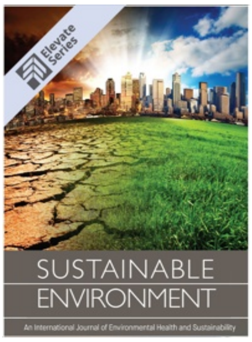

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Maps of major soil parameters: A reference for monitoring soil fertility in Burundi

Samson Musonerimana [a,b], Niyonkuru Anicet [a], Privat Ndayihanzamaso [a], Elena Semenova [a], Marie Chantal Niyuhire [a], Marcien Sendegeya [c], Salvator Kaboneka [b], Soter Ndihokubwayo [b], Oscar Nduwimana [d], Micael Beun [d] and Anaclet Nibasumba [e]

[a]Institut des Sciences Agronomiques du Burundi (ISABU), Bujumbura, Burundi; [b]Faculté d'Agronomie et de Bio-Ingénierie (FABI), Université du Burundi, Bujumbura, Burundi; [c]Faculté des Sciences, Département de Géologie, Université du Burundi, Bujumbura, Burundi; [d]Département des Productions Végétales, International Fertilizer Development Center (IFDC), Bujumbura, Burundi; [e]Département Agriculture, Institut Supérieur de Formation Agricole (ISFA), Université du Burundi, Bujumbura, Burundi

ABSTRACT

Soil fertility is a key factor for ensuring both the quantity and quality of agricultural production. To evaluate the fertility level, 1,377 soil samples were collected and analyzed from six AgroEcological Zones (AEZs) across Burundi. These samples were collected during June—July 2021 using a 4 km grid mesh. The geographical coordinates of each sampling point were recorded. The analyzed parameters included pH (water), soil organic carbon (SOC), total nitrogen (N), available phosphorus (P), exchangeable potassium (K), calcium (Ca), and magnesium (Mg). Fertility maps were developed using the Inverse Distance Weighting (IDW) method with sampling density of 0.25 samples/km^2. Comparison of means were performed using Tukey's test. Results showed significant differences soil parameters across AEZs. More than 73% of soils in all AEZs were highly acidic, 99% had low phosphorus availability and 53% had low potassium levels. Among AEZs, Congo-Nile Crest had the highest percentage of SOC and N, Imbo plain and North depressions had higher content of Ca, Mg. The spatial distribution of these parameters was heterogeneous, with strong variations even between nearby points within the same AEZ. This heterogeneity limits the possibility of providing general fertilization recommendations per AEZ, necessitating adaptations at the farm or low subdivision level.

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KEYWORDS
Fertility-maps; fertility-assessment; soil; agro-ecology; Burundi

Introduction

The soil fertility plays a critical role in agricultural productivity and food security (FAO, 2022). Improving soil fertility remains a key strategy in combating hunger (Sanchez, 2002). Under real conditions, low soil fertility can lead to yield reduction of nearly 50% (Kintché et al., 2017). Specifically, increasing the soil carbon pool can enhance productivity by several tons per ha with large increases especially for cereals (Lal et al., 2007). Agricultural production is closely linked to nitrogen availability (Spiertz, 2012). Therefore, regions with nitrogen-deficient soils are more vulnerable to food insecurity. The rational fertilization not only increases yield but also improves the nutritional quality of production for the same crop, in particular by increasing the content of protein (Kadam et al., 2020), vitamins and mineral nutrients (Adekiya et al., 2019). The agricultural production then depends upon soil fertility, which is a crucial factor for ensuring food security and food quality (FAO, 2005).

The loss of fertility can occur due to several factors, but the main ones are erosion, leaching and exportation by crops (Martínez-Mena et al., 2020; Rose et al., 2015). Studies carried out in Burundi, for example, have shown that soil losses can reach more than 150 t/ha in the context of heavy rainfall, unsuitable farming practices and high population density (FAO, 2011). Nutrient exports through harvests can deplete soils if not returned (Blanco-Canqui & Lal, 2009). Some crops, such as bananas, act as nutrient pumps by extracting large amounts of N, K, Ca, and Mg (Bamett et al., 1995).

To control soil fertility loss, various solutions have been implemented in different c agricultural production contexts (Blanco-Canqui, 2009; Sanchez, 2002). Improving fertility consists in the conservation of water and soil by implementing appropriate techniques (Martínez-Mena et al., 2020) and correction of deficient parameters and nutrients (Mng'ong'o et al., 2021). For the correction of deficient parameters, supplying mineral nutrients in micro-doses is widely applied (Ouedraogo & Tapsoba, 2022; Pythagore et al., 2017). This technique consists of supplying nutrients that are below the crop requirement to stimulate soil nutrient

CONTACT Anaclet Nibasumaba anaclet.nibasumba@gmail.com Département Agriculture, Institut Supérieur de Formation Agricole (ISFA), Université du Burundi, Gitega-Burundi, Bujumbura BP 241, Burundi

uptake. While effective in increasing yields, this method risks depleting soil reserves over time. Alternatively, organic amendments improve yields and nutrient content in harvested products, including fruits/seeds and biomass (Ouedraogo & Tapsoba, 2022). On the other hand, application of organic amendments allow to increase production which can be observed in terms of yields and nutrient contents in harvested products, namely fruits/seeds and biomass (Vanhercke et al., 2019). Conservation agriculture, which consists of leaving crop residues in place, can quadruple the infiltration rate and double the water available to plants (Blanco-Canqui, 2009). Several organic sources of nutrients exist with varying nutrient concentrations and the long-term effect remains very unanimous for all the different organic compounds (Cai et al., 2019; Craddock et al., 2015). In general, a synergy between mineral fertilizers and organic fertilizers has been observed in several tropical soils.

In Burundi, intrinsic and extrinsic agricultural factors significantly increase the risk of fertility loss. In fact, population density is very high with a direct effect on land and food needs (FAO, 1997; ISTEEBU, 2022). This leads to overuse of land and increased nutrient exportation from soil. Furthermore, the application of microdoses of fertilizers with its corollary effects leads to the depletion of soil reserves (Bielders & Gérard, 2015; Pythagore et al., 2017). Application of organic manure is very limited because the production of manure is only possible for some breeders because composting is not widespread. Under these conditions, it is important to monitor soil fertility to know the level of major soil parameter content.

Soil mapping studies have been carried out in similar areas (Mulualem et al., 2024; Tiruneh, Alemayehu, Allouche, et al., 2021; Tiruneh, Meshesha, et al., 2023; Tiruneh, Alemayehu, Meshesha, et al., 2021; Tiruneh, Alemayehu, et al., 2023; Tiruneh, Meshesha, et al., 2023) using a variety of methods (Tiruneh et al., 2022). But few studies have been carried out in extreme conditions with steeply sloping soils and continuous soil cultivation, high population density and sub-optimal cropping conditions, high level of exportation of crop and residues which lead to rapid soil degradation. Or, the use of geostatistical tools is effective, both in Africa and elsewhere (Jena et al., 2024; Lanki & Onwu, 2024; Trigunasih et al., 2023). Therefore, a better understanding of soils fertility through fertility maps enables productivity to be increased through management practices adapted to each level of fertility. In Burundi in particular, no study using the same methodology has been conducted to our knowledge. The objectives of the study were i) to map the spatial distribution of key soil fertility parameters and ii) support decision-making in agricultural planning and rural development through thematic maps that provide to managers and users easily usable database visualized through maps. The basic hypotheses are that i) Geostatistical methods can produce reliable maps of the spatial distribution of soil fertility and ii) Site-specific soil management based on fertility status leads to improved long-term agricultural productivity.

Material and methods

Description of sampling zone

Soil samples were collected across Burundi, stratified by agroecological zones (AEZs), namely Imbo Plain, Mumirwa, Congo-Nile Crest, Central Plateaux, Depressions of Moso and North depressions (Baramburiye et al., 2010). The characteristics of the zones are mentioned in Table 1.

Soil sampling

Systematic sampling was used to select sampling points. The study area was divided using a regular 4 km grid, and samples were collected from the center of each cell (Figure 1). Sampling density was 0.25 samples/km^2. This is enough for large scale studies. For example, in his study, Dash et al. (2024) found an optimal soil sampling density of 0.1 sample/km2 for the spatial interpolation of multiple soil nutrients at a regional scale. This is the most appropriate method to capture the soil heterogeneity, since each soil type has the same probability to be sampled. Coordinates of the predetermined sampling points were found using a GPS. All the sampled points were uniformly distributed throughout Burundi. When the sampling point fell in impractical spaces for sampling (rivers, roads and houses, national parks and protected areas) it was moved to a distance from 15m to 50 m and the new coordinates were mentioned. These new coordinates were used in this mapping. The sample points that fell within nature reserves and parks or within 1 km of borders with other countries were eliminated. The soil sampling was performed between June and July 2021 at a deep of 30 cm using an auger.

The composite sample consisted of 5 sub-samples taken in the homogeneous zone in relation to the sampling point was labelled and introduced in laboratory for analysis. In total, a number of 1377 samples were collected throughout Burundi.

