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Research Article

Soil carbon and nitrogen distribution under contrasting land cover types in Kibale National Park, Uganda

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ABSTRACT

Avoided deforestation in Africa's tropical forests between 2003 and 2012 saved about 615.8 million Mg CO_2 from being emitted into the atmosphere. However, little is known about how land cover type (LCT) and land cover change (LCC) influence the sequestration of carbon (C) and nitrogen (N) in soils under these forests. We evaluated the impact of LCT on the distribution of soil C and N stocks and changes in these stocks with LCC in Kibale National Park, Uganda. Soil core samples were extracted manually down to 0.6 m at 0.15 m intervals under - intact forest, restored forest, degraded forest and annual cropping (maize) on a red Ferralsol soil. There was a significant effect of LCT/LCC on the depth distribution of soil C and N stocks in the area. Highest soil C stocks (19.0±0.86 Mg ha^{-1}) were observed under maize whereas the smallest (16.4±1.54 Mg C ha^{-1}) were under intact forest. However, about 70% of the soil C stocks under the forest covers (11.2 Mg C ha^{-1}) were accumulated deeper than 0–0.15 m compared with only about 47% (about 8.9 Mg C ha^{-1}) under maize. The 2.3 Mg C ha^{-1} in the 0.15–0.6 m layer of soil under intact and restored forest covers in excess of what we observed under maize, highlights the importance of forest covers in sequestering C and N in the area and potentially in related ecosystems elsewhere in Uganda.

Key words: land cover, degraded forest, tropical high forest, restored forest, soil C, soil N

Introduction

Forests represent a non-geological form of removing and storing atmospheric carbon (C) in the terrestrial sink and mitigation of greenhouse gas emissions (FAO 2010). Globally, forests store about 289 Gt of carbon (1 Gt = 10^{12} g) in biomass alone (FAO 2010). In Africa, the estimated C emission mitigation from avoided deforestation during the period 2003–2012 was 615.8 million Mg CO_2 (FAO 2007). Consequently, a number of projects have been initiated for C sequestration in tropical forests (Lyon and Westoby 2014; FAO 2010; Jindal et al. 2008; UNEP 2008). In Uganda, Forest Rehabilitation Project promotes reforestation of 24,000 ha in Mount Elgon and Kibale National Parks (Jindal et al. 2008). However, estimates of the sequestration potential of Uganda's public forests for C have been based on aboveground biomass for example, on Mt. Elgon National Park (Buyinza et al. 2014), in Kibale National Park (UWA-FACE 2015; Omeja et al. 2012), and in Bwindi Impenetrable Forest (Otukei and Male 2015).

Highlights

- Land use (LU) and land cover change (LCC) impact the depth to which C is placed in soil;
- About 70% of soil C under forest covers in Kibale National Park was in the 0.15–0.6 m depth compared to 47% under maize cover;
- The deeper the C is located in soil, the less available it is for losses into the atmosphere.

About 75% of terrestrial C is in the soil (Schimel 1995), more than 90% of it in the form of soil organic matter (Schmidt et al. 2011). Yet, we could not find a single study that had investigated the C sequestration potential of soils under Uganda's tropical high forests and how changes in land cover have impacted these stocks. Metadata on global estimates of soil organic carbon (SOC) in forests (Eclesia et al. 2012; Guo and Gifford 2002) had very limited coverage of tropical forest soils, especially in Africa. Moreover, there is as yet, no consensus on how much C is lost by changes in tropical land uses (Eclesia et al. 2012; van der Werf et al. 2009). In southwest Rwanda, Wasige et al. (2014) evaluated SOC stocks as a function of contemporary and historical LCTs, soil group and soil type and observed that SOC stocks were best explained by current LCTs and not by soil group or land cover conversion history. Forest clearing for annual cropping resulted in the loss of 72% of SOC that had been sequestered under the forest whereas conversion of annual cropping into plantation forestry increased SOC by 193% (Wasige et al. 2014).

Given the rampant unplanned clearing of remnant public forests in Africa in general and in Uganda in particular for agricultural, industrial and other competing land uses, factual insights into the functions of these endangered ecosystems are needed to ensure that any changes to existing cover do not undermine these functions. Emerging evidence indicates that deforestation of privately owned tree plantations could be up to eight times that on public forests (Bakiika 2013). Moreover, 50% of aboveground biomass is used as fuelwood (Tabuti et al. 2003; Naughton-Treves et al. 2007), implying that sequestration of C belowground could be a better option. In a previous study Wasige et al. (2014) evaluated SOC stocks in the 0–0.5 m layer but sampled the soil at only two depths: 0 – 0.2 m and 0.2 – 0.5 m and therefore, failed to address the possibility that the impact of LCT on SOC and SON stocks might be depth-specific. This information might aid identification of LCTs that not only accumulate C in soil but also locate a higher portion of that C in deeper soil layers for long-term storage (Rasse et al. 2005). Our study, therefore, evaluated the impact of LCTs on sequestration of total SOC and SON stocks and examined the depth-specific impacts of LCTs within the 0.0–0.6 m depth at 0.15 m depth intervals under KNP, south-western Uganda.

Materials and methods

Description of the study area

The study was conducted in Kibale National Park (KNP) located about half an hour's drive to the southeast of Fort Portal Town, Kabarole District in southwestern Uganda. The park is located near the foothills of the Ruwenzori Mountains, 200 km north of the equator (UWA-FACE 2015; Chapman and Lambert 2000; Struhsaker 1997) on bearings 0°12$^{//}$ – 0°40$^{//}$ North and 30°20$^{//}$ – 30°35$^{//}$ East in the counties of Burahya, Kibale and Mwenge (Figure 1; UWA-FACE 2015).

