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Research Article

Soil Fertility in relation to Landscape Position and Land Use/Cover Types: A Case Study of the Lake Kivu Pilot Learning Site

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This study determined the change and distribution of land-uses/covers along the landscape, and evaluated the nutrient status of the top soil layer in the Lake Kivu Pilot Learning Site (LKPLS) benchmarked micro-catchments. Soil physical and chemical properties were quantified using triplicate soil samples collected from each land-use/cover at two depths (0–15 and 15–30 cm) in three LK PLS Learning Innovation Platform (IP) sites (Bufundi in Uganda, Mupfuni-Shanga in D.R. Congo, Gataraga in Rwanda). Small scale agriculture has increased in all the benchmarked micro-catchments at the expense of other land-uses/covers. In the settlement areas land-use/cover distribution along the landscape varied across sites and countries; the major one being eucalyptus woodlots, wetland, and perennials and annuals crops in Bufundi; annuals and perennials crops in Mupfuni-Shanga; and annuals crops in Gataraga. Perennial crops tended to occur at the footslope and valley bottoms, while the annuals occurred at the upper backslopes and summits. Available P and K were relatively higher and C/N ratio (7.28) was the lowest in Mupfuni Shanga. Annual crops had the lowest available P and N across site ($P < 0.05$). The key nutrients N, P and K were below the critical values for plant growth for Bufundi.

1. Introduction

Land-use/cover change and population dynamics are central in understanding soil fertility dynamics in the sub-Saharan Africa [1, 2]. Although parent material, climate, geological, and management history are viewed as the drivers of soil properties at regional and continental scales [3, 4], landscape position and land-use/cover are key factors influencing soil properties under a hillslope and microcatchment scale [5, 6]. These properties define hillslope processes, including flow patterns and other dynamic topographic influences and their feedbacks [7, 8]. These processes include runoff generation, drainage, soil temperature variation, and soil erosion and consequently soil formation and nutrient redistribution within the catchment [9–15]. Land-use/cover change has also been associated with changes in microclimate [16–20]. Thus, land-use and type of vegetation must be seriously taken into account when relating soil nutrient status with environmental conditions [21, 22], a proxy indicator of soil quality [23–26].

The Lake Kivu Pilot Learning Site (LK PLS) is a region believed to be endowed with unique natural resources base including among the most fertile soils in the region [27]. However, in the last two decades soil fertility has been widely reported declining [28–32]. Supply- and demand-induced scarcities have gravely stressed the ability of food production to keep pace with population growth [33]. There is little land available for agricultural expansion, particularly in Rwanda; yet the number of people placing demands on existing cropland is on the increase [32]. Consequently, farmers have been forced to intensify crop production on existing lands and expand cultivation into more marginal land [34, 35]. In a region known for rough terrain, steep slopes, this may create serious risks of land degradation [36, 37]. It is, therefore, important to understand the status and dynamics of soil nutrients in relation to land-use and landscape position. Such an understanding is essential to estimate nutrient status in seminatural and cultivated ecosystems and potential changes in relation to land-use change at local and regional scales. It is hypothesized that amount and distribution of a wide array of soil nutrients may vary among land-uses and landscape positions. The objectives of this paper were therefore to (i) determine the change in land-use/cover between 1986 and 2009, (ii) determine the distribution of different land-use/cover along the landscape (summit, upper backslope, footslope, and valley) in the 3 benchmarked watersheds of Lake Kivu, and (iii) evaluate the nutrient status on smallholder farms with respect to land-use class (perennials, annuals, and woodland) and slope position (upper, middle, and lower) in the two benchmarked watersheds Bufundi and Mupfuni Shanga.

