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Original Research Paper

Optimizing Soil Fertility Management Decision in Mali by Remote Sensing and GIS

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Understanding soil variability is significant for agriculture soil planning and management. Soil test is also a widely accepted methodology in nutrient management. However, its applicability is curtailed in Mali due to the high cost of implementation. Thus, soil fertility maps could be used as a soil fertility management decision support tool. In the current study, Remote Sensing, Geographic Information System and laboratory analysis were used to identify soil fertility status. Stratified randomized sampling was performed using landsat image and visual interpretation. 52 points were sampled at 0-20 cm depth and analysed to determine soil clay, sandy and silt content as well as soil pH, C, N, P and K. The combined use of visual interpretation, kriging and thematic analysis function of ArcGIS allowed determining clay, sand and silt spatial distribution. Soil texture triangle was used to identify the textural classes. Ordinary Kriging method was used to analyse the spatial variability of soil pH, C, N, P and K. Soil clay content was low (1.22 - 12%), soil sandy was high (47 - 85%), soil pH was from extremely to moderate acidic (4.7 - 6.1). Carbon, Nitrogen, Phosphorus and Potassium were below the critical levels, ranging from negligible to 0.4%; negligible to 0.03%; 2.22 to 5.5 mg/kg and from 0.01 to 0.07 cmol respectively. The overall current soil status was poor.

Keywords: Remote Sensing, Geographic Information System, Soil, Management, Decision, Mali.

INTRODUCTION

The challenge for agriculture in Mali is to meet the increasing demand for food in sustainable way. Soil fertility degradation has made this task difficult. In Mali, Agriculture is dominated by the poor scattered smallholder farmers and generally based on soil nutrients mining. Deficiency in rainfall, declining soil fertility and mismanagement of plant nutrients constitute the major constraint for agriculture production and food security today. Fertilizer application based on soil test is the best way to know how many nutrients a farmer needs to apply in a given year on a given soil in order obtain a good yield.

However, soil test applicability is severely limited due to the high cost of implementation. Thus, information on the spatial extent and the levels of soil physical and chemical properties at large (village) scale can improve and optimize decision in soil fertility management for the smallholder farmers. The objective of this study was to assess the use of remote sensing (RS) and Geographic Information System (GIS) in soil fertility management decision.

MATERIALS AND METHODS

Study site

Research was carried out at Siguidolo in the Sahelian zone of Mali, between 6° 44' 54" and 6° 46' 12" W and 12° 54' 00" and 12° 56' 24" N. The total area was 1,157 ha. Rainfall is unimodal and ranges from 600 – 800 mm. The landscape of the region is dominated by plane surfaces with an average altitude between 300 and 352 meters from sea level. Soils in the area were classified as Ultisol (USDA, 1999).

Soil mapping

Visual interpretation of Landsat image was used to stratify and delineate soil units. Stratified random sampling was done. Fifty-two locations were sampled and georeferenced. A composite of soil samples bulked from three points spaced about 20 m apart were taken from a 0-20 cm depth and saved

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in plastic bags for laboratory analysis. The locations of the sampled points are presented in Figure 2.1. The spatial variability of the selected soil parameters was evaluated using Gen-Stat edition 9. Laboratory analysis data of clay, silt and sand were used to generate their respective maps using Arc-GIS combined with visual interpretation of images. The soil textural triangle was used to determine soil texture classes for mapping purposes. Figure 2.2 shows the process of producing soil physical properties maps.

Spatial structure and variability of the selected soil chemical properties

Various methods were used to generate information on the spatial structure and variability in the measured soil chemical properties (pH, SOC, N, P and K). These comprised: Genstat statistical package, semivariograms and kriging. Genstat package was used to summarize the measured data and to describe the degree of spatial variability. Normality test was used to check whether the data are normally distributed or not.

Semivariogram was used to characterize the degree of dependency among the measured data. Kriging was used to extrapolate information from the sampled point to unsampled location and to provide the spatial structure of the selected soil nutrients. The flowchart for the spatial structure analysis is presented in Figure 2.3. An overlay of the three classes of N P K and C in the ArcGIS environment allowed generating soil fertility status map. Figure 2.4 shows the process used to produce the soil fertility map.

RESULTS AND DISCUSSION

The major constraint limiting agriculture production is the low inherent fertility of the soils and its continued decline over the years. In order to reverse this trend, there is the need to replenish the lost nutrients which result from crop uptake and harvest, erosion and leaching. This will require the development and implementation of spatially-oriented soil fertility management strategies to benefit the many scattered farms of smallholder farmers.

The requirements for the development of an effective nutrient management strategy for a given agroecology include among others, the delineation of the soils and their physical and chemical characteristics. The spatial distribution of data on these parameters and their magnitudes facilitate the establishment of the fertility status of the soils in the entire area which in turn, will support what site-specific nutrient management strategy to adopt. This approach is recognized as a better alternative to the current prevailing blanket nutrient application rates often recommended in most sub-Saharan countries.