The KNP is a remnant of a transitional forest between savannah and mid-altitude tropical forest spanning over an area of 795 km^2 on an undulating terrain on the main Uganda plateau slightly tilted to the south, with an altitude ranging from 1,110 m to 1,590 m asl in the south and extreme north, respectively (UWA-FACE 2015; Omeja et al. 2012). About 69 km^2 of KNP lies below 1,250m and 464 km^2 at 1,250–1,500 m while 27 km^2 lies above 1,500 m asl.

The climate of KNP is tropical with a bimodal rainfall pattern where first rains start in March, lasting up to May and second rains from September to November. Total rainfall ranges from 1,100 – 1,697 mm yr^{-1} with the North receiving significantly more rainfall than the South (UWA-FACE 2015; Omeja et al. 2012). Rainfall average of 1707 mm yr^{-1} was reported between 1990 and 2010, falling mainly during the two rainy seasons (Omeja et al. 2012; Stampone et al. 2011; Chapman and Lambert 2000). The two rainfall seasons are interrupted by dry spells with December to February being the hottest and driest period. Mean temperature ranges from a minimum of 14°C-15°C with a mean daily minimum of 15.5^{o}C to a maximum of 26°C–27°C, with a mean daily maximum temperature of 23.8^{o}C (Stampone et al. 2011; Chapman and Lambert 2000).

From soil map (1:50,000, FAO, 1988 classification), about 90% of the Park is overlain by red Ferralitic soils of which 70% are sandy clay loams in the North and 30% are clay loams in the South. These soils were derived from the rocks of the Precambrian era, which are sedentary, strongly folded and metamorphosed (Yost and Eswaran 1990). The Toro system overlaying these rocks forms prominent ridges of quartzite and sometimes schists and phyllites, which are intruded by amphibolites, gneiss and granites. Some hills have layers of hard laterite exposed on them. The soils, therefore are deeply weathered; > 54% sand with little differentiation in the horizon and are moderate to strongly acidic attributable to low exchangeable bases (especially Ca and Mg) and are therefore, of very low to moderate fertility (Table 1). The remaining 10% is where fertile eutrophic soil occurs on a base of volcanic ash limited to Mpokya and Isunga areas on the western edge of the park.

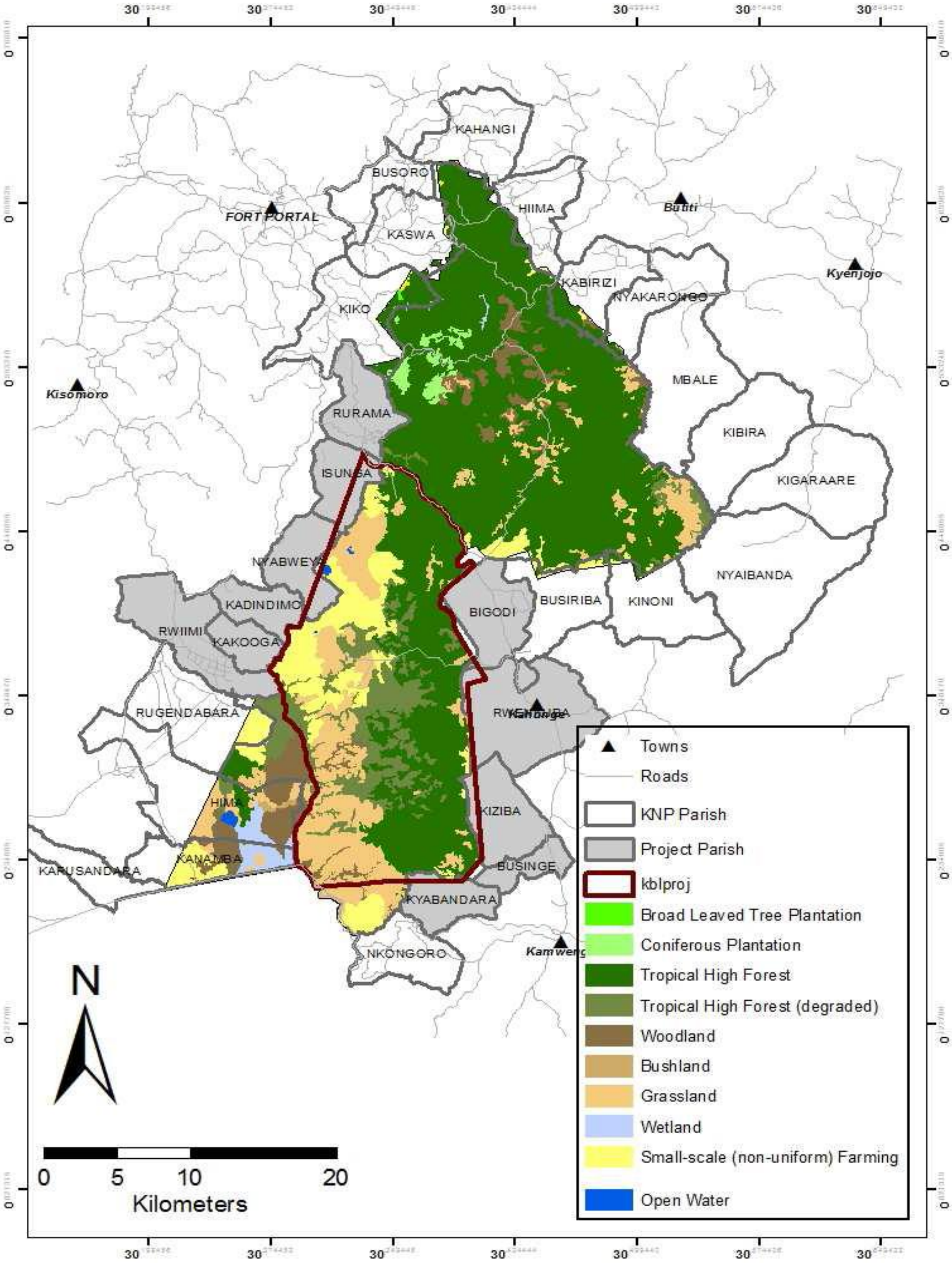

Figure 1. Map of the study area (Source: www.wri.org/resources/data-sets/uganda-gis-data)

The land cover of KNP can broadly be classified into at least eight vegetation types: intact tropical high forest (ITHF), degraded (restored) tropical high forest (RTHF), broad-leaved tree plantation, coniferous plantation, woodland, bushland, grassland, wetland and non-uniform cropping. Forest cover is further

Table 1. Soil properties (means±SE) under intact tropical high forest (ITHF), restored tropical high forest (RTHF), degraded tropical high forest (DTHF) and maize under Kibale National Park, western Uganda as of December, 2014.

