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Full Length Research Paper

Soil carbon and nutrient accumulation under forest plantations in southern Rwanda

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Tree and soil interactions may result in changes in soil carbon and nutrient contents. Forest plantations made up of monodominant stands of 17 different species, some native and some exotic to Rwanda, as well as a stand with mixed native tree species were investigated. Biosequential sampling was used followed by basic soil chemical analyses. Results revealed that the plantation species composition influenced the soil chemical properties. Total soil C and N, C: N ratio, available P, pH, and cation exchange capacity (CEC) differed significantly between plantation stands of different species ($P < 0.001$, $N = 54$). Increases in the levels of soil C, total N, CEC and base saturation (BS) were observed mainly in mixed native species (MNS), *Polyscia fulva*, *Casuarina equisetifolia* and *Eucalyptus saligna*. The pH declined slightly in soil beneath some *Eucalyptus* species treatments and increased in others. The high nutrient uptake by fast-growing trees and the acidic parent material were involved in the acidification process. The findings suggest that the species used in afforestation maintain soil fertility and protect the environment. It is recommended that afforestation of abandoned and less productive lands in Rwanda should utilize fast growing *Eucalyptus* species in combination with agroforestry and native species in order to maintain or improve soil chemical properties.

Key words: Afforestation, base saturation (BS), cation exchange capacity (CEC), forest plantation, soil carbon, total N, Rwanda.

INTRODUCTION

Forest plantations have become common landscapes across many parts of the world. For instance in 2000, forest plantations occupied 116 Mha (million hectare) in Asia, 32 Mha in Europe, 28 Mha in America and 8 Mha in Africa. In East African countries, the largest forest plantations are found in Sudan (641 000 ha), Rwanda (261 000 ha) and Kenya (231 000 ha) (FAO, 2001) . Forest plantations were introduced to tropical regions to supply fuelwood, charcoal, fodder, sticks and building materials. They were also planted to restore degraded lands, to control soil erosion or to serve as buffer zones around roads and areas of natural forests (Evans, 1999; Hartemink, 2003; Jagger and Pender, 2003; Mishra et al., 2003). Today, afforestation is considered an option to reduce the concentration of atmospheric carbon dioxide by increasing carbon sequestration in tree biomass and soils (IPCC, 2000; Paul et al., 2002; Turner et al., 2005).

Although the area of forest plantations has increased, there has been concern over their ecological and environmental effects. It is believed that: they sustain a low diversity of wildlife; they are high consumers of water and nutrients, and increase soil acidification (Cannell, 1999; Jagger and Pender, 2003). This has led to studies of soil properties under forest plantations in comparison to natural forests, pastures, natural savannas and croplands all over the world including Brazil, Australia and India (Lilienfein et al., 2000; Zdenko, 2002; Hartemink, 2003; Jobbágy and Jackson, 2003; Mishra et al., 2003; Turner et al., 2005).

In Rwanda, a tropical mountainous region, plantation forests were introduced since 1910 as a tentative solution to control soil erosion and restore degraded lands, but also to respond to the increased demands for fuelwood,

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wood products and building materials (Burren, 1995; Roose and Ndayizigiye, 1997). Foresters have utilized mainly exotic species in plantations in Rwanda, including the following genera: *Eucalyptus, Grevillea, Cedrella, Pinus, Cupressus* and *Callitris.* The genus *Eucalyptus* has shown a high adaptability to the soil environment and fast growth rate that have made it successful and it now occupies 65% of the total plantation area in Rwanda (Minitere, 2003). However, adverse impacts of forest plantations were also speculated in Rwanda, including low soil pH and loss of soil fertility attributed to *Eucalyptus* species. Therefore, a study of effects of tree species on soil chemical properties may clarify that belief.