Fertile and productive soils have the ability to supply nutrients and water to enable plants maximizes the climatic resources of a given location. Understanding the physical and chemical properties of the soil is essential for developing measures to sustain higher crop yields.

Assessment and mapping of soil physical properties

Soil clay content

The clay content of the topsoil is presented in Figure 3.1. Clay percentage ranged from 1.22% to 12% classified as 1.22-4.51%; 4.51-8.11%; and 8.11 - 12% with their respective area of coverage as 363.66 ha (41.13%), 459.25 ha (51.95%) and 60.87 ha (6.88%). The low amount of clay content observed in the area reduces water and nutrient holding capacity.

Silt content

Figure 3.2 illustrates silt content in the study area. Silt percentage was between lowest of 16% and highest of 40.44%. These were categorized into class 16 - 22.30%; 22.30 - 33.50%; and 33.50- 40.44% for mapping purposes. Their areas of coverage were 405.2 ha (45.83%), 233.46 ha (26.19%) and 231.87 ha (26.01%) respectively. Silt has a smooth or floury texture.

Sand content

Sand content is presented in Figure 3.4. The percentage of sand ranged from a lowest of 46.52% to a highest of 85%. The lowest sand content 46.52 - 59.28% was found in 19.59% of area; 59.28 - 71% was observed in 36.84% and 71 - 85% was in 43.56%. Higher amount of sand content significantly reduces water and nutrient holding capacity.

Soil texture

Figure 3.5 shows the geographic location of soil textures and their spatial distribution at Siguidolo. The texture comprised: loam, loamy sand, sandy loam, and sand which occupied 8.84%, 7.80%, 77.94% and 5.42% of the area respectively. The main soil texture observed was sandy loam. As sandy soils, they generally have high bulk density, infiltrability and hydraulic conductivity and low water holding capacity.

Values for these parameters, however, differ with the texture. Typical values (Landon, 1994) for bulk density are 1.2 to 1.8 Mg m-3 for sands and sandy loam. Infiltration rates (cm h-1) range from 0.1 to 2.0, 1.0 to 8.0 and 2.0 to 25 for loam, sandy loam and sand respectively. The ranges of values for hydraulic conductivity (cm h^{-1}) are 6-12, 12-25 and 25-50 for loamy sand, sandy loam, and sand respectively. Available water capacity (mm m^{-1}), on the other hand, vary from 80 for sand, through 120 and 150 for sandy loam and loamy sand, to 170 for loam.

The management of these soils should be directed at practices that will optimize soil infiltrability and hydraulic conductivity, reduce erosion, enhance soil moisture storage and reduce non-productive evaporation losses. Such sustainable land management practices include reduced tillage, plough-plant, ridge and furrow system, tied ridging, zai, circular bunds, mulching and appropriate residue management to add organic matter to the soil.

Assessment and mapping of soil chemical properties

Spatial structure and variability of soil chemical properties

Table 3.1 shows the results of the basic statistical analysis of the selected soil parameters. The mean values give the general magnitude of the measured parameters at the site. Of great importance to the development of sustainable land management strategies are the measures of variability in the measured values and their dispersion about the mean. These include the coefficient of variation, skewness and kurtosis. The CV ranged from a low of 5.54% for pH to a high of 92.2% for C. Total N, P and K presented variable intermediate values from 29.81% to 60.1%. The skewness values were positive for C, N, P and K and negative for pH.