Soil property	**Land cover type**			
	ITHF	RTHF	DTHF	Maize
SOM (%)	**5.62 ± 0.42a**	**3.80 ± 0.32a**	2.93 ± 0.17b	2.60 ± 0.22(3)b
Sand (%)	39.3 ± 1.54a	30.5 ± 2.58b	**51.8 ± 2.22c**	39.5 ± 1.83a
Silt (%)	15.5 ± 0.82a	**34.7 ± 2.68b**	11.5 ± 0.78a	16.7 ± 1.08a
Clay (%)	**45.2 ± 1.29a**	34.8 ± 0.88b	36.7 ± 2.21b	**43.7 ± 2.27a**
Bd (Mg m^{-3})	1.28 ± 0.01a	1.31 ± 0.01a	**1.34 ± 0.01b**	1.29 ± 0.01a
pH(H_2O)	5.3 ± 0.04a	4.5 ± 0.12a	5.4 ± 0.21a	**6.8 ± 0.1**(5.5–6.5)b
K^+ (cmol(+) kg^{-1}	0.3 ± 0.02a	**0.8 ± 0.31b**	0.4 ± 0.06a	**0.8 ± 0.09 (0.4)b**
Ca^{2+} (cmol(+) kg^{-1}	4.7 ± 0.20a	2.6 ± 0.27b	**6.0 ± 0.35c**	**7.7 ± 0.34 (10)c**
Mg^{2+} (cmol(+) kg^{-1}	1.6 ± 0.10a	1.4 ± 0.14a	1.9 ± 0.10a	3.7 ± 0.28(10)b

Key: Bd (bulk density, ρ_b). Means with the same letter(s) across a row did not differ significantly (P > 0.05). Values in bold were typically higher than the rest and those parentheses are threshold levels for agricultural productivity in the tropics

classified into three broad categories: mid-altitude, moist evergreen in the north, gradually decreasing in elevation to moist semi-deciduous in the south and a mixture of deciduous and evergreens in the central parts. The moist semi-deciduous forests occurring at an altitude of 1,100 to 1,200 m are dominated by *Pterygota mildbraedii*, *Olea welwitschii*, *Cynometra alexandri*, *Celtis* spp., *Warbugia ugandensis*, *Lovoa swynnertonii*, *Markhamia platycalyx* and *Diospyros abyssinica*. Other species are *Prunus africanum*, *Trichilia splendida*, *Chrysophyllum* spp., *Parinari excelsa*, *Strombosia scheffleri*, *Blighia unijugata* and *Elaeodendron* sp (UWA-FACE 2015).

KNP is home to chimpanzees (*Pan troglodytes*), gorillas (*Gorilla gorilla berengei*), elephants (*Loxodonta africana*), lions (*Panthera leo*), and many smaller endemic primates that are of high conservation and tourism importance (Ryan and Hartter 2012). Habituated chimpanzees attract over 7,000 foreign tourists per year. Such large fauna tend to have specific needs that make KNP a unique habitat, including large home ranges for foraging and hunting, with corridors for movement between parks (Newmark 1993). KNP is also endowed with undisturbed old-growth forests, connected canopies and sufficient feeding resources needed by large primates (Tewksbury et al. 2002). Faunal connectivity remains a high priority from a conservation perspective but how this impacts changes in land cover and sinking of C and N in the soil is not well known and therefore, informed this study.

Identification of the study sites

A one-day reconnaissance field tour of KNP was conducted in November 2014 with the help of the KNP tour guide, ranger and support staff under the instruction the KNP administration. From this reconnaissance, the following LCTs were identified: ITHF, RTHF, Degraded Tropical High Forest (DTHF) dominated (> 60%) by elephant grass (*Pennisetum purpureum*) and annual cropping, mainly maize (*Zea mays* L.) intercropped with common bean (*Phaseolus vulgaris* L.).

Study design, site marking and soil sample collection

Care was taken to ensure that the LCTs identified were matched in a manner that would permit pair-wise comparisons of their impacts on soil C and N stocks to be made. Since each of the LCTs was in its own pre-existing compartment (UWA-FACE 2015; Omeja et al. 2012), we ruled out the possibility of establishing true replications within KNP. Therefore, from each of the four LCTs, three plots representative of each compartment where a particular LCT was located (Figure 2) and within an elevation of 1,250–1,500 m asl (about 60% of KNP lies at this elevation), were randomly demarcated to constitute pseudoreplicates. Wasige et al. (2014) observed that soil C stocks were explained more by contemporary LCT than by topography, soil type and climatic conditions.