2. Materials and Methods

The study was conducted in three microcatchments one in Uganda (Bufundi), one in DRC (Mupfuni Shanga/Kirotshe), and one in Rwanda (Gataraga) all located in the LK PLS of the sub-Saharan Challenge Programme. LK PLS is located at the boundary between the western part of Rwanda, the Kivu region of D.R. Congo, and south-western of Uganda. The LK PLS is demarcated on the D.R. Congo side by the famous Virunga chain of volcanic mountains consisting of several volcanoes. The terrain is dominated by hills and valleys with most slopes ranging between 12 and 50%; however in some areas slope above 80% are observed and used for cultivation. The rainfall is bimodal that provides opportunity for two cropping seasons in a year. The "long rains" occur from mid-February through early June while the "short rains" occur from mid-September to mid-December. The average annual rainfall in the entire region varies between 800 mm to 2000 mm. In the northern highlands of Rwanda, the average annual rainfall is about 1,300 mm and average temperatures of 16°C prevail. In Uganda (Kabale), the annual rainfall ranged from 931 to 1147 mm between 2004 and 2007, with an annual long-term average of 994 mm. In D.R. Congo rainfall varies from 1200 to 2000 mm. Most soils of the pilot learning site are volcanic Andosols except in Bufundi-Uganda and east of Ruhengeri where deeply weathered, lateritic Ferralsols occur. Andosols are relatively fertile and support intensified farming in absence of fertilizer inputs; however, they are very susceptible to soil erosion. The Ferralsols are considerably lower in potassium and other cation bases [38].

2.1. Land-Use/Cover Change. Land-use/cover changes in the area were determined by analyzing Landsat images of 1986 and 2009 covering the study area. Both supervised and unsupervised classification were used in Integrated Land and Water Information System (ILWIS) version 3.3. They were validation of using targeted interviews with farmers during the 2009 field work and field observations. Field observations were also used to update the USGS 2005 map of the study area and generate a land-use/cover map of the year 2009. The land-use/cover map of 1986 was obtained from the National Biomass Study (1996) for Uganda [39]. The major land-use/cover classes included natural forest, grassland, small-scale cultivation and large scale agriculture, and woodland.

2.2. Soil Mapping. Selected benchmarked watersheds were mapped during the field work exercise of 2009. The soil map of Uganda generated at National Agricultural Research Laboratory in 2010, and the sorter soil maps of D.R. Congo and Rwanda were used as base maps. Five transects cutting across the different soil units were laid down for updating the soil maps. An attempt was also made to match soil map units with major landforms. The landform map of the area was obtained from an updated subset of USGS-2005 layer using the Digital Elevation Model slope derived and 120 field slope measurements in the Uganda and D.R. Congo. The three global landform classes, level land: slopes less than 5%, sloping land: slopes between 5 and 30%, steep land: slopes > 30%, were used. Slope measurements were done using clinometers. Standard soil profile pits of 2X1X1 m were dug in the identified soil units. The soil profiles were described using standard procedures [40].

The obtained soil and 2009 land-use/cover maps were overlaid in ArcView GIS 3.3 software. Five transects cutting across the dominant land-use/cover-soil units were drawn in Arc View GIS 3.3 environment. A minimum of three soil samples were collected from each of the dominant units in the two countries at 0–15 and 15–30 cm soil depths and across the landscape positions. In addition, historical and management information were collected. Soil samples were air-dried and analyzed for soil pH, soil organic matter (SOM), total N, available P, and exchangeable bases (Ca, Mg, and K) following standard methods [41]. Soil pH was measured using a pH meter (1 : 2.5 soil : water), SOM using Walkley and Black

(1934) method, and total N (Kjedhal method). Soil texture was determined using Bouyoucos hydrometer method. Soils were classified according to the FAO classification [42].

2.3. Soil Fertility in relation to Land-Use/Cover. Properties of soils under the different land-use/cover and at different landscape positions were compared to the existing critical values [43].

3. Results and Discussions

3.1. Land-Use/Cover Change in the Selected Benchmarked Microcatchments. Figure 1 and Table 1 show the land-use/cover for two time series in the three microcatchments (Bufundi and Gataraga) and the village of Kirotshe (Mupfuni Shanga/Kirotshe). For the period of 1986, small-scale farming (64.6%) and eucalyptus tree plantations (27.7%) were the dominant land-use/cover types in Bufundi. A small portion (7.7%) of the microcatchment and generally along the stream was covered by papyrus wetland.

