Geoderma 193–194 (2013) 282–289

Contents lists available at SciVerse ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Variability of Soil Organic Carbon stocks under different land uses: A study in an afro-montane landscape in southwestern Uganda

R. Twongyirwe [a,b,c,*], D. Sheil [b,d,e], J.G.M. Majaliwa [c], P. Ebanyat [f], M.M. Tenywa [g], M. van Heist [b], L. Kumar [h]

[a] *Department of Geography, University of Cambridge, Downing Place, Cambridge, CB2 3EN, UK*
[b] *Institute of Tropical Forest Conservation, Mbarara University of Science and Technology, P.O. Box 44, Kabale, Uganda*
[c] *Department of Geography, Geo-Informatics and Climate Sciences, School of Forestry Environmental and Geographical Sciences, College of Agricultural and Environmental Sciences, Makerere University, P.O. Box 7062, Kampala, Uganda*
[d] *Center for International Forestry Research (CIFOR), P.O. Box 0113 BOCBD, Bogor 16000, Indonesia*
[e] *School of Environment, Science and Engineering, Southern Cross University, P.O. Box 157, Lismore, NSW 2480 Australia*
[f] *Department of Agricultural Production, College of Agricultural and Environmental Sciences, Makerere University, P.O. Box 7062, Kampala, Uganda*
[g] *Makerere University Agricultural Research Institute, Kabanyolo, College of Agricultural and Environmental Sciences, Makerere University, P.O. Box 7062, Kampala, Uganda*
[h] *School of Environmental and Rural Science, University of New England, Armidale, NSW 2351, Australia*

ARTICLE INFO

Article history:
Received 3 December 2011
Received in revised form 12 September 2012
Accepted 20 September 2012
Available online 21 November 2012

Keywords:
SOC stocks
Sampling depth
Landscape position
Bwindi
Southwestern Uganda

ABSTRACT

We explore and compare quantities and patterns of Soil Organic Carbon (SOC) in protected forest and neighboring land around Bwindi Impenetrable National Park (a mountain protected area in Southwestern Uganda). We assessed paired sites of natural forest and major land uses (potato, tea and grazing lands) converted between 1973 and 2010. These pairings were replicated at three altitudinal zones. Plots (20 m by 50 m) were demarcated within each site. Five composite soil and core samples were obtained from 0 to 15 cm (top-soil) and 15–30 cm (sub-soil) at each plot. In total, 192 composite soil and core samples were collected. Within forest we found marked site to site variation in SOC from 54.6 to 82.6 Mg/ha. There was a tendency for higher SOC in converted land, associated with higher bulk density suggesting quality based land use selection with forest left on inferior soils. Cultivation, landscape position, slope and sampling depth were all significantly ($P<0.05$) related to variation in SOC stocks following forest conversion but time since conversion had no detectable impact. Interestingly, there was no significant relationship between SOC in the top and sub-soils. Higher SOC is largely determined by higher bulk density. The large SOC stocks in these afro-montane soils are less predictable and more persistent than anticipated.

1. Introduction

Forest vegetation and soils are important reserves and sinks of carbon, sequestering about 1200 Gt globally (Lewis et al., 2009; Luyssaert et al., 2008; Slik et al., 2009; Wang et al., 2004). Most terrestrial carbon is stored in soils, on average about three times more than the carbon in vegetation and in total about twice what is present in the atmosphere (Batjes and Sombroek, 1997). Conversion of forests to other land uses adds to greenhouse gas emissions (DeFries et al., 2007; Van der Werf et al., 2009) contributing to climate change (Gullison et al., 2007), but also affects soil properties although this remains poorly quantified (Cotler and Ortega-Larrocea, 2006).

Carbon storage in forest soil is the balance between inputs, mainly from plant material, and losses from decomposition, erosion and other processes (Sun et al., 2004). Carbon enters the soil from litter fall, root and mycorrhizal turnover, plant exudates and microbial fixation (Feller and Beare, 1997). Under steady-state conditions, the carbon gain is matched by equivalent carbon losses (Kirschbaum, 2000). This balance is greatly affected by forest clearance and subsequent land management practices (Korkanc et al., 2008).

SOC is affected by environmental factors such as topography, parent material, soil depth, and land use (Fu et al., 2004; Johnson et al., 2000; Ollinger et al., 2002). Often the key relationships are indirect and potentially complex. Topography influences precipitation and temperature (Tsui et al., 2004), solar radiation, and relative humidity (Finney et al., 1962; Franzmeier et al., 1969). Aspect determines length of exposure to sun light and can influence weathering and vegetation (Rech et al., 2001; Sidari et al., 2008; Yimer et al., 2006).

With advances in climate change mitigation through Reducing Emissions from Deforestation and forest Degradation (REDD), much emphasis has been put on above ground carbon (Cerbu et al., 2010; Harris et al., 2008) but less attention given to below ground carbon (Cole and Ewel, 2006; Navar, 2009). But if SOC changes with forest loss, and varies with land use, such carbon may play a significant role in local, national and global carbon budgets. We therefore need more data on SOC stocks (Gibbs et al., 2007).

---

* Corresponding author at: Department of Geography, University of Cambridge, Downing Place, Cambridge, CB2 3EN, UK. Tel.: +44 7552043333.
E-mail addresses: rt369@cam.ac.uk, twongyirwe@gmail.com (R. Twongyirwe).

0016-7061/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geoderma.2012.09.005

Our exploratory study assesses SOC stocks in and around the protected forest landscape of Bwindi Impenetrable National Park ("Bwindi") in southwestern Uganda. We hypothesized that SOC stocks are higher on foot-landscape positions, higher altitude sites and sites that are less exposed to the sun. Also, we expected that SOC will decline following forest conversion especially on back-slopes, but would be influenced by land use and time since forest loss.

2. Materials and methods

2.1. Study area

The study was conducted between September 2009 and September 2010 in and around Bwindi Impenetrable National Park in Southwestern Uganda (0°53′–1°08′N; 29°35′–29°50′E) (Fig. 1). The protected forest covers an area of 331 km^2 and spans an altitudinal range from 1160 to 2607 m.a.s.l. The forest is classified as "medium altitude moist evergreen forest" and "high altitude sub-montane vegetation" (Langdale-Brown et al., 1964), and is rich in biodiversity (Butynski and Kalina, 1998). The terrain is rugged and deeply weathered. About 90% of the forest was pitsawed between 1932 and 1991 (Howard, 1991) and 7.8% of area under forest in 1973 – mostly outside the protected area – was converted to agricultural land uses by 2010 (Twongyirwe et al., 2011). Population density in the mainly agricultural lands bordering the forest was 260 persons per km^2 in 2001 (UBOS, 2002). The characteristics of sites sampled are summarized in Table 1.

