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The Impact of Land use Types on Selected Soil Fertility Indicators: A Comparative Study of Natural Forest, Forest Plantation, and Cropland in Ndola District, Zambia

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Abstract

Soil fertility plays a very important role in sustaining agricultural productivity and ecosystems stability. This study investigated the impact of three different land use types, namely: Natural Forest (NF), Forest Plantation (FP), and Cropland (CL) on core soil fertility indicators in Kaniki area of Ndola District, Zambia. Soil samples were collected and analyzed for pH, total nitrogen (N), available phosphorus (P), exchangeable potassium (K), and bulk density (BD). Results showed that FP had the highest soil pH (5.1 ± 0.17), while NF had the highest nitrogen content (0.153%). Available phosphorus was highest in FP (0.543 mg/kg), while K was most abundant in CL (0.015 ppm). Bulk density was relatively consistent across all land use types, ranging from 1.43 g/cm³ in NF to 1.45 g/cm³ in FP, respectively. These findings illuminate the important role of natural vegetation in maintaining soil fertility and, therefore, stress the need for sustainable land management practices. The study provides evidence-based recommendations for preserving soil health in the face of land use changes.

Keywords: *Bulk density, land use change, phosphorus, potassium, soil fertility, soil pH, total nitrogen*

1. Introduction

Soil fertility is an essential factor influencing agricultural productivity, ecosystem sustainability, and land management strategies. The fertility of soil is determined by its physical, chemical, and biological properties, which are, in turn, influenced by various land use types. Land use changes, such as conversion from forests to croplands, grasslands to settlements, or agricultural intensification, significantly alter soil nutrient dynamics and organic matter content (Tembo and Sarjanov, 2013; Lal, 2015). In the Kaniki area of Ndola District, Zambia, diverse land use types, including agricultural fields, residential areas, and natural vegetation, impact soil fertility status in varying degrees.

Different land use types affect soil fertility parameters such as soil organic matter, nitrogen, phosphorus, potassium levels, pH, and microbial activity (Tembo et al., 2025). Agricultural lands, for instance, often experience nutrient depletion due to continuous cropping, overuse of chemical fertilizers, and soil erosion (Mugendi et al., 2020). On the other hand, forested lands tend to exhibit higher organic matter content and enhanced nutrient cycling due to litter decomposition and minimal soil disturbance (Chen et al., 2018; Muyabe et al., 2025). In Kaniki, where land use patterns include smallholder farming, pasture lands, and urban settlements, soil fertility variations are expected due to differential management practices and land degradation levels.

Soil degradation due to unsustainable land use practices is a pressing concern in sub-Saharan Africa, where nutrient depletion, acidification, and erosion reduce land productivity (Sanchez, 2019). Studies have shown that intensive land use without adequate replenishment of soil nutrients results in declining soil fertility, which negatively affects crop yields (Hengl et al., 2017; Tembo et al., 2025). In Ndola District, soil erosion and loss of organic matter are exacerbated by deforestation, poor agronomic practices, and unregulated land conversion, making soil fertility management a crucial research area.

Several studies in Zambia have examined soil fertility dynamics across different agroecological zones. A study by Phiri et al. (2021) in Central Zambia indicated that land use significantly affects soil pH, organic carbon, and macronutrient content, with agricultural lands showing lower fertility compared to forested regions. Similarly, Mulenga and Lungu (2019) found that soil fertility depletion in peri-urban areas of Zambia is linked to improper land management and increased human activities. The Kaniki area, being part of the Copperbelt Province, experiences land use transitions due to urban expansion and agricultural intensification, necessitating localized soil fertility assessments. This research will provide empirical data on soil fertility variations, informing policymakers and farmers on best management practices to enhance soil productivity and mitigate degradation. Additionally, it will contribute to the broader discourse on land use impacts on soil health in sub-Saharan Africa

