history of grazing, 2) plant species composition (as reflected by lignin and cellulose content), and 3) soil type.

Model predictions

The SNAP model predictions matched well with observed SOC density. We tested this in two ways: 1) by comparing predictions with the mean values observed across management types, and 2) by comparing predictions with individual sites.

Across management types, mean SOC densities predicted by the SNAP model were significantly different from each other (F= 4.38, df=3,54, P = 0.011). However, the *predicted* mean for each management type was not significantly different from the *observed* mean SOC density for that management type (P > 0.41)(Fig. 9). Estimates of SOC density from the SNAP model for each management type were well within the 95% confidence intervals of the observed mean SOC density for each management type.

For individual sites, the predicted SOC density from the SNAP model at each individual site was highly correlated with observed SOC density at the same site for the all the NRT Conservancies (Fig. 10). We ran two regressions to deal with the single outlier site that contained extremely high SOC density (6881 g/m^2 SOC). Including this outlier site (Fig. 10A), the model predicted observed SOC with an $R^2 = 0.92$, while excluding this site, the SNAP model predicted observed SOC density with $R^2 = 0.88$ (Fig. 10B). [2] Excluding the high SOC site (Fig. 10B), the SNAP model predicted observed SOC density with $R^2 = 0.88$[3]. Three sites from Samburu National Reserve contained soils with extremely low SOC and were poorly predicted by the SNAP model, which used input grazing intensities < 90%.

Discussion

Grazing management influence on soil carbon

The results overwhelmingly support the hypothesis that grazing management influences SOC in the NRT Conservancies. This influence can be detected both directly through impact on plants in the form of grazing intensity, and indirectly on species composition by eliminating perennial grasses in favor of annual grasses, or in the most extreme cases, only annual herbs. Management types differed significantly in current

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[2] Confidence intervals included a slope = 1 and intercept = 0 which indicate a lack of bias.

[3] Also with slope = 1 and intercept = 0 included within the 95% confidence intervals for the regression.

and past grazing intensity (Fig. 5,6), and in the lignin and cellulose content of vegetation (Fig. 7). ANCOVA analyses revealed that the primary management-oriented driver of these patterns is historical grazing intensity, current grazing intensity, and species composition (lignin + cellulose), since management type was not a significant factor once these variables were introduced into the analysis (Table 1, 2). These results are not too surprising, given a rather extensive literature showing negative impacts of heavy grazing on SOC (Li et al. 2008, McClaran et al. 2008, Wang et al. 2008, McSherry and Ritchie submitted). However, these results further emphasize the importance of species composition (annual herbs, annual grasses, perennial grasses) as an outcome of past management and a goal of range restoration for recovering SOC stocks (Ganjegunte et al. 2005, Frank et al. 2011).

Ability to predict current soil organic carbon

The results also support the ability of the SNAP model to predict SOC stocks following prolonged period of similar management types and impacts. On the NRT Conservancies, the model was nearly 90% accurate in predicting SOC stocks on a variety of soil types from sandy to clay loam, across a rainfall gradient of 300 – 550 mm/yr, and with plant lignin and cellulose content varying from 15-40%. The SNAP model would appear to be a valid tool for assessing impacts of different grazing management plans on SOC and its concomitant benefits on soil fertility and plant and animal productivity (Abdelkadir and Yimer 2011, Marshall 2011, Teague et al. 2011).

The model poorly predicted observed SOC stocks in Samburu National Reserve (Fig. 10). The observed stocks were extremely poor in SOC, and were significantly lower ($P < 0.001$) than SOC stocks even in village areas of the NRT Conservancies. In our modeling, we assumed that grazing intensities were less than 90% because the Reserve is has not been used for livestock grazing since 1985 when the Reserve was established. However, even under an assumption of 99% grazing, the SNAP model's predictions were well above the levels of SOC observed. Low SOC density can be a powerful indicator of past land abuses, and all our sampling sites were within 0.6 km of the Ewaso Nyiro River, a major regional water source during dry seasons and droughts for the entire archaeological period of human activity in the region. It is possible that centuries of heavy use prior to 1985 have depleted SOC to unprecedented levels from which the soil is only beginning to recover. However, this is a difficult hypothesis to test rigorously, and so the low SOC and failure of the SNAP model to predict it requires further investigation in the next phase of sampling.

Limitations of our analyses and model predictions

The principal limitation to even better predictability of the SNAP model is likely better input data. Grazing intensity estimates were subjective, and some sort of historical measurement of standing crop, such as NDVI-based methods of interpreting satellite imagery (Feng and Zhao 2011) would help build confidence in model inputs. The inclusion of lignin and cellulose was an extremely important input because sites within conservancies and management types differed dramatically in species composition, and by proxy lignin and cellulose content varied as well. The SNAP model could account for only 40-50% of the variation in observed SOC without site-specific lignin and cellulose data. Nevertheless, it is not clear whether current lignin and cellulose content was present historically, or if it was, how long it was present. Finally, our confidence in rainfall maps for the NRT region is less than full, as different maps produced by different agencies, such as the International Livestock Research Institute (ILRI) and the Kenyan government were very different. We need to develop better rainfall interpolations from more modern GIS databases in future analyses.