In Rwanda open broadleaved trees plantations (61.7%) and small-scale farming (37.3%) with scattered trees were the dominant land-use/covers. In D.R. Congo, the forest covers (83.6%) and small-scale farming (7.9%) were the dominant land-use/covers accounting for about 91.5% of the study area. Other land-use/covers included water body (8.5%).

Generally, small-scale farming areas have increased in the LK PLS. In Bufundi, a relative change of small-scale farming area of 25.4% was observed from 1986 to 2009. This was to the expense of woodlot eucalyptus. In Rwanda a relative increment of 19% was observed for the same period on the expense of open broadleaved trees (eucalyptus). The relative change observed in small-scale farming area across the LK PLS is attributed to demographic pressure [44, 45] and poor management of the already cultivated lands accelerating land degradation and recently observed negative effects of eucalyptus trees on soils of Bufundi [31, 34]

The trend in land-use/cover in the three benchmarks watershed is similar to that observed in the region [44, 46, 47]. Small-scale farming had significantly increased to the expenses of the other land-use/cover in the three sites. Population growth has long been considered the primary driver of the change in the benchmarked watersheds. In Mupfuni Shanga, poor implementation of laws and regulations could have contributed to the expansion of agricultural land.

3.2. Soils of the Selected Benchmarked Microcatchments. The soil maps of the three benchmarked areas of the LK PLS are given in Figures 1, 2, and 3. The major soil units in Gataraga watershed included the Mollic Andosols and Vitric Andosols (Figure 4). In Bufundi, the major soils included Acric Ferralsols Luvisols and Histosols (Figure 5). In Mupfuni Shanga the major soils units were Haplic Acrisols (44.2%), Humic Cambisols (1.0%), and Umbric and Mollic Andosols (54.8%) (Figure 6). Mollic and Vitric Andosols cover the relatively equal area in Gataraga microcatchment; Mollic Andosols are located in the valley and the footslope. In Uganda, 54.9% of the microcatchment is covered by Luvisols mainly on the backslopes, while Acri Ferralsols (13.5%) are found at the summit and Histosols (24.4%) and cover the remaining part of the microcatchment which is not the lake.

In the village of Kirotshe in Mupfuni Shanga, Haplic Acrisols cover the biggest of upper backslopes and summit of the hills, while Mollic Andosols occupied the lower backslopes and footslopes near the lake and along the road Kirotshe-Goma. Two hills on the road to Goma are covered by Umbric Andosols (5.2%) and one hill is covered by Humic Cambisols (0.92%). The rest is the Lake Kivu covering (5.02%) of the benchmarked site.

Selected soil properties of Bufundi and Mupfuni Shanga are presented in Table 2. The soil properties varied from one benchmarked watershed/site to the other. Generally, in Mupfuni Shanga, no significant variation was observed in terms of soil properties across land-uses and at both depths ($P < 0.05$). In Bufundi, perennials tended to have relatively higher OM, Av. P, and N than eucalyptus and annuals at the footslope. At the summit, perennials tended to have more OM, Ca and Mg than eucalyptus and annuals. In the valley, OM and Av. P were highest under eucalyptus followed by perennials ($P < 0.05$). Soil properties such as pH, Av. P, and K tended to be relatively higher in Mupfuni Shanga than Bufundi. Generally in Mupfuni Shanga (D.R. Congo), pH, OM, N, and K were within the critical range for plant growth for the three landscape position, while av. P, Ca, and Mg were outside the optimal range for plant growth. Available P and Ca were below the critical level, while Mg the texture of the soils of Mupfuni Shanga was generally sandy loam.

In Bufundi, pH was adequate in the 0–15 cm topsoil under Annuals in the foot slope, perennials on the summit, and 0–30 cm under perennials in the valley. Organic matter content was generally high except under perennials in the valley; 15–30 cm soil under annuals in the valley; and the topsoil (0–15 cm) under annuals at the summit were it was moderate.