2.2. Study design

Paired sites on either side of the forest boundary were demarcated. Each pair included natural forest and one of the major land uses; potato cultivation, tea and grazing land. Landscape positions represented back-slope and foot-slope (upper slope and lower slope respectively, defined according to Chun-Chih et al., 2004) and all four aspects (North, South, East and West). The two plots in each site were located no more than 50 m apart (one inside the forest, one outside) and were matched in terms of landscape position and soil type. Based on our data, the latter was loosely classified as 'Andosols', with evidence of volcanic ash present in some samples, although with a well developed soil structure. We lacked soil profile pits across the various sites which would have clarified this — a limitation to a conclusive classification of the soil type. Time since forest clearing was recorded where applicable based on interviews with the local residents. Each pair of cover types was recorded in three altitudinal ranges when possible [2100–2500 m.a.s.l. (High); 1800–2100 m.a.s.l. (Medium); 1450–1800 m.a.s.l. (Low)], resulting in a total of seventy two (72) different sites.

2.3. Determination of soil organic carbon stock

Sampling plots of 20 m by 50 m were demarcated within each site. An undisturbed composite soil sample was obtained by pooling soil from 5 positions within the plot, using a soil auger, for carbon content determination at two depths [0–15 cm (top-soil) and 15–30 cm

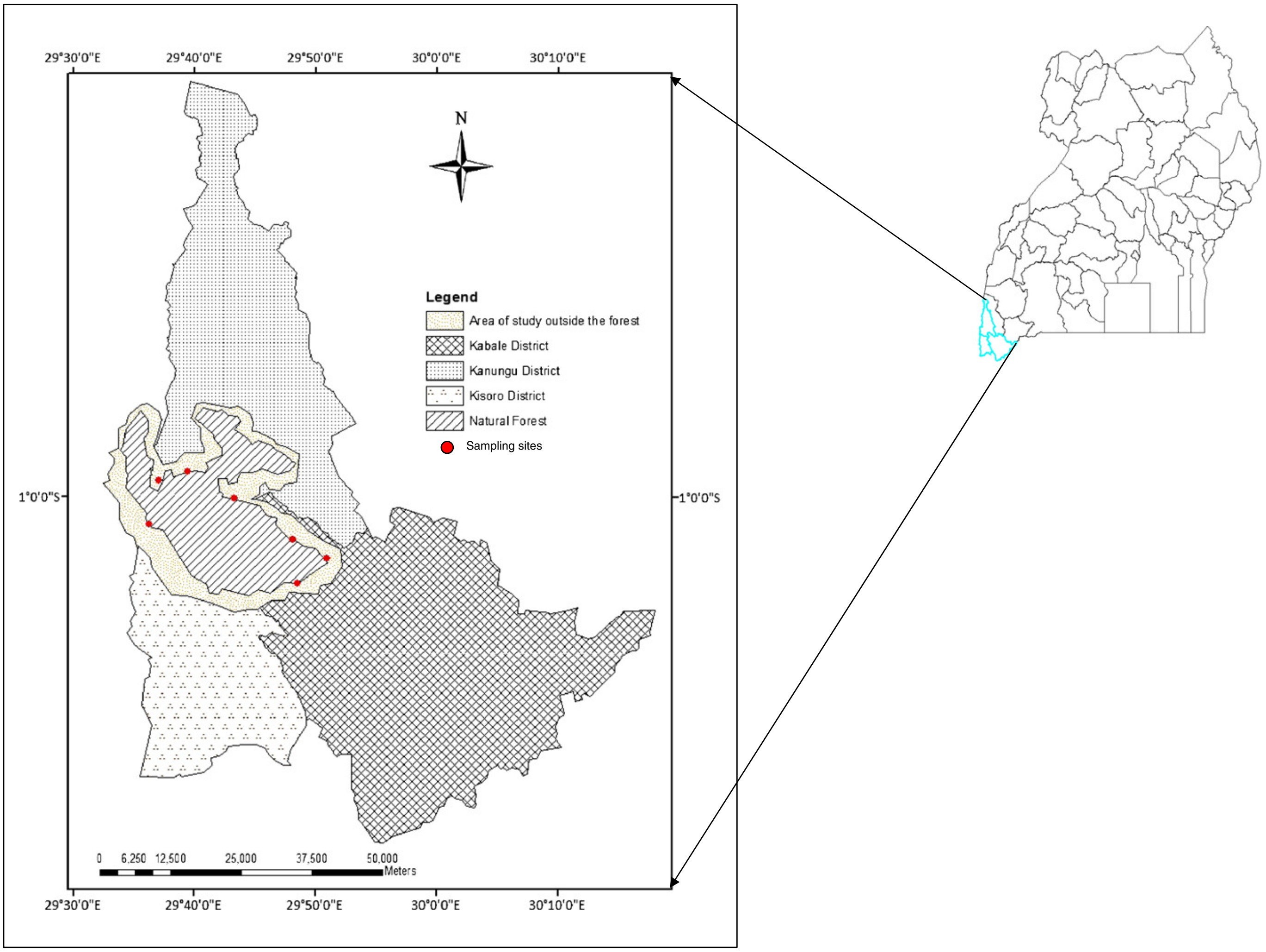

Fig. 1. A map showing location of sampling sites around Bwindi in SW Uganda.

Table 1
Characteristics of sampling sites.

Altitudinal range (m.a.s.l.)	Altitude classification	Mean annual rainfall (mm)	Mean annual temp. (°C)	Observed years for calculation of the means	Sites within the altitudinal range	Land uses/cover available within the sites	Management practices
2100–2500	High	1236	17.6	20	Ruhija, Rwamunyonyi	Forest, small scale farming, tea, grazing land	Fertilizer application (mainly NPK) on tea estates; seasonal crop rotation and terraces used on small scale farmlands.
1800–2100	Medium	1688	19.1	6	Nkuringo, Mpungu	Forest, small scale farming, tea, grazing land	Fertilizer application (mainly NPK) on tea estates; fallowing and crop-rotation on small scale farmlands
1450–1800	Low	1826	21.5	11	Buhoma, Kayonza	Forest, small scale farming, tea, grazing land	Fertilizer application (mainly NPK) on tea estates; controlled (rotational) grazing on grazing lands

(Source: Adapted from Nkurunungi et al., 2004).

(sub-soil) respectively]. The 0–30 cm depth was chosen because it is the agricultural layer, most affected by tillage (defined by Tenywa, 1998) and has the highest soil disturbance. One core sample was collected in both the top and sub-soils from each plot for bulk density determination using the core method and corrected for stone content (Okalebo et al., 2002). In total, 192 composite soil and 192 core samples were collected for laboratory analysis and estimation of bulk density (4 treatments × 4 slope faces × 2 sampling depths × 2 landscape positions × 3 replications = 192 samples). Soil samples were air-dried at room temperature for 48 h and passed through a 2 mm sieve. Identifiable crop residues, root material, and stones were removed during sieving. Soil samples for carbon analyses were ground to powder using a ball-mill grinder and passed through a 1 mm sieve. SOC concentration (% wet weight) was determined by wet acid oxidation method (Okalebo et al., 2002).

SOC was calculated using the following formula:

$$\text{SOC stock(Mg/ha)} = \%\text{SOC} \times \text{bulk density}\left(\text{g cm}^{-3}\right) \times \text{depth(cm)} \\ \times \text{Area(area of plot projected to 1 ha)}.$$

2.4. Analysis

We consider our study exploratory. We have small sample sizes that are not able to clarify overall patterns of variation and therefore prefer to employ non-parametric tests. We do not feel that formal requirements for more sophisticated statistical modeling (e.g. use of Generalized Linear Models) are met, but we do pool data in some exploratory regressions. To simplify our analyses, we assume that any edge effects were minor (this is something that could be examined further in the future), making the difference within each pair of local observations our primary interest.