2. MATERIALS AND METHODS

2.1. Description of the Study Area

This study was conducted in Kaniki area of Ndola district in the Copperbelt province of Zambia. Ndola is the industrial and commercial center of the Copperbelt, Zambia's copper mining region, and capital of Copperbelt province. The district has borders with three (3) districts namely; Masaiti, Luanshya and Kitwe and shares an international boundary with the Democratic Republic of Congo (DRC) to the north. The City of Ndola has total land coverage of 1,108 km²; it falls within the gently sloping Copperbelt penne plain at an altitude ranging from 1250 m to 1455 m above sea level. It is characterized by undulating terrain of less than 10 slopes and is dissected by the Mwambashi, Muliashi, Kafubu and Luansobe Rivers, the principle drainage lines to the Kafue River (Moore, 1967). It has three dominant hills though there are isolated highly outcrops at Dola hill, Nakaputa and Kaloko hills.

2.2. Site selection and land use classification

For site selection and classification of land use, a reconnaissance survey was conducted to assess the physiographic characteristics of the study area using a 1: 50,000-scale base map prepared by the Zambian Ministry of Lands. Consultations with local foresters, farmers, elders, and developmental agents helped establish the historical background of the dominant land use types (LUTs). Three primary land use types were identified based on field observations and consultations (Figure 1). These land use types included: Natural Forest Land Use (undisturbed indigenous forest with native tree species, serving as the control), Forest Plantation Land Use (pine plantations established on previously forested land, representing managed land use), and Crop Land Use, which has been cultivated for over 10 years with intensive fertilizer use. Practices under this land use type include annual crops, perennial crop, pasture land and Fallow (Table 1). The coordinates to represent land use type were taken from the center of each of the established sample plots in Decimal Degree (D.D) value.

Table 1. *Description of the selected land use type where soil samples were collected*

Land-Use Types (LUTs)	Description of the Existing LUTs
Natural Forest Land Use	The land is covered with native dense tree species with bushes and grasses. Dominant trees of *Brachystegia spp, Julbernardia paniculata, Cryptosepalum exfoliatum, Pseudotaxus and Erythopheum africunum*. Since it is a less disturbed area, it was used as a reference (control). The soil samples were collected from the altitude of 1341 m above sea level. Plot 1 (-12.87819 latitude, 28.53313 longitude), Plot 2 (-12.87805 latitude, 28.853305 longitude), Plot 3 (-12.87788 latitude, 28.53285 longitude)
Forest Plantation Land Use	The land use type is mainly covered with pine species "*Pinus kesiyei & Oocarpa*"; established predominantly on former Natural forest. The samples were collected from the forest plantation that has been exposed to all post planting Silvicultural operations and fire management operations. This was treated as (treatment 1). The soil samples were collected from the altitude of 1341 m above sea level. Plot 1 (-12.87866 latitude, 28.53243 longitude), Plot 2 (-12.87855 latitude, 28.53224 longitude) and Plot 3 (-12.87934 latitude, 28.53228 longitude).
Crop Land	Land used for annual rain - fed field crops (maize "*Zea mays*", peanuts "*Arachis hypogaea*", soybeans "*Glycine max*", Bean "*Phaseolus vulgaris*" etc.) at least for 10 years, with crop rotation and intensive use of inorganic fertilizer (NPK, DAP and Urea). Predominantly on former Natural forest.

	This was treated as (treatment 2). The soil samples were collected from the altitude of 1340 m above sea level. Plot 1 (-12.87218 latitude, 28.52847 longitude), Plot 2 (-12.87190 latitude, 28.52830 longitude), Plot 3 (-12.87150 latitude, 28.52805 longitude).