Bulk soil sampling

From each plot of the three plots per LCT, soil samples were collected using Johnson's Bucket Auger of internal diameter 0.075 m and core length 0.3 m and handle length 0.9 m at three random spots within the plot (Figure 2) and at four depths per spot: 0–0.15, 0.15–0.3, 0.3–0.45 and 0.45–0.6 m. Sampling was done per depth and all the three samples for a particular depth per plot under each LCT were bulked using a basin and quarter-sampled to collect a representative composite soil sample in

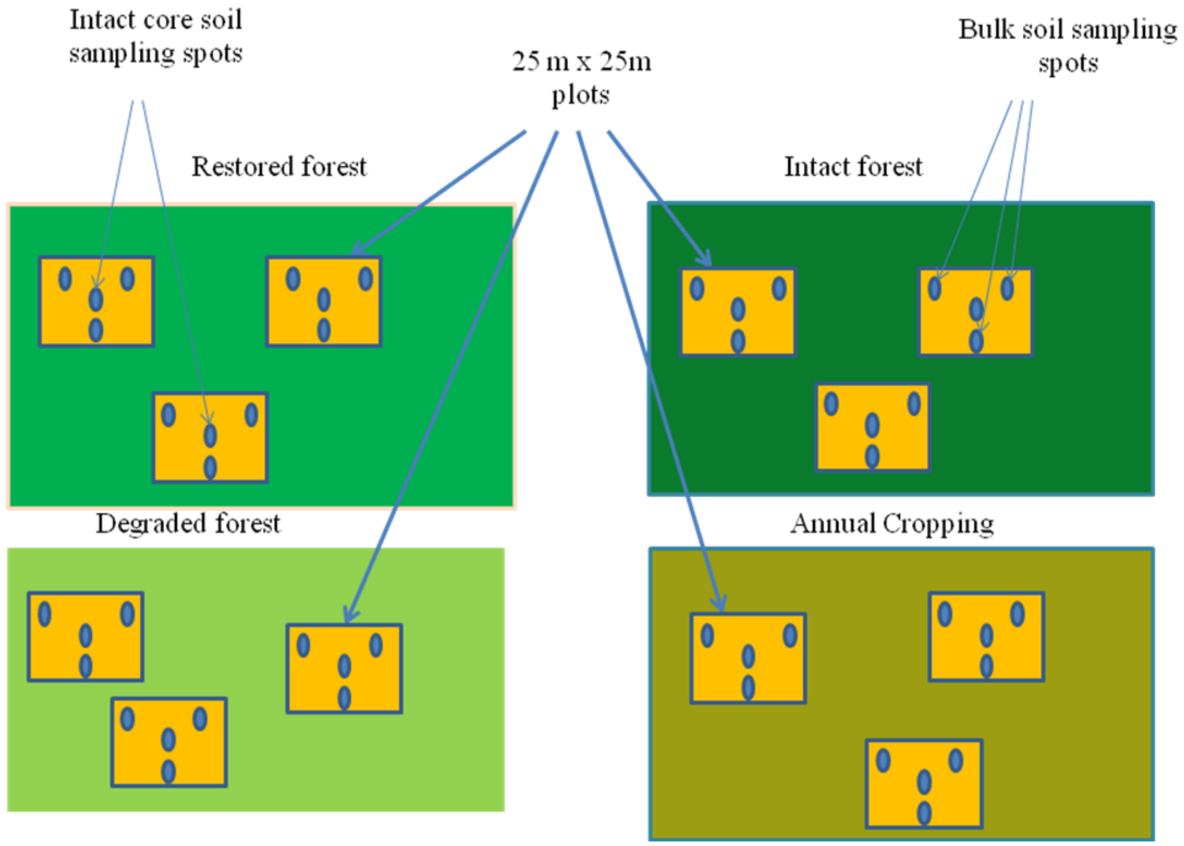

Figure 2. The four compartments of different land cover types: restored forest, intact forest, degraded forest and annual cropping (maize intercropped with common bean) from which three plots of 25 m x 25 m were marked out for collection of both bulk soil samples and intact core soil samples were extracted per compartment in Kabale National Park, south-western Uganda in November 2014.

the range of 1.0–1.5 kg (field weight). This gave a total of 144 spot samples (4 cover types x 4 depths x 3 spots x 3 plots). Soil samples were further composited by spot to constitute one composite soil sample per plot, which was immediately sealed in a white polythene bag using rubber bands. This gave a total of 48 composite samples (4 cover types x 3 compartments x 4 depths).

Intact soil core sampling

One intact soil core sample was collected from the centre of each of the three compartments per LCT to the same 0 – 0.6 m depth using a core sampler of internal diameter 0.045 m and sliced into 0 – 0.15, 0.15 – 0.3, 0.3 – 0.45 and 0.45 – 0.6 m depth portions. This gave a total of 48 samples (4 LCTs x 4 depths x 3 compartments). Each intact core soil sample was immediately sealed in an air-tight white zip-lock bag and further fastened using a rubber band. The core soil samples were used for estimation of bulk density, which is needed for computation of soil C and Stocks.

Soil samples processing and laboratory analyses

The soil samples collected were transported to the Soil Science Laboratory in the School of Agricultural Sciences, Makerere University for subsequent processing and analyses. Composite soil samples were air-dried, weighed, crushed and sieved through a 2mm sieve. Any material that could not go through the 2mm sieve was weighed to obtain the weight of coarse soil fraction (*cf*) as a percentage of the entire composite soil sample air-dried before it was discarded. The soil was thereafter subsampled for respective routine analyses following the methods compiled in Okalebo et al. (2002). Briefly, soil organic C (SOC) was determined using the Walkley-Black method, which is recognised for Africa (see - Wasige et al. 2014; IPCC 2003 for details). This method involves wet combustion of 0.5 g soil with a combination of $K_2Cr_2O_7$ and concentrated H_2SO_4 at 150 ^oC for 30 minutes and titration of the $Cr_2O_7^{2-}$ residue with $FeSO_4$. A correction factor of 1.3 is used in the calculation of the results to compensate for the incomplete oxidation of organic matter in the soil in the process (van Reeuwijk 2006). We used the conservative 1.724 Van Bemmelen factor (Schumacher 2002) to convert %SOM into %SOC, based on the assumption that 58% of SOM is SOC (van Reeuwijk 2006). Wasige et al. (2014) have comprehensively reviewed alternative methods for determination of SOC.