Ability to predict the rate of change in soil organic carbon due to grazing management
Despite these caveats, the SNAP model may provide a useful tool in assessing rates of change in SOC from proposed grazing management changes in NRT. As a test of this, we calculated expected SOC stocks for core and buffer areas under two different, hypothetical management scenarions. Under the first scenario, long-term heavy grazing (>90%) was followed by no management changes in place for an average of 7 years. Under the second scenario, long-term heavy grazing was followed by 7 yrs of relaxed grazing (<90%). Under the first scenario, without the short-term management changes included, the SNAP model predictions averaged 250 g/m^2 less SOC than was observed. This suggests that after only 7 years of altered management, measureable differences in SOC can result, and that altered grazing management that eases the intensity of grazing below 90% will improve SOC. **Based on the SNAP model predictions, the relaxation of grazing intensity in core and buffer areas added an average of 0.3 – 0.5 tons SOC/ha each year.**

Not enough time has passed following the range restoration efforts to assess associated changes in SOC. Most of the treatments have been employed for less than 5 years and generally SOC must increase at least 0.1% to be detectable with standard methods. A 0.1% increase in SOC translates to more than 200 g/m^2 in SOC in a 20 cm deep sample, and SNAP model calculations suggest that at least 7 years of improved grazing would be required to yield a 0.1% increase in SOC. Furthermore, dry conditions through 2010 and most of 2011 prevented expression of seeds and ungrazed plants in most treatments further delaying any detectable increases in SOC.

The predicted additional carbon added as a consequence of reducing grazing intensities in core and buffer areas predicted by the SNAP model of 0.3 – 0.5 tons SOC/ha/yr translates to carbon dioxide sequestration of 1.1 – 1.84 tons CO_2 per year. This is virtually the same range of carbon dioxide sequestration predicted by the SNAP model in previous assessments. Based on pending methodologies on the Verified Carbon Standard, and using a base rate of $3.00 USD per ton of carbon on the open market, this rate of carbon sequestration (0.3 - 0.5 tons SOC/ha/year from grazing management) would result in enough revenue generation for a viable carbon offset project.

Next Steps

In the coming months, we expect to complete our baseline analysis. To do this, more soil and vegetation samples will be collected from the sites that were not possible to sample in the first round. This will help to validate findings for all Conservancies currently envisioned as participating in the grazing management program and as part of a potential carbon offset project (e.g., Melako and Buliqo Bulesa). Additional sites will be added to help explain some of the discrepancies found during the first suite of sites (e.g., outliers with high carbon content on lava plateaus, and low carbon content in Samburu National Reserve).

Once the baseline analysis is complete, we will rerun the model and report on our findings. Based on the results of this baseline assessment, we will then look to sample more intensively within Conservancies where active grazing management is occurring, and develop better estimates on the rate of carbon sequestration, and the scale and scope of recovery in order to better estimate the potential for a carbon offset project.

Conclusion

The results of this study affirm that grazing management influences SOC by altering grazing intensity and species composition. Changes in SOC from different management strategies can be predicted well with the SNAP carbon dynamic model developed in Tanzania. Improvements in model predictions could be achieved with better historical data on grazing intensity and species composition and improved rainfall interpolations. However, even without improved data, the model results suggest that prolonged, heavy, continuous grazing in the NRT Conservancies over the past 30 years has greatly depleted SOC stocks, but that reduction in grazing intensity leads to recovery of SOC. Such recovery, if implemented across multiple Conservancies, could produce an economically viable carbon offset project with pending methodologies on the Verified Carbon Standard.

Methods

Study site

The study was conducted in eight conservancies, Il Ngwesi, Lekurruki, Mpus Kutuk, Kalama, Meibae, West Gate, Namunyak, and Sera within the Northern Rangelands Trust Conservancies (Fig. 1). Sometime in the past 3-10 years, each Conservancy except Meibae and Namunyak established a "core area" designated to be free of livestock, surrounded by a "buffer area" that received only partial livestock use. These contrasted with "village" areas in which there were no restrictions on livestock use. Another type of management area was designated "treatment," in which various range improvements, such as moving bomas, re-seeding, and cutting an undesirable tree, *Acacia reficiens*, have occurred since 1999. Finally, we also sampled at three sites within Samburu National Reserve, which lies just south of the Kalama Conservancy.

Rainfall in the area and for specific sampling sites was determined by interpolating mean annual rainfall isopleth maps for Samburu, Isiolo, and Laikipia Districts published by Hijmans et al. (2005) (Fig. 2) Rainfall varies from 300-350 mm/yr in the eastern portion of the NRT Conservancies to 550 mm/yr in the southernmost Laikipia District Conservancies. Soil maps published by Sombroek and van der Pouw (1982) (Fig. 3) for Samburu, Isiolo, and Laikipia Districts were used as a basis for initially stratifying our sample sites. Our overall design strongly resembles a systematic sample of eight Conservancies with a proportional stratification according to soil type.

Survey design

Site locations were pre-selected by superimposing soil maps onto GIS layers with Conservancy boundaries, the location of core and buffer areas, the location of range improvements, and the location of previous NRT vegetation inventory sampling locations. We attempted to produce replicate sites within each major soil type, and management area, and wherever possible, to place sites near previous NRT vegetation inventory sampling locations. We initially identified more than 100 sites for sampling, but time and field logistics limited the number we eventually sampled in this phase to 86. Even so, we were able to sample multiple sites within each of the eight Conservancies and, where soils were variable within a Conservancy, in sandy loam and clay loam soils.

Soil and Vegetation Sampling

At each site, in February 2012, we marked the GPS location (GPS point) with a cairn of stones. Two soil cores were taken with a hand-held corer to a depth of 20 cm approximately 4 m N of the GPS point[4]. Vegetation at each sampling site was assessed in several ways. Vegetation species composition and bare ground were measured using the "stick-intercept" method developed by Corinna Riginos at the Mpala Research Centre in Laikipia District (Riginos 2011). However, we do not report the results of these measurement in this report, as the data have yet to be entered into electronic form. A visual assessment of woody plant cover was made for the area 50 m in radius around the GPS point. We also clipped aboveground vegetation from two 25 x 25 cm quadrats near each GPS point. Clipped plants were sorted to live, standing dead, and litter (gray vegetation left from previous growing seasons)[5].