Few reports have described the historical changes in soil and environmental aspects of Rwanda. The few soil chemical assessments were conducted on large land areas with many soil types, land uses, climatic and agro-ecological zones (Zaag et al., 1984; Verdoodt and Van Ranst, 2003). Therefore, this study intended to fill the gap by focusing on soil chemical changes under similar environmental and soil conditions, within a long-term plantation forest. The purpose of this study was to compare soil properties under 18 forest plantation species, selected among the most used by foresters in Rwanda. The hypothesis was that following plantation establishment, nutrient and soil C concentrations were modified by plant uptake and wood harvest, and increased by litter fall and root exudates. Thus, the soil C and nutrient content may differ from one tree species to another

MATERIAL AND METHODS

Study site

The Arboretum of Ruhande in southwestern Rwanda (altitude: 1737 m; lat. 2°36´S and long. 29°44´E), is a unique forestry resource inter-nationally appreciated for its fine collection of *Eucalypts* (Burren, 1995). The area was used as human settlement and multiple croplands until 1933, when the population was displaced and the plantation was established. The Arboretum of Ruhande is conceived as a center that may produce ecologically adapted silvicultural species and provide tree seeds at a national level. It is composed of over 207 native and exotic species, including 143 hardwoods with 69 *Eucalyptus* species, 57 softwood and 3 bamboo species. This plantation covers a surface of 200 ha; each species is planted in a plot of 50 x 50 m. The site is unique as most species were replicated. Plots are intercalated by alleys of about 6 m wide (Burren, 1995). Such biodiversity established on one soil type offers an opportunity to examine the effects of tree species on soil properties. This site was also selected for the study because its land-use history was maintained for a long period.

The climate in the region is tropical humid, the average annual temperature is 19.6°C and the mean annual precipitation is 1232 mm (Burren, 1995). The rainfall has a bimodal pattern: the heavy rainy season extending from March to May and the mild rain from October to December. The two rainfall seasons alternate with two dry seasons, one from January to February and the other from June to September. The soil in arboretum is classified as a Ferralsols according to FAO (1998), formed from the parent material of schists and granites mixed with mica schist and quartzite (Steiner, 1998; Verdoodt and Van Ranst, 2003). To determine the role of tree species on C and nutrient storage in soil, the biosequantial method was used: sampling soils under adjacent different land-use systems at the same time (Hartemink, 2003, 2006). Eighteen treatments were selected in the Arboretum for the study: eleven exotic species plots including 7 *Eucalyptus* species, three agroforestry species plots, three native species plots and a MNS plot (Table 1). Each treatment had 3 replicates. Three plots of 50 x 50 m were also selected in the MNS area. Plantations plots were 25 to 65 years old (Table 1). The reference was an arable soil, located adjacent to the experimental stands. Except for the mixed native species treatment, all plots were yearly managed by clearing the ground vegetation and undesirable shrubs and regrowth and periodic thinning and harvesting. Litter was always left on the surface. The MNS area has developed through natural regeneration dominated by *Polyscia fulva* mixed with other native shrubs including *Lantana camara*, *Desmodium repandum*, and *Acanthus pubescens*.

Soil sampling and analyses

Nine core samples of surface soils (0 - 10 cm) were taken in May 2005 from each plot and bulked to give one sample per plot. The sampling was done at the intersecting lines of a 3 x 3 grid, with intersecting lines of 12 m distance, centering to the middle of the plot. The litter layer was removed prior to sampling. Soil samples were sieved (< 2 mm), air-dried and ground prior to laboratory analyses. Samples used for C and N analysis were oven-dried at 70 ºC for 48 h and then milled in a ball mill (Model: MM 200, Retsch, Germany). The C and N concentrations were determined by dry combustion using an elemental analyzer (Model: EA 1108 CHNS-O, Fisons Instruments, Italy) and the 2,5-Bis-[5-tert.-butyl-benzoxazol-2-yl]-thiophen (BBOT) as a standard. Soil pH was measured in a soil-water suspension in the ratio 1:2.5, using a glass electrode. Available P was extracted by Bray 1 method and determined colorimetrically using the ascorbic acid method (IITA, 1979; Page et al., 1982). Soil exchangeable bases were extracted with 1 M ammonium acetate at pH 7. Concentrations of Ca^{2+} and Mg^{2+} in the extracts were read by atomic absorption spectrophotometer, while K^{+} and Na^{+} were determined by flame photometer. Exchangeable acidity (Al^{3+} and H^{+}) was determined by atomic absorption spectrophotometer (Page et al., 1982). The CEC was calculated as sum of exchangeable bases and exchangeable acidity. Percentage of BS was calculated following the method of Burleigh and Yamoah (1997). The soil C and N analysis was conducted at Göteborg University, Sweden. Other soil analyses were done at the Laboratory of Soil Sciences at Rubona, Rwanda. The reference samples were also analyzed following the same protocol.