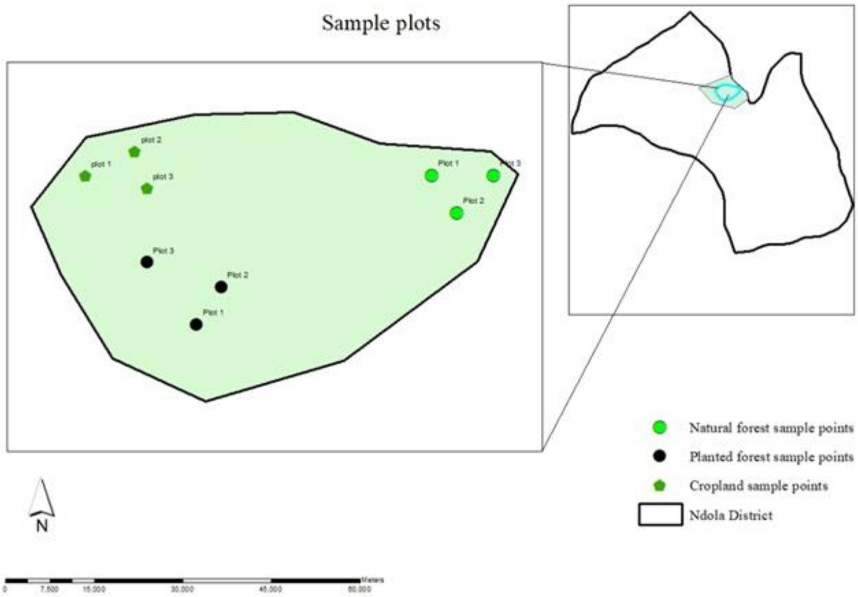


Figure 1. *Research site*

2.3. Materials

The study utilized the following materials: GPS device for geolocation and altitude data collection, soil auger for sample collection, measuring tape for defining plots, plastic bags for sample storage, a spade for surface litter removal, a weighing scale, plastic bowls, labeling materials, and a record-keeping notebook.

2.4. Methods

2.4.1. Soil sampling methodology

Three representative sampling plots were established for each land use type. Each land use type comprised three randomly selected and replicated plots, each measuring 50 m x 50 m (2,500 m²). Each plot was subdivided into 5 m x 5 m (25 m²) grids for soil sample collection. Soil samples were collected randomly at a depth of 0-20 cm from each grid using simple random sampling (Birhane, 2014). Each land use type yielded a total of 75 soil samples, ensuring comprehensive spatial representation.

2.4.2. Sample size and composite sample preparation

A composite soil sample was prepared from 20-25 randomly collected subsamples per land use type. The subsamples were thoroughly mixed to form a pooled composite sample of approximately 1 kg per plot. In total, nine disturbed composite soil samples (three per land use type) were collected and sealed in polyethylene bags to prevent contamination before laboratory analysis.

2.4.3. Laboratory analysis of soil fertility parameters

In the laboratory, soil samples were air-dried, homogenized, and sieved through a 2 mm mesh. The samples were then divided to obtain representative portions for analysis while maintaining sample integrity. The cardinal rule of crushing before you divide the sample was observed. The soil pH was determined using the PEECH method (1965) in a 1:2.5 soil-to-water suspension. Total Nitrogen (N) was analysed using the macro-Kjeldahl method (Bremner, 1960), while exchangeable acidity was extracted using 1 M KCl solution and determined titrimetrically (Bertsch & Bloom, 1996). Other chemical properties that were analysed included available Phosphorus (P), which was extracted using the Bray-1 method (Bray & Kurz, 1945) and Potassium (K), which was determined by extracting soil with 1 M NH_4OAc, followed by quantification using a flame photometer (Rowell, 1994; Baruah & Barthakur, 1997). The soil physical property that was analysed in this study was Bulk Density. This was measured using the core method, where soil mass was divided by total volume, including pore spaces (Standards Association of Australia, 1977).

2.5. Data analysis

Descriptive statistics, including measures of central tendency and dispersion, were calculated for all soil fertility parameters. (Willy, Muyanga, & Jayne, 2019).

3. RESULTS AND DISCUSSIONS

Salient characteristics of soil fertility indicators such as pH, nitrogen (N), phosphorus (P), and potassium (K) were analysed in soils collected from various land use types, namely Natural Forest (NF), Forest Plantation (FP), and Cropland (CL). Results, summarised in Table 2 and figure 2, respectively, provide detailed information on the influence of various land use types on soil fertility indicators.