Data were analyzed using a two sample non parametric test (Wilcoxon matched pairs test) in Genstat statistical package (version 3). Regression analyses were conducted to determine how SOC varies with land use, aspect, altitude, landscape position and depth. Values for $P<0.05$ were considered significant.

3. Results

On average, there are 68.6 ± 14.0, 69.6 ± 10.0, 79.7 ± 19.0, 78.8 ± 17.0 Mg/ha (mean ± 95% confidence interval) SOC stocks in the top 30 cm of soil covered by forest, tea, potato and grazing lands respectively. Variation among sites is high. Forests have the lowest SOC stocks and lowest bulk density at depths 0–15 cm (top-soil), 15–30 cm (sub-soil) and the overall depth 0–30 cm. (Tables 2a, 2b and 2c). The highest SOC stocks are recorded in soils under potato cultivation. However, no significant difference is observed in SOC content for the different land uses.

3.1. How SOC stocks varied within the forest

Surprisingly, there is little correlation ($r^2 = 0.04$) between SOC stocks in the top and sub-soils within the forest (Fig. 2a). Variation of SOC stocks within both soil layers is high and seems to be influenced by aspect and altitude. Tables 3a, 3b and 3c show how SOC stocks vary in forest and other land uses in relation to altitude, landscape position and aspect respectively.

Generally, there is 15.3% more SOC in the sub-soil than the top-soil within forest although this difference is not significant (attributable to the large Confidence Interval [CI]). However, landscape SOC variation in both the top and sub-soils is marked and significant (from Wilcoxon matched pairs test; the top-soil's mean carbon content was 68.92 ± 15.10 Mg/ha on back-slopes and 68.30 ± 23.54 on foot-slopes; and for the sub-soil, the figures for back-slopes and foot-slopes are 68.23 ± 37.37 and 78.35 ± 41.61 Mg/ha respectively; in both top-soil and sub-soil, $P<0.001$). Across the altitudinal gradient low altitude landscapes have the highest mean SOC stock in the top-soil but the least in the sub-soil. The overall pattern is one of high sample-to-sample variation with a little general trend (Fig. 2b, c and d). At high altitudes SOC stocks are highest in the sub-soil due to two high value points found among foot-slope samples (Fig. 2b).

East facing slopes in the sub-soil yielded the highest SOC stocks (Fig. 2c) while some points on the South facing slopes had very low SOC stocks. For comparison at both top and sub-soils, the aspect related differences are significant (from Wilcoxon matched pairs test; the mean (± 95% CI) SOC in the top-soil was 86.18 ± 34.69, 71.01 ± 39.37, 60.80 ± 20.12 and 40.81 ± 15.25 Mg/ha in the N, S, E and W facing slopes respectively; and for the sub-soil layer this was 78.28 ± 49.95, 78.28 ± 24.23, 107.22 ± 69.06 and 62.19 ± 32.84 Mg/ha on N,

Table 2a
Means of bulk density and SOC at 0–15 cm (top-soil) under different land use/cover.

Land use/cover	Mean bulk density ± 95% CI (g/cm^3) at 0–15 cm depth	Mean SOC ± 95% CI (Mg/ha) at 0–15 cm depth
Forest	0.85 ± 0.12	65.9 ± 15.9
Tea	1.04 ± 0.13	69.7 ± 12.6
Potato	1.01 ± 0.16	75.5 ± 10.1
Grazing land	1.14 ± 0.17	87.4 ± 26.8

Table 2b
Means of bulk density and SOC at 15–30 cm (sub-soil) under different land use/cover.

Land use/cover	Mean bulk density ± 95% CI (g/cm^3) at 15–30 cm depth	Mean SOC ± 95% CI (Mg/ha) at 15–30 cm depth
Forest	0.86 ± 0.12	71.1 ± 22.9
Tea	1.05 ± 0.12	69.5 ± 15.3
Potato	1.02 ± 0.16	71.7 ± 10.8
Grazing land	1.15 ± 0.17	75.9 ± 17.9

Table 2c
Means of bulk density and SOC at 0–30 cm under different land use/cover.

Land use/cover	Mean bulk density ± 95% CI (g/cm^3) at 0–30 cm depth	Mean SOC ± 95% CI (Mg/ha) at 0–30 cm depth
Forest	0.86 ± 0.09	68.6 ± 14.0
Tea	1.02 ± 0.11	69.6 ± 10.0
Potato	1.04 ± 0.09	73.3 ± 19.0
Grazing land	1.14 ± 0.12	78.8 ± 17.0

Table 3a
Variation of SOC with altitude and depth under the different land cover.

Altitude	Depth (cm)	Land use	Mean ± 95% CI (Mg/ha)
2100–2500 (High)	0–15	Forest	53.2 ± 9.8
	15–30	Forest	74.7 ± 33.7
	0–15	Tea	41.5 ± 9.9
	15–30	Tea	74.0 ± 49.8
	0–15	Potato	84.5 ± 24.4
	15–30	Potato	84.5 ± 24.4
	0–15	Grazing land	62.3 ± 20.2
	15–30	Grazing land	71.7 ± 19.9
1800–2100 (Medium)	0–15	Forest	73.7 ± 62.7
	15–30	Forest	67.3 ± 37.6
	0–15	Tea	67.5 ± 19.6
	15–30	Tea	69.5 ± 25.1
	0–15	Potato	95.6 ± 44.3
	15–30	Potato	95.6 ± 44.3
	0–15	Grazing land	63.3 ± 14.9
	15–30	Grazing land	105.2 ± 40.4
1450–1800 (Low)	0–15	Forest	102.9 ± 43.3
	15–30	Forest	61.5 ± 27.5
	0–15	Tea	78.5 ± 21.9
	15–30	Tea	68.3 ± 23.9
	0–15	Potato	N/A
	15–30	Potato	N/A
	0–15	Grazing land	119.4 ± 50.5
	15–30	Grazing land	71.8 ± 31.3

N/A — not available at this altitude.

S, E and W facing slopes respectively; in both the top-soil and sub-soil layers, mean differences in SOC were significant $P<0.001$).

SOC stocks in the sub-soil are higher (PP<0.001) on foot-slopes (120.0 ± 100.6 Mg/ha) than back-slopes (36.7 ± 25.9 Mg/ha) as shown in Fig. 2d. There is a variability though depicted by the spread in the sub-soil layer on foot-slopes which could have influenced this kind of result.

3.2. How SOC stocks varied within the other land uses

Although there is no significant effect of altitude and aspect within *tea* at either depth, there is greater variation in SOC stocks in the sub-soil (Fig. 3a). Sub-soil samples from foot-slopes under tea plantations had the greatest spread of SOC values, with two outliers (high and low). In tea plantations, on back-slopes, there is an average of 13.4 Mg/ha higher SOC stock ($P=0.32$) in the sub-soil than the top-soil and that figure is 12.6 Mg/ha ($P=0.31$) for foot-slopes (Fig. 3a).