Table 1. Characteristics of agroecological zones of Burundi

Name of AZE	Altitude (Baramburiye et al., 2010)	Annual mean temperature (Baramburiye et al., 2010)	Rainfall (Baramburiye et al., 2010)	Dominant soils according to classification INEAC (Lee et al., 2023)
Imbo Plain	770–1100	23–29	800–1100	Cambisols, Ferralsols, vertisols, Regosols
Mumirwa	1100–1750	18–28	1100–1900	Ferrisols, Feralsols and Regosols
Congo-Nile crest	1750–2600	14–15	1300–2000	Kaolisols, Ferralsols, Lithosols
Central lateaus	1400–2000	17–20	1200–1500	Ferrisols, Ferralsols, Regogley, Lithosols, Regosols
Moso depressions	1100–1400	20–23	1100–1200	Cambisols, Ferrisols, Ferralsols, Regogley; Kaolisols; Lithosol
Northern depressions	1300–1700	19–22	1100–1500	Ferrisols, Ferralsols, Cambisols, Regogley; Regosols

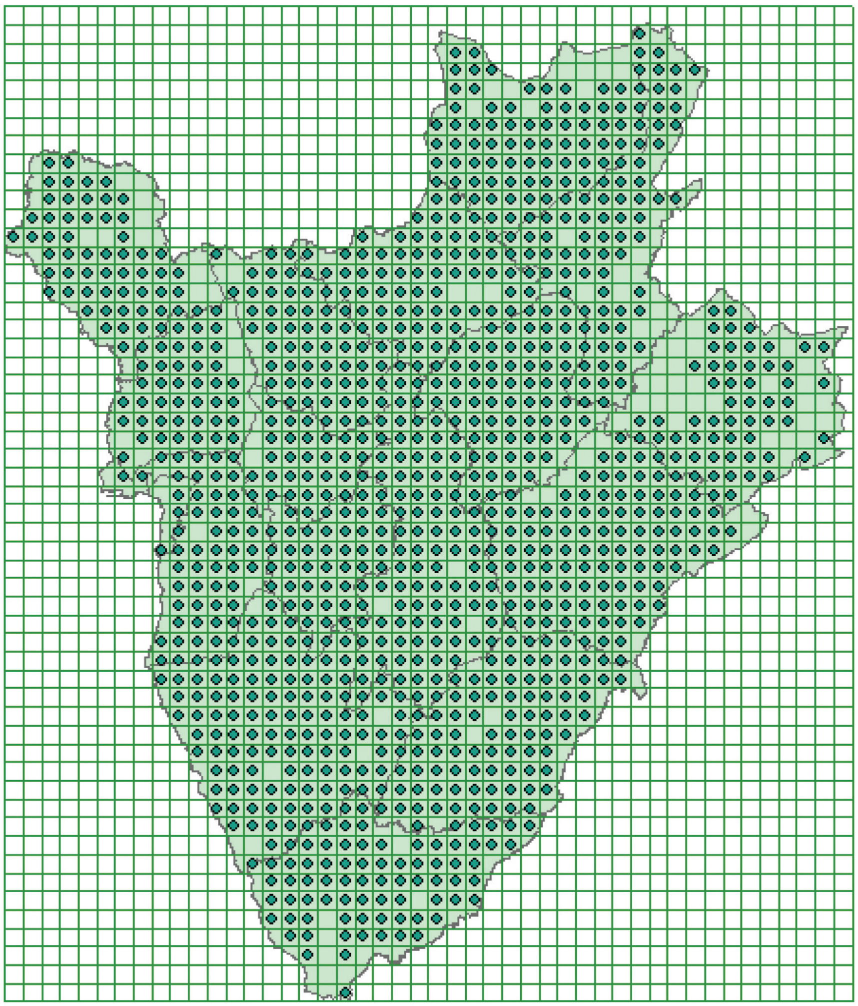

Figure 1. Square mesh over all of Burundi and the soil sampling points in the middle of the squares with equidistance of 4 km. Light areas without dots represent areas excluded from sampling, namely parks, nature reserves, protected areas and forests.

Soil analysis and results interpretation

The soil samples were analysed in Soil and Agri-Food Analysis Laboratory (LASPA) at the Institut des Sciences Agronomiques du Burundi (ISABU); an accredited laboratory. The parameters analysed for each sample were pH_{water}, soil organic carbon (SOC), total nitrogen (N), available phosphorus (P), exchangeable potassium (K), calcium (Ca), magnesium (Mg).

The soil samples were dried under shading. Soil pH was measured using a pH meter in a 1:5 soil water suspension. Organic carbon was determined using Walkley-Black method. Total nitrogen was determined using the Kjeldahl digestion method and measured calorimetrically. Exchangeable cations were extracted using Metson method and measured with an atomic absorption spectrometer. Available phosphorus was determined with Olsen-Dabin method. Results were interpreted according to the criteria listed in Table 2.

Table 2 : Standards for interpreting soil test results

pH (Brady & Weil 2008; Tessens & Gourdin, 1993)	Orgnic carbon of soil (%) (Tessens & Gourdin, 1993)	Total N (%) (Tessens & Gourdin, 1993)	Avalible P (ppm) (Tessens & Gourdin, 1993)	Exchangle K (cmolckg^{-1}) (Tessens & Gourdin, 1993)	Exchange Ca (cmolckg^{-1}) (Tessens & Gourdin, 1993; Boyer, 1978)	Exchange Mg (cmolckg^{-1}) (Tessens & Gourdin, 1993; Boyer, 1978)
– pH< 5: very strongly acidic; – 5-5.5: strongly acidic; – 5.6-6.0: acidic; – 6.1-6.5: weakly acidic; – 6.6-7.5: Neutral – pH > 7.5: Alkaline.	– <1%: very low; – 1-2%: low; – 2-3.5%: medium; – 3.5%: high to very high.	– < 0.1: Very low; – 0.1-0.2: Low; – 0.2-0.5: Medium – 0.5-1.0: High – >1.0: Very high.	– 0-5: very low availability; – 5-20: low availability; – 20-50 : average availability; – 50-100: good availability and – >100: very good availability.	– < 0.25: Poor soil; – 0.25-0.5 : Medium soil; – 0.5-1.0: Rich soil; – >1.0: Very rich soil.	– < 1: very low; – 1-2: low; – 2-3.5: medium; – 3.5-5: high; – >5: very high.	< 0.2: very low; – 0.2-0.5: low; – 0.5-1.5: medium; – >1.5: high.

Soil fertility mapping

Among the spatial interpolation methods, the inverse distance weighting (IDW), ordinary kriging and ordinary co-kriging are the most frequently used methods in environmental sciences (Li & Heap, 2011). The IDW method was used to map the soil fertility of Burundi because it is one of the simplest and most readily available method. It assumes that a value of an attribute at a no sampled location is a linearly weighted average of known data points occurring within a local neighbourhood surrounding the no sampled location (Robinson & Metternicht, 2006). The other reason is that it has the prediction accuracy than the ordinary kriging as demonstrated by (Qiao et al., 2018) during arsenic assess in Beijing. IDW was also used to produce high-quality spatial soil nutrient maps for Coastal regions in India (Mitra, 2014). Maps have been done using QGIS.1.7.4.

Data analysis

Data were analyzed using R version 3.5.0. Normality was first tested, and comparisons between AEZs were made using ANOVA. Principal Component Analysis (PCA) and correlation analyses were also performed. The significance level was set at $p < 0.05$. Mean comparisons were conducted using Tukey's test, and figures were produced using Microsoft Excel 2016.

Results

Comparison of agroecological zones

Significant differences ($p < 0.05$) were observed among the various AEZs for all analyzed soil parameters (Table 3). The highest pH values were observed in the Imbo Plain, followed by the Northern Depressions, with respective averages of 6.05 and 5.62. The lowest values were observed in the Congo-Nile Crest, averaging 5.02. The highest SOC values were observed in the Congo-Nile Crest, with an average of 4.53%, while the lowest values were observed in the Moso Depressions and Imbo Plain, with respective averages of 1.76% and 1.79%. The other AEZs had intermediate values. The highest *N* values were observed in the Congo-Nile Crest and the lowest in the Moso Depressions and Imbo Plain. The highest *p* values were observed in the Northern Depressions, while the rest of the AEZs were in the same group and were therefore not statistically different. The highest values of exchangeable K and Ca were observed in the Imbo Plain and the Northern Depressions. The respective means of exchangeable K were 0.40 and 0.45 cmolkg^{-1}, and the respective means of exchangeable Ca were 5.96 and 5.39 cmolkg^{-1}. The lowest averages of exchangeable K and Ca were observed in the Congo-Nile Crest, at 0.23 cmolkg^{-1} for K and 1.28 cmolkg^{-1} for Ca, respectively. The highest Mg average was observed in the Imbo Plain, at 2.82 cmolkg^{-1}, while the lowest average was

Table 3. Comparison of parameters with agro-ecological zones

Agro-ecological zones	pH	Total Soil Organic Carbon (SOC) (%)	Total N (%)	Available P (ppm)	Exchangeable K (cmolckg^{-1})	Exchangeable Ca (cmolckg^{-1})	Exchangeable Mg (cmolckg^{-1})
Imbo Plain ($N = 87$)	6.05^{a}	1.79^{c}	0.20^{c}	6.38^{b}	0.40^{a}	5.96^{a}	2.82^{a}
Northern Depressions ($N = 109$)	5.62^{b}	2.60^{b}	0.23^{bc}	12.50^{a}	0.45^{a}	5.39^{a}	1.81^{b}
Central Plateaus ($N = 623$)	5.23^{d}	2.56^{b}	0.25^{b}	5.40^{b}	0.26^{c}	2.54^{b}	0.77^{d}
Mumirwa ($N = 150$)	5.22^{d}	2.56^{b}	0.24^{b}	4.12^{b}	0.32^{b}	2.65^{b}	1.19^{c}
Congo-Nile Crest ($N = 202$)	5.02^{e}	4.53^{a}	0.30^{a}	6.19^{b}	0.23^{c}	1.28^{c}	0.50^{e}
Depressions of Moso (206)	5.39^{c}	1.76^{c}	0.20^{c}	5.40^{b}	0.27^{bc}	2.79^{b}	1.21^{c}
p-value	‹2^{-16}***	‹2^{-16}***	3.96^{-16}***	6.1^{-7}***	2.96^{-16}***	‹2^{-16}***	‹2^{-16}***

Codes: 0.0000–0.001***; 0.001–0.01**; 0.01–0.05*; 0.5–0.1.
Values with the same letters in the columns are not statistically different at $p < 0.05$.