Data analysis

To investigate if forest plantation species contributed positively to soil properties, the soil status under a present land use was compared to reference sample. The rate of change ( ) in soil chemical properties was calculated as a difference between treatment and reference values (Hartemink, 2003, 2006) . The rate of change shows what happens to the soil properties after the afforestation. Positive values refer to an increase and negative values refer to a decline in soil properties (Hartemink, 2003).

Statistical analyses were performed using the Statistical Package for Social Scientists (SPSS) software (SPSS Inc., 2005). All data were expressed as means ± standard deviation. Mean values of soil attributes were tested for differences using one-way analysis of variance (ANOVA), with the Tukey's honest significant difference at the 5% probability level. The relationship between soil property values was also explored using the Pearson's linear correlation coefficient.

Table 1. Characteristics and geographic location of studied treatment plots at the Ruhande Arboretum in Southern Rwanda.

Plot number	Geographic location		Treatments	Plantation year	Tree category
-	S 02º36.65	E 29º44.65	Mixed native species (MNS)	-	Natural regeneration
-	S 02º36.59	E 29º45.63		-	»
-	S 02º36.68	E 29º45.51		-	»
58	S 02º36.96	E 29º44.85	*Eucalyptus citriodora*	1940	Exotic
211	S 02º36.72	E 29º45.27		1983	»
456	S 02º37.06	E 29º45.16		1949	»
109	S 02º36.73	E 29º45.57	*Eucalyptus tereticornis*	1943	»
110	S 02º36.81	E 29º45.59		1945	»
450	S 02º37.08	E 29º45.07		1949	»
77	S 02º36.82	E 29º45.12	*Eucalyptus microcorys*	1943	»
367	S 02º36.62	E 29º45.19		1949	»
448	S 02º37.08	E 29º45.05		1949	»
6	S 02º36.93	E 29º44.86	*Eucalyptus maculata*	1954	»
446	S 02º37.09	E 29º45.00		1949	»
458	S 02º37.05	E 29º45.21		1949	»
179	S 02º36.66	E 29º45.61	*Eucalyptus maidenii*	1946	»
377	S 02º36.59	E 29º45.32		1949	»
452	S 02º37.07	E 29º45.09		1949	»
20	S 02º36.89	E 29º45.06	*Eucalyptus saligna*	1934	»
375	S 02º36.59	E 29º45.32		1949	»
442	S 02º37.10	E 29º44.96		1950	»
218	S 02º37.03	E 29º44.83	*Eucalyptus grandis*	1951	»
220	S 02º37.03	E 29º44.86		1951	»
265	S 02º36.72	E 29º45.17		1985	»
111	S 02º36.75	E 29º45.60	*Cedrela serrata*	1945	»
112	S 02º36.78	E 29º45.62		1946	»
159	S 02º36.76	E 29º45.30		1984	»
104	S 02º36.84	E 29º45.51	*Grevillea robusta*	1941	»
150	S 02º36.97	E 29º44.96		1947	»
203	S 02º36.79	E 29º45.00		1984	»
92	S 02º36.86	E 29º45.35	*Pinus patula*	1981	»
211	S 02º36.74	E 29º45.14		1983	»
410	S 02º37.00	E 29º45.36		1981	»
108	S 02º36.81	E 29º45.57	*Cupressus lusitanica*	1940	»
167	S 02º36.72	E 29º45.44		1980	»
114	S 02º36.80	E 29º45.64		1946	»
44	S 02º36.81	E 29º45.42	*Entandrophragma excelsum*	1949	Native
54	S 02º36.78	E 29º45.57		1952	»
78	S 02º36.90	E 29º45.12		1952	»
2	S 02º36.93	E 29º44.80	*Podocarpus falcatus*	1955	»
156	S 02º36.95	E 29º45.05		1947	»
226	S 02º37.01	E 29º44.93		1952	»
240	S 02º36.96	E 29º45.15	*Polyscia fulva*	1950	»
262	S 02º36.91	E 29º45.46		1950	»
268	S 02º36.88	E 29º45.54		1950	»
273	S 02º36.69	E 29º45.30	*Calliandra calothyrsus*	1985	Agroforestry
265	S 02º36.71	E 29º45.18		1985	»
267	S 02º36.72	E 29º45.21		1985	»