Also under *potato* cultivation, SOC stocks in the sub-soil are higher ($P=0.02$) than in the top-soil (for foot-slopes the difference is 37.1 Mg/ha and for back-slopes 26.2 Mg/ha (Fig. 3b)). In *grazing lands*, there is significantly higher ($P<0.001$) SOC stock at low altitude compared to high and medium altitude (higher by 57.1 and 56.2 Mg/ha

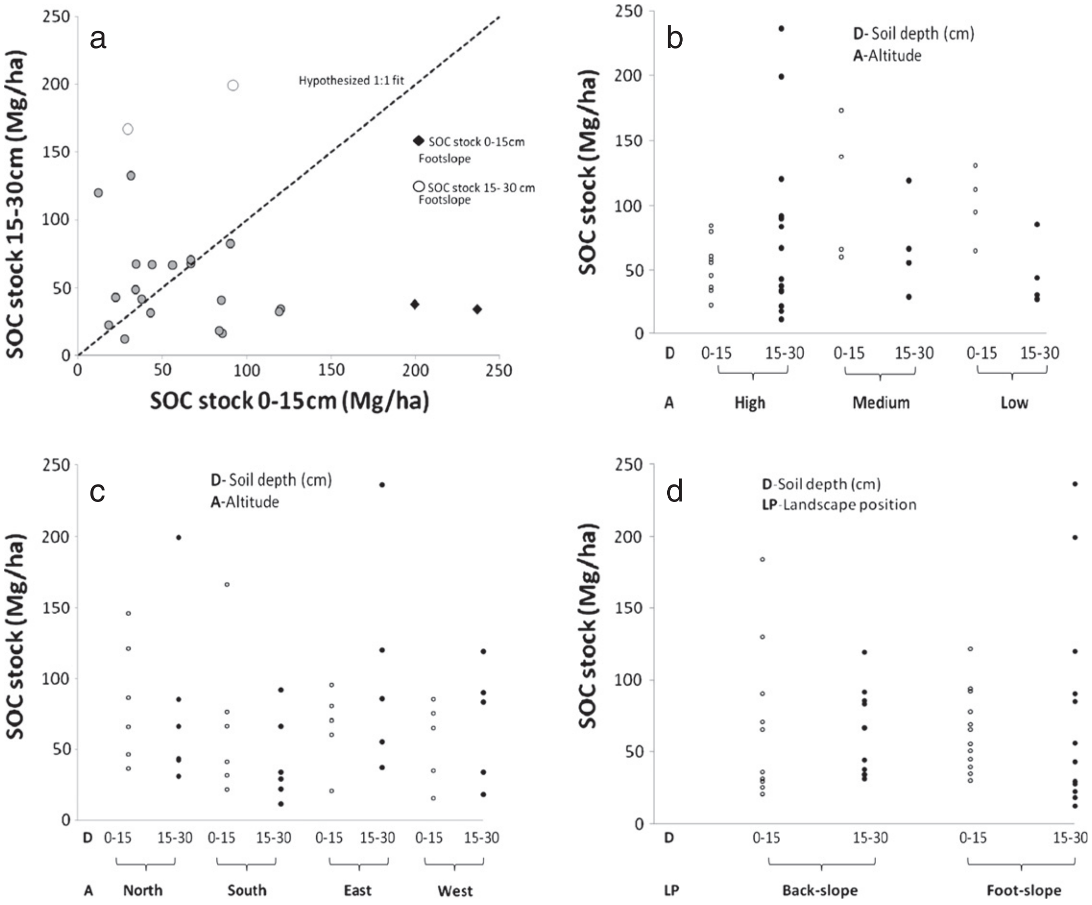

Fig. 2. Variation of SOC stock in forest: a) relationship between SOC in 0–15 cm (top-soil) and 15–30 cm (sub-soil) [poor correlation]; b) the effect of altitude; c) the effect of aspect; d) the effect of landscape position.

Table 3b
How SOC varies with landscape position and depth under different land cover.

Landscape position	Depth (cm)	Land use	Mean ± 95% CI (Mg/ha)
Backslope	0–15	Forest	68.9 ± 15.1
	15–30	Forest	63.2 ± 37.4
	0–15	Tea	63.5 ± 14.6
	15–30	Tea	62.1 ± 16.8
	0–15	Potato	78.9 ± 25.1
	15–30	Potato	53.5 ± 23.2
	0–15	Grazing land	88.9 ± 27.5
	15–30	Grazing land	65.0 ± 20.2
Footslope	0–15	Forest	68.3 ± 23.5
	15–30	Forest	78.4 ± 41.6
	0–15	Tea	76.9 ± 22.5
	15–30	Tea	74.7 ± 23.4
	0–15	Potato	105.0 ± 33.8
	15–30	Potato	90.6 ± 71.4
	0–15	Grazing land	85.8 ± 27.5
	15–30	Grazing land	86.9 ± 29.1

respectively) within the top-soil (Fig. 2c). SOC stocks in the top-soil are also significantly higher ($P<0.001$) on foot-slopes than on back-slopes (115.9 ± 57.8 and 85.2 ± 44.8 Mg/ha respectively) (Fig. 3d).

3.3. SOC content under different land uses

Paired sites generally showed no significant difference in top-soil SOC stocks in converted land uses compared to forest (Fig. 4a), nor in sub-soil stocks (Fig. 4b). Using the paired plots we find that at higher altitudes there is 31.4 Mg more (significant at $P=0.02$) SOC in the top-soil of potato fields than in those of the nearby forest. On West facing slopes there is significantly more (42.2 Mg) SOC in top-soil under tea than under forest (by Wilcoxon matched pairs test $r^2=0.8$; $P<0.001$); also on West facing slopes, there is 49.9 Mg more SOC stock in the top-soil of grazing land than in the nearby forest $r^2=0.8$; $P=0.02$).

Table 3c
How SOC varies with aspect and depth under different land cover.

Slope face	Depth (cm)	Land use	Mean ± 95% CI (Mg/ha)
North	0–15	Forest	86.2 ± 34.7
	15–30	Forest	78.3 ± 49.9
	0–15	Tea	68.9 ± 35.4
	15–30	Tea	111.7 ± 23.3
	0–15	Potato	103.6 ± 0.2
	15–30	Potato	77.1 ± 0.4
	0–15	Grazing land	67.5 ± 12.2
	15–30	Grazing land	105.1 ± 23.3
South	0–15	Forest	71.0 ± 39.4
	15–30	Forest	42.8 ± 24.2
	0–15	Tea	61.3 ± 4.3
	15–30	Tea	26.0 ± 18.8
	0–15	Potato	97.9 ± 4.3
	15–30	Potato	26.5 ± 1.3
	0–15	Grazing land	70.0 ± 33.1
	15–30	Grazing land	49.2 ± 26.4
East	0–15	Forest	60.8 ± 20.1
	15–30	Forest	107.2 ± 69.1
	0–15	Tea	44.3 ± 52.8
	15–30	Tea	66.5 ± 42.6
	0–15	Potato	68.4 ± 30.1
	15–30	Potato	90.4 ± 15.3
	0–15	Grazing land	79.3 ± 69.5
	15–30	Grazing land	40.7 ± 35.7
West	0–15	Forest	40.8 ± 15.2
	15–30	Forest	41.1 ± 32.8
	0–15	Tea	83.0 ± 24.2
	15–30	Tea	65.9 ± 12.9
	0–15	Potato	99.5 ± 75.1
	15–30	Potato	68.4 ± 27.5
	0–15	Grazing land	90.8 ± 52.1
	15–30	Grazing land	33.2 ± 26.6