Nitrogen was generally ranging from moderate to high in the two bench-marked micro-catchments. In Mupfuni-Shanga it was high for the landscape positions and land-use/covers except under perennials (15–30 cm). In Bufundi, moderate nitrogen content were observed under annuals (0–15 cm) at the footslope, eucalyptus (0–15 and 15–30 cm), perennials (15–30 cm) and annuals (0–15 cm) for the summit. In the valley, moderate nitrogen levels were observed under annuals (15–30 cm) and perennials for both soil layers. Except under eucalyptus in the valley phosphorus content was generally below the critical value in Bufundi. Potassium, calcium, and magnesium were below the critical range for all the soil across the different landscape positions. Sodium was generally within the critical range for all the land-uses across the different landscape positions. Bufundi soils were sand clay loam in texture. It is worthwhile to note that annual crops had the lowest available phosphorus and nitrogen across site ($P < 0.05$).

Variation in soil properties across the land-uses and benchmarked sites is attributed to the nature of soils on which eucalyptus, annuals, and perennial crops were grown and how these soils and their associated land-use/covers have been managed. These soils were Mollic Andosols and Luvisols in Mupfuni Shanga and Bufundi, respectively. The soils from studied eastern part of DRC are generally highly productive

Table 1: Area coverage of the dominant land-use/cover of selected areas of the LK PLS.

Microcatchment	Land-use/cover types	1986/87		2009	
		ha	%	ha	%
Gataraga	Tree plantations	1145.4	61.7	1003.9	54.1
	Small-scale agriculture	709.5	38.3	851.7	45.9
Bufundi	Wetland	126.5	7.7	123.2	7.5
	Small-scale agriculture	1067.1	64.6	1339.2	81.0
	Woodlot (eucalyptus)	458.0	27.7	190.0	11.5
Mupfuni Shanga	Dense moist forest	47853.4	45.5	52949	50.3
	Forest/savanna mosaic	27484.1	26.1	4216.3	4.0
	Small-scale agriculture	8338	7.9	16486	15.7
	Secondary forest	12600.8	12.0	22624.8	21.5
	Water	9011.4	8.5	9011.4	8.5

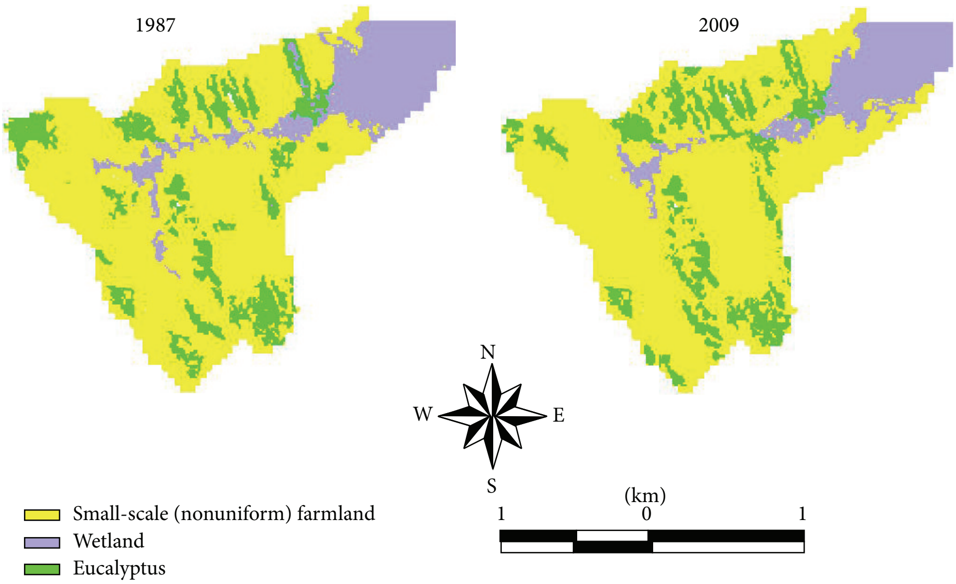

Figure 1: Land-use/cover distribution in Bufundi benchmarked watershed (Uganda).

and were under fallow for about twenty years due to rebel activities, while those of Bufundi though highly weathered, receive a lot of manure. Soils of Mupfuni Shanga had a relatively low C/N ratio (7.28) compared to those of Bufundi (10.4) despite the relatively high rainfall in Mupfuni Shanga compared to Bufundi. The C/N ratio (10.4) of the Bufundi soils should favour net mineralization of N. Unfortunately, N turnover on this soil is poorly documented.