Grazing Intensity

Current grazing intensity was estimated from visual methods developed and calibrated in Serengeti National Park based on the mean height of grasses. Past grazing history was estimated on the basis of percent bare ground and plant species composition[6].

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[4] Cores were pooled, mixed, and a 100 g sample was saved for later analysis. Soils samples were analyzed by Crop Nutrition Laboratory Services, Nairobi with a Carlo-Erba autoanalyzer for the concentration of soil organic carbon (g SOC/g soil) and with the clod method for bulk density (g soil/cm^3). A smaller subset of samples, representing sites with from the major soils categories listed on the soils map, were analyzed for texture (percent sand, silt, and clay) using liquid settling methods.

[5] Live and standing dead plant material was dried at 60^{o}C and weighed to determine biomass. These two types of material were combined and ground through a 0.8 mm mesh screen in a Wiley Mill and then digested for 24 hrs while agitated in a solution of acid and detergent (Claessens et al. 2005). The remainder (mass R) was then placed in a 400^{o}C muffle furnace for 48 hrs to yield ash content (mass A). The Lignin + cellulose content (mass L) = (R-A)/T, where T is the total dry mass of the sample.

[6] Current grazing history was estimated as the percent that grazing reduced the average estimated above ground height of vegetation if it had not been grazed. For example, grass that would grow to 1 meter high but is grazed to 30 cm lost 70 cm to grazing, and therefore would be estimated at 70% (70cm/100cm) current grazing intensity. For historic or past grazing intensity, species composition and bare ground are factored in. For example, past grazing history was estimated on sites that featured mostly bare ground and only annual herb species as having a 99% grazing intensity. The presence of annual grasses but still 90-95% bare ground was assessed as 95%. The presence of perennial grasses implied a lower historical grazing intensity, and we assumed that that intensity was proportional to the amount of bare ground.

Statistical Analysis

Differences in various measures were compared among different management types using ANCOVA with percent sand as a covariate, and significance was evaluated at $P < 0.05$.

SNAP model

The soil carbon dynamic model we tested for management in the NRT Conservancies was the new "SNAP" model. Its essential features are described in Fig. 4. The model predicts soil carbon stocks for tropical grazed and burned grasslands following some period of management that adjusts fire frequency, grazing intensity and vegetation species composition, which affects lignin and cellulose. The model tracks the fate of carbon from assimilation into roots and shoots and then the fate of these as grazed, burned, or respired during decomposition (Fig. 4). A major distinguishing characteristic of this model is that there are only a few (five) critical variables necessary to run the model, and all are relatively easily measured. The five key inputs to the model are:

(1) mean annual rainfall, which determines total productivity and C assimilation and its allocation belowground,
(2) fraction of lignin and cellulose in aboveground live and standing dead plants, which driven by plant species composition,
(3) fire frequency, which in this study was assumed to be zero because fire is not used as a management tool,
(4) mean grazing intensity (percent of standing crop removed by grazers), and
(5) soil texture (percent sand in the soil).

These inputs are assumed to represent average conditions over the time period in which management occurred.

In this study, we wanted to predict how short-term changes in management altered soil organic carbon. To do this, we estimated the soil carbon stocks that would be found following a long period of unrestricted continuous grazing and then estimated changes in SOC following an assumed 7 years of management in core and buffer areas. It is likely that not all core and buffer areas in the NRT Conservancies have been in place for 7 years, but this was the simplest first approximation we used.

Predicted SOC stocks were compared against observed stocks in two ways. First we calculated the SOC stocks predicted for each site based on regionally derived inputs of rainfall and soil texture (Fig. 2 and 3) and site-specific inputs of grazing intensity and lignin and cellulose. These were averaged across all sites with similar soil types (sandy loam vs. black cotton) and management type (core, buffer, village, treatment) and compared against mean observed SOC stocks for these same categories with a least squares calculation of variance left unexplained. Second, we regressed observed SOC stocks for each site against the predicted SOC from the SNAP model for that site (*N* = 86).

From the regressions, we evaluated bias in the model by comparing the regression intercept (±SE) to zero and the slope to 1. If the model under-predicts high SOC values (i.e. was biased against yielding higher SOC values, the slope will be different from 1. Likewise, if the model consistently under (or over)-estimates observed SOC by the same amount across all SOC values, the intercept will be different from zero. Under both of these scenarios, one could obtain a R^2 > 0.90, but the model would be under-performing in some way.

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Table 1. Results of ANCOVA to detect the influence of conservancy on SOC density after controlling for the influence of soil texture (percent sand) and historical grazing intensity, and lignin and cellulose content of plants.

Tests of Between-Subjects Effects

Dependent Variable:ObsSOC

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	40776081.754[a]	10	4077608.175	11.035	.000
Intercept	8476164.592	1	8476164.592	22.939	.000
Sand	3028641.288	1	3028641.288	8.196	.006
AnnualGIEst	5986246.678	1	5986246.678	16.201	.000
LigCell	7529980.502	1	7529980.502	20.379	.000
Conservancy	2526230.787	7	360890.112	.977	.457
Error	22170255.588	60	369504.260		
Total	4.087E8	71			
Corrected Total	62946337.342	70			

a. R Squared = .648 (Adjusted R Squared = .589)

Table 2. Results of ANCOVA to detect the influence of management type on SOC density after controlling for the influence of soil texture (percent sand), plant lignin and cellulose, and historical grazing intensity.