3.1. Soil pH

As illustrated in Table 2 below, the results of this study reveal significant variations in soil pH across different land use types. Specifically, soils under Crop Land and Natural Forest exhibit more acidic conditions, with mean pH values ranging from 4.8 to 4.9. In contrast, Forest Plantation soils demonstrate a comparatively higher mean pH of 5.1, indicating a shift toward more neutral conditions. These findings are consistent with previous studies emphasizing the influence of organic matter decomposition, microbial activity, and human-induced management practices on soil acidity (Hinsinger, 2001; Brady & Weil, 2010). Natural forests typically contain substantial amounts of organic matter, which, through decomposition, releases organic acids that contribute to soil acidification (Binkley & Fisher, 2013). This process explains the lower pH values observed in natural forest soils. Similarly, cropland soils are subject to continuous cultivation, fertilization, and land-use intensification, which lead to nutrient depletion and alterations in soil chemical properties, further exacerbating soil acidification (Lal & Stewart, 1995).

Table 2. *Summary statistics of soil fertility indicators ((pH, Nitrogen (N), Phosphorus (P), and Potassium (K)) in Natural Forest, Forest Plantations, and Crop Land*

Variable	Obs	Mean	Std. Dev.	Min	Max	Method
(NF) pH	3	4.867	0.153	4.700	5.000	[$CaCl_2$ 1:2:5]
(FP) pH	3	5.100	0.173	5.000	5.300	[$CaCl_2$ 1:2:5]
(CL) pH	3	4.800	0.100	4.700	4.900	[$CaCl_2$ 1:2:5]
(NF) N (%)	3	0.153	0.032	0.133	0.190	[Micro-Kjeldhl]
(FP) N (%)	3	0.040	0.002	0.039	0.042	[Micro-Kjeldhl]
(CL) N (%)	3	0.027	0.002	0.025	0.029	[Micro-Kjeldhl]
(NF) P (mg/ Kg)	3	0.460	0.407	0.210	0.930	[Bray 1]
(FP) P (mg/ Kg)	3	0.543	0.051	0.500	0.600	[Bray 1]
(CL) P (mg/ Kg)	3	0.365	0.005	0.360	0.370	[Bray 1]
(NF) K (Ppm)	3	0.007	0.001	0.006	0.007	[1MNH_4OAc]
(FP) K (Ppm)	3	0.010	0.002	0.008	0.012	[1MNH_4OAc]
K (Ppm)	3	0.015	0.001	0.014	0.016	[1MNH_4OAc]

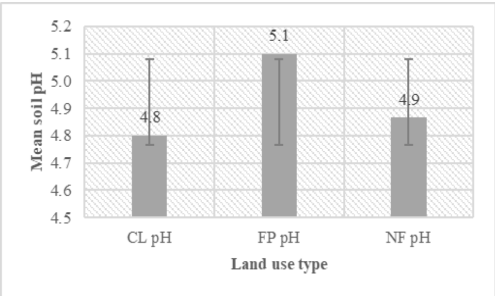
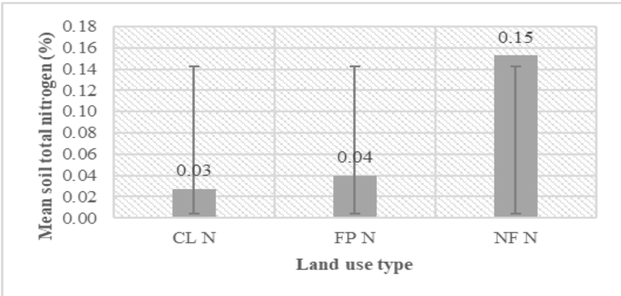
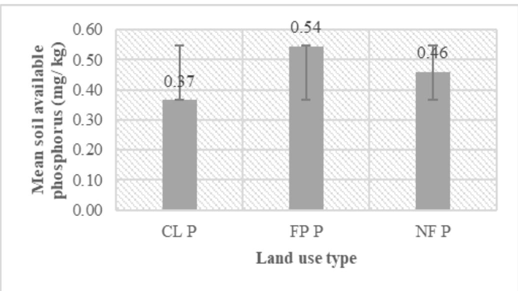
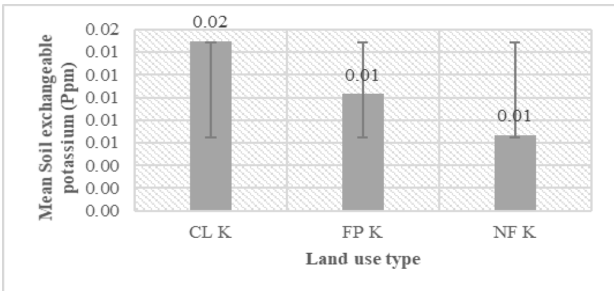
Key: pH (Potential hydrogen), N (Total nitrogen "percentage"), P (Available Phosphorus "milligrams per Kilogram") and K (Exchangeable Kalium or Potassium "parts per million")