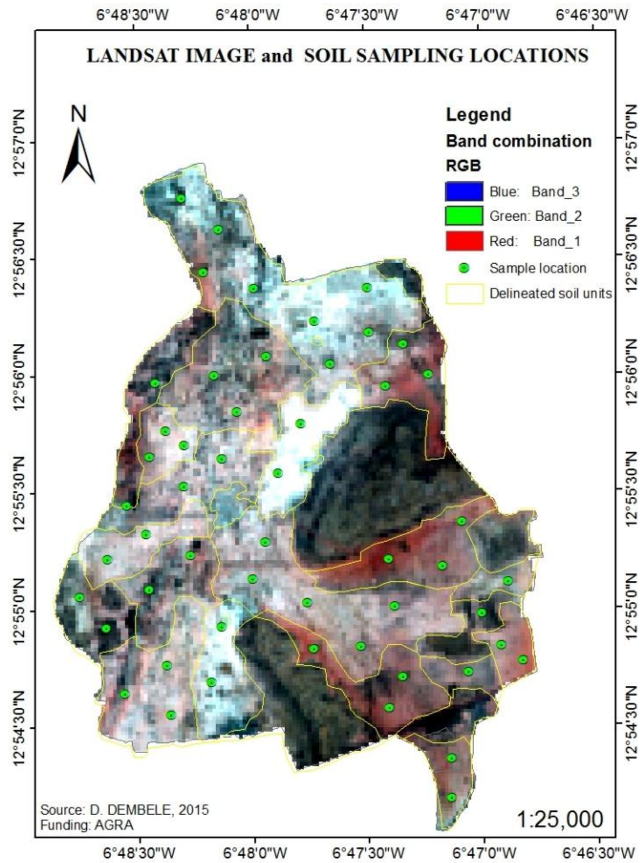

Figure 2.1: Landsat image and soil sampling location

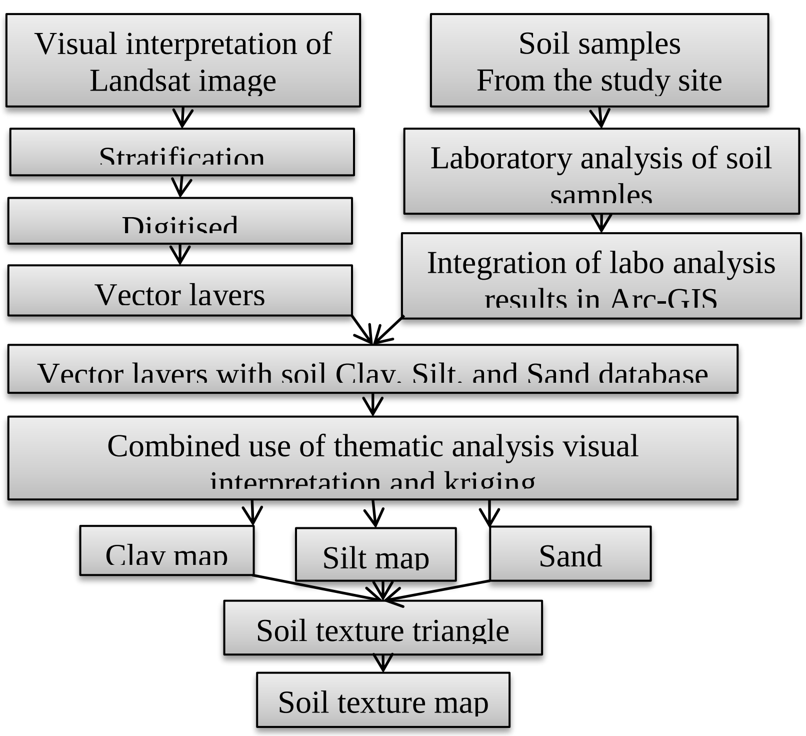

Figure 2.2: Flowchart of soil physical properties mapping

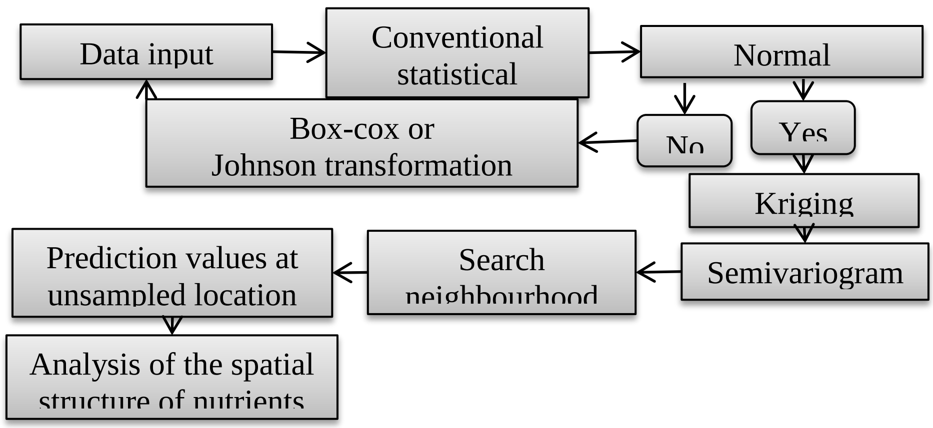

Figure 2.3: flowchart for the spatial structure analysis

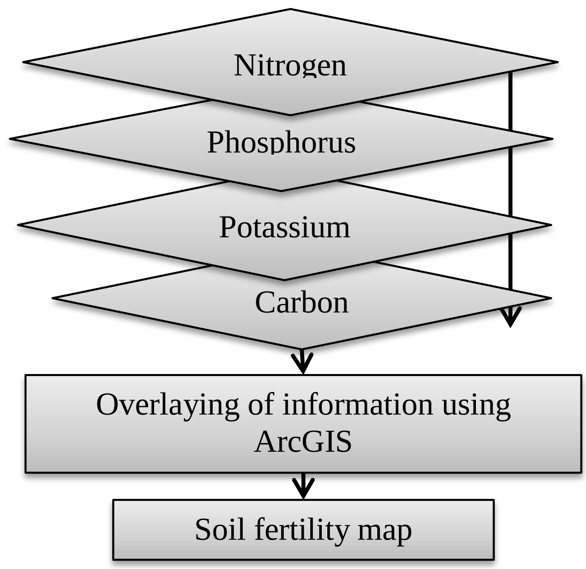

Figure 2.4: Flowchart for generating soil fertility status map

These values have implications for the magnitude of most values relative to those of extreme values and their spread about the mean. Kurtosis, on the other hand, indicates the degree of dispersion about the mean depending on whether it is less (< 0) (highly dispersed) or greater (> 0) (less dispersed) than zero. The former and the latter classes covered C, N and K and pH and P respectively.

The data were further subjected to Anderson-Darling test for normal distribution to satisfy the requirements for kriging. The data are presented in figures 3.6, 3.7, for pH and phosphorus and the transformed data in figures 3.8, 3.9 and 3.10 for C, N, and K respectively. The figures show the mean, standard deviation and the probability values of the mean parameters.

In order to generate the spatial structure of the selected soil parameters, semivariograms were calculated. According to ESRI (2010), a semivariogram is one of the significant functions to indicate spatial correlation in observations measured at sample locations. It is commonly represented as a graph that shows the variance in the measured parameters relative to the distance between all pairs of sampled locations. In this study, several models were tested and the best that described the spatial structures were chosen. Gaussian and exponential models were the best. The spatial variations identified by the semivariogram models are presented in Table 3.2 with the respective for pH, C, N, P and K, and in Figures 3.11, 3.12, 3.13, 3.14 and 3.15

The Table 3.2 shows the parameters of semivariogram models generated. The Gaussian and exponential models were used. The nugget ranged from highest 0.310 for available phosphorus to lowest 0.0002 for potassium. The sill oscillated between a highest of 1.061 for available phosphorus to a lowest of 0.0005 for potassium. The range, with values between 1185.47 to 2090 m, ranked in decreasing order of K > N > C > P > pH. The ratio of nugget/sill was in the order of total nitrogen > exchangeable potassium > pH > available phosphorus > SOC with a range of 16.6 to 140.5%. The spatial dependence was strong for SOC, medium for soil pH, soil available phosphorus and soil exchangeable potassium and weak for soil total nitrogen.