Tests of Between-Subjects Effects

Dependent Variable:ObsSOC

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	38556529.390[a]	6	6426088.232	16.862	.000
Intercept	11948412.924	1	11948412.924	31.353	.000
Sand	3001666.199	1	3001666.199	7.877	.007
AnnualGIEst	10666630.112	1	10666630.112	27.990	.000
LigCell	6884641.178	1	6884641.178	18.066	.000
Type	306678.423	3	102226.141	.268	.848
Error	24389807.951	64	381090.749		
Total	4.087E8	71			
Corrected Total	62946337.342	70			

a. R Squared = .613 (Adjusted R Squared = .576)

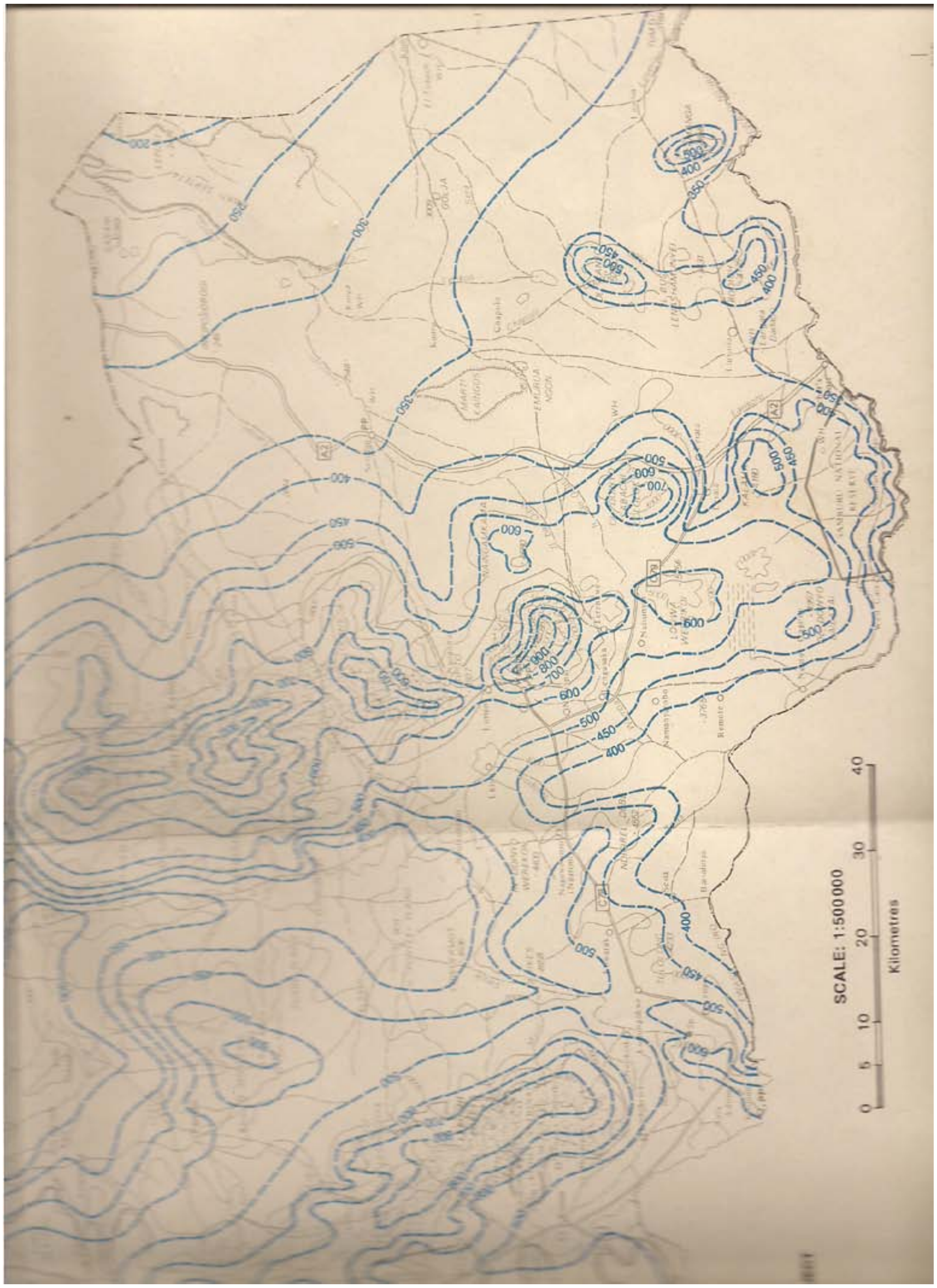

Figure 1. Scanned map of mean annual rainfall isopleths for the Samburu District used to interpolate annual rainfall for each site in Kalama, West Gate, Namunyak, and Meibae Conservancies. Similar maps for the Isiolo and Laikipia Districts were used for sites in the Sera and Mpus Kutuk (Isiolo) and Il Ngwesi and Lekurruki (Laikipia) Conservancies.