Key: NF: Natural forest, FP: Forest plantations, CL: Crop land.

Conversely, forest plantations, particularly those managed for timber production (as is the case in this study) tend to maintain slightly higher pH levels due to reduced soil disturbance and the accumulation of base cations from litter decomposition. The comparatively higher pH values in forest plantations suggest improved nutrient retention and availability, which aligns with the findings of Brady and Weil (2010). These researchers noted that soil organic matter decomposition and microbial processes significantly influence soil pH through the release of hydrogen ions and other acidic compounds. The relatively neutral pH range (5-7) observed in forest plantations is particularly relevant for soil nutrient availability. Hinsinger (2001) highlighted that this pH range is optimal for nutrient accessibility, as extreme acidity can limit the availability of essential elements such as phosphorus, calcium, and magnesium. Therefore, the findings of this study on soil pH reinforce the broader understanding that land use type plays a crucial role in shaping soil chemical properties, influencing both soil fertility and overall ecosystem health.

3.2. Nitrogen (N) Content

In relation to soil nitrogen content (Figure 2), Natural Forest (NF) soils recorded the highest nitrogen content, with a mean nitrogen percentage of 0.15, compared to 0.04 in Forest Plantation (FP) and 0.03 in Cropland (CL). These results align with previous studies by Schlesinger (2009), which identified natural forests as crucial reservoirs of soil nitrogen due to the continuous decomposition of organic matter, releasing nitrogen in the form of ammonium and nitrate ions. The relatively lower nitrogen levels in FP and CL soils can be attributed to limited organic matter inputs and higher rates of nutrient removal associated with agricultural practices. Forest plantations, often managed for timber production, experience reduced litter deposition and less diverse microbial activity, which can limit nitrogen cycling in the soil. Croplands, on the other hand, are subjected to intensive cultivation practices, including frequent tillage and fertilization, which can deplete soil nitrogen reserves over time (Brady & Weil, 2010). In addition, the low nitrogen availability in cropland soils may be worsened by continuous cropping without adequate replenishment of organic matter or nitrogen-fixing leguminous crops – through crop rotation. A study by Lal & Stewart (1995) highlighted that agricultural systems relying on monoculture often experience declines in soil fertility, including reductions in nitrogen content, due to insufficient nutrient recycling and loss through leaching. The absence of sustainable soil management strategies, such as crop rotation with nitrogen-fixing species, further contributes to nitrogen depletion in croplands (Binkley & Fisher, 2013).

<table>
<tr><td>Mean Soil pH in different rural land use types</td><td>Mean soil total nitrogen concentration in different rural land use types</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Key: categories of soil pH values (Ranges): < 5.1 (Strongly acidic), 5.2 – 6.0 (Moderately acidic), 6.1 – 6.5 (Slightly acidic) and 6.6 – 7.5 (Neutral) Horneck et al (2011) CL (Crop Land), FP (Forest plantation) and NF (Natural forest) pH (Potential hydrogen)</td><td>Key: CL (Crop Land), FP (Forest plantation) and NF (Natural forest) N: Soil total nitrogen (mg/ Kg)</td></tr>
<tr><td>Mean soil available P concentration in in different rural land use types</td><td>Mean soil exchangeable K concentration in different rural land use types</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Key: low < 20 mg/kg, Medium 20 – 40 mg/ kg, high 40 – 100 mg/ kg and excessive > 100 mg/ kg (Horneck et al, 2011)</td><td>Key: CL (Crop Land), FP (Forest plantation) and NF (Natural forest)</td></tr>
</table>