Forest conversion to other land uses does not show a clear pattern of increase or loss of SOC stocks with time. Fig. 4c shows the differences in SOC between forest sites (the reference point) and nearby land converted to other uses, plotted against 'time since conversion' on the X axis. However, the highest increments in SOC were registered in old grazing lands. We considered that these differences may, at least to some degree, reflect soil compaction and therefore also examined and compared the same relationships for % SOC by mass. Although there is, again, no clear pattern following forest conversion, forest sites generally have higher % SOC content than the matched paired sites of other land uses (Fig. 4d). This difference is however not significant. Soils under potato cultivation generally show a slightly lower % SOC content, and those under grazing generally show a slight increase. Soils under tea were similar to forest in terms of % SOC content (Fig. 4d). There is no meaningful difference in SOC in the land uses following conversion as shown in Fig. 4d. Fig. 4c portrays greater differences within the matched paired sites (especially in the forest and grazing land sites).

4. Discussion

Our exploratory study provides novel insights on SOC stocks of the forest and cultivated land around Bwindi. Our measurements of SOC stocks are generally higher than those recorded in other regions (e.g. Beets et al., 2002; Harms et al., 2005; Yimer et al., 2006). Due to the pilot nature of our study, the small data sets, and our uncertainty concerning underlying patterns of variation, we have used simple – but robust – and easily understood exploratory statistics. We have assumed that distance-to-edge effects have little influence but acknowledge that this is unproven. While there have been various studies on the biological impact of edge effects on tropical lowland forests (e.g. Harper et al., 2005; Laurance, 2008; Murcia, 1995) few have considered soil relevant processes (e.g. Sizer et al., 2000) or mountain forests more generally (but for a fuller account of some edge effects in Bwindi see Olupot et al., 2009; Olupot, 2009). The often open and fragmented nature of the park's tree cover (Babaasa et al., 2004) means that any climate related "edge effects" will in reality be influential over much of the forest interior. Nonetheless we highlight as an important caveat that the influence of edge effects on soil carbon remains unexamined.

Generally, there is very high site to site variation both within the forest and within other land uses. This variation could be explained by the rugged and heavily dissected terrain causing different microclimates over short distances. The accumulation of SOC along the altitudinal gradient could also be attributed to the temperature/rainfall gradients and pedogenic processes including tree throw, wind throw, and bioturbation that result in pits and mounds and create a zone of litter and water accumulation. The highly local role of these processes has been recognized by other studies (e.g. Johnson et al., 2000; Liechty et al., 1997).

The poor correlation between SOC content in the 0–15 cm (topsoil) and 15–30 cm (sub-soil) across all land uses was striking and unexpected. This could reflect high variability in SOC even within the agricultural layer (0–30 cm). Generally SOC stock at any given point in time can be summarized as a balance between input and output of carbon. The equilibrium between the inputs and outputs is influenced by the soil type and by environmental variables such as temperature and precipitation, which have direct and indirect effects on both C inputs and outputs (West and Andsix, 2007). Climate affects plant growth and yield, and it mediates decomposition rates thus impacting the quantity and rate of C cycling. Management practices will alter this balance by affecting the system's productivity and the speed of residue and soil organic matter decomposition (Martellotto, 2010). A combination of all the factors that affect SOC stock budgets

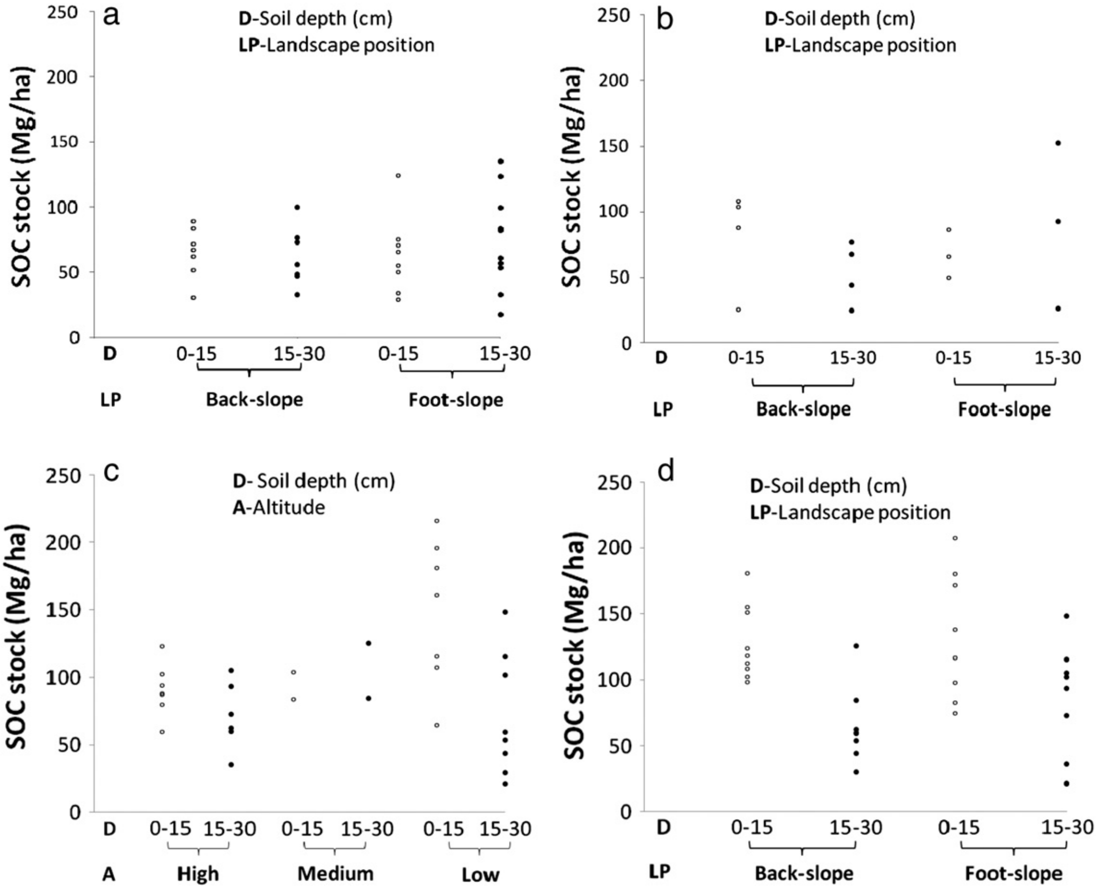

Fig. 3. Variation of SOC stock with landscape position, under various land uses: a) tea plantation; b) potato fields; c) grazing land (effect of altitude); d) grazing land.

could explain the poor correlation between the top and sub-soil layers in Bwindi.