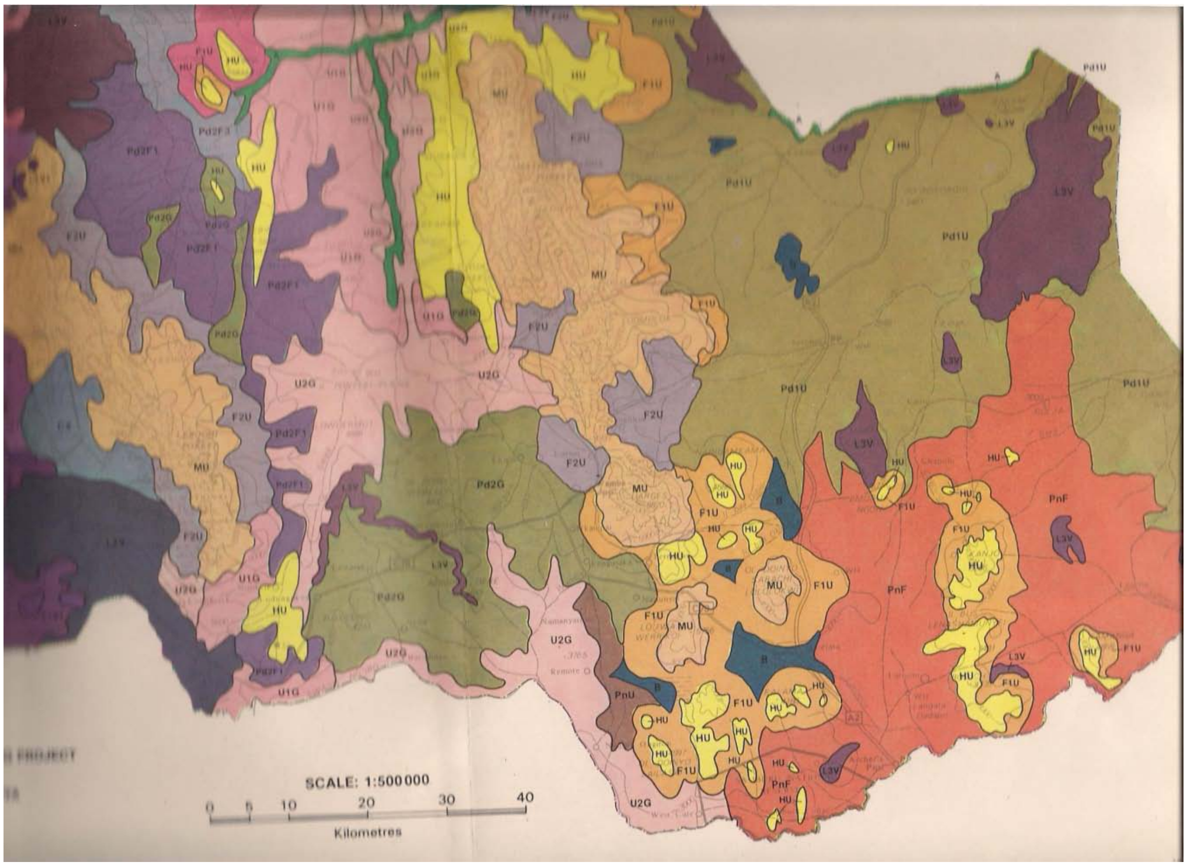

Figure 2. Scanned soils map for the portion of the Samburu District containing the NRT The major soil types were red sandy loam (red, and orange), white sandy loam (pink and gray-brown), rocky (beige and yellow) and dark clay "black cotton" (dark purple and dark blue). These soil types were used to stratify the choice of sites so as to include multiple replicates of these soil types across and within the different Conservancies.Conservancies we studied. Similar maps were used for the conservancies in Isiolo and Laikipia Districts.