Table 1 Contd.

169	S 02º36.72	E 29º45.46	*Casuarina equisetifolia*	1944	»
194	S 02º36.85	E 29º45.58		1945	»
194	S 02º36.85	E 29º45.58		1945	»
180	S 02º36.89	E 29º45.41	*Leucaena leucocephala*	1982	»
400	S 02º37.02	E 29º45.24		1983	»
402	S 02º37.02	E 29º45.21		1983	»

Table 2. Soil chemical properties in the 0-10 cm soil layer under plantation stands of different species*

Treatments	Soil C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	C : N ratio	Avail. P ($mg\ kg^{-1}$)	pH_{water}	CEC ($cmol\ kg^{-1}$)	BS (%)
MNS	50.7 ^{b}	4.3 ^{c}	11.9 ^{a}	25.6 ^{c}	6.1 ^{b}	19.5 ^{b}	94.9 ^{a}
Eucalyptus citriodora	42.7 ^{ab}	2.9 ^{ab}	14.5 ^{b}	19.8 ^{c}	3.9 ^{a}	8.8 ^{ab}	94.1 ^{a}
Eucalyptus tereticornis	41.4 ^{ab}	3.3 ^{c}	12.6 ^{ab}	12.2 ^{b}	4.9 ^{ab}	11.9 ^{ab}	83.6 ^{a}
Eucalyptus microcorys	29.8 ^{a}	1.9 ^{a}	16.3 ^{d}	13.2 ^{b}	4.5 ^{ab}	5.6 ^{a}	79.1 ^{a}
Eucalyptus maculata	44.1 ^{ab}	2.4 ^{ab}	18.2 ^{d}	13.5 ^{b}	4.1 ^{ab}	8.2 ^{ab}	63.4 ^{a}
Eucalyptus maidenii	42.3 ^{ab}	3.1 ^{bc}	13.8 ^{ab}	10.4 ^{ab}	4.2 ^{ab}	7.5 ^{ab}	59.3 ^{a}
Eucalyptus saligna	45.2 ^{ab}	2.9 ^{ab}	15.9 ^{c}	14.4 ^{b}	4.5 ^{ab}	7.2 ^{a}	75.3 ^{a}
Eucalyptus grandis	32.7 ^{a}	2.2 ^{ab}	14.9 ^{c}	13.9 ^{b}	4.3 ^{ab}	7.0 ^{a}	88.5 ^{a}
Cedrela serrata	39.3 ^{ab}	3.0 ^{ab}	12.9 ^{ab}	8.5 ^{ab}	5.2 ^{ab}	16.2 ^{ab}	94.7 ^{a}
Grevillea robusta	31.9 ^{a}	2.4 ^{ab}	13.5 ^{ab}	17.6 ^{b}	5.3 ^{ab}	16.8 ^{ab}	94.1 ^{a}
Pinus patula	29.4 ^{a}	2.3 ^{ab}	12.9 ^{ab}	11.3 ^{ab}	4.9 ^{ab}	13.0 ^{ab}	94.8 ^{a}
Cupressus lusitanica	44.3 ^{ab}	3.1 ^{bc}	14.2 ^{ab}	6.6 ^{ab}	5.5 ^{b}	18.3 ^{ab}	93.7 ^{a}
Entandrophragma excelsum	37.8 ^{ab}	2.9 ^{ab}	13.1 ^{ab}	6.0 ^{a}	5.3 ^{ab}	17.3 ^{ab}	94.8 ^{a}
Podocarpus falcatus	39.7 ^{ab}	2.9 ^{ab}	13.6 ^{ab}	18.5 ^{c}	5.7 ^{b}	12.3 ^{ab}	91.3 ^{a}
Polyscia fulva	44.3 ^{ab}	3.5 ^{c}	12.8 ^{ab}	8.5 ^{ab}	5.6 ^{b}	15.7 ^{ab}	93.4 ^{a}
Calliandra calothyrsus	35.9 ^{ab}	2.7 ^{ab}	13.4 ^{ab}	7.5 ^{ab}	4.8 ^{ab}	10.0 ^{ab}	92.1 ^{a}
Casuarina equisetifolia	44.3 ^{ab}	3.4 ^{c}	13.1 ^{ab}	10.2 ^{ab}	5.8 ^{b}	9.5 ^{ab}	87.1 ^{a}
Leucaena leucocephala	36.1 ^{ab}	3.0 ^{ab}	12.2 ^{ab}	9.2 ^{ab}	4.9 ^{ab}	11.1 ^{ab}	92.9 ^{a}
Mean	39.6	2.89	13.87	12.59	4.99	11.98	87
P value	0.001	0.001	0.001	0.001	0.001	0.001	0.09