As we had predicted foot-slopes had higher SOC stocks than back-slopes possibly because of matter and nutrients accumulating in the lower slopes at the expense of material eroded from the upper slopes. Slope steepness has been regarded as one of the most important abiotic factors that control the pedogenic process on a local scale (Buol et al., 1997; McDaniel et al., 1992). Steeper slopes contribute to greater runoff, as well as to greater translocation of surface materials down-slope, through surface erosion and movement of the soil mass (Hall, 1983). Studies on soil erosion and nutrient accumulation would help substantiate the effect of slope on SOC stocks in Bwindi and similar landscape settings.

Although studies elsewhere have shown that conversion of forest to other land uses resulted in a loss in SOC (Fujisaka et al., 1998; Nyssen et al., 2008; Rhoades et al., 2000), the differences in SOC between forest soils and those of cultivated land around Bwindi were neither consistent nor significant. This observation in highly heterogeneous landscapes may reflect the preferential conversion of relatively more fertile forest land into other land uses leaving soils with low fertility (and low carbon stocks) under forest. In most sites a decline would be anticipated following forest cover loss because forest derived carbon inputs are diminished while decomposition and other processes of loss are maintained or accelerated. In Bwindi, the higher SOC densities observed in some cases may at least partly reflect differences in bulk density. Generally, forest soils had the lowest bulk density at total depth 0–30 cm followed by those under potato crop and tea plantations. Soils under grazing land had the highest bulk density (probably due to trampling) — though these differences were not statistically significant. Cultivation tends to break soil aggregates and can cause compaction (Murty et al., 2002). If the soil is only sampled to a fixed depth then a greater mass of soil is sampled in the more compacted soil. If results are given as mass of carbon per soil area (e.g. t C/ha), then an apparent increase in soil carbon in more compacted agricultural soil could be viewed as an artifact (Murty et al., 2002). Nonetheless we find no clear trend in % SOC by mass following forest conversion (Fig. 4d). We conclude that bulk density plays a major role in influencing local SOC but large site to site level variation still tends to obscure any more general patterns.

High SOC stocks have been found in grazing lands elsewhere and attributed to good management practices such as rotational grazing and addition of fertilizers to the grasslands (Takashashi et al., 2007). For example large increases in SOC of 164% and 162%, at 33 and 44 years respectively after conversion from native vegetation to leguminous pastures are reported in Western Australia and have been attributed to low initial content of SOC, and careful management that avoided overgrazing and included the use of fertilizer (Murty et al., 2002). Grazing areas around Bwindi are not degraded: they have relatively low stocking while adding manure to the soil.

Sampling depths can significantly influence soil bulk density and total carbon estimates (Murty et al., 2002). Forest soils typically have most of their organic matter in the litter and upper soil layers. When the soil is tilled, soil organic matter is mixed throughout the tilled soil profile which could be 30 cm deep. In our study, in contrast, we noted a tendency for SOC densities to increase with depth even in the forest soils. Deep SOC has been recognized in literature as an important component of the terrestrial C cycle although poorly understood, with four main sources of input (often in dissolved form) into sub-soils identified as: 1) plant roots and root exudates, 2) dissolved organic matter, 3) bioturbation, 4) translocation of particulate organic

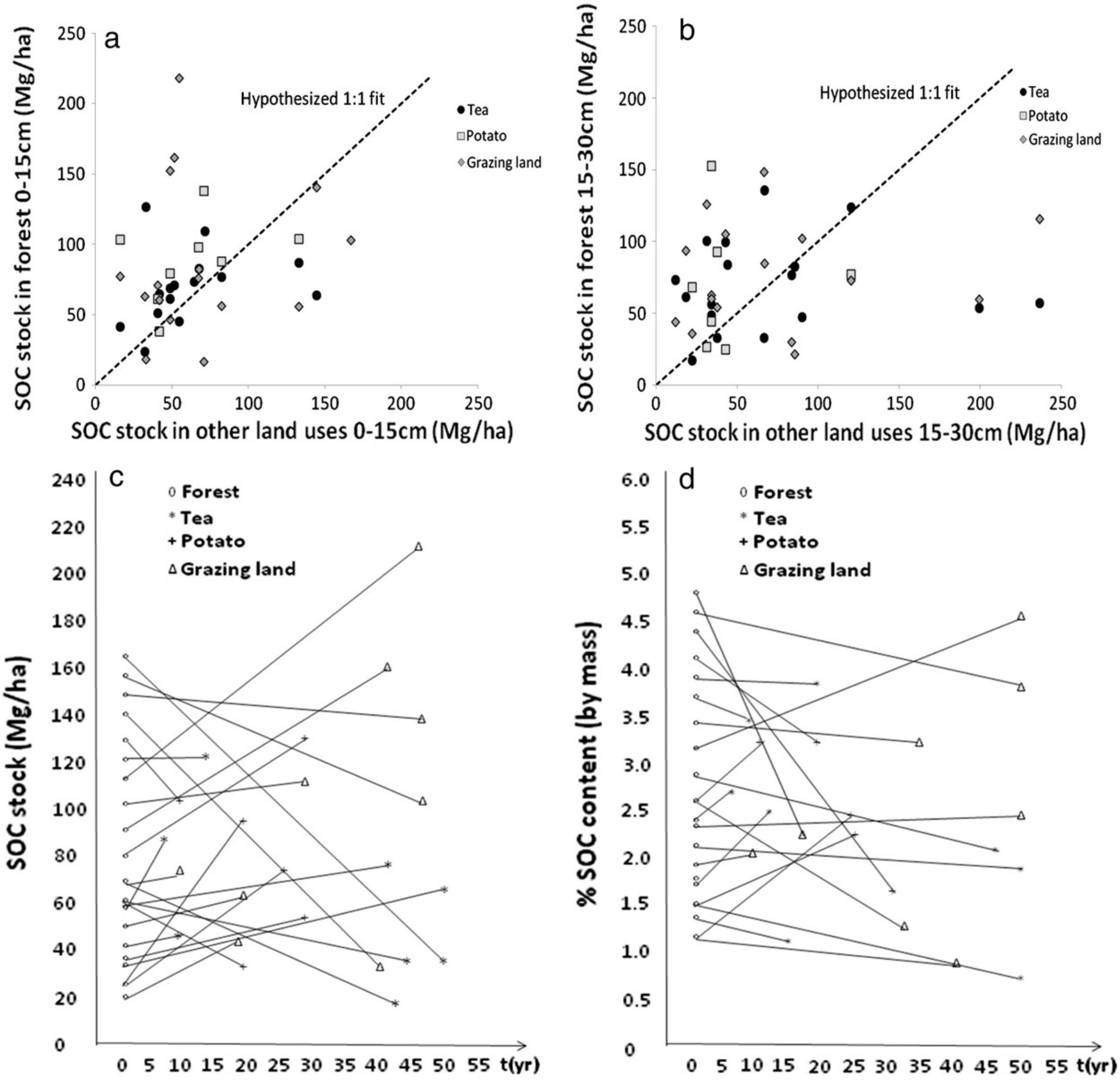

Fig. 4. SOC stock under various land uses, against that under forest: a) SOC at 0–15 cm (top-soil); b) SOC at 15–30 cm (sub-soil); c) SOC stock difference against time-since-conversion, in paired sites at 0–30 cm; d) % SOC content against time-since-conversion, in paired sites at 0–30 cm.

matter and transport of clay-bound organic matter in certain soil types (Rumpel and Kögel-Knabner, 2011). The role of these processes is dependent on climatic parameters, inherent soil characteristics as well as land use; the residence times of SOC in deep soil horizons could be up to several thousand years (Rumpel and Kögel-Knabner, 2011). The role of land use change and soil erosion has also been recognized as contributing to SOC in the deeper horizons (e.g. Thothong et al., 2011). The higher SOC stocks in the sub-soil (e.g. in the forest on East facing slopes, North facing tea and grazing lands, grazing lands located in the high and medium altitudes) in Bwindi are rather surprising, depicting complexity in the landscape possibly influenced by the processes discussed above, and thus requires further investigation.