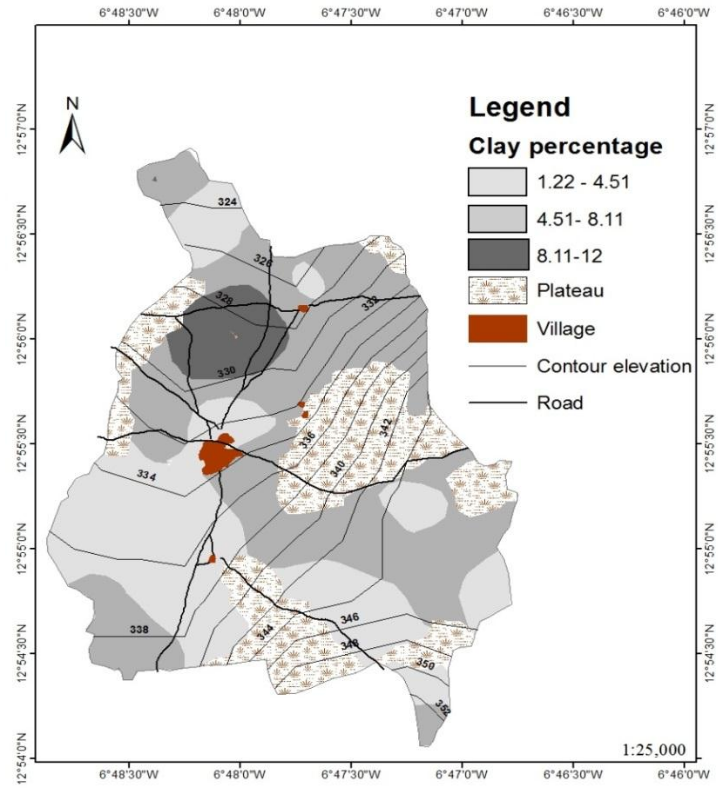

Figure 3.1: Spatial distribution of clay at Siguidolo in 2013

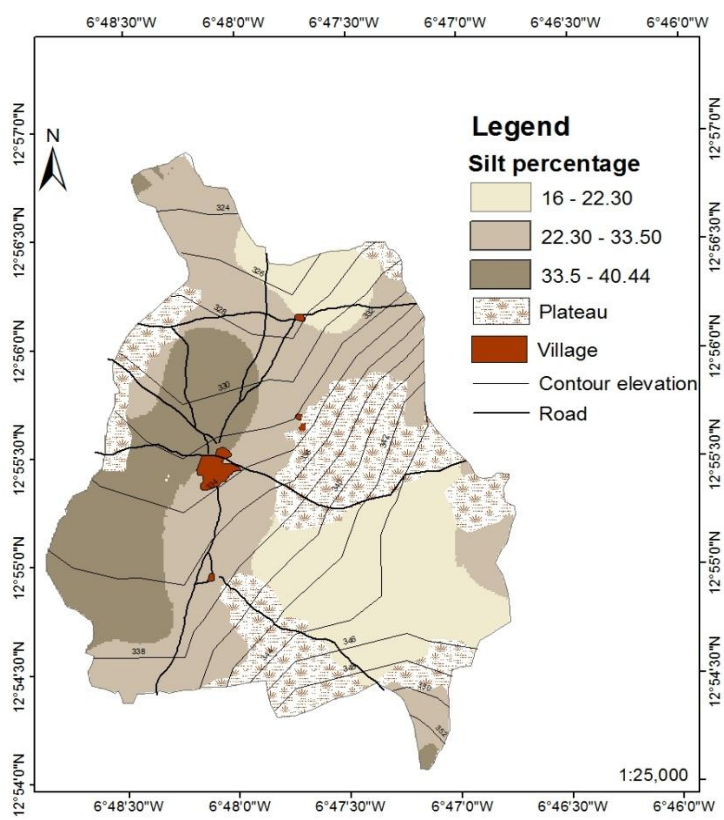

Figure 3.3: Spatial distribution of silt at Siguidolo in 2013

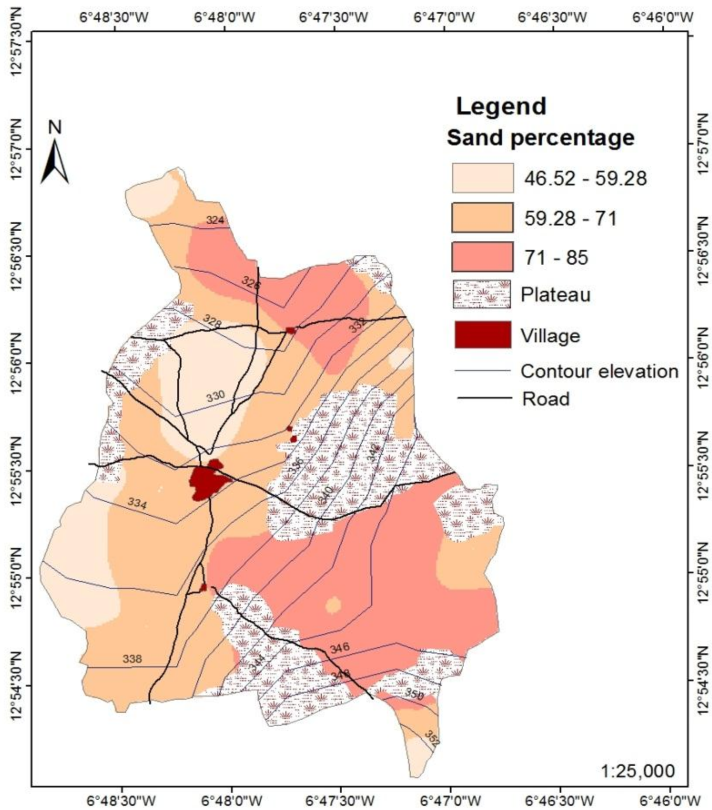

Figure 3.4: Spatial distribution of sand at Siguidolo in 2013

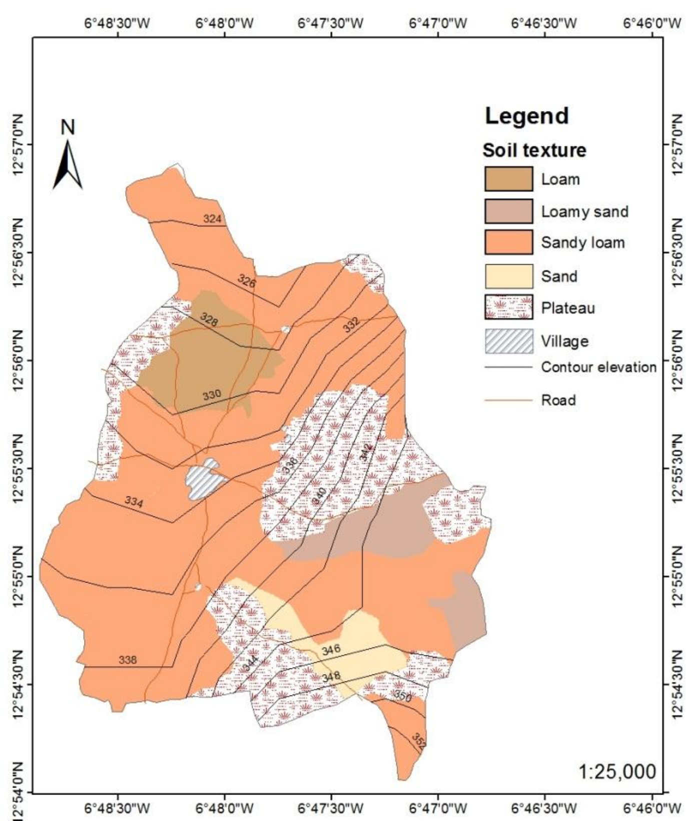

Figure 3.5: Spatial distribution of soil texture at Siguidolo in 2013

Table 3.1: Results of basic statistical analysis for the selected soil parameters

Soil nutrient	pH	C %	TN %	Avail P Mg kg^{-1}	K Cmolc kg^{-1}
Mean	5.47	0.15	0.016	3.76	0.02
Median	5.48	0.10	0.02	3.68	0.02
Minimum	4.70	0.01	0.00	1.38	0.01
Maximum	6.22	0.50	0.03	7.11	0.05
Coefficient of variation (CV)	5.54	92.20	43.72	29.81	60.61
Standard deviation	0.30	0.14	0.007	1.12	0.01
Skewness	-0.26	0.58	0.33	0.40	0.58
Kurtosis	0.44	-0.92	-0.54	0.76	-1.29