Total soil %N was determined using the Kjeldahl method based on the principle that all the N-containing components of the soil, which are not present in the crystal lattice of soil minerals, are reduced to ammonium compounds by the Kjeldahl digestion procedure (Okalebo et al. 2002). A number of other soil parameters were determined as part of routine analyses, including - soil texture by the hydrometer (Bouycous) method, pH in a water to soil ratio of 2.5:1, exchangeable basic cations: Na^+, K^+, Ca^{2+} and Mg^{2+}, and available phosphorus (Bray I method) following the methods compiled by Okalebo et al. (2002).

Determination of soil bulk density

Intact soil core samples were oven dried to constant weight at 105 °C (about 48 hours) and cooled in a desiccator before their dry weights were taken. The volume of each intact core soil sample was estimated from the dimensions (diameter and height) of the core sampler used to extract the intact core soil samples. Bulk density was thereafter estimated using the intact core method compiled by Okalebo et al. (2002).

Calculation of soil C and N stocks

We modified the IPCC (2003) equation for calculation of soil organic C (SOC) and N (SON) stocks:

$$\mathrm{SOXstock} = \sum_{depthi}^{depthn} (SOX * bd * (1 - cf\ ) * sd * 10$$

Where, SOXstock is the SOC or SON stock (Mg ha^{-1}); $depth_i$ is the initial depth sampled (0–0.15m) whereas $depth_n$ is the final depth portion (0.45 – 0.6 m); SOX is the SOC or SON content (g C or g N kg^{-1} soil) in a given depth portion sampled; *bd* is the soil bulk density of each intact soil core sample (Mg m^{-3}); *cf* is the coarse fraction of soil (> 2mm) that was discarded (% weight of total air-dried soil in a single sampled soil depth); sd is the soil depth portions (m) and 10 is the factor for converting mass in kg ha^{-1} into mg ha^{-1}.

Estimation of the impact of land cover change on soil C and N stocks

Ideally, assessing the impact of land cover change on SOC and SON stocks would require long term monitoring data (repeated measurement of SOC and SOC stocks in compartments) before and after a land cover change that is, chronosequence (Powers 2004). Because this is the first study to quantify SOC and SON stocks under KNP and therefore, no such data exist, we used the paired-site approach (biosequence). The paired-site approach for evaluating impact of LCT or LCC on SOC and SON stocks presupposes that land uses occur on sites with similar soil and climatic regimes, which was the case for this study. It also assumes that the SOC and SON stocks were in equilibrium prior to land cover or land use change and that a new equilibrium is reached after some time following a LCC, normally ≥ 10 years.

The southwestern part of KNP was heavily encroached between the 1960s and 1992, during years of political unrest (Klomp 2009). This led to large-scale forest destruction (15,000 ha) and grassland clearing (about 6870 ha). In the early 1990s the Uganda government evicted and relocated encroachers in 1992, regaining full control over the forest reserves. After the eviction, most of the grassland areas and open spaces within KNP became dominated (61%) by elephant grass (*Pennisetum purpureum* and *Cenchrus purpureus*) due to recurring fires that were set by poachers or that spread into the park from neighbouring areas, preventing natural forest regeneration (UWA-FACE 2015; Ryan and Hartter 2012; Omeja et al. 2011; Struhsaker 2003). The formerly logged compartment recovered considerably, both in tree cover and avifaunal richness (UWA-FACE 2015), and shows evidence of persistent and stable forest for almost 30 years now, essentially indistinguishable from the original intact forest, typical of the northern compartment of KNP. All the land cover types considered in this study were more than 20 years old, with the exception of maize fields whose age under annual cropping could not be established with certainty but certainly, well over 10 years too.

The percentage of SOC and SON were estimated from the following equation (Eclesia et al. 2012):

$$SOXch = \left(\frac{SOXcu - SOXor}{SOXor}\right) * 100$$

Where, SOXch is the change in SOC or SON stock (%) after a change in land cover type; SOXcu is the SOC or SON stock (Mg ha^{-1}) in the soil under the current land cover type; and SOXor is the SOC or SON stock (Mg ha^{-1}) in the soil under the native vegetation (assumed to be the ITHF in this study).

Data exploration and statistical analyses

We used the R statistical package (R Development Core Team 2012) for data processing and analyses to test for the impact of land cover type on SOC and SON stocks and how land cover interacted with soil depth to influence stratification of SOC and SON stocks down the soil profile. Data were first explored to check for equal variances using the 'Residual versus Fitted Plot'. The normality assumption was tested using the 'Normal Q-Q plot of Standardised Residuals versus Theoretical Quantiles' and 'Shapiro-Wilk Formal Test for Normal Distribution'. We used 'Cook's Distance Plots' to calculate Cook's distances for potentially influential points so as to inform any action needed to mitigate the effects of outliers. All influential points were genuine observations and could therefore, not be deleted. The box cox plot was used to identify appropriate transformation functions where the data were found to violate assumptions for conducting ANOVA. The data for % sand, % clay, % silt and bulk density (ρ_b) were subjected to ANOVA without any transformation because they conformed to the assumptions. Log-transformation worked well for soil pH, SOC and SON stocks. Square root transformation solved the problems of unequal variances and normal distribution for Bray I phosphorus whereas data for SOM were inverse-transformed. We performed a two-way ANOVA with LCT and soil depth as factors for all parameters except total soil C and N stocks where we performed a one-way ANOVA, with LCT as the only factor. We used Tukey's Honestly Significant Difference to compare means where ANOVA was significant. Unless otherwise stated, all mean comparisons were conducted at 1.96 standard deviations.