Key: *CL (Crop Land), FP (Forest plantation) and NF (Natural forest). P: Available Phosphorus*	*K: Soil exchangeable Potassium*

Figure 2. *Soil fertility indicators ((pH, Nitrogen (N), Phosphorus (P), and Potassium (K)) in Natural Forest, Forest Plantations, and Crop Land*

3.3. Soil Phosphorus (P) content across different land use types

The phosphorus levels were highest in forest plantation soils (Mean P = 0.54 mg/kg), while lowest in Crop Land (0.37 mg/kg). The elevated phosphorus content in forest plantation soils may be attributed to specific management practices in forest plantations, such as periodic fertilization and reduced soil disturbance, which promote phosphorus retention and availability. These findings are consistent with a study by Raghothama (1999), which indicated that soil phosphorus availability is strongly influenced by land management strategies and soil pH levels. Phosphorus availability is optimal in slightly acidic to neutral soils (pH 5-7), which aligns with the relatively higher pH of FP soils in this study. In contrast, Natural Forest (NF) and Cropland (CL) soils exhibited lower phosphorus levels, which can be attributed to phosphorus fixation in more acidic soil conditions. Research has shown that in acidic soils, phosphorus readily binds with iron and aluminum oxides, forming insoluble compounds that limit its bioavailability to plants (Schut and Reymann, 2023). This phenomenon is particularly common in tropical soils, where high clay content and strong phosphorus sorption capacity further contribute to its limited availability (Brenner et al., 2019).

The lower phosphorus levels observed in cropland soils may also result from continuous cropping and inadequate replenishment of phosphorus through fertilization. Intensive agricultural practices, including frequent tillage and crop harvesting, often lead to phosphorus depletion over time (Smil, 2000). Without proper soil amendments, such as organic matter incorporation or phosphorus-rich fertilizers, cropland soils are likely to experience further declines in phosphorus availability, negatively impacting crop productivity. These findings align with those of previous researchers who have emphasized the role of soil management in determining phosphorus availability. Studies by Hinsinger (2001) and Roberts & Johnston (2015) suggest that phosphorus cycling in soil is highly dependent on biological and chemical interactions, with land use practices playing a crucial role in modulating these processes. Additionally, research on tropical soil fertility by Schut and Reymann highlighted phosphorus as a key limiting factor due to its strong fixation tendencies in highly weathered soils.

3.4. Potassium (K) Availability

The potassium content was lowest in the natural forest soils 0.007 ppm, possibly due to the natural cycling and leaching of potassium under forest cover, as potassium is highly soluble and can be easily leached from the soil profile (Batjes, 1997). In contrast, cropland (CL) soils exhibited higher potassium levels (0.015 ppm), which is likely due to agricultural management practices, particularly the application of potassium-based fertilizers aimed at sustaining soil fertility for intensive crop production. Agricultural soils typically receive external nutrient inputs to replenish the potassium lost through crop uptake and removal during harvesting. Additionally, tillage practices may influence potassium availability by affecting soil structure and the distribution of nutrients within the soil profile (Mengel & Kirkby, 2001). Forest plantation (FP) soils exhibited moderate potassium content compared to croplands, suggesting that periodic fertilization or nutrient management practices contribute to maintaining potassium availability. Forest plantations, particularly those managed for timber production, often receive nutrient amendments to promote tree growth and sustain biomass production (Augusto et al., 2002). In forest ecosystems, potassium is predominantly retained in biomass and is continuously cycled through litterfall and decomposition. However, due to the absence of external nutrient inputs, a net loss of potassium may occur over time, especially in older, undisturbed forests. These findings align with previous studies that highlight the role of land use and management practices in influencing soil potassium dynamics. For instance, Tripathi (2019) reported significantly lower potassium levels in undisturbed forest soils compared to managed plantations and agricultural lands, emphasizing the importance of external nutrient inputs in maintaining soil fertility. Similarly, Schut and Reymann (2023) noted that potassium leaching is a major concern in natural ecosystems with high precipitation, whereas agricultural and managed forest systems often compensate for these losses through fertilization and soil amendments.