observed in the Congo-Nile Crest, at 0.50 $cmolkg^{-1}$. Overall, the Imbo Plain had higher averages for pH, exchangeable K, exchangeable Ca, and exchangeable Mg. The Northern Depression had the highest averages for P, exchangeable K, and exchangeable Ca. The Congo-Nile Crest had higher means for SOC and N.

pH, SOC, total N and available phosphorus

The Figure 2a showed that soils in Burundi are generally acid. With total area of 22,677.2 km, 22.3% were very strongly acid, 50.6% were strongly acid, 21.1% were acid and 5.0% were weakly acid. Neutral soils accounted for only 1.1% while alkaline soils covered

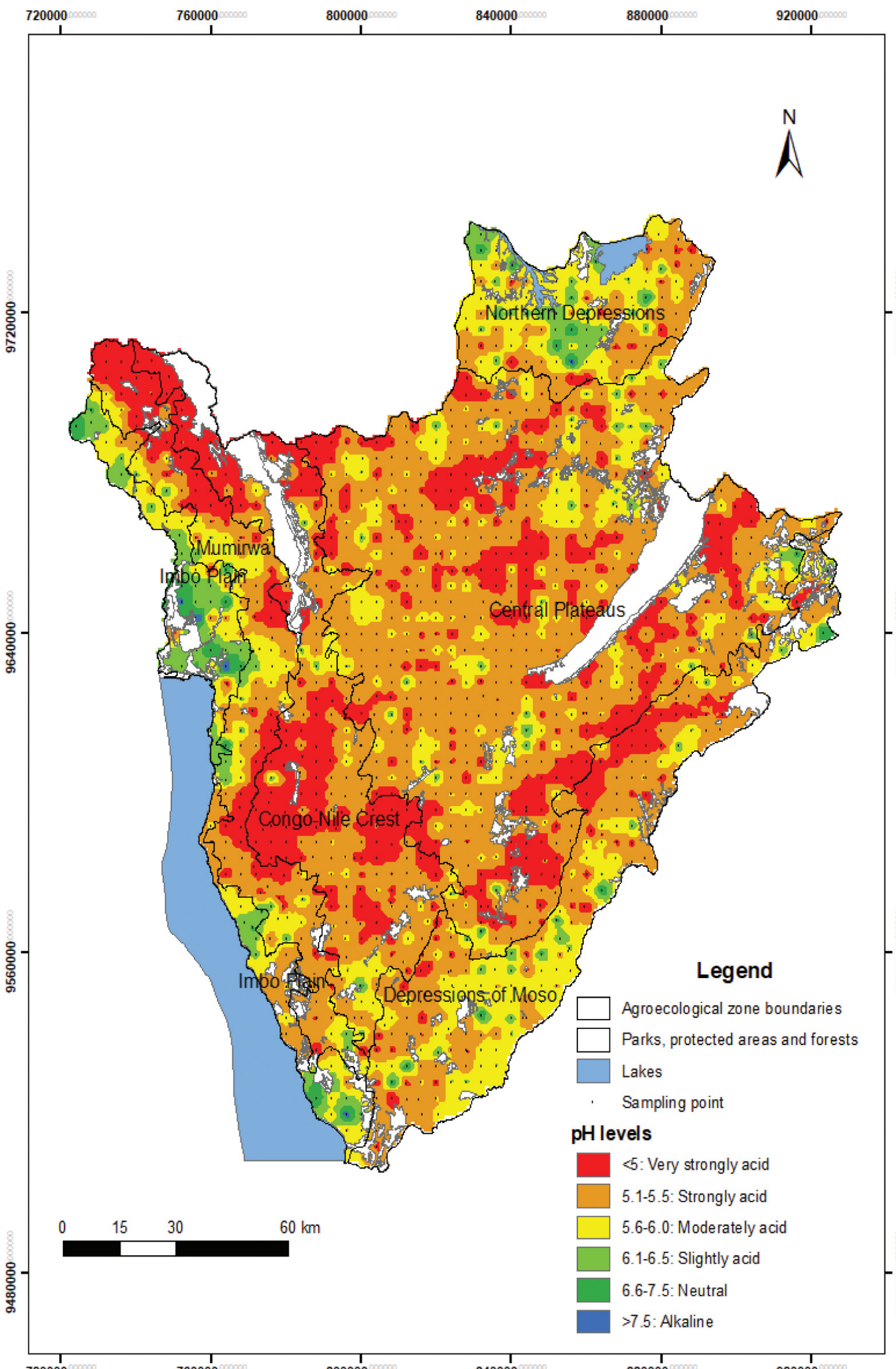

Figure 2a. pH map with boundaries of agro-ecological zones.

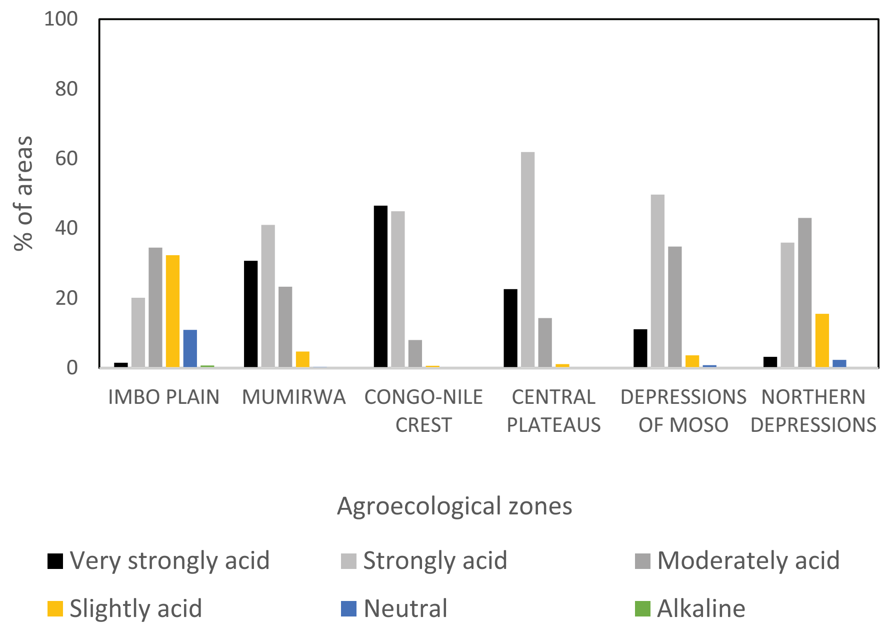

Figure 2b. Percentage of different pH categories in relation to agro-ecological zones.

0.1% of the total area analysed. Very strongly acid and strongly acid soil accounted for 73% of the total area. In the Congo-Nile Crest AEZ, 91% of soils had very strongly acidic or strongly acidic pHs (Figure 2b). In the Central Plateaux, 85% of soils had very strongly acid or strongly acid pHs. In Mumirwa, 72% of soils were very strongly acid or strongly acid pHs. In the Moso Depressions, 61% of soils had very strong or strong acidity. In the Northern Depressions, 38% of soils had very strongly or strongly acidity. In the Imbo Plain, 22% of the soils had very strongly or strongly acidic pHs. Thus, the acidity characterised by the pH values by AEZ was higher, in descending order, in Congo-Nile Crest >Central Plateaux >Mumirwa > Moso Depressions > Northern Depressions and Imbo Plain.

More than 78% of the soils had SOC values between 1 and 3.5%, of which 40% had values in the range of 2 to 3.5% (Figure 3a). More specifically, 3% of the soils had very low SOC contents, 38% had low contents, 40% medium contents and 19% had high values of SOC. Congo-Nile Crest had higher SOC values with 93% of the soils having medium to high contents (Figure 3b). The Moso depressions had lower SOC values with 70% of the soils with low to very low SOC values, followed by the Imbo Plain with low and very low SOC values accounting for 68% of the total area.

Almost 35% of the Burundi soil had very low to low nitrogen contents while 65% of soils had medium or high nitrogen contents (Figure 4a). In the Congo-Nile Crest, 88% of soils had medium to very high N contents against 76% for Mumirwa, 70% in the Northern Depressions and 64% in the Central Plateaux (Figure 4b). The Moso Depressions had 59% of the soils with low to very low N contents against 52% in the Imbo Plain.

The soils with very low phosphorus availability accounted for 56% of the area studied against 43% of soils with low phosphorus availability (Figure 5a). The soils with average phosphorus availability accounted for 0.8% while soils with good availability and very good availability accounted for only 0.4% of the total area. Available phosphorus maps showed that more than 99% of the soils in all AEZs had very low phosphorus availability or low availability except for the Northern Depressions where this percentage was 89% (Figure 5b).