*Significant differences in mean values are indicated by different letters, a < ab < b < c < d (Tukey test at 5% significance level).

RESULTS

Total soil C and N, C: N ratios, available P, pH, and CEC differed significantly between plantation stands of different species (N = 54; P < 0.001; Table 2). Changes in soil C levels were highest under the MNS, *E. saligna, C. equisetifolia, C. lusitanica* and *P. fulva* stands, and lowest under *P. patula* and *Eucalyptus microcorys* plantation stands (P < 0.001). Total N showed a broadly similar trend with land use to soil C (Table 2). Changes in total N were remarkably high under native trees (*P. fulva* and MNS stands), *C. equisetifolia*, and *E. tereticornis* stands (P < 0.001). All the *Eucalyptus* species except for *E. tereticornis* showed highest C: N ratios that varied between 13.8 and 18.2. Other species stands had a C: N range of 11.9-13.6 (Table 2) . A clear positive change in available P was observed in soils from MNS stand while other treatments showed a decline in soil P (P < 0.001).

Soil pH declined under all *Eucalyptus* species, except for *E. tereticornis* stands. Increases in soil pH were observed under MNS stand, as well as the plantation species stands of *C. equisetifolia, P. falcatus* and *P. fulva* (P < 0.001). Highest increases in CEC were measured under MNS, *C. lusitanica*, *E. excelsum*, *C. serrata*, *G. robusta* and *P. fulva* stands and lowest under *Eucalyptus* plantation stands (P < 0.001). Changes in BS levels were not statistically different between stands (P = 0.09). Largest standard deviation for pH, CEC, and BS values was observed under *Eucalyptus* species stands.

Increases in exchangeable bases differed among plantation species stands (Table 3). Values of exchangeable Ca were markedly higher in soils from the MNS stand, and from the stands of *P. fulva*, *E. excelsum, P. falcatus, C. lusitanica* and *L. leucocephala* (6.1 - 12.1 $cmol\ kg^{-1}$). Highest values in exchangeable Mg were found under the MNS stand, and stands of *P. fulva*, *P. falcatus*, *C. calothyrsus*

Table 3. Changes in exchangeable bases (mean ± SD) in the 0-10 cm soil layer under forest plantations stands of different species*.