Many other studies on volcanic soils demonstrated that N turnover in the volcanic soil may not be solely interpreted in terms of C/N ratios [48–50]. Perhaps temperature differences, the level of weathering of the parent rock, landuse/cover change, soil management, and hillslope processes and interactions explain the differences in C/N ratios between the two soils of volcanic origin [50–53].

Variation of nutrients with landscape position and land-use in Bufundi is in line with Wang et al. [5] observations in small catchment in loess plateau and Wang et al. [54] findings on commercial tea plantations in China that received nitrogen fertilizers. It also corroborates the findings of Majaliwa et al. [44] in Kibale-Uganda. In loess, Wang et al. [5] observed significant differences among land-uses in terms of SOM, TN, and available N (AN). They also observed that woodland, shrub land, and grassland had relatively higher levels of SOM, TN, and AN compared to fallow land and cropland. In Uganda, Majaliwa et al. [44] observed that landscape position, land-use, and their interaction had significant effects on top soil properties. They also observed that changes from natural forest to tea and eucalyptus induced significant changes in nutrient status of the top-soil.

4. Conclusions and Recommendations

In light of the information presented and discussions the small-scale agriculture increased in all the benchmarked watersheds at the expense of all other land-use/covers. The distribution of land-use/cover types varied with landscape

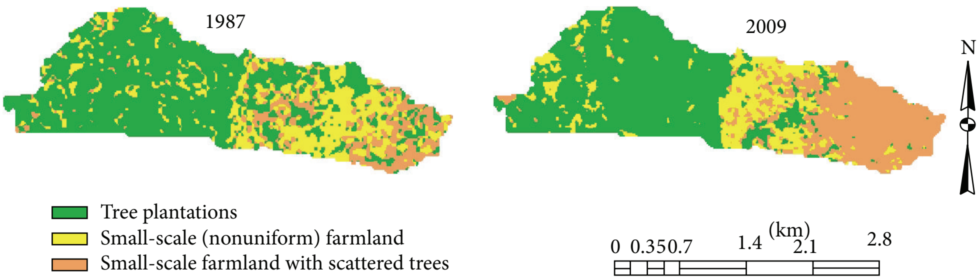

FIGURE 2: Land-use/cover distribution in Gataraga benchmarked watershed (Rwanda).

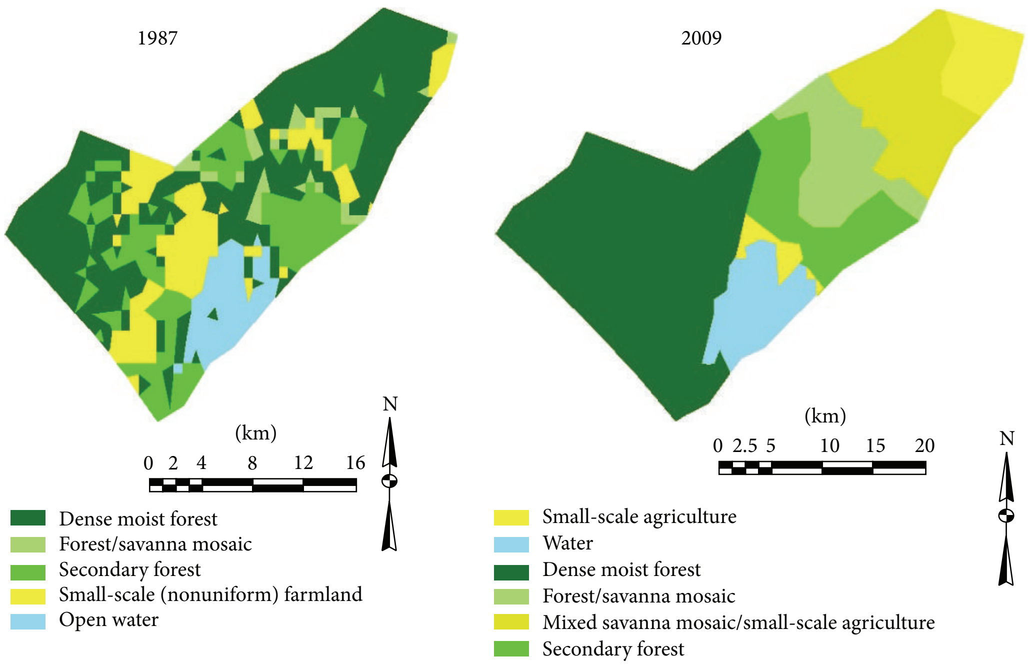

FIGURE 3: Land-use/cover distribution in Mupfuni Shanga benchmarked site (D.R. Congo).