Exchangeable K, Ca and Mg

The soils with low potassium contents accounted for 53% of the total area studied while the soils with medium contents accounted for 38% (Figure 6a). The potassium-rich soils accounted for 8.5% and the very rich soils accounted for 2% of the total area surveyed. The soils with low potassium contents accounted for 65% of the area in the Congo-Nile Crest zone, 58% in the Central Plateaux zone and 53% in the Moso depressions zone (Figure 6b). The

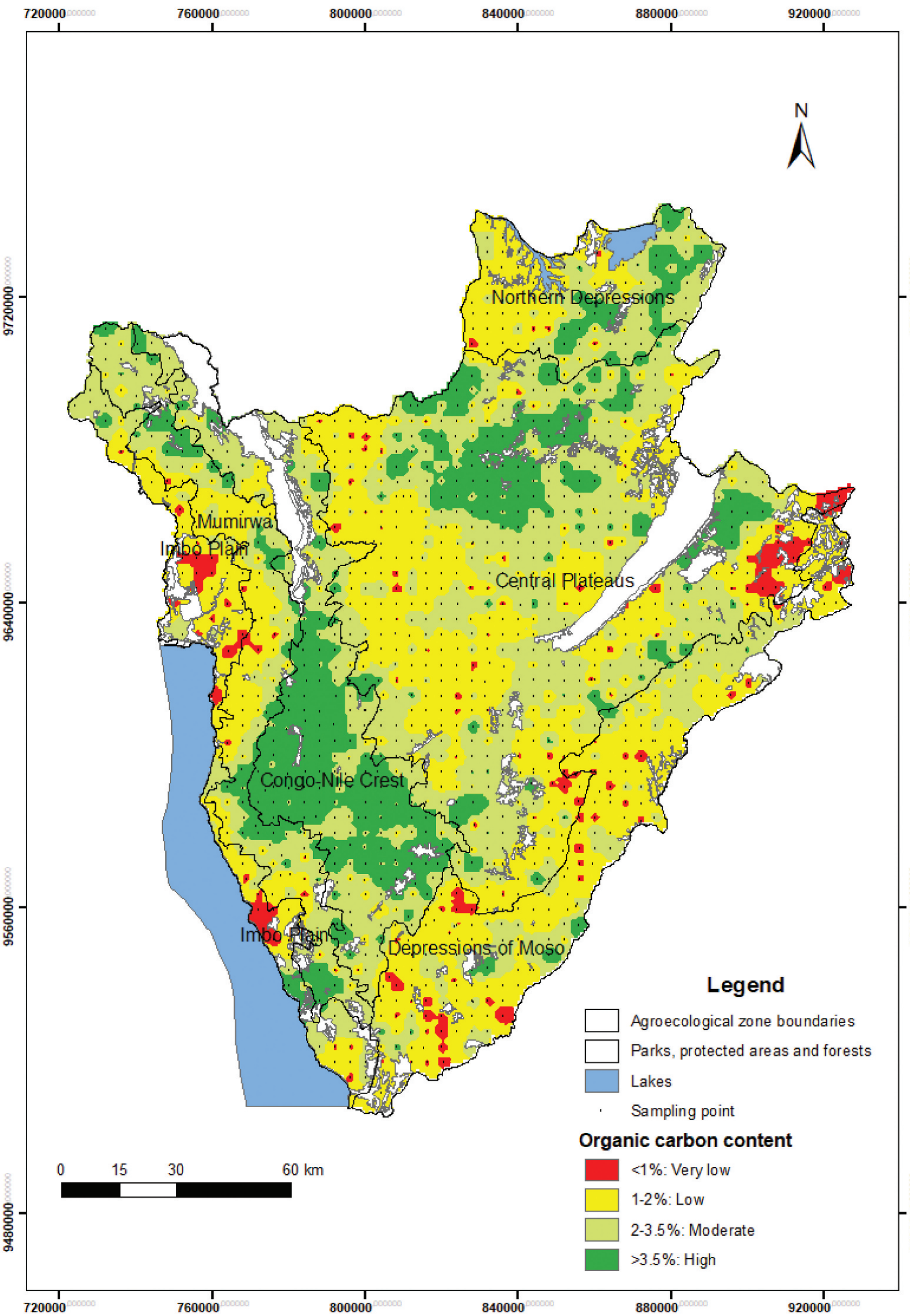

Figure 3a. Map of total soil organic carbon (SOC) content with boundaries of agro-ecological zone.

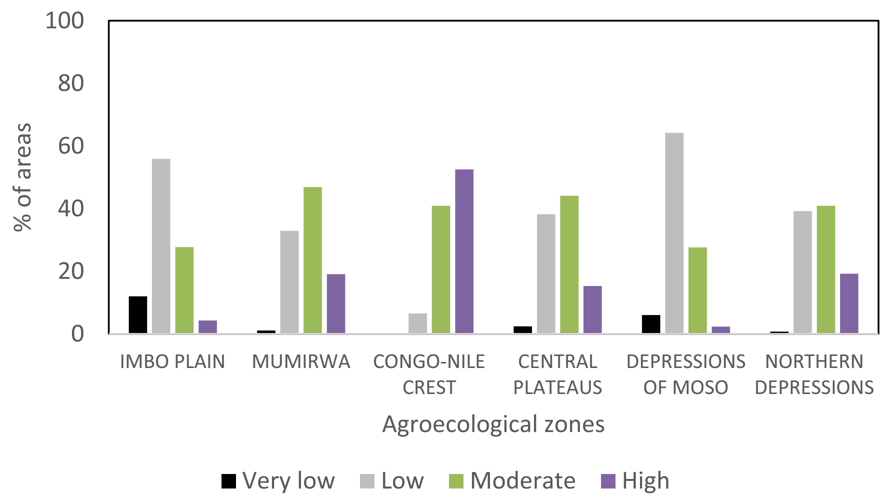

Figure 3b. Percentage of different categories of total soil organic carbon (SOC) in relation to agroecological zones.

soils with medium grades accounted for 48% of the total area in the Imbo plain zone, 47% in Mumirwa zone and 45% in the Northern depressions zone. Soils with high to very high grades accounted for 24% in the Imbo plain zone and 30% in the Northern depressions zone. For the other AEZs, these percentages were below 10%.

The soils with very low exchangeable calcium contents represented 18% of the total area studied, the soils with low calcium contents represented 27%, the soils with medium calcium contents represented 26% and soils with high and very high calcium contents represented 28% (Figure 7a). The soils with low or very low calcium content accounted for 78% in the Congo-Nile Crest, 47% in Mumirwa, 48% in the Central Plateaux and 43% in the Moso Depressions zones (Figure 7b). The soils with medium calcium content accounted for 31% in the Central Plateaux and 32% in the Moso Depressions zones. The Congo-Nile Crest zone had lower calcium contents while the Northern Depressions zone had the highest contents.

The soils with very low magnesium contents represented 6% of the total area studied, the soils with low magnesium contents 23.5%, the soils with medium magnesium contents 49% and the soils with higher magnesium contents represented 21% (Figure 8a). The soils with higher magnesium content accounted for 65% of the area in the Imbo Plain and 63% in the Northern Depressions zones (Figure 8b). The soils with medium magnesium content represented 57% in the Central Plateaux, 51% in the Moso Depressions and 50% in Mumirwa zones. The soils with low to very low magnesium content accounted for 59% in the Congo-Nile Crest and 34% in the Central Plateaux zones.

Mapped parameters' correlation

Based on the contribution of the six soil chemical properties content, Principal Component Analysis revealed a diversity 63.5% among our study areas sampled. The variation in the first Principal Component explained a variation of 38.5% while the variation in PC2 explained was 28%.The different components such as PH, K,P, Mg, as well as Ca, were found to have a significant positive correlation. Addition, N and CO are strongly positive correlated and negatively correlated to the four others components. In the Dim1 (PC1), the contributions values for the six chemical soil components into the two first components were 26.6% versus 2.758 % for pH, and 28.89% versus 1.33% for Ca content while it was 26.969% vs 0.058 for Mg component. Likewise, for the PC2 (Dim2), contributions were 48.212% versus 0.01% for CO and 47.633% versus 0.082% for N. (Figure 9 and Table 4).

After generating the different Component, total amount of variance explained by the five first principal components (Eigenvalue) and the percentage of variation were carried in each Principal. Thought out ranking them, highest to lowest and subsequently, five first principal components per order of significance were identified (Table 4).

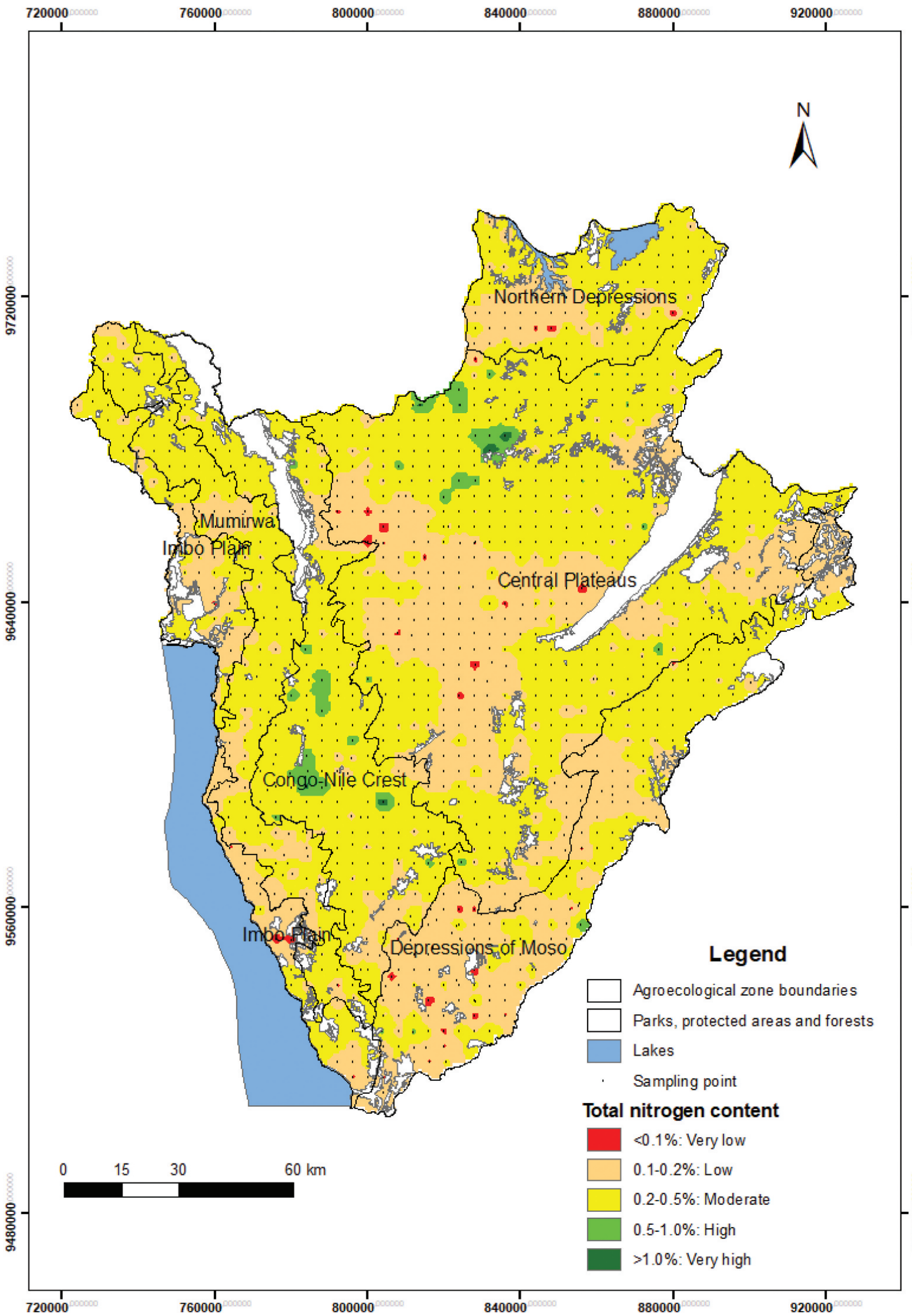

Figure 4a. Map of total nitrogen content with delimitation of agro-ecological zone.