5. Conclusion

SOC stocks under forest and the neighboring cultivated land around Bwindi are generally high and represent a large stock of carbon. There is considerable local variation among local SOC that is only poorly explained by site factors and land use history. Nonetheless soil depth and landscape position appeared to influence sampled SOC stocks though generally they did not differ significantly among the different land uses and histories. Cultivated land and grazed lands were generally more compacted than soils under natural forest. We conclude that the organic carbon stocks in soils appears: a) more variable at a local scale, b) less predictable from site conditions and c) more persistent under forest loss than we had expected. We require more studies to understand the temporal and spatial differences in SOC and related carbon stocks across different land uses in these and other afro-montane forest regions.

Acknowledgment

We are grateful to the entire staff of Institute of the Tropical Forest Conservation, and to the John D. and Catherine T. MacArthur Foundation for having supported and funded this research.

References

Babaasa, D., Eilu, G., Kasangaki, A., Bitariho, R., Mcneilage, A., 2004. Gap characteristics and regeneration in Bwindi Impenetrable National Park, Uganda. African Journal of Ecology 42, 217–224.

Batjes, N.H., Sombroek, W.G., 1997. Possibilities for carbon sequestration in tropical and sub tropical soils. Global Change Biology 3, 161–173.

Beets, P.N., Oliver, G.R., Clinton, P.W., 2002. Soil carbon protection in podocarp/hardwood forest and effects of conversion to pasture and exotic pine forest. Environmental Pollution 116, S63–S73.

Buol, S.W., Hole, F.D., Mccracken, R.J., Southard, R.J., 1997. Soil Genesis and Classification, 4th edition. Iowa State Univ. Press, Ames, IA.

Butynski, T.M., Kalina, J., 1998. Gorilla tourism: a critical look. In: Milner-Gulland, E.J., Mace, R. (Eds.), Conserv. of Bio. Res. Blackwell, Oxford, pp. 294–313.

Cerbu, G.A., Swallow, B.M., Thompson, D.Y., 2010. Locating REDD: a global survey and analysis of REDD readiness and demonstration activities. Environmental Science & Policy http://dx.doi.org/10.1016/j.envsci.2010.09.007.

Chun-Chih, T., Zueng-Sang, C., Chang-Fu, H., 2004. Relationships between soil properties and landscape position in a lowland rain forest of southern Taiwan. Geoderma 12–3, 131–142.

Cole, T.G., Ewel, J.J., 2006. Allometric equation for four valuable tree species. Forest Ecology and Management 229, 351–360.

Cotler, H., Ortega-Larrocea, M.P., 2006. Effects of land use on soil erosion in a tropical dry forest ecosystem, Chamela watershed, Mexico. Catena 65, 107–117.

Defries, R., Achard, F., Brown, S., Herold, M., Murdiyarso, D., Schlamadinger, B., Desouzajr, C., 2007. Earth observations for estimating greenhouse gas emissions from deforestation in developing countries. Environmental Science Policy 10, 385–394.

Feller, C., Beare, M.H., 1997. Physical control of soil organic matter dynamics in the tropics. Geoderma 79, 69–116.

Finney, H.R., Holowaychu, N., Heddleson, M.R., 1962. The influence of microclimate on the morphology of certain soils of the Allegheny Plateau of Ohio. Soil Science Society of America Proceedings 26, 287–292.

Franzmeier, D.P., Pederson, E.J., Longwell, T.J., Byrne, J.G., Losche, C.K., 1969. Properties of some soils in the Camberland Plateau as related to slope aspect and position. Soil Science Society of America Proceedings 33, 755–761.

Fu, B.J., Liu, S.L., Ma, K.M., Zhu, Y.G., 2004. Relationships between soil characteristics, topography and plant diversity in a heterogeneous deciduous broad-leaved forest near Beijing, China. Plant and Soil 261, 47–54.

Fujisaka, S., Castilla, C., Escobar, G., Rodrigues, V., 1998. The effect of forest conversion on annual crops and pastures: estimates of carbon emissions and plant species loss in a Brazilian Amazon colony. Agriculture, Ecosystems and Environment 69, 17–26.

Gibbs, K.H., Brown, S., Niles, J.O., Foley, J.A., 2007. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environmental Research Letters 2 http://dx.doi.org/10.1088/1748-9326/4/045023.

Gullison, R.E., Frumhoff, P., Canadell, J., Field, C.B., Nepstad, D.C., Hayhoe, K., 2007. Tropical forests and climate policy. Science 316, 985–986.

Hall, G.F., 1983. Pedology and geomorphology. In: Wilding, L.P., Smeck, N.E., Hall, G.F. (Eds.), Pedogenesis and Soil Taxonomy: I. Concepts and Interactions. Elsevier, Amsterdam, pp. 117–140.

Harms, B.P., Dalal, R.C., Cramp, A.P., 2005. Changes in soil carbon and soil nitrogen after tree clearing in the semi-arid rangelands of Queensland. Australian Journal of Botany 53, 639–650.

Harper, K.A., Macdonald, S.E., Burton, P.J., Chen, J.Q., Brosofske, K.D., Saunders, S.C., Euskirchen, E.S., Roberts, D., Jaiteh, M.S., Esseen, P.A., 2005. Edge influence on forest structure and composition in fragmented landscapes. Conservation Biology 19, 768–782.

Harris, N.L., Petrova, S., Stolle, F., Brown, S., 2008. Identifying optimal areas for REDD intervention: East Kalimantan, Indonesia as a case study. Environmental Research Letters 3 http://dx.doi.org/10.1088/1748-9326/3/3/035006 035006 (11 pp.).

Howard, P., 1991. Nature Conservation in Uganda's Tropical Forest Reserves. IUCN Conservation Library, IUCN, Gland, Switzerland/ Cambridge, U.K.

Johnson, C.E., Ruiz-Mendez, J.J., Lawrence, G.B., 2000. Forest soil chemistry and Terrain attributes in a Catskill watershed. Soil Science Society of America Journal 64, 1804–1814.

Kirschbaum, M.U.F., 2000. Will changes in soil organic matter act as positive or negative feedback on global warming? Biogeochemistry 48, 21–51.

Korkanc, S.Y., Ozyuvaci, N., Hizal, A., 2008. Impacts of land use conversion on soil properties and soil erodibility. Journal of Environmental Biology 29 (3), 363–370.

Langdale-Brown, I., Osmaston, H.A., Wilson, J.G., 1964. The Vegetation of Uganda and its Bearing on Land Use. Government Printer, Entebbe.