Treatments	Exch. Ca (cmol kg^{-1})	Exch. Mg (cmol kg^{-1})	Exch. K (cmol kg^{-1})	Exch. Na (cmol kg^{-1})
MNS	12.1±2.4^{b}	3.6±1.8^{b}	0.6±0.7^{ab}	0.12±0.2^{a}
Eucalyptus citriodora	2.8±1.2^{ab}	1.8±0.3^{ab}	1.4±1.4^{b}	0.12±0.2^{a}
Eucalyptus tereticornis	5.8±4.9^{ab}	2.1±1.3^{ab}	0.6±0.7^{ab}	0.12±0.0^{a}
Eucalyptus microcorys	1.4±2.8^{a}	0.8±1.2^{ab}	0.3±0.5^{ab}	0.2±0.1^{a}
Eucalyptus maculata	3.5±6.5^{ab}	0.2±0.3^{a}	0.2±0.4^{ab}	0.2±0.1^{a}
Eucalyptus maidenii	2.2±4.3^{ab}	0.9±1.4^{ab}	0.1±0.2^{ab}	0.2±0.1^{a}
Eucalyptus saligna	1.4±1.8^{a}	0.5±0.7^{a}	0.1±0.3^{ab}	1.73±2.9^{a}
Eucalyptus grandis	0.2±0.6^{a}	-0.1±0.0^{a}	-0.1±0.1^{a}	4.1±0.6^{ab}
Cedrela serrata	5.1±5.1^{ab}	0.9±0.9^{ab}	-0.2±0.1^{a}	7.4±0.9^{b}
Grevillea robusta	5.4±2.3^{ab}	0.9±0.3^{ab}	0.2±0.3^{ab}	7.1±0.8^{b}
Pinus patula	1.5±1.0^{a}	1.1±1.5^{ab}	0.1±0.3^{ab}	7.6±0.6^{b}
Cupressus lusitanica	6.4±3.1^{ab}	1.3±0.3^{ab}	-0.1±0.2^{a}	7.5±0.7^{b}
Entandrophragma excelsum	8.5±3.2^{ab}	2.2±0.7^{ab}	0.3±0.1^{ab}	3.3±5.6^{ab}
Podocarpus falcatus	6.6±0.8^{ab}	2.4±0.4^{ab}	0.2±0.1^{ab}	-0.1±0.0^{a}
Polyscia fulva	9.7±1.3^{ab}	2.8±1.0^{ab}	0.1±0.2^{ab}	-0.1±0.0^{a}
Calliandra calothyrsus	4.3±2.3^{ab}	2.3±1.3^{ab}	0.2±0.2^{ab}	0.3±0.5^{a}
Casuarina equisetifolia	4.6±2.1^{ab}	2.0±0.7^{ab}	-0.1±0.3^{a}	-0.1±0.1^{a}
Leucaena leucocephala	6.1±1.9^{ab}	2.1±0.7^{ab}	0.1±0.2^{ab}	-0.1±0.1^{a}
Mean	4.9±2.6	1.6±0.8	0.2±0.3	2.2±0.8
P value	0.007	0.004	0.079	< 0.001

*Positive values indicate increases in soil properties and were observed under almost treatments. Negative values (in bold) indicate a decline in soil properties. Tukey multiple comparisons (at 5% significance level) in mean values are indicated by different letters a < ab < b.

Table 4. Pearson correlation coefficients between some soil chemical properties that were investigated

	Soil C	Total N	C: N ratio	Ca	Mg	CEC	BS
pH	0.27	0.60**	-0.64**	0.78***	0.67**	0.75***	0.57*
Soil C		0.82***	-0.04	0.50*	0.41	0.23	-0.18
Total N			-0.58*	0.75***	0.75***	0.52*	0.20
C: N ratio				-0.57*	-0.70**	-0.61**	-0.64**
Ca					0.83***	0.80***	0.45
Mg						0.52*	0.50*
CEC							0.63**

*P < 0.05; *P < 0.01; P < 0.001

and *L. leucocephala* (2.1 – 3.6 cmol kg^{-1}). Changes in values of exchangeable K ranged from -0.2 to 1.4 cmol kg^{-1} with highest numbers under *E. citriodora*, *E. tereticornis* and MNS stands. Increases in exchangeable Na were remarkably high under *G. robusta, C. serrata, C. lusitanica* and *P. patula* plantation stands (7.1-7.6 cmol kg^{-1}). In general, Mg and K values were low compared to exchangeable Ca and Na. Exchangeable Ca was the most dominant base but it showed lowest levels under *Eucalyptus* species and *P. patula* stands. There were linear correlation coefficients between soil properties (Table 4). Soil pH was positively associated with total N, exchangeable Ca and Mg, CEC and BS. Highest correlation coefficients were found between soil C and total N, Mg and Ca, and between CEC and Ca. Regression coefficients between C:N ratios and all other soil variables were negative (Table 4).