3.5. Soil bulk density

Table 3 presents the mean soil bulk density (BD) values across different land use types: natural forest (NF), forest plantation (FP), and cropland (CL). The results indicate slight variations in BD across these land uses. The observed variations in BD can be attributed to differences in soil organic matter content, root biomass, and anthropogenic disturbances.

Table 3. *Soil bulk density (BD) in different rural land use types*

Variable	Obs	Mean	Std. Dev	Min	Max	Method
NF BD (g/ cm^3)	3	1.43	0.10	1.35	1.55	[A]
FP BD (g/ cm^3)	3	1.45	0.07	1.38	1.52	[A]
CL BD (g/ cm^3)	3	1.44	0.14	1.33	1.60	[A]

Key: NF (Natural forest), FP (Forest plantation) and CL (Crop land).

BD: Bulk density and g/ cm3: grams per cubic centimeter

Natural forests (NF) exhibit the lowest bulk density (BD) – 1.43 g/cm^3, likely due to high organic matter input, minimal human disturbance, and an extensive root system that enhances soil porosity (Gong et al., 2006). In contrast, forest plantations (FP) demonstrate slightly higher BD – 1.45 g/cm^3, which may result from periodic timber harvesting, soil compaction due to logging activities, and lower organic matter input compared to NF (Fonge et al., 2018). Croplands (CL) show the highest BD variability (standard deviation = 0.14), primarily reflecting the effects of frequent tillage, heavy machinery use, and a decline in organic matter content (Lal, 2004).

These findings are consistent with studies conducted in various geographic regions. For instance, research by Silva et al. (2017) in Brazil reported lower BD values (1.2 - 1.4 g/cm^3) in natural forest soils compared to cultivated land (1.4 - 1.6 g/cm^3), attributing this difference to reduced soil organic carbon and increased compaction in agricultural systems. Similarly, Yimer et al. (2006) found that cropland soils in Ethiopia (1.42 - 1.58 g/cm^3) were more compacted than natural forest soils (1.38 - 1.46 g/cm^3) due to continuous cultivation and organic matter depletion. A European study by Nave et al. (2010) observed BD values of approximately 1.45 g/cm^3 in afforested lands, comparable to FP in this study, suggesting moderate compaction from reforestation activities.

4. Conclusion

This study demonstrated that land use significantly influences soil fertility characteristics in the Kaniki area of Ndola, Zambia. Natural Forest (NF) soils had superior nitrogen content, indicating better organic matter decomposition and microbial activity. Forest Plantation (FP) soils showed relatively higher pH and phosphorus levels, likely due to managed silvicultural practices and minimal soil disturbance. Cropland (CL) soils, while rich in potassium due to fertilizer inputs, displayed lower overall fertility, including acidity and nitrogen depletion. Bulk density remained fairly consistent but slightly higher in disturbed lands like CL and FP, highlighting anthropogenic influence. Overall, the findings underscore that undisturbed ecosystems, such as natural forests, support higher soil fertility compared to intensively cultivated croplands. This indicates a need to integrate conservation measures and sustainable practices into land use planning and agricultural management to curb the decline of soil health in Zambia and similar regions.

Recommendations

Based on the findings of this study, some important recommendations have been proposed to promote sustainable land management and enhance soil fertility. Measures should be taken to limit deforestation while supporting large-scale reforestation initiatives. Preserving natural forest cover is essential for maintaining soil fertility and ensuring the overall health of the ecosystem. To further support sustainable land use, the regular monitoring of soil fertility should be institutionalized. This will provide essential data to guide proper land use planning and targeted fertilizer application.

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