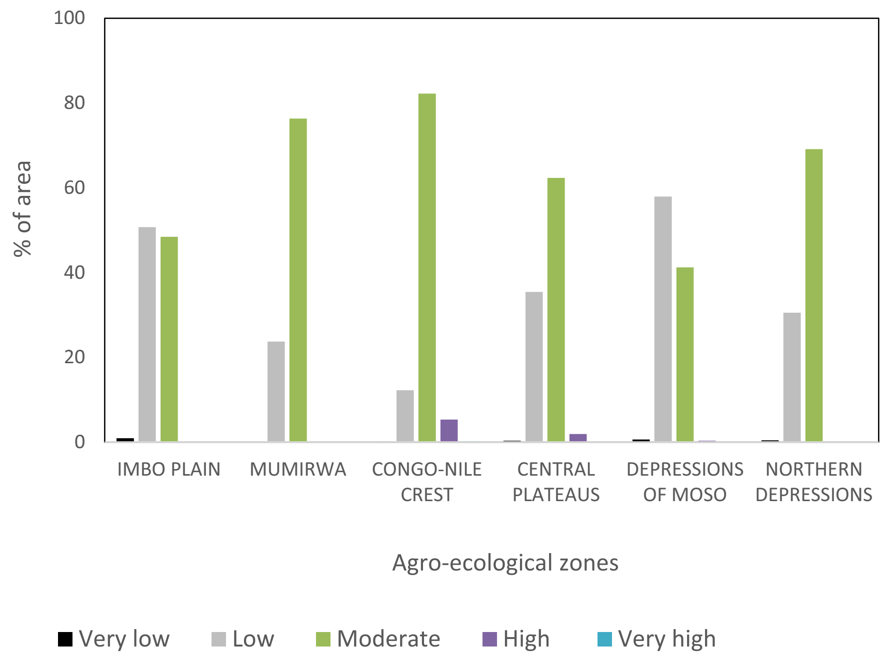

Figure 4b. Percentage of different categories of total nitrogen content in relation to agro-ecological zones.

Discussions

Analysis of the current situation

The pH values obtained were below 5.5 in 73% of the soils of Burundi (Figure 2a) with more acid soils in Congo-Nile Crest agroecological zone (Figure 2b). The low pH values have consequences on nutrient availability (Brady & Weil, 2008; McCauley et al., 2009) and on aluminium toxicity because Al^{3+} ions are abundant in acid soils (Brady & Weil, 2008). Indeed, there is a functional relationship between pH (H_2O and KCl) and exchangeable soil aluminium (Yerima et al., 2020) where high values of aluminium in soil solution are obtained at low pH (Edmeades & Wheeler, 2016). Although some advantages of exchangeable aluminium have been mentioned by some authors (Muhammad et al., 2019), the high concentration of exchangeable aluminium affects the morphology, anatomy, physical-biochemistry and molecules of the plant (Rahman & Upadhyaya, 2020). The presence of high concentration of exchangeable aluminium in the soil leads to inhibit the root growth, the nutrient deficiencies and the yield loss (Almeri et al., 2009). From the above, the low pH observed in Burundi would significantly affect the national agricultural production.

The soil organic matter contents are generally higher in the Congo-Nile Crest agro-ecological zone while they are average in the other agro-ecological zones (Figure 3a; Figure 3b). This is due to the low temperature (Table 1) and low pH (Table 3; Figure 2a; Figure 2b) observed in this agro-ecological zone. These factors reduce the rate of mineralisation of organic matter. The negative effect of low pH on soil microorganisms has been confirmed by Rasheed et al. (2008); Rousk et al. (2009). The abundance of bacteria increases with pH, soil microorganisms are in low numbers at low pH (Rasheed et al., 2008). Although this was nuanced by (Shen et al., 2013) where certain groups of bacteria were abundant at low pH. The soil fungi profile is abundant at pH between 6 and 7 (Rousk et al., 2009). Thus, lower populations of microorganisms will take longer to mineralise organic matter present in the soil. The other factor that affects the decomposition of organic matter is temperature. The optimum temperature for the mineralization of organic matter is around 25°C (Curtin et al., 2012; Zuoxin et al., 2017). However, the average temperature of the AEZ of the Congo-Nile crest is well below these optimal temperatures (Table 1). This makes this area richer in organic carbon. The quality of this soil organic matter may be low because the nitrogen and phosphorus contents remain almost the same in the Congo-Nile crest compared to the other AEZs (Figures 4a, 4b, 5a, 5b) for values higher levels of organic carbon (Figure 4; Figure 5). This leads to higher ratios of carbon-nitrogen (C/N) and carbon-phosphorus (C/P). These higher ratios will further limit the soil organic matter mineralisation (Arenberg & Arai, 2019; Bengtsson et al.,

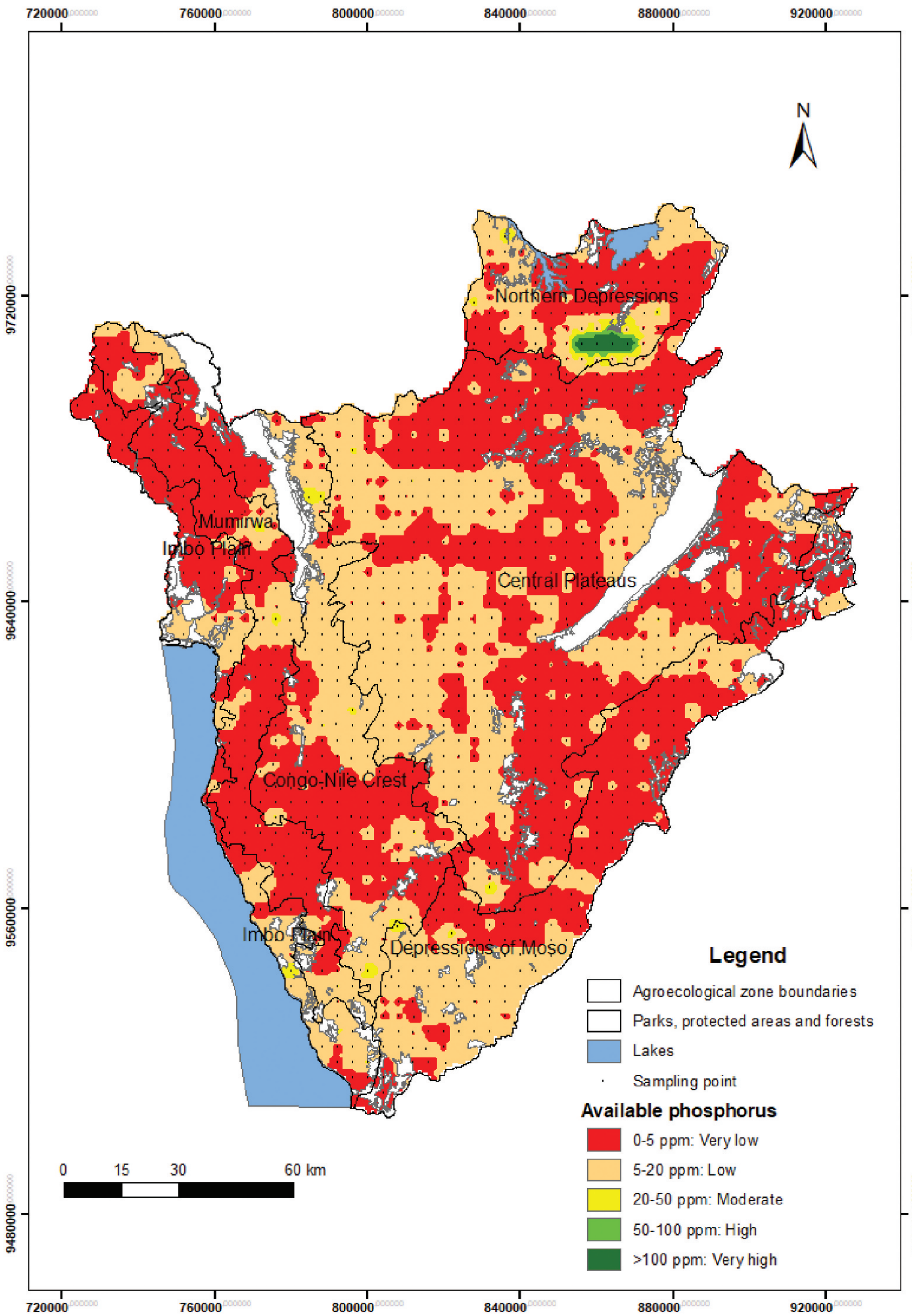

Figure 5a. Map of available phosphorus content with delimitation of agro-ecological zones.