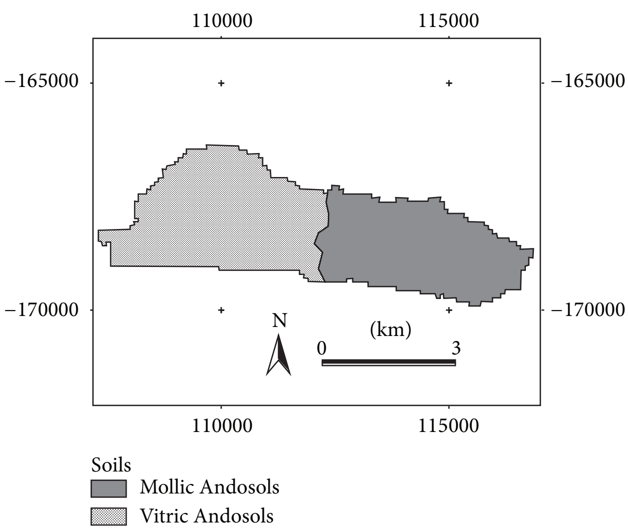

FIGURE 4: Soils of Gataraga microcatchment (2009).

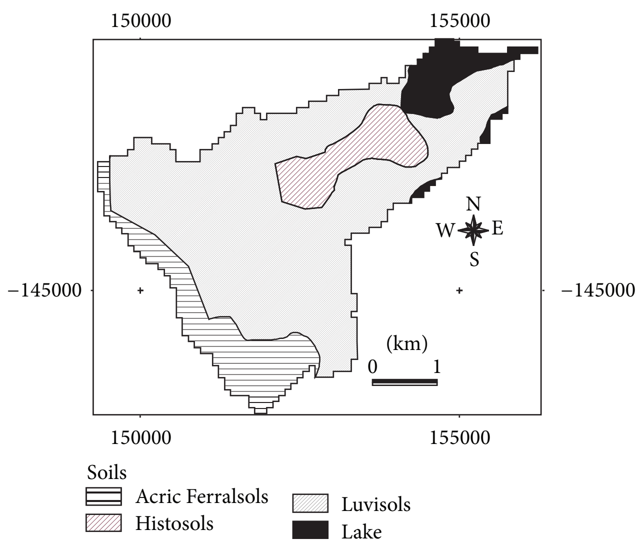

FIGURE 5: Soils of Bufundi microcatchment (2009).

Table 2: Soil properties under the different land-use/cover in two selected microcatchments.