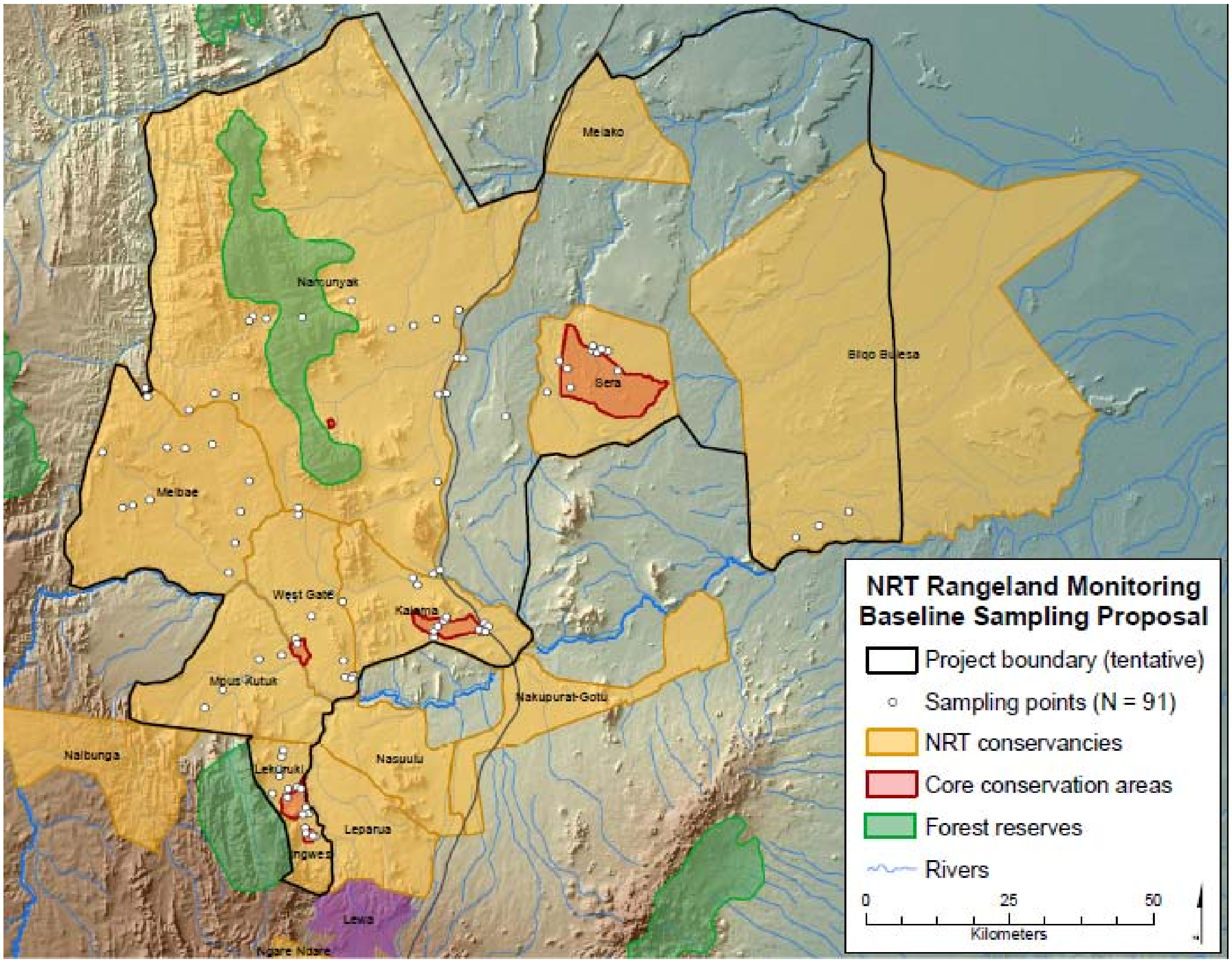

Figure 3. Map of NRT Conservancies with field sampling sites indicated by the white dots. Note, most sites in Namunyak, Melako, and Biliqo Bulesa were not sampled due to time limitations and inaccessibility. The black outline is a suggested boundary for a potential carbon sequestration project.

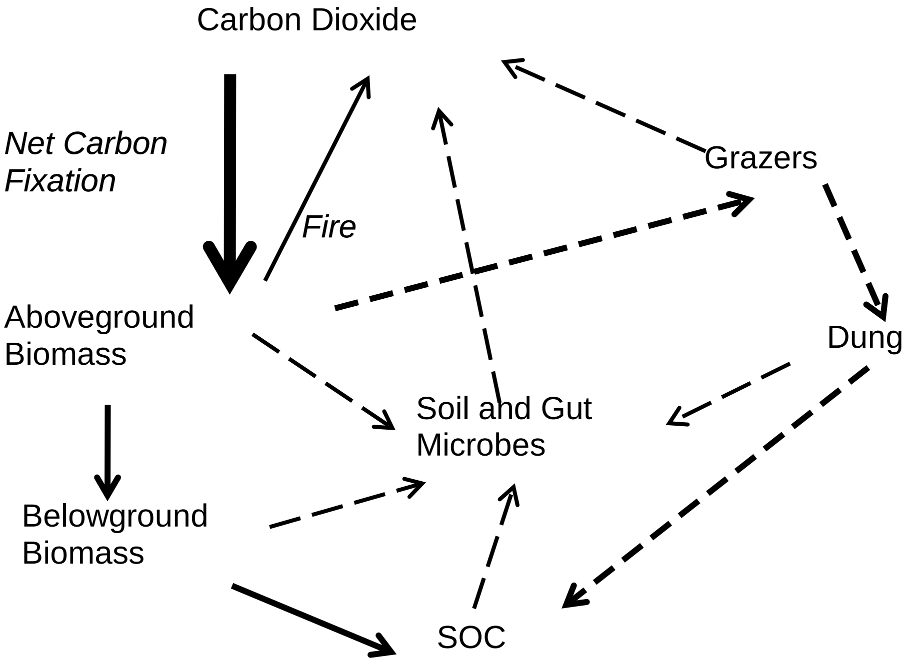

Figure 4. Hypothetical diagram of the major fates of carbon in the SNAP model following fixation of carbon dioxide (thickest arrow). Thick solid arrows show transfer of carbon to roots and then to SOC following decomposition. The thin arrow indicates combustion. Thick dashed arrows follow carbon through consumption by grazers, deposition as dung, and incorporation into SOC. Thin dashed arrows show consumption of dead plant material, dung, and SOC by free-living soil microbes and gut microbes of invertebrate detritivores (termites and dung beetles) followed by respiration of carbon dioxide to the atmosphere. Respiration of carbon by grazers is also shown with a thin dashed arrow. The magnitudes of carbon transfer in each arrow are determined by lignin and cellulose content of plants, rainfall, grazing intensity, fire frequency, and soil texture (percent sand) ((Ritchie submitted)).

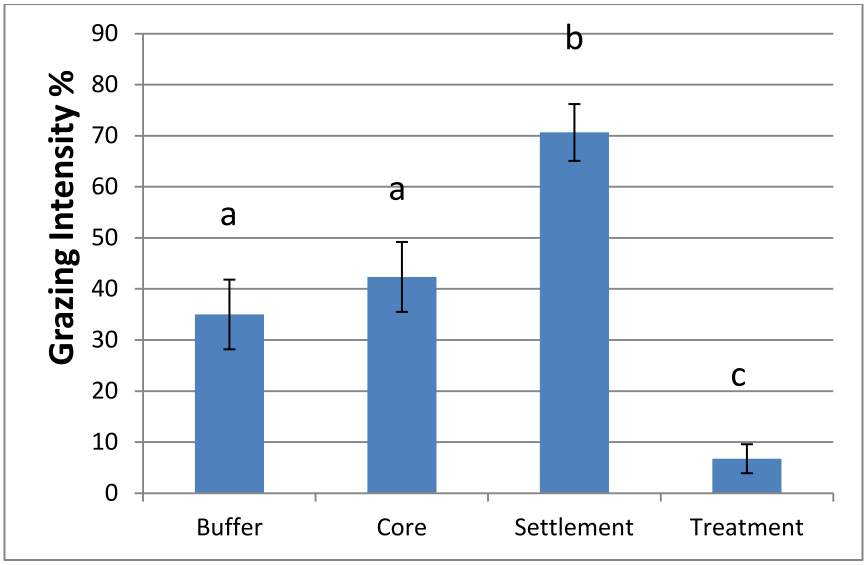

Figure 5. Mean (± SE) visually estimated current grazing intensity at sites with different types of management in the NRT Conservancies, Kenya, in February 2012. Differences in lower case letters indicate significant differences between means.