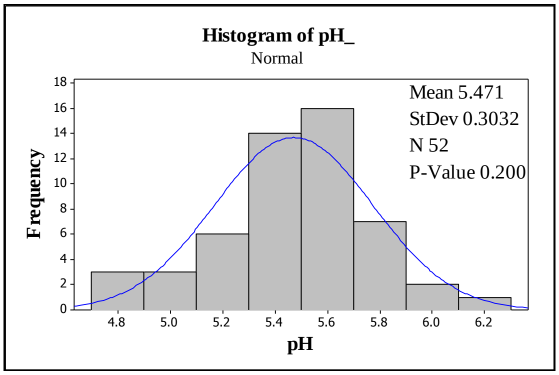

Figure 3.6: Anderson-Darling normality test for pH

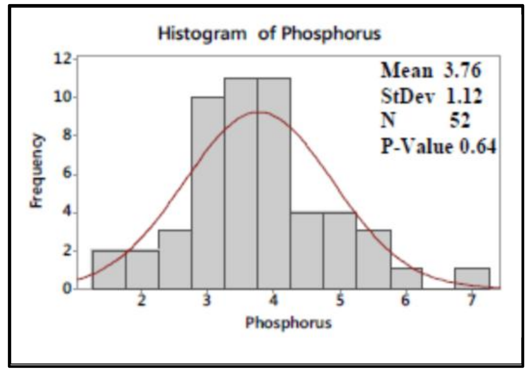

Figure 3.7: Anderson-Darling normality test for phosphorus

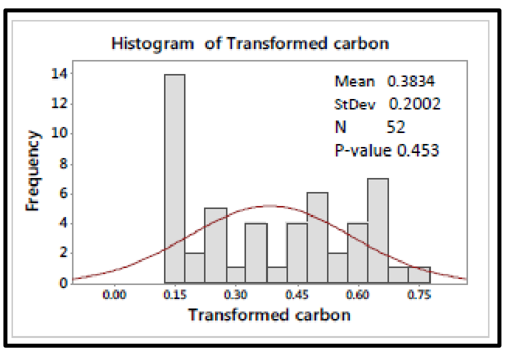

Figure 3.8: Anderson-Darling normality test for carbon

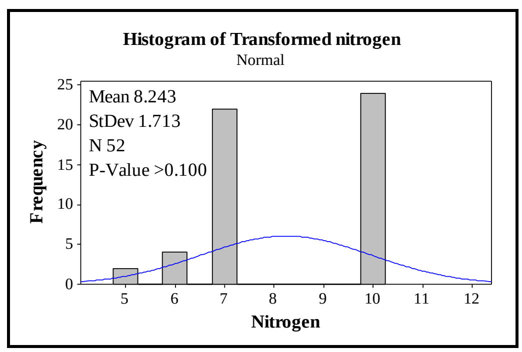

Figure 3.9: Anderson-Darling normality test for Nitrogen

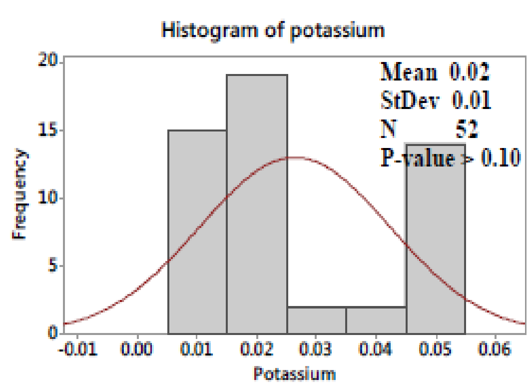

Figure 3.10: Anderson-Darling normality test for potassium

Table 3.2: Parameters of semivariogram models for the study

Soil nutrients	Theoretical Model	Nugget (Co)	Sill (Co+C)	Range (A) (m)	(Co/Co+C) (%)	Spatial dependence
pH	Gaussian	0.023	0.072	1185.47	31.9	Medium
Carbon (%)	Exponential	0.003	0.018	1793.37	16.6	Strong
Total Nitrogen (%)	Exponential	0.111	0.079	1994.2	140.5	Weak
Av. Phosphorus (mg kg^{-1})	Exponential	0.310	1.061	1248.80	29.2	Medium
Exh. Potassium ($cmol_c$ kg^{-1})	Exponential	0.0002	0.0005	2090	40	Medium