Results

Impact of land cover type on total soil C and N stocks

There was no significant impact of LCT on total soil C and N stocks (Table 2). However, *Z. mays* tended to have larger soil C (19.0±0.86 Mg ha^{-1}) and soil N (1.61±0.04 Mg ha^{-1}) stocks than all the other LCTs (Table 2). Stocks of soil C (16.4±1.54 Mg ha^{-1}) and soil N (1.4 ± 0.08 Mg ha^{-1}) under intact forest was the smallest observed. There was also no significant evidence that soils under ITHF or RTHF accumulated more soil C and N stocks than soils under DTHF and *Z. mays* LCTs. Instead, we observed 15.8% more soil C and 12.6% more soil N stocks in soils under *Z. mays* cover. Similarly, soils under DTHF also had a slight edge in stocks of soil C (1.8%) and soil N (9.8%) over the intact forest. The RTHF also had 0.8% soil C and 2.1% soil N stocks above the ITHF.

Table 2. Summary results of ANOVA tables for parameters investigated under intact tropical high forest, restored tropical high forest, degraded tropical high forest and *Z. mays* land cover types down the soil profile in Kibale National Park, western Uganda in December 2014.

Source of		Parameters and investigated and their significance levels											
variation	df	SOC	SON	Sand	Clay	Silt	Bd	SOM	P_{av}	pH	K	Ca	Mg
LCT	3	ns	ns	***	***	***	***	ns	ns	***	***	***	***
LCC	3	ns	ns	na	na	na	na	ns	na	na	na	na	na
Depth	3	***	***	***	***	***	***	***	***	ns	ns	ns	ns
LCT: Depth	9	**	ns	*	**	ns	•	*	*	ns	ns	ns	ns
Residuals	30												

Key: SOC (soil organic carbon), SON (soil organic nitrogen), Bd (bulk density, ρ_b), SOM (soil organic matter), P_{av} (Bray I phosphorus). Levels of significance: not significant (ns), not applicable (na), marginally significant at P = 0.05 (•), significant at $P < 0.05$, 0.01 and 0.001, respectively (*, ** and ***).

Impact of land cover type on distribution of soil C and N Stocks down the soil profile

There was a significant effect of LCT on soil C stocks when averaged over the effect of depth (Table 2), implying that the distribution of soil C down the soil profile was not consistent when averaged across the land cover types. For example, we observed the largest soil C stocks in the 0 – 0.15 m depth (10 ± 0.3 Mg ha^{-1}) under *Z. mays* whereas the smallest soil C stock in the same depth (5.0 ± 0.83 Mg ha^{-1}) was under RTHF (Figure 3). The fraction of soil C stocks located in the 0.15 – 0.6 m by LCT was in the order of RTHF > (70%) > ITHF (66%) > DTHF (59%) > *Z. mays* (47%). Thus, RTHF and ITHF have a significantly larger fraction of their soil C stocks in the 0.15 – 0.6 m layer than DTHF and *Z. mays*.

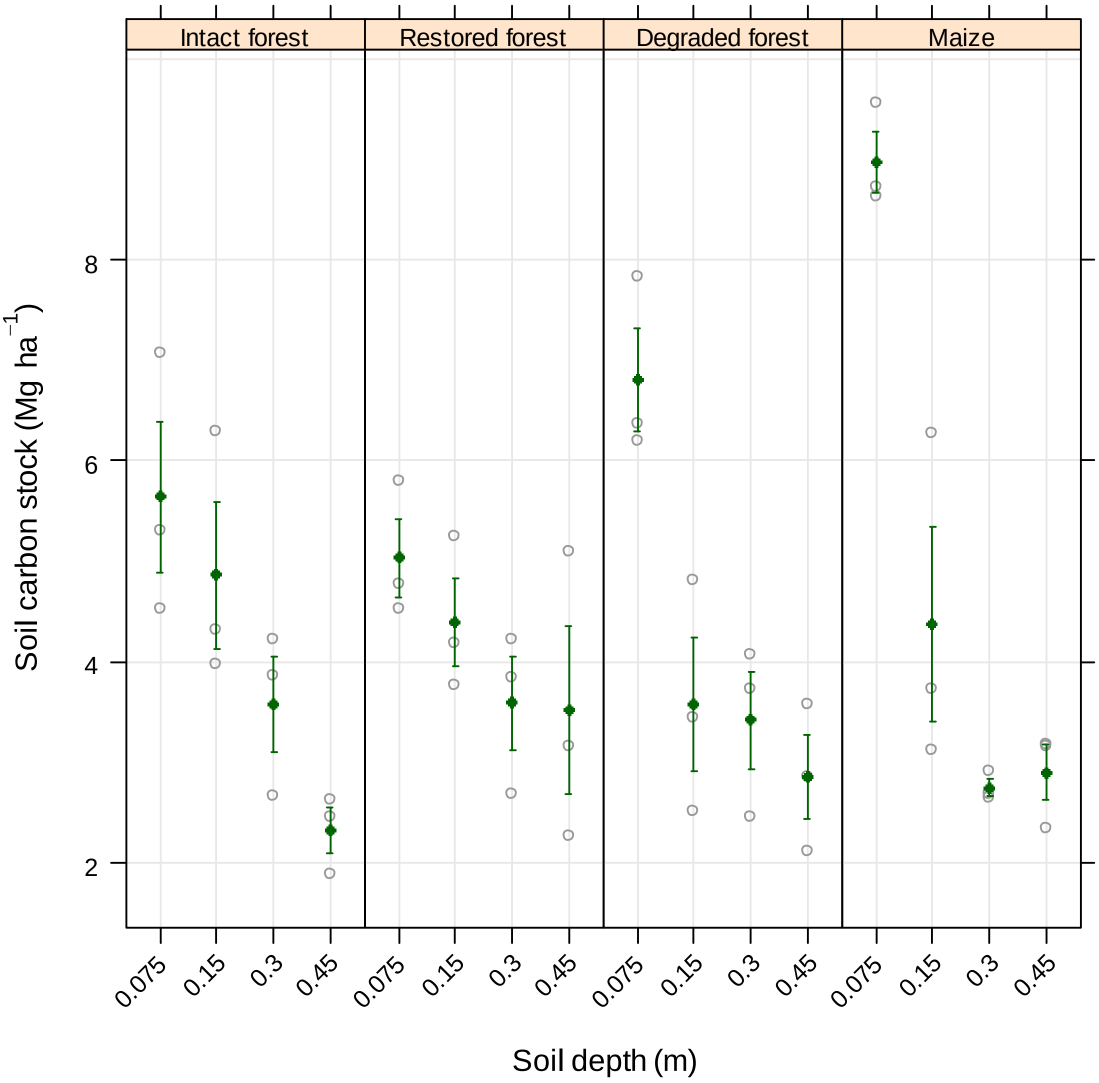

Figure 3. Impact of land cover type (top x-axis) on distribution of SOC stocks (Mg ha^{-1}) with soil depth (in m) in Kibale National Park, western Uganda as of December, 2014. Depth is reported as mid-points of the respective soil depth intervals sampled.