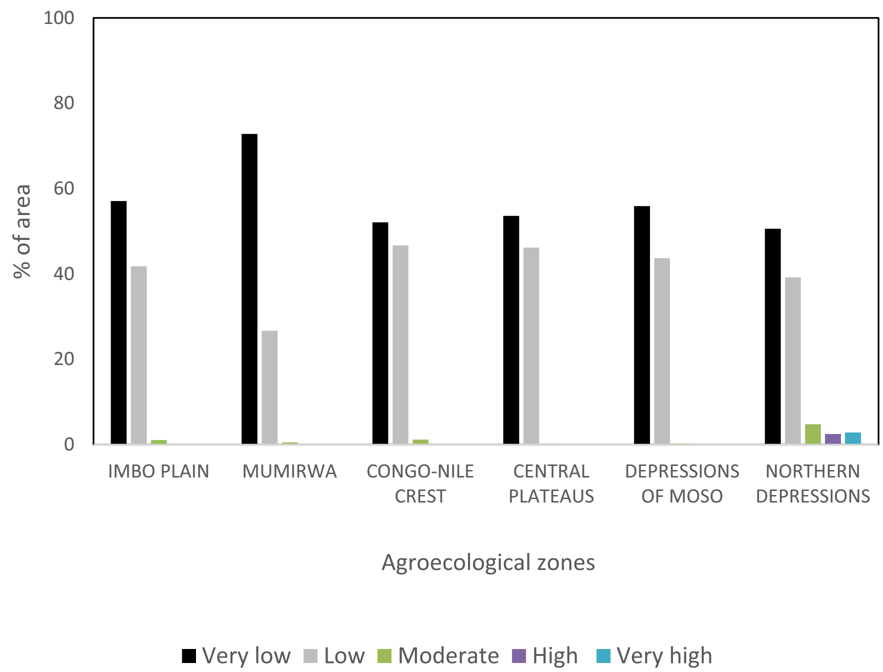

Figure 5b. Percentage of different categories of available phosphorus content in relation to agro-ecological zones.

2003). The nitrogen contents were mostly medium (Figure 4a; Figure 4b) with a strong correlation between soil organic carbon and total nitrogen ($R^2 = 0.55$). This was confirmed by the results of the principal component analysis (Figure 9 and Table 4), which showed a strong correlation between N and SOC on the one hand, and Ca, Mg and K on the other hand. This shows that most of the nitrogen is from SOC. Available phosphorus levels were low in all agro-ecological zones of Burundi (Figure 5a; Figure 5b). This has been observed in different soils. For weathered soils, the poverty of available phosphorus has been observed by other authors (Kintché et al., 2017; Margenot et al., 2017; Neufeldt et al., 2000). But for other types of soil, this phosphorus deficiency has other causes than the nature of the soil. This is the case of the soils of the Imbo plain where there are soils that are naturally rich in phosphorus such as vertisols (Sahrawat & Warren, 1989). The low availability of phosphorus may also be due to the low pH values recorded in some AEZs (Figures 2a and 2b). The effect of pH on phosphorus availability has been confirmed by many authors (Barrow, 2016; Ho et al., 2018; Mkhonza et al., 2020).

The exchangeable potassium content was low in the most soils in Burundi (Figure 6a; Figure 6b). However, tropical soils such as those dominant in Burundi have selectivity for potassium, than divalent cations (Parfitt, 1992) because of the dominance of 1:1 alumina-silicates (Levy et al., 1988; Takahashi et al., 2018). With this potassium selectivity, we should expect soils rich in potassium. However, the potassium element is the second most deficient element after phosphorus (Figure 5a; Figures 5b, 6a; Figure 6b).

The cations contents were higher in the Northern Depressions, Eastern Depressions and Imbo Plain but lower in the Congo-Nile Crest and Central Plateaux (Figure 6a; Figures 6b, 7a, 7b, 8a; Figure 8b). The difference in rainfall (Table 1) would have led to the accumulation of the cations in the Northern Depressions, the Eastern Depressions and the Imbo Plain and a leaching of these cations in the Congo-Nile Crest and the Plateaux Centrals.

In addition, the Northern Depressions, the Eastern Depressions and the Imbo Plain are areas of sedimentation; which leads to enrichment in cations and other nutrients (Craft & Casey, 2000).

The low content of soils in major nutrients, especially phosphorus and potassium, are due to different factors, including export by crops, the application of micro-doses of fertilizers and erosion. The crop exports lead to soil depletion. The banana crop, for example, exports, under Burundian conditions, 70 kg of N and 200 kg of K per ha and per year (Syldie, 2017). The correction of low fertility by the application of micro-doses of fertilizer makes allows to

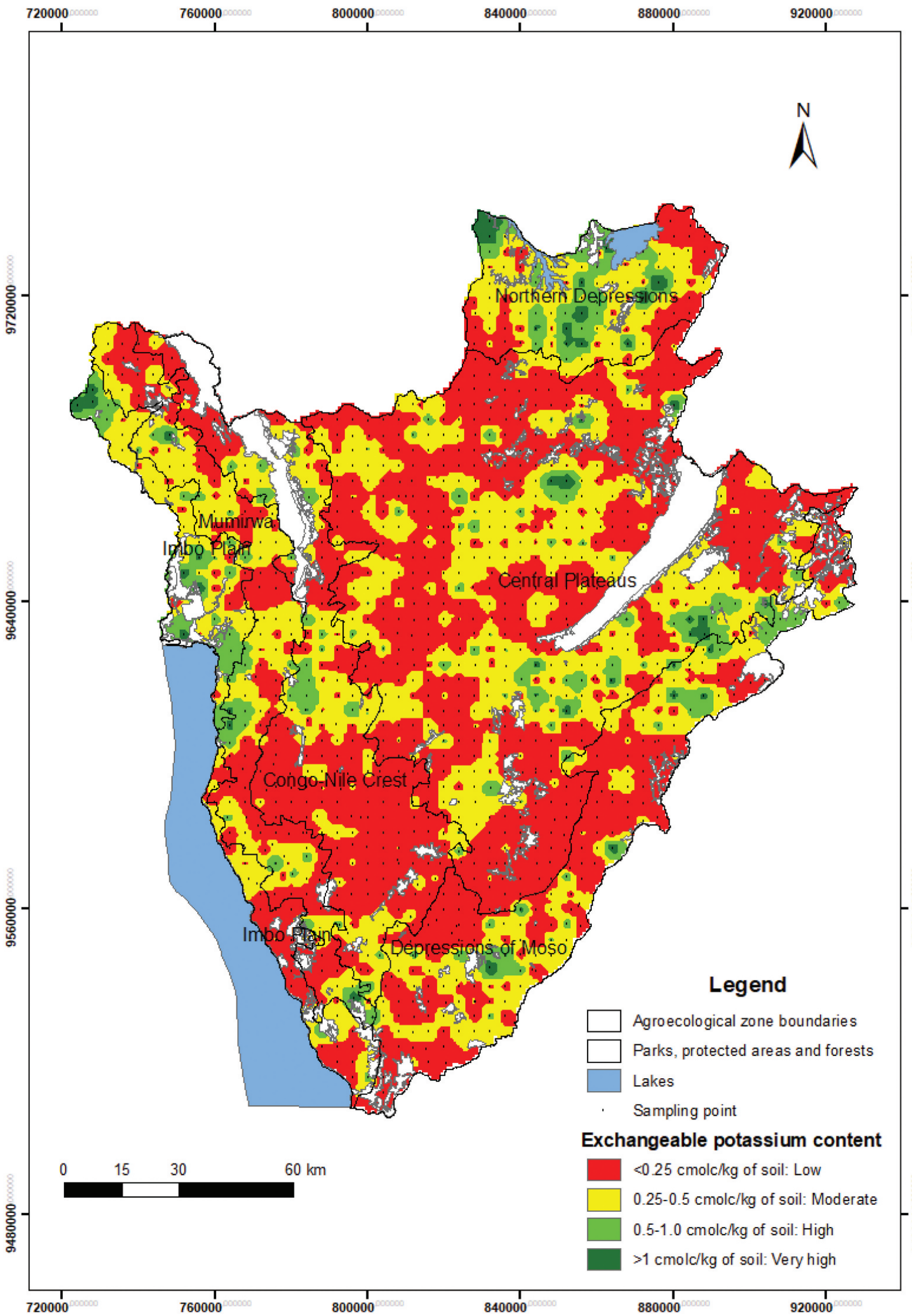

Figure 6a. Map of exchangeable potassium contents with delimitation of agro-ecological zones.

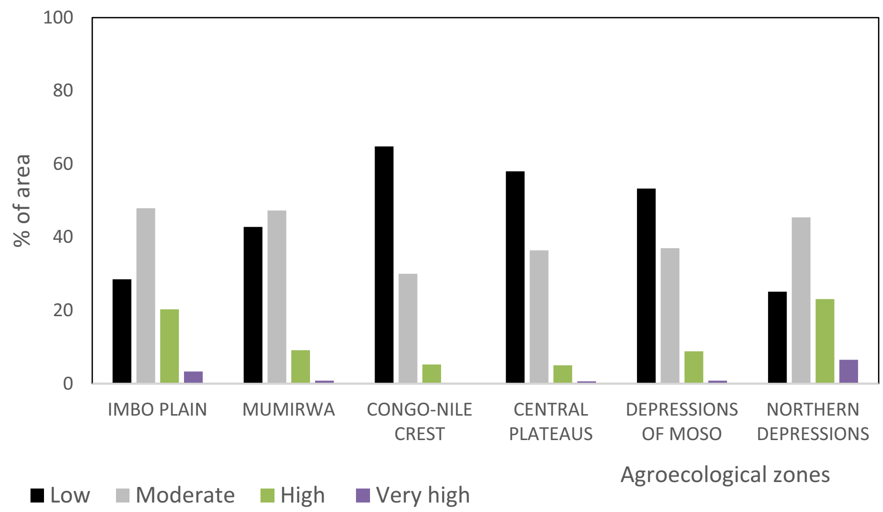

Figure 6b. Percentage of different classes of exchangeable potassium content relative to agro-ecological zones.

increase the yield but with long-term risks because crops draw more nutrients from the soil than those supplied (Ouedraogo & Tapsoba, 2022). Both factors, combined with erosion (Martínez-Mena et al., 2020) should lead to a fast decrease in nutrient levels. The consequence of low fertility is the unavailability of food in quantity and quality. Some authors showed that crop yields increase with the availability of nutrients in the soil (Bai et al., 2013; Pradipta et al., 2016). In addition, the food quality such as richness in protein, richness in trace elements such as Zn and Fe and richness in vitamins depend on the richness of the soil in nutrients (Alkier et al., 1972; Chandel et al., 2010).