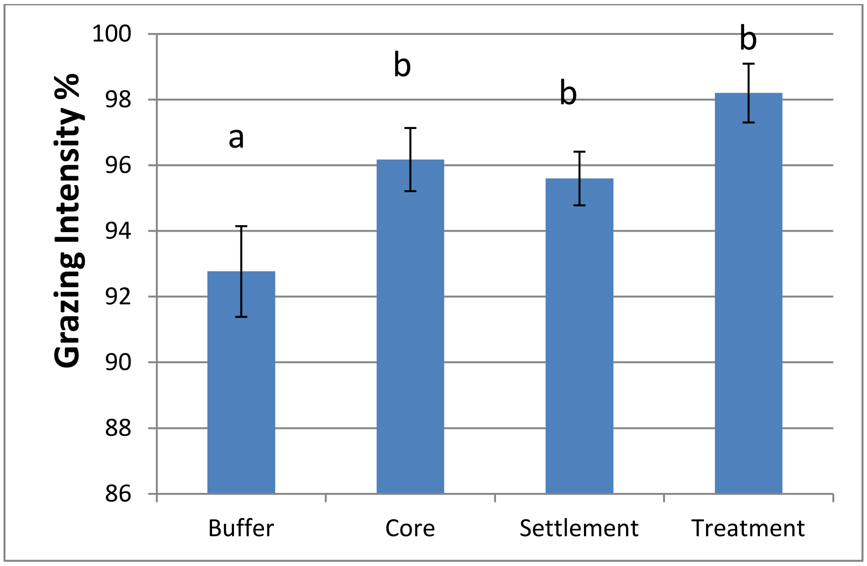

Figure 6, Mean (± SE) estimated historical grazing intensity in four types of management areas in the NRT Conservancies, Kenya. Differences in lower case letters indicate significant differences between means.

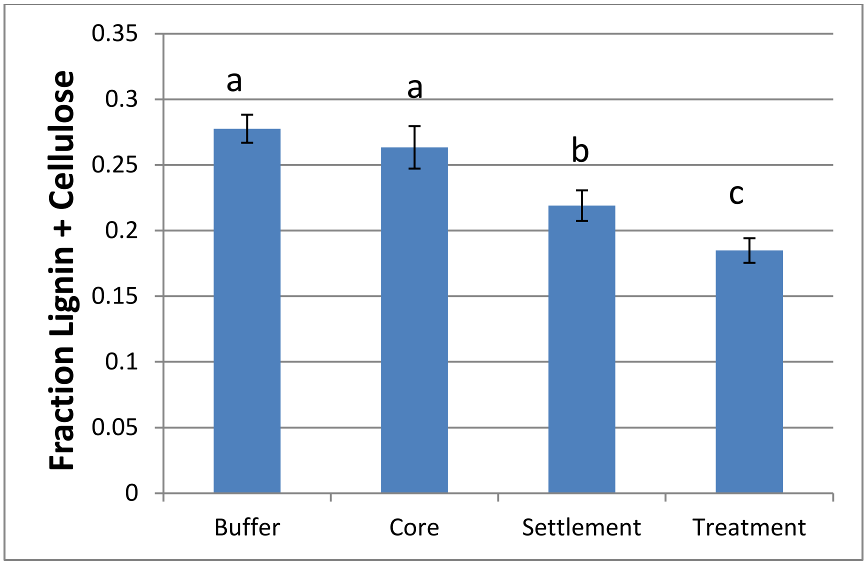

Figure 7. Mean (± SE) fraction of aboveground live and standing dead tissue composed of lignin and cellulose for different types of management within the NRT Conservancies, Kenya. Different lower case letters indicate significant differences among different management types.

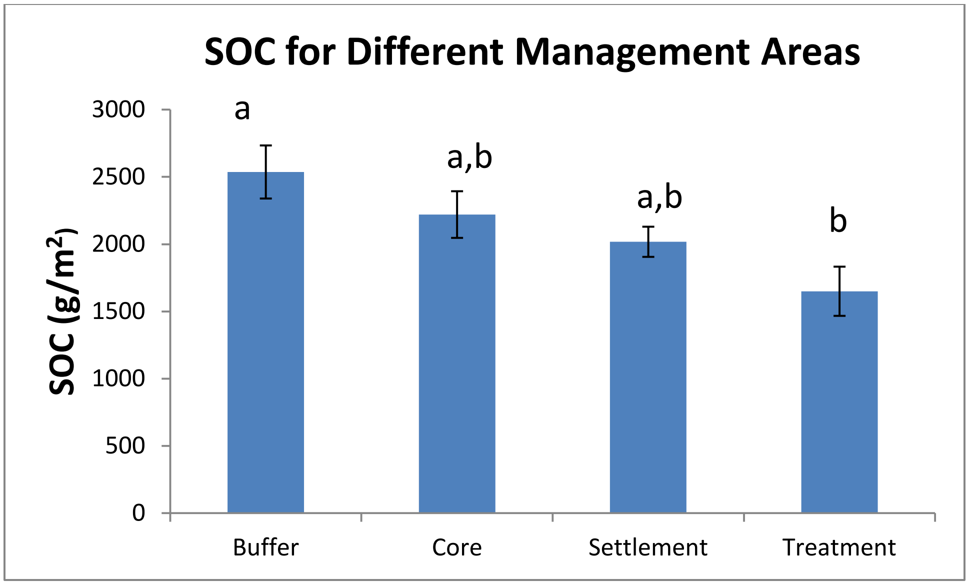

Figure 8. Mean(± SE) density in the four types of management in the NRT Conservancies, Kenya. Differences in lower case letters indicate significant differences between means.