There was no significant effect of LCT on depth distribution of soil N stocks (Table 1), implying that the distribution of N down the soil profile was influenced by LCT independent of the soil factor. However, there was a pattern in which DTHF and *Z. mays* tended to have larger soil N stocks in the 0 – 0.15 m depth (0.57 ± 0.06 Mg ha^{-1}) than the forest cover types, which could have been masked by large errors (Figure 4). This soil N stock represented approximately 37% of the total soil N stock under the DTHF (1.57 ± 0.15 Mg ha^{-1}) and 34% the total SON stock under *Z. mays* cover (1.61 ± 0.04 Mg ha^{-1}) (Table 2). These soil N stocks were higher than the 27% and 29% under the ITHF and RTHF, respectively. Deeper than 0.3 m, soil N stocks tended to increase linearly with each incremental depth under *Z. mays* cover, with the 0.45 – 0.6 m depth alone accounting for about 26% of total SON stock, compared with 19% under the DTHF.

Impact of land cover change on changes in soil C and N stocks

We selected ITHF as the reference land cover against which soil C and N stocks from the other land cover types were compared. All the land cover changes from the ITHF were positive pointing to the tendency to accumulate higher soil C and N stocks above the ITHF, although the changes were not statistically significant. The highest soil C (15.8%) and N (12.6%) were under *Z. mays* whereas the smallest soil C and N changes (0.8% C and 2.1% N, respectively) were under RTHF.

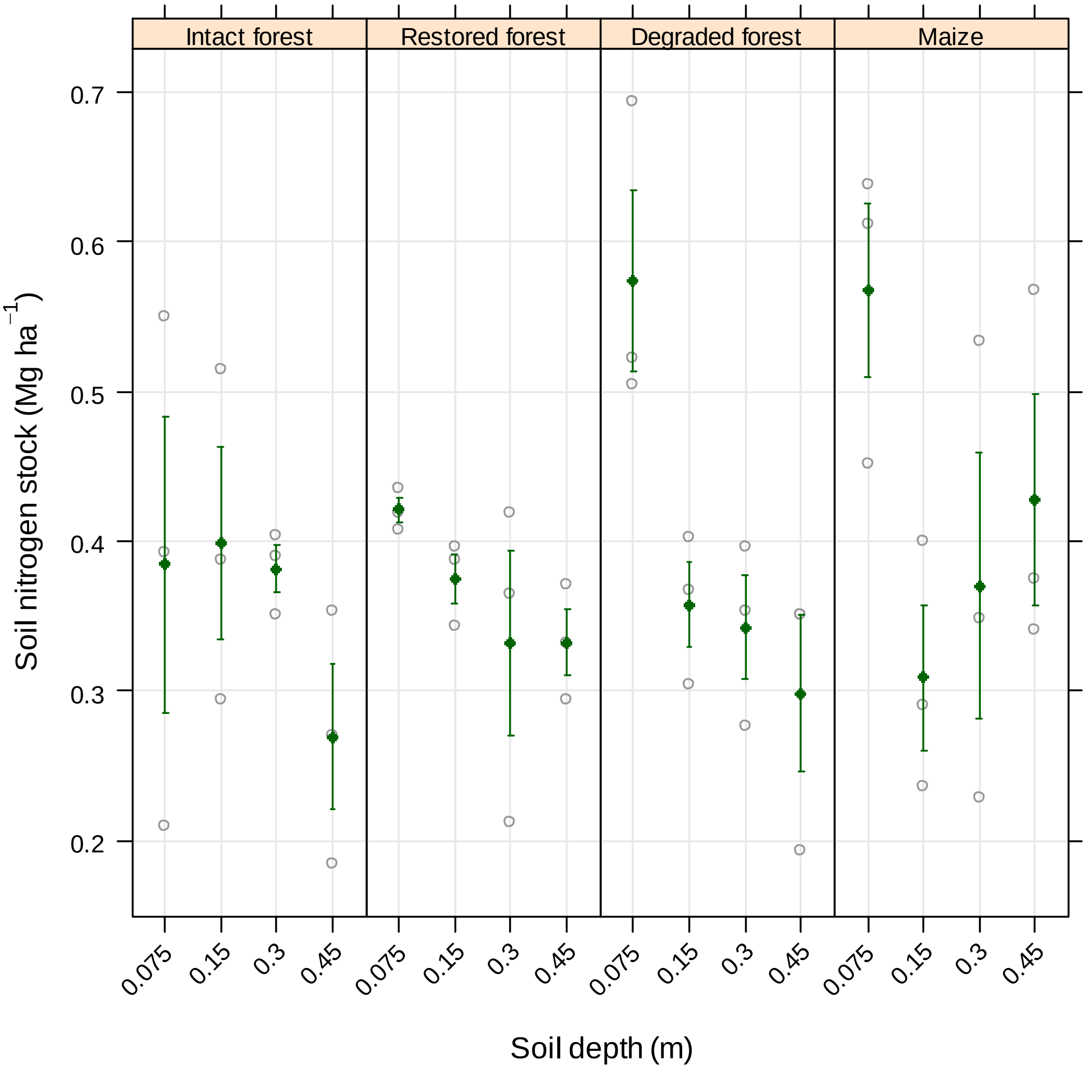

Figure 4. Impact of land cover type (top x-axis) on distribution of SON stocks (Mg ha^{-1}) with soil depth (in m) in Kibale National Park, western Uganda as of December, 2014. Depth is reported as mid-points of the respective soil depth intervals sampled.