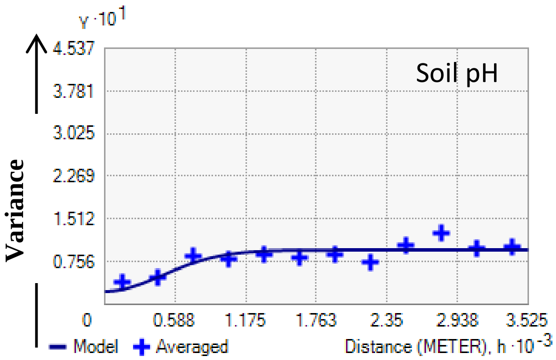

Figure 3.11: Semivariogram for soil pH

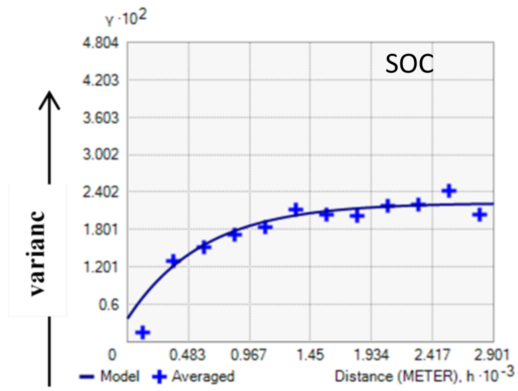

Figure 3.12: Semivariogram for soil organic carbon

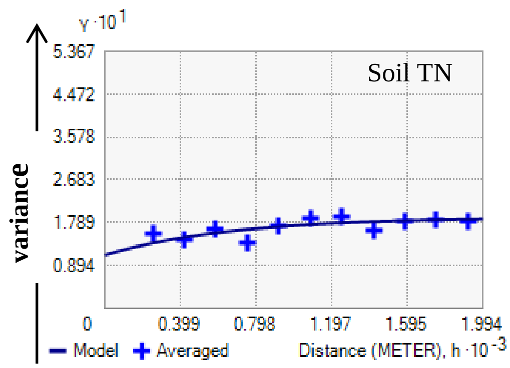

Figure 3.13: Semivariogram for total nitrogen

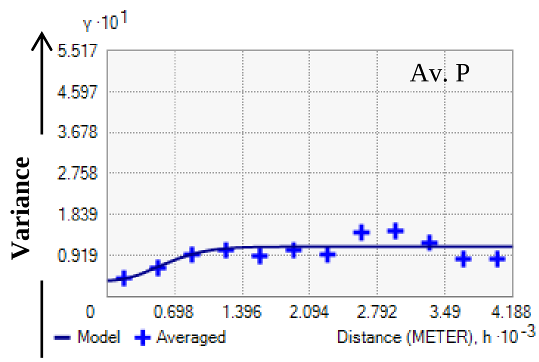

Figure 3.14: Semivariogram for available phosphorus

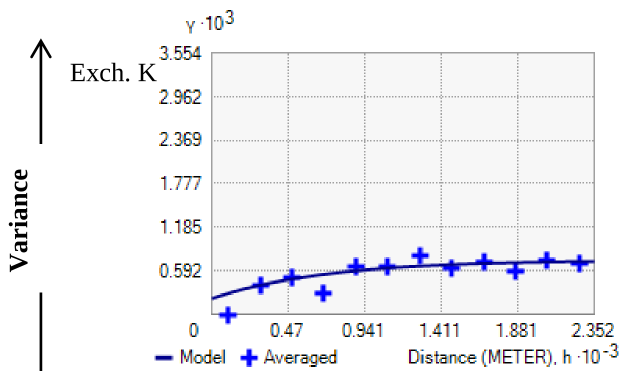

Figure 3.15: Semivariogram for exch. potassium

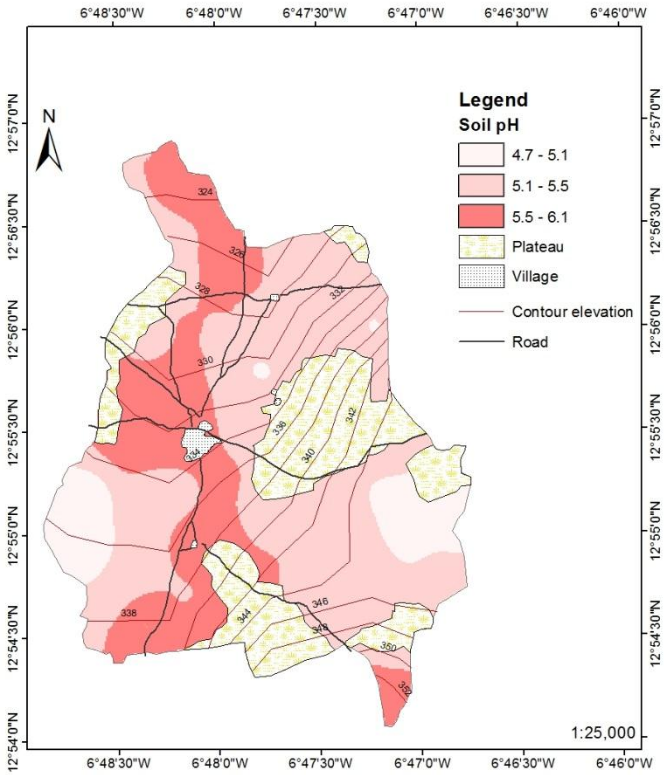

Figure 3.16: Spatial distribution of soil pH at Siguidolo in 2013

Spatial distribution of soil pH

Figure 3.16 shows the spatial distribution of soil pH at Siguidolo in 2013. Soil pH ranged from 4.7 to 6.1. Following the classification in Landon (1991), the values were grouped into three classes. These were very strongly acidic, strongly acidic and moderately acidic with their respective areal coverage of 9.28%, 61.38% ha and 29.34% of the area. The strongly (pH 47 to 5.5) covered 624.65 ha (70.66%) of the arable land. The low pH may be due to the losses of basic cation and other nutrients through erosion, leaching and crop uptake and harvest without replenishment and poor crop residue management which leads to low levels of SOM.

The very strongly to strongly acidic conditions have implications for nutrient availability and management. The low pH is favourable for aluminium and manganese toxicity, deficiency and/or unavailability of plant nutrients such as P, Ca, K, Mg and Mo as observed by Tisdale et al. (1985) and Wang et al. (2006). Under such conditions, bacterial activity is reduced and nitrification of organic matter is significantly retarded (Landon, 1991). Sivarugu and Horst (1998) also reported that in acid soils, excess aluminium primarily injures the root apex and inhibits root elongation. The poor root growth leads to reduced water and nutrient uptake with a consequent reduction in plant growth and yield. The acidic conditions of the soils in the study area therefore present a major constraint to crops