Laurance, W.F., 2008. Theory meets reality: how habitat fragmentation research has transcended island biogeographic theory. Biological Conservation 141, 1731–1744.

Lewis, S.L., Lopez-Gonzalez, G., Sonke, B., Affum-Baffoe, K., Baker, T.R., 2009. Increasing carbon storage in intact African tropical forests. Nature 457 http://dx.doi.org/10.1038/nature07771.

Liechty, H.O., Jurgensen, M.F., Mroz, G.D., Gale, M.R., 1997. Pit and mound topography and its influence on storage of carbon, nitrogen, and organic matter within an old-growing forest. Canadian Journal of Forest Research 27, 1992–1997.

Luyssaert, S., Schulze, E.D., Börner, A., Knohl, A., Hessenmöller, D., Law, B.E., Ciais, P., Grace, J., 2008. Old-growth forests as global carbon sinks. Nature 455, 213–215.

Martellotto, A., 2010. The impact of long-term tillage, crop rotation and N application on soil carbon sequestration. Dissertations on Agronomy and Horticulture, University of Nebraska-Lincoln.

Mcdaniel, P.A., Bathke, G.R., Boul, S.W., Cassel, D.K., Falen, A.L., 1992. Secondary manganese/iron ratios as pedochemical indicators of field-scale through flow water movement. Soil Science Society of America Journal 56, 1211–1217.

Murcia, C., 1995. Edge effects in fragmented forests: implications for conservation. Trends in Ecology & Evolution 10, 58–62.

Murty, D., Kirschbaum, M.U.F., Mcmurtie, R.E., Mcgilvray, H., 2002. Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. Global Change Biology 8, 105–123.

Navar, J., 2009. Allometric equations for tree species and carbon stocks for forests of New Mexico. Forest Ecology and Management 257, 427–434.

Nkurunungi, J.B., Ganas, J., Robbins, M.M., Stanford, C.B., 2004. A comparison of two mountain gorilla habitats in Bwindi Impenetrable National Park, Uganda. African Journal of Ecology 42, 289–297.

Nyssen, J., Temesgen, H., Mulugeta, L., Zenebe, A., Haregeweyn, N., Mitiku, H., 2008. Spatial and temporal variation of soil organic carbon stocks in a lake retreat area of the Ethiopian Rift Valley. Geoderma 146, 261–268.

Okalebo, J.R., Gathua, K.W., Woomer, P.L., 2002. Laboratory Methods of Soil and Plant Analysis, KARI, SSSEA, Moi University and SACRED Africa2nd edn.

Ollinger, S.V., Smith, M.L., Martin, M.E., Hallett, R.A., Goodale, C.L., Aber, J.D., 2002. Regional variation in foliar chemistry and N cycling among forests of diverse history and composition. Ecology 83, 339–355.

Olupot, W., 2009. A variable edge effect on trees of Bwindi Impenetrable National Park, Uganda, and its bearing on measurement parameters. Biological Conservation 142, 789–797.

Olupot, W., Barigyira, R., Chapman, C.A., 2009. The status of anthropogenic threat at the people–park interface of Bwindi Impenetrable National Park, Uganda. Environmental Conservation 36, 41–50.

Rech, J.A., Reeves, R.W., Hendricks, D.M., 2001. The influence of slope aspect on soil weathering processes in the Springerville volcanic field, Arizona. Catena 43, 49–62.

Rhoades, C.C., Eckert, G.E., Coleman, D.C., 2000. Soil carbon differences among forest, agriculture and secondary vegetation in lower montane Ecuador. Ecological Applications 10, 497–505.

Rumpel, C., Kögel-Knabner, I., 2011. Deep soil organic matter — a key but poorly understood component of terrestrial C cycle. Plant and Soil 338, 143–158.

Sidari, M., Ronzello, G., Vecchio, G., Muscolo, A., 2008. Influence of slope aspects on soil chemical and biochemical properties in a *Pinus laricio* forest ecosystem of Aspromonte (Southern Italy). Soil Biology 44, 364–372.

Sizer, N.C., Tanner, E.V.J., Ferraz, I.D.K., 2000. Edge effects on litterfall mass and nutrient concentrations in forest fragments in central Amazonia. Journal of Tropical Ecology 16, 853–863.

Slik, J.W.F., Shin-Ichiro, A., Brearley, F.Q., Cannon, C.H., Forshed, O., Kitayama, K., Nagamasu, H., Nilus, R., 2009. Environmental correlates of tree biomass, basal area, wood specific gravity and stem density gradients in Borneo's tropical forests. Global Ecology and Biogeography http://dx.doi.org/10.1111/j.1466-8238.2009.00489.x.

Sun, O.J., Campbell, J., Law, B.E., Wolf, W., 2004. Dynamics of carbon stocks in soils and detritus across chronosequences of different forest types in the Pacific Northwest, USA. Global Change Biology 10, 1470–1481.

Takashashi, S., Nakagami, K., Sakanoue, S., Itano, S., Kirita, H., 2007. Soil organic carbon storage in grazing pasture converted from forest on Andosol soil. Grassland Science 53, 210–216.

Tenywa, M.M., 1998. Agricultural potential in the Rwenzori Mountains; special reference to the lower slopes in Bwamba. In: Osmaston, H., Tukahirwa, J., Basalirwa, C., Nyakaana, J. (Eds.), The Rwenzori Mountains National Park, Uganda. Fountain Publishers LTD. ISBN: 9970-429-01-9, pp. 180–189. Copyright: Department of Geography, Makerere University.

Thothong, W., Huon, S., Janeau, J., Boonsaner, A., de Rouw, A., Planchon, O., Bardoux, G., Parkpian, P., 2011. Impact of land use change and rainfall on sediment and carbon accumulation in a water reservoir of North Thailand. Agriculture, Ecosystems and Environment 140, 521–533.

Tsui, C.C., Chen, Z.S., Hsieh, C.F., 2004. Relationships between soil properties and landscape position in a lowland rain forest of southern Taiwan. Geoderma 123, 131–142.

Twongyirwe, R., Majaliwa, J.G.M., Ebanyat, P., Tenywa, M.M., Sheil, D., Heist, M., Oluka, M., Kumar, L., 2011. Forest cover conversion dynamics around Bwindi Impenetrable Forest in south-western Uganda. JASEM 15, 189–195.

Van Der Werf, G.R., Morton, D.C., Defries, R.S., 2009. Carbon-dioxide emissions from forest loss. Nature Geoscience 2, 737–738.

Wang, S., Shao, M., Mickler, R., Ji, K.J., 2004. Vertical distribution of soil organic carbon in China. Environmental Management 33, 200–209.

West, O.T., Andsix, J., 2007. Considering the influence of sequestration duration and carbon saturation on estimates of soil carbon capacity. Climate Change 80, 25–41.

Yimer, F., Ledin, S., Abdelkadir, A., 2006. Soil property variations in relation to topographic aspect and vegetation community in the south-eastern highlands of Ethiopia. Forest Ecology and Management 232, 90–99.

2002 Preliminary Census Data. from http://www.ubos.org/2002censuspreliminarytable.pdf (now a dead link, retrieved 2003-09-13).