Discussion

Impact of land cover type on soil C and N stocks

The impact of land cover type on soil C and N stocks was depth-specific, implying that reporting total soil C and N stocks without accounting for the pattern of their distribution down the soil profile can mask localised depth-specific effects of LCT on these stocks. This information is needed to identify LCTs that are sequestering C in deeper soil horizons and those that are not. For example, although largest soil C and N stocks were observed under maize, only about 47% of the stocks were located deeper than 0.15 m compared with 66% and 70% under ITHF and RTHF, respectively. The 53% of soil C stock (> 10 Mg C ha^{-1}) concentrated near the soil surface (0–0.15 m depth) as observed under maize where soil moisture, temperature and microbial gradients, as well as soil disturbances associated with tillage and other agronomic practices are high, is prone to loss into the atmosphere (van der Werf et al. 2009; FAO 2005; Rasse et al. 2005). In contrast, the typically large SOC stocks in deeper soil horizons under ITHF, RTHF and DTHF highlight the importance of these forests in long-term sequestration of C belowground. Deeper soil layers experience less disturbance, low temperatures, high micro-porosity, anoxic conditions and low microbial activities that favour accumulation of C (Rasse et al. 2005). Tropical forests tend to root deeper with as much as 76% of the root systems being fine roots (Kirsi and Sisko 1999), which can transfer large quantities of photo- assimilated C into soil. The linear increase in soil N stocks with soil depth deeper than 0.15 m as observed under maize suggests that high rates of N leaching could be taking place. The source of this N should be investigated for purposes of minimising wastage (if fertilisers are used) and for ensuring mitigating of groundwater contamination.

Lack of a significant impact of LCT on total soil C and N stocks could be due to large errors resulting from few (three) replications and the bulking of spot soil samples to get composite samples that could be logistically handled in this study. Besides, all the LCTs considered had been in place for over 20 years, the period for the soil C and N stocks to approach new equilibrium levels after a land cover change (Wasige et al. 2014). Interestingly, total soil C stocks under forest covers in KNP (> 16 Mg C ha^{-1}) were higher than the 7.1 Mg C ha^{-1} or 2.1 Mg C ha^{-1} reported for aboveground biomass of planted vs and naturally regenerated trees, respectively in KNP (Omeja et al. 2011). Our total SOC stocks were also higher than the 2.9 to 12.3 Mg C ha^{-1} range for the aboveground biomass in Bwindi Impenetrable Forest (Otukei and Male 2015). These SOC and SON stocks could have been even higher, had we extended the sampling beyond 0.6 m and indicate that there is more C in soils under forests than there is in the aboveground biomass.

The claim that the C in aboveground biomass constitutes the largest pool of all C pools in tropical forests (Buyinza et al. 2014) may have its own limitations. For example, it fails to account for accumulation of C and N in red soils typical of KNP, owing to physico-chemical protection by Fe^{3+} and Al^{3+} oxides (FAO 2005; Rasse et al. 2005). It also often fails to account for root contributions to belowground biomass C (Buyinza et al. 2014). Our findings indicate that the debates about pricing and marketing C are incomplete without accounting for soil C, especially with accurate information about the mean residence times of C in soil and how LCT and LCC impact soil C stocks.

Impact of land cover change on soil C and N stocks

Although no significant changes in soil C and N stocks with LCC were observed, it is important to note that at least 53% of the soil C under maize was mainly in the top 0.15 m whereas 26% of N was located in the 0.45 – 0.6 m depth. The vulnerability of that C to loss and N to leaching cannot be overemphasised (Rasse et al. 2005). We also found use of the phrase ‘Degraded Forest’ quite misleading as it was used to describe grassland cover. From the records, observations and informal interviews with one of the rangers during field reconnaissance, there appear to be two vegetation types competing to colonise KNP. A closed canopy favours growth of forest (C_3) vegetation whereas deforestation and repeated burning as happened between the 1970s and 1990s (Klomp 2009), favour establishment of grassland (C_4) vegetation. The grassland cover is actually dominated (> 67%) by *P. purpureum* (UWA-FACE 2015) and this is what is called DTHF in KNP. Grasses are among the most important of vegetation types in sinking C in soils (Guo et al. 2007; Quideau 2002).

Implications of the study and areas for further research

Tropical high forests in KNP play a critical role in sequestering belowground carbon. Future studies should extend the sampling to larger soil depths and replicate the work across all the national parks and wildlife conservation zones in Uganda. Rigorous studies to establish the nature and quality of soil C and N stocks in soils and how they have been impacted on by land cover change under KNP and related ecosystems across the country should be prioritised. Coupling the above studies with forensic laboratory and *in situ* measurements of soil respiration rates will aid identification of land cover types that sequester carbon in soils for longer periods. This information is needed to initiate and inform the on-going debate about pricing the carbon stored belowground, which is currently left out. It is also important to note that the soils of KNP are strongly acidic with low available phosphorus and exchangeable bases and are, therefore, not generally conducive to the agricultural conversion that these forests suffered between the 1970s and the early 1990s. These soils can, however, be instrumental in storing carbon especially when kept under the tropical high forest vegetation as demonstrated by our findings. The success of this will depend on how the communities are made to realise better benefits from conservation programmes than from agricultural conversion of the forests. Lastly, the accumulation of N in deeper layers under maize should be of major concern as it points to leaching, which not only represents wasteful N losses but potential pollution of groundwater and should be investigated.

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