Site	Land-use	Landscape position	Depth cm	pH	OM %	*N* %	Av_P $mgkg^{-1}$	K	Ca	Mg	Na	Textural classes
								cmolkg^{-1}				
Mupfuni Shanga	Footslope	Perennials	0–15	7.4	4.39	0.32	10.0	3.9	0.17	22.9	6.9	Silty loam
			15–30	6.8	5.34	0.12	23.1	4.12	0.22	20.3	5.08	Sandy loam
	Backslope	Perennials	0–15	7.04	5.20	0.29	13.7	4.92	0.31	21.9	6.94	Sandy loam
			15–30	7.15	4.68	0.26	14.1	3.91	0.21	24.3	7.57	Sandy loam
	Summits	Annuals	0–15	6.75	5.16	0.27	10.2	2.34	0.20	22.0	7.41	Sandy loam
			15–30	6.90	5.43	0.22	15.7	2.35	0.28	23.4	6.30	Sand clay loam
Bufundi	Footslope	Annuals	0–15	5.67	4.07	0.23	10.1	0.60	3.88	1.47	0.07	Sand clay loam
			15–30	5.00	4.57	0.23	4.24	0.41	2.18	0.77	0.05	Sand clay loam
		Eucalyptus	0–15	4.23	5.76	0.29	1.30	0.53	1.33	0.52	0.04	Sand clay loam
			15–30	4.50	4.20	0.57	14.27	0.72	1.69	0.66	0.06	Sand clay loam
		Perennials	0–15	5.07	6.35	0.56	23.74	0.74	4.21	1.73	0.05	Sand clay loam
			15–30	4.23	6.79	0.32	8.00	0.50	2.64	1.30	0.05	Sand clay loam
	Summit	Annuals	0–15	5.53	2.74	0.18	10.88	0.64	2.20	1.15	0.06	Sand clay loam
			15–30	5.00	3.41	0.68	2.26	0.42	1.38	0.64	0.04	Sand clay loam
		Eucalyptus	0–15	4.60	3.77	0.20	4.13	0.25	1.01	0.54	0.07	Sand clay loam
			15–30	4.83	3.67	0.19	4.70	0.28	1.56	0.78	0.05	Sand clay loam
		Perennials	0–15	6.43	5.82	0.26	4.09	1.18	8.01	3.17	0.06	Sand clay loam
			15–30	5.33	3.44	0.18	7.83	0.65	3.67	1.36	0.05	Sand clay loam
	Valley	Annuals	0–15	5.40	4.84	0.23	4.13	0.46	3.28	1.08	0.06	Sand clay loam
			15–30	5.40	2.16	0.12	7.54	0.40	1.93	1.00	0.04	Sand clay loam
		Eucalyptus	0–15	3.65	9.73	0.54	27.99	1.31	5.10	1.29	0.08	Sand clay loam
			15–30	4.15	10.3	0.39	5.71	0.94	2.96	1.81	0.94	Sand clay loam
		Perennials	0–15	6.10	2.41	0.15	9.64	0.47	3.30	1.38	0.03	Sand clay loam
			15–30	5.60	2.37	0.15	4.90	0.38	3.44	1.31	0.03	Sand clay loam
Critical value				5.5–6.5	>3	>0.22	>15	2–5	65–85	6–12	<1	

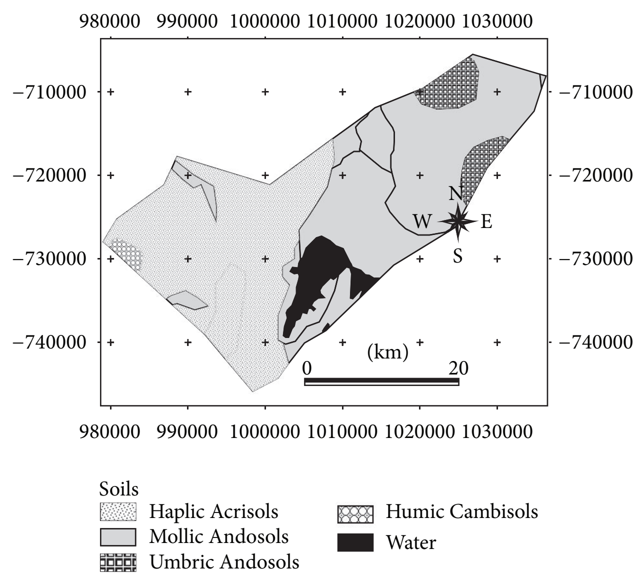

Figure 6: Soils of Mupfuni Shanga benchmarked site (D.R. Congo) (2009).

position across sites and countries. The major land-use/cover type in the human settled portion of the sites is eucalyptus woodlots, wetland, and small-scale agriculture (perennials and annuals crops) in Bufundi/Uganda; small-scale agriculture (annuals and perennial crops) in Mupfuni Shanga/D.R. Congo; and annuals crops in Gataraga/Rwanda. Difference in soil fertility levels and management are evident across the LK PLS sites. Soils of Mupfuni Shanga have relatively higher values pH, Av. P, and K than those of Bufundi and annual crops had the lowest available phosphorus and nitrogen within the LK PLS; and the key nutrients (N, P, and K) were below the critical values for plant growth for Bufundi.