Correction alternatives

The implementation of practices for water erosion management is the basis for ensuring the sustainability of other practices to increase soil fertility because the erosion accelerates the loss of fertility (Rose et al., 2015). These practices should be adapted to the high population density observed in Burundi. To minimise nutrient exportation, maximum recycling of crop residues is recommended to improve the nutrient availability, increase the soil organic carbon content and correct the pH (Blanco-Canqui, 2009).

These residues can be used as mulch (Blanco-Canqui, 2009). The correction of acid pH can also be done using dolomite, which is in large quantities in Burundi and has high concentrations of CaO and MgO (IFDC 2022). The pH correction could partly solve the low availability of phosphorus (Barrow, 2016; Ho et al., 2018; Mkhonza et al., 2020) observed in acid zones (Figure 2; Figure 3; Figure 8) especially in the AEZs of Congo-Nile crest, the Central Plateaux and Mumirwa. The low availability of phosphorus can be solved by the application of phosphate rocks (Nabahungu et al., 2007, Sutriadi et al., 2014). These authors observed an effect of the direct application of phosphate rocks on the yield and availability of phosphorus when they are used alone (Sutriadi et al., 2014) or combined with green manures (Nabahungu et al., 2007). Research on the use of phosphate rock initiated in Burundi by Scott (1988) should be continued with purpose to offer alternative and local inputs to correct phosphorus unavailability. To improve the level of soil fertility in Burundi, increasing the quantity of phosphorus and potassium in fertilizers used will correct the low availability observed (Figure 8). This will involve the supply of mineral fertilizers rich in these elements and the combination of these fertilizers with organic fertilizers (Adekiya et al., 2019). This not only increases yields but also increases the nutritional quality of feed (Adekiya et al., 2019)

Usefulness of fertility maps

The similar fertility maps have been developed by other authors and the fertility maps show the distribution of nutrients in a territory (Jena et al., 2015).

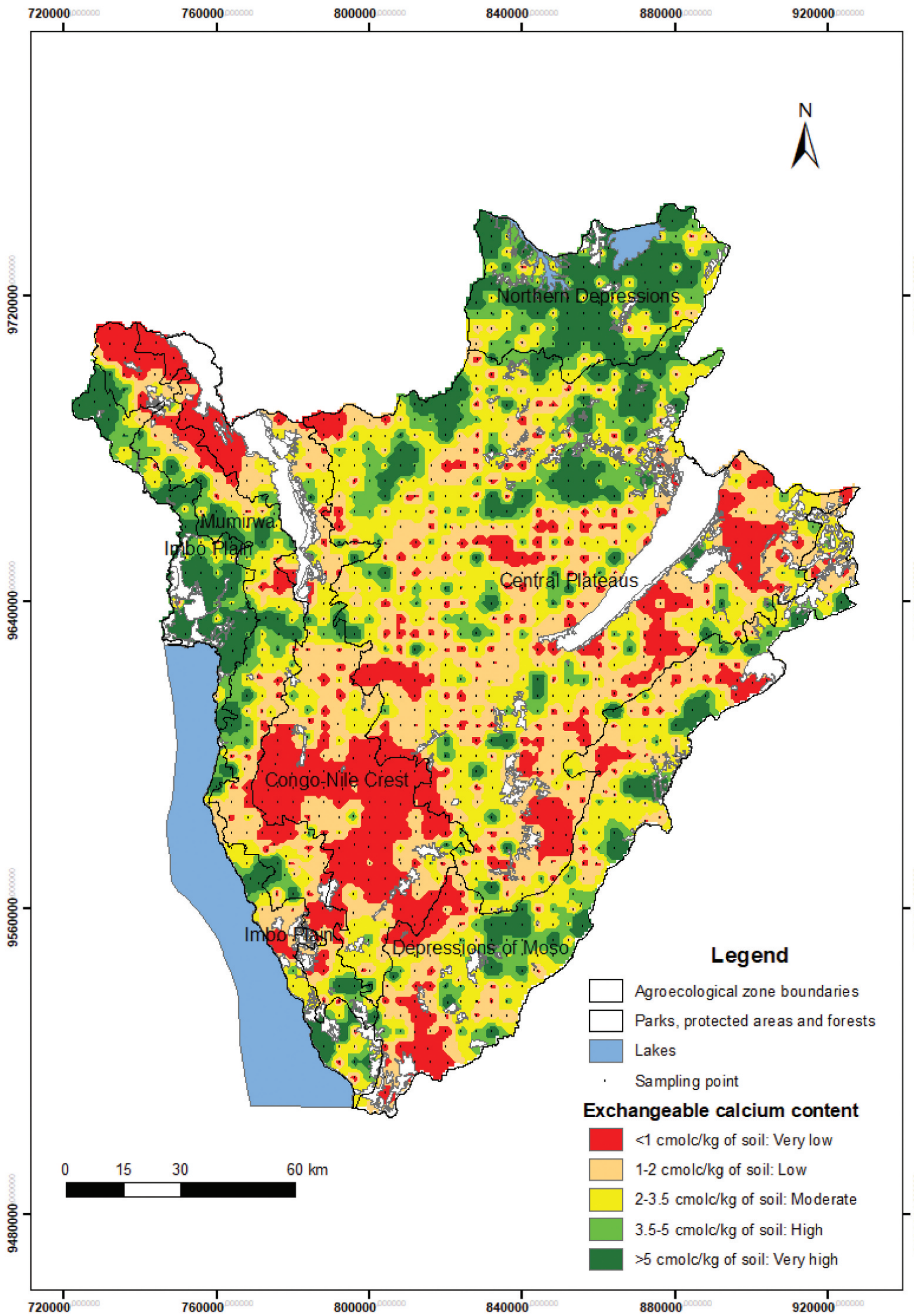

Figure 7a. Map of exchangeable calcium content with delimitation of agro-ecological zones.

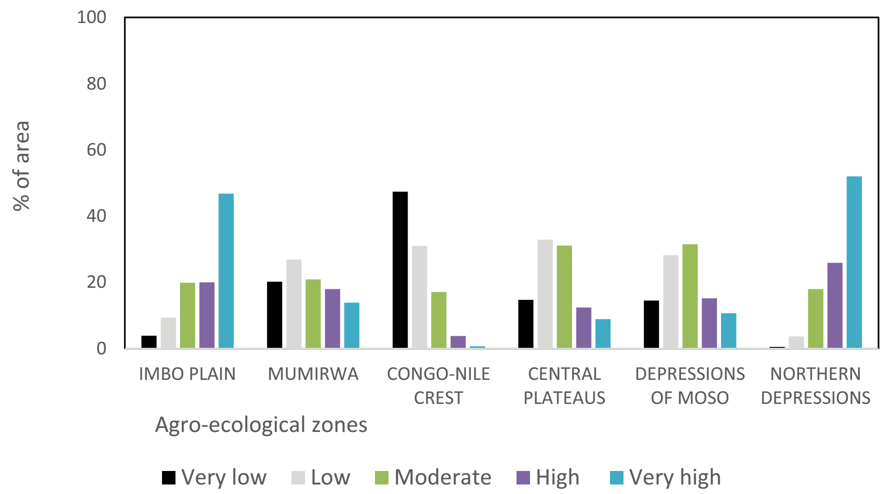

Figure 7b. Percentage of different categories of exchangeable calcium in relation to agro-ecological zones.

The distribution can be homogeneous in the subdivisions of a territory (Jena et al., 2015), i.e. certain subdivisions are enriched in nutrients than others. The distribution can be heterogeneous with variations within subdivisions of a territory (Patil, 2011). This is the case of Burundi where the different mapped parameters are distributed in a heterogeneous way within the AEZs (Figures 2, 4, Figures 6, 8). This heterogeneous distribution does not allow to have a specific fertilisation recommendation for each AEZ but rather to adapt to specific conditions of farms or lower subdivisions. The fertility maps also help to assess soil fertility (Khadka et al., 2019). With soil samples taken from sites with known geographic coordinates (Figure 1), this allows to always return to the same site to sample and analyse the samples to follow the evolution of the fertility.

It allows verifying that the practices implemented to improve the level of fertility have produced the expected effects. In the short and medium term, the fertility maps allow fast decision-making to correct the fertility (Rawal et al., 2018).

The overall percentages of the most deficient areas are known and the decision makers can quantify the inputs needed for the correction. This allows the implementation of a soil correction planning and policy.