DISCUSSION

Effects of plantation forests on total soil C and N

The results show that silvicultural species contributed markedly to soil chemical changes. The soil C and N levels in Ruhande Arboretum were higher compared to arable lands previously investigated in Rwanda. For instance, Steiner (1998) found the C content of 13 g kg^{-1} and total N of 1.1 g kg^{-1} in the agricultural soils of the Institute of Agronomic Research at Rubona, situated about 15 km from Arboretum of Ruhande. In the northern Rwanda, the C content of 21- 28 g kg^{-1} and total N of less than 2.5 g kg^{-1} were found in arable soils on which agro-forestry systems were applied (Yamoah et al., 1990; Burleigh and Yamoah, 1997). A comparison with our study site, all species stands averaged, [C content: 39.6 ± 7.89 g kg^{-1}, total N: 2.89 ± 0.63 g kg^{-1}] indicates that soil C and N accumulated over time in the afforested sites (Table 2); thus, afforestation has improved soil quality. Increases in soil chemical values as compared with reference measurements were expected as a result of: (i) increased carbon input through root exudation, fine root turnover and leaf litter production; (ii) decreased rate of decomposition as soil temperature decreases owing to tree canopy development.

Results from other studies in tropical and temperate regions show that soil C and N changes following afforestation or reforestation are quite variable, with soil C and N levels either increasing or decreasing. For instance, Mishra et al. (2003) observed an increase in total soil C and N during 9 years of *E. tereticornis* plantation on an Indian degraded sodic soil. In Australia, in a chronosequence study of *P. radiata* established on basalt-derived soils, Turner et al. (2005) observed a 35% loss in soil C after 10 years of plantation establishment. In a comparative study of native forest and mature *P. radiata* plantation, Turner and Lambert (2000) found that soil organic C under *Pinus* was lower than that under adjacent native forest. In a chronosequence study under *P. radiata* and *E. grandis*, Turner and Lambert (2000) observed an ongoing decline in soil organic carbon for 12 years; thereafter, soil C stabilized and increased nearly age 20 years. Paul et al. (2002) reviewed 43 published studies, and noted a soil C decline of 3.46% per year following afforestation; however, when plantations were established on ex-cropped land in tropical and subtropical regions, an accumulation of soil C was observed. Hartemink (2003), also looking at cross-country studies of tropical regions found either a decline or increase in soil attributes depending on stand types including *Pinus*, *Eucalyptus*, *Acacia*, and *Casuarina* genera. Therefore, we conclude that carbon sequestration in forest soils is markedly variable depending on tree species, soil type, climate, management practices and initial soil status.

Soil C: N ratio is an index of N mineralization (Bengtsson et al., 2003; Springob and Kirchmann, 2003). There was a strong inverse relationships between C: N ratio and total N, CEC, BS and exchangeable Ca, and Mg. That is, the mineralization rate is low at higher C: N ratios, and as a consequence soil nutrient levels decrease. Large C:N ratios under *Eucalyptus* plots likely resulted from low mineralization rates and consequently their levels of total N and exchangeable bases were low. Leaf litter of *Eucalyptus* decomposes very slowly and releases toxic phenolic substances (Paul et al., 2002; Hartemink, 2003). These toxic substances affect the decomposition and nitrification processes by inhibiting soil microbial and faunal activities (Chapuis-Lardy et al., 2002). Plant growth inhibition and a thick layer of leaf litter were observed under *Eucalyptus* and *Pinus* plantation stands.