It is recommended that farming communities of the LK PLS be sensitize and trained on soil fertility assessment and management and on natural resource management in order to improve their livelihood and conserve the environment.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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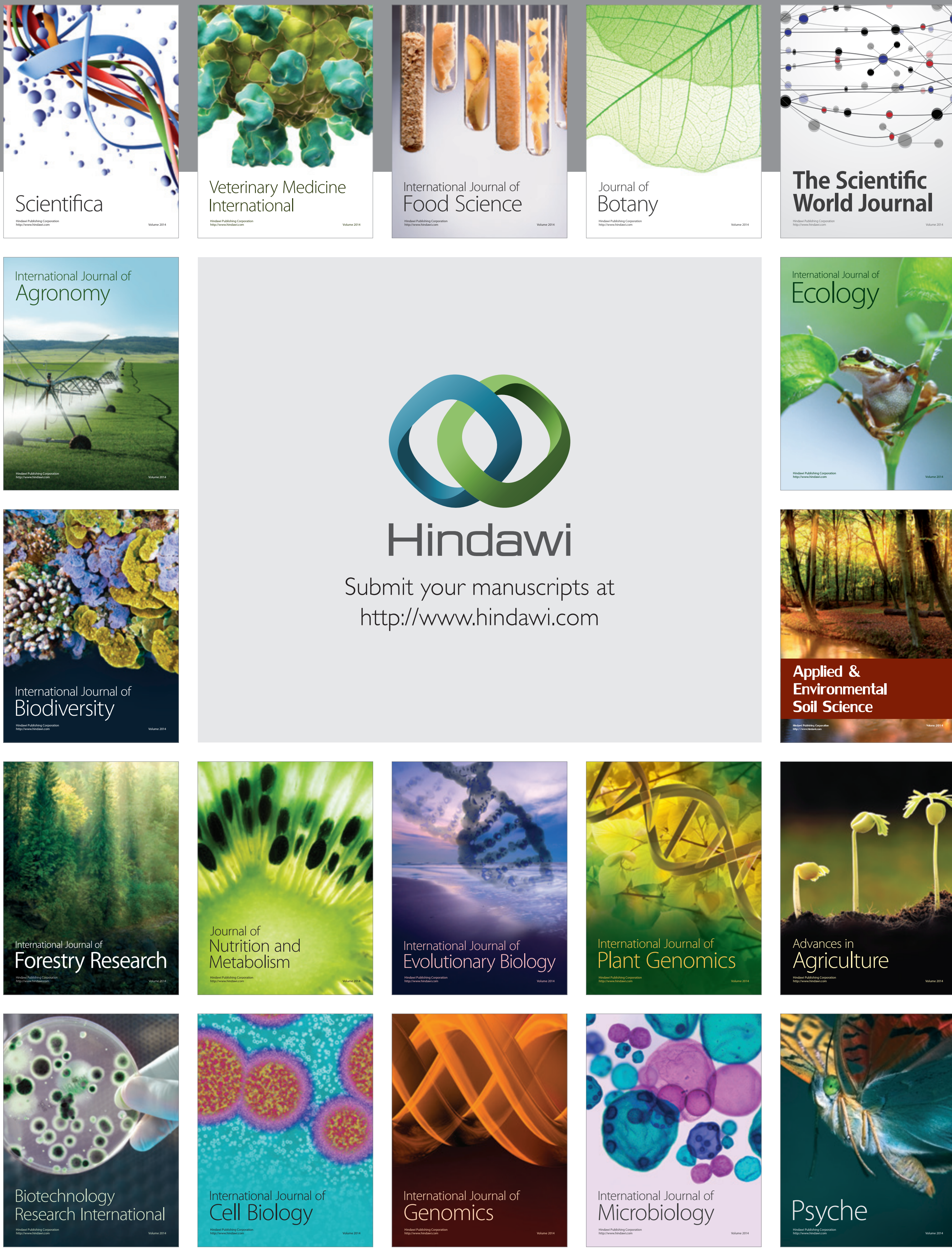
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