Conclusion

The present study reveals that soil fertility is constrained by low pH, available phosphorus, and exchangeable potassium, which negatively affect nutrient availability and exacerbate aluminum toxicity. These deficiencies are particularly pronounced in the Congo-Nile crest, Central Plateaux, and Mumirwa agroecological zones (AEZs). Phosphorus and potassium deficiencies are geographically heterogeneous, requiring localized intervention. pH correction can be prioritized in areas with low pH, while phosphorus and potassium supplementation should be adapted to specific conditions. The fertility maps produced provide critical data for soil management and decision-making, supporting interventions such as erosion control, nutrient recycling, and targeted supplementation with fertilizers. These maps offer a foundation for long-term fertility monitoring and sustainable agricultural practices, not only for Burundi but also for regions with similar soil conditions. The generated soil fertility maps provide valuable insights that can inform national strategies for soil fertility management, guide policy-making, and support targeted fertilizer recommendations. By highlighting the spatial variability of soil fertility parameters across agroecological zones, these maps enable decision-makers to allocate resources efficiently and tailor agricultural interventions to local conditions. The maps can also assist in the development of site-specific nutrient management plans, enhancing the effectiveness of fertilization practices. Looking ahead, future research should focus on updating these maps over time to capture temporal changes in soil fertility. Integrating crop yield data with soil fertility information would also provide a more comprehensive understanding of soil-plant interactions. Finally, expanding the scope of the study to include precision nutrient management recommendations can further improve agricultural sustainability and productivity.

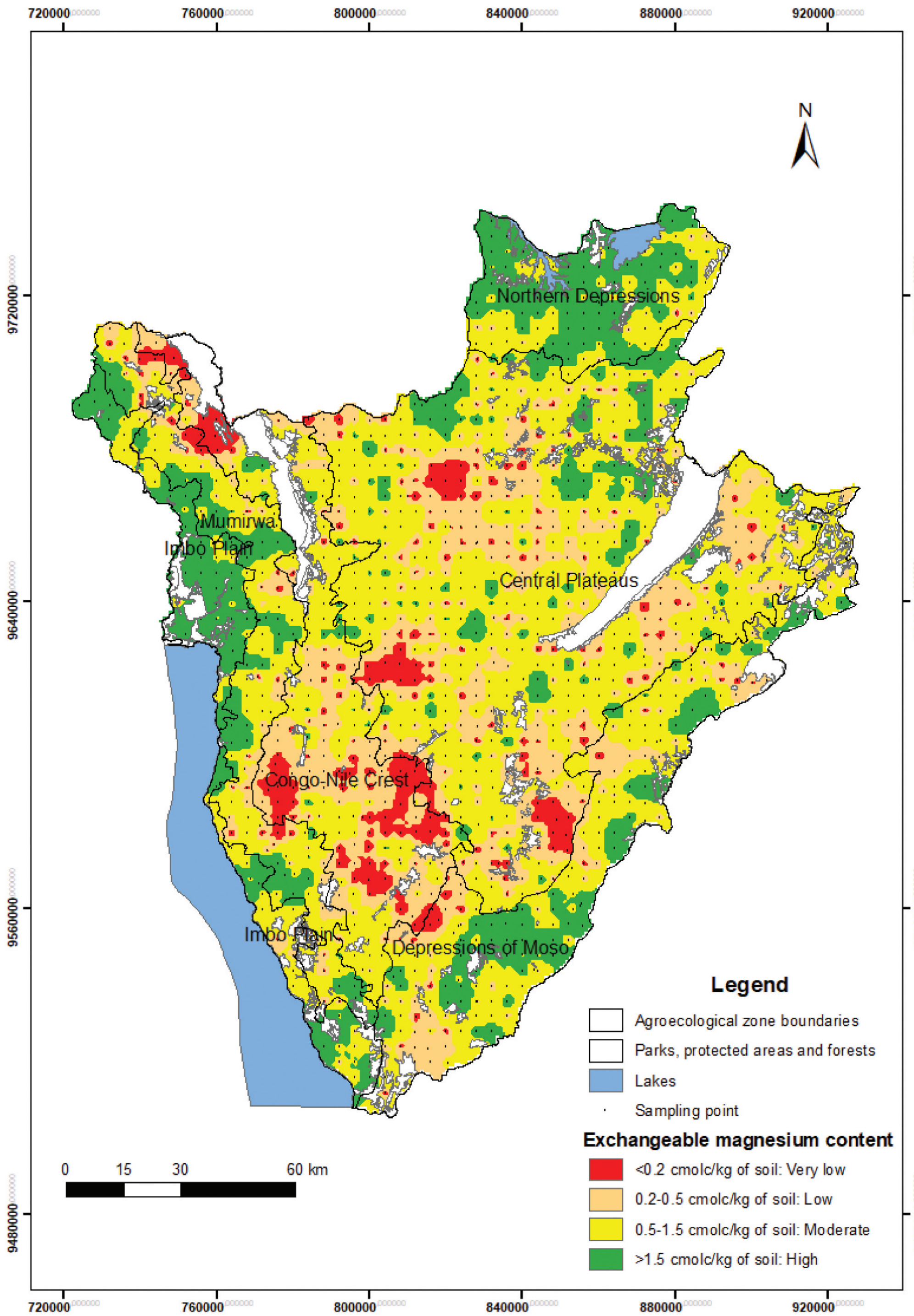

Figure 8a. Map of exchangeable magnesium contents with delimitation of agro-ecological zones.

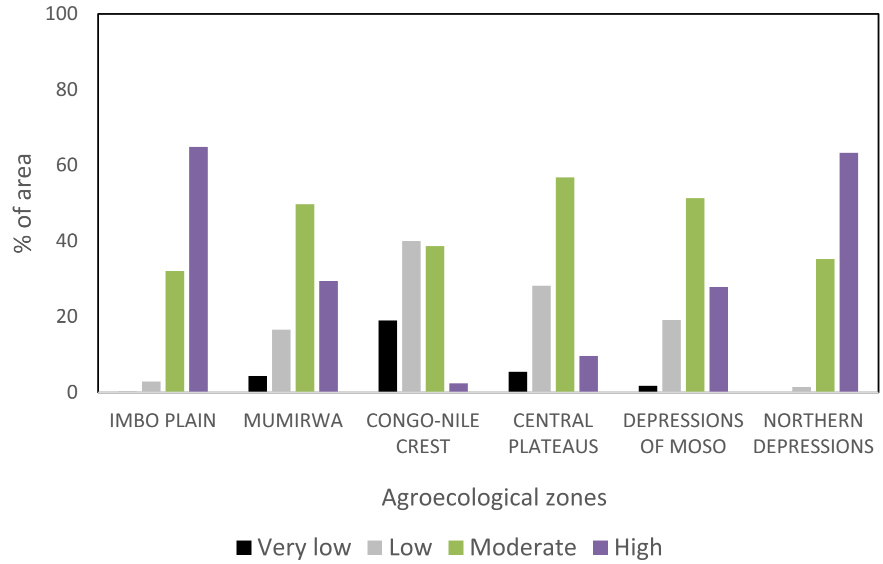

Figure 8b. Percentages of different categories of exchangeable magnesium content in relation to agro-ecological zones.

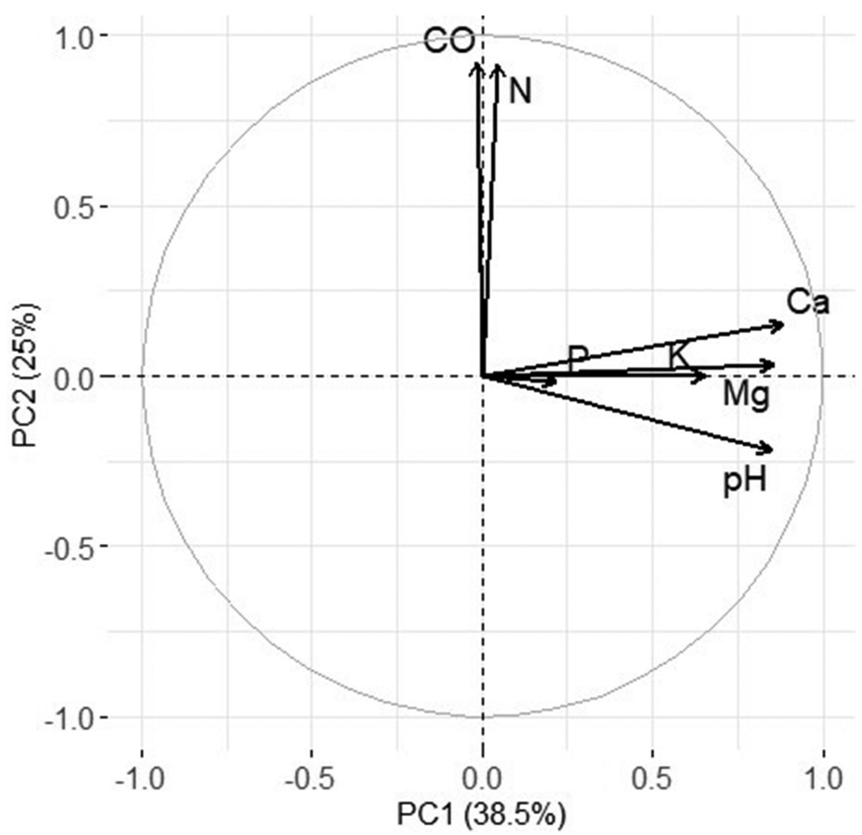

Figure 9. Principal component analysis between soil characteristic.

Table 4. Proportion of soil properties content variation and traits contribution explained by the five first principal component analysis

Variables	Dim.1	Dim.2	Dim.3	Dim.4	Dim.5
pH	0,266	0,028	0,000	0,000	0,616
SOC	0,000	0,482	0,000	0,001	0,000
N	0,001	0,476	0,001	0,001	0,050
Ca	0,289	0,013	0,022	0,079	0,004
Mg	0,270	0,001	0,043	0,102	0,257
K	0,157	0,000	0,027	0,747	0,066
P	0,017	0,000	0,906	0,070	0,006
Eigenvalue	2.69	1.75	1.00	0.70	0.35
% variance	38.48	25.00	14.22	10.05	5.00
cumulative % of variance	38.48	63.48	77.71	87.76	92.76

SOC: Soil organic carbon.

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