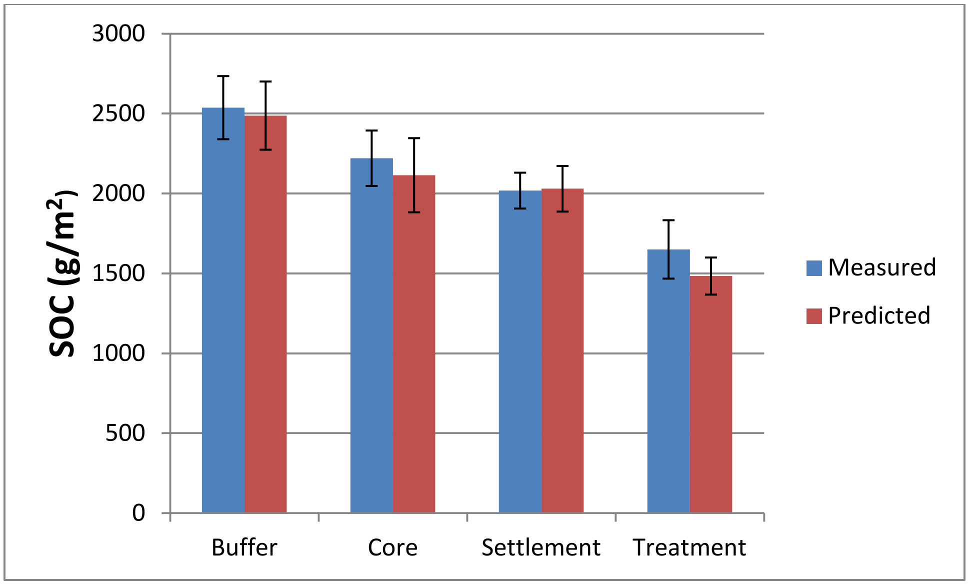

Figure 9. Predicted mean (± SE) SOC density (red columns) compared to observed mean SOC (± SE) density for the four types of management in the NRT Conservancies, Kenya.

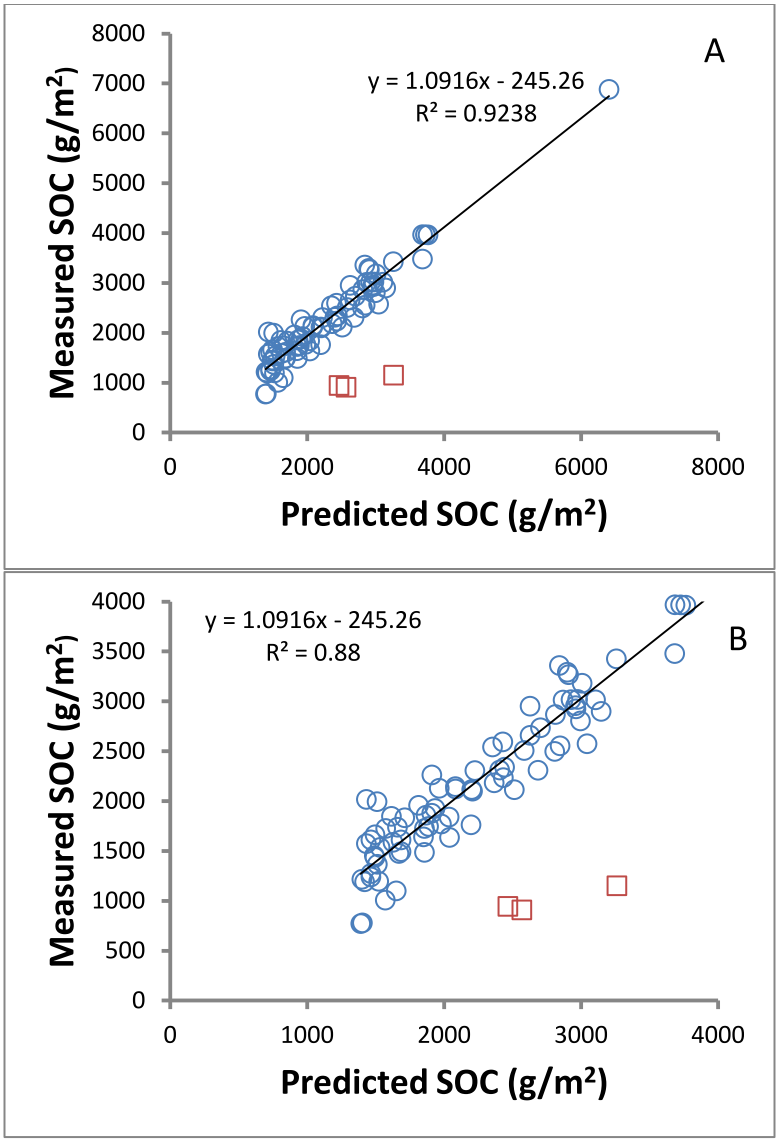

Figure 10. Regressions of observed SOC density at each of the survey sites versus the predicted SOC density from the SNAP model based on rainfall, historical grazing intensity, soil texture, and plant lignin and cellulose at each site. Open blue circles are data from NRT Conservancies, Kenya. Open squares are data from Samburu National Reserve. A. All sample points. B. Eliminating the single point of high SOC density from atop a lava plateau in Lekurruki Conservancy. For both regressions of NRT Conservancy sites, slopes are not significantly different from one and intercepts are not significantly different from zero.