Soil acidification and nutrient depletion

The results indicate that *Eucalyptus* stands the most acidic (pH between 3.9 and 4.5 and had a negative change in pH levels; Table 2) in comparison to other species stands investigated that had a pH range of 4.8 - 6.1. Rwandan soils originate from the parent material constituted of schists and granites mixed with mica schist and quartzites (Steiner, 1998; Verdoodt and Van Ranst, 2003). These soils are strongly acidic, deficient in base cations, N and P, have a high level of exchangeable alumi-num, and are therefore not productive (Vander Zaag et al., 1984; Yamoah et al., 1990; Burleigh and Yamoah, 1997; Sanchez et al., 2003). Forest plantations further acidify the soil by accumulating basic cations in the forest biomass, increasing production of organic acids from decomposing litter and by increasing cation leaching by organic acids. Being higher consumers of water, forest plantations may increase solute concentrations and the mineralization of organic sulfur in the soil (Cannell, 1999; Jobbágy and Jackson, 2003; Mishra et al., 2003). Soil acidification under *Eucalyptus* stands at Ruhande Arboretum may be a process that involved the interaction of these mechanisms. Intense root uptake and the removal of nutrients by thinning and harvest, especially for the fast-growing *Eucalyptus* species could have been the main factor controlling the acidity measured under such plantations. Biological soil acidification under forest ecosystems has been previously reported in the tropics: Argentina (Jobbágy and Jackson, 2003), India (Mishra et al., 2003), and Brazil (Lilienfein et al., 2000).

Soils from the *Eucalyptus* stands had lower levels of CEC, BS and Bray 1- P (Table 2) than those under other tree species stands we sampled. Three factors may explain the low levels of nutrients in soils from *Eucalyptus* stands. First, *Eucalypts* could have higher nutrient uptake than other species; as a result, *Eucalyptus* stands exhibit higher tree biomass (Burren, 1995). Second, clay particles lose their capacity to adsorb base cations when soil acidity increases. As a consequence, higher amounts of cations are present in soil solution and are free to leach into deeper soil profiles (Yamoah et al., 1990; Lilienfein et al., 2000; Zdenko, 2002; Hartemink, 2003; Jobbágy and Jackson, 2003). Third, under low pH, the organic matter is difficult to mineralize and therefore, soil nutrient levels are not enhanced. This is illustrated by the absence of a significant relationship between soil C and exchangeable cations. In addition, the ratio between CEC and soil C is low for *Eucalyptus* stands (0.2) in comparison to that of other tree species stands we sampled (0.44). In conclusion, we think that soil acidity and low levels of nutrient content under *Eucalyptus* stands resulted from a high nutrient uptake and a low decomposition rate of the litter layer. The exchangeable bases increased under species stand investigated (Table 3) in comparison to that under arable lands in Rwanda (Zaag et al., 1984; Yamoah et al., 1990; Verdoodt and Van Ranst, 2003). Similarly, increases in soil exchangeable bases following afforestation were noted in other tropical regions (Hartemink, 2003; Mishra et al., 2003). This shows that afforestation protects soil chemical properties.

Under acid and nutrient-depleted soils of Rwanda, we suggest that forestry sector could use less acidifying species. For instance, in this study, the native species (e.g., *E. excelsum*, *P. fulva* and *P. falcatus*) showed great potential to improve soil quality, and may be preferred if they have also a high biomass production. It is recom-mended that foresters should also plant exotic species such as *G. robusta*, *C. serrata*, *E. tereticornis* and *C. lusitanica* as they showed minor soil acidification.

Conclusions

The sequestration of carbon and nutrients in soil was associated with forest species. Although exotic species were introduced to Rwanda for the rehabilitation of degraded lands, some *Eucalyptus* species contributed to soil acidification and nutrient depletion, while others showed the potential to optimize soil nutrient and C content. For the extension of forest areas in Rwanda, foresters should select fast-growing tree species that maximize soil C and nutrient content from those investigated in this study. A combination of exotic, fast-growing tree species with native and agroforestry species may maintain or improve soil quality under forest plantations, especially those established on acidic parent materials. Regardless of tree species and their origin, soil chemical characteristics at the study site were higher than in arable lands of Rwanda. Therefore, afforestation will play a fundamental role in ecosystem productivity and environmental protection. Afforestation of abandoned and less productive lands will restore soil quality and contribute to climate change mitigation by increasing carbon storage in soils.

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