production by the smallholder farmers who depend mainly on rainfall and the nutrient stocks of their soils. Thus, soil nutrient management for sustained crop growth and yield should be directed at strategies to address acidity problem through liming and organic matter management, taking into consideration the spatial magnitude of the pH.

Spatial distribution of SOC

Figure 3.17 presents the spatial distribution of soil organic carbon content in Siguidolo in 2013. SOC ranged from 0.12 to 0.4%. The three classes of negligible to 0.12%; 0.12 to 0.23%; and 0.23 - 0.42% covered 42.02%; 32.72% and 25.26% of the arable land respectively.

Soil organic carbon (SOC) is an indicator of soil organic matter (SOM) which has important beneficial effects on the physical, chemical and biological properties of the soil. Thus, Maurice et al. (1998) used SOM as an indicator of soil fertility, aggregate stability and erosion. As SOM increases, available N, P, K as well as some micronutrients also increase (Oates, 1998). Acquaye (1990) reported that organic matter is the main source of N, P and S for plant growth in no-fertilizer smallholder agriculture. In addition, SOM contributes to enhanced soil water storage and maintenance of stable pH.

These beneficial effects of SOM have eluded the many smallholder farmers at the study area because the soils are very low in organic carbon with values ranging from 0.12 to 0.4%. These values compare with the critical level of 0.6% in Mali (soil water and plant laboratory of Mali, 2008) and 2% for tropical soils (Barrows, 1991). According to the latter author, such low levels of SOM are indicative of soil degradation and high risk of soil erosion.

The competing uses of crop residues as animal feed which constrain their return to the soil and the general sparse vegetation and intensive cropping may account for the low SOC content of the soils. Farmers should, therefore be encouraged to return as much crop residue as possible to the soil in addition to application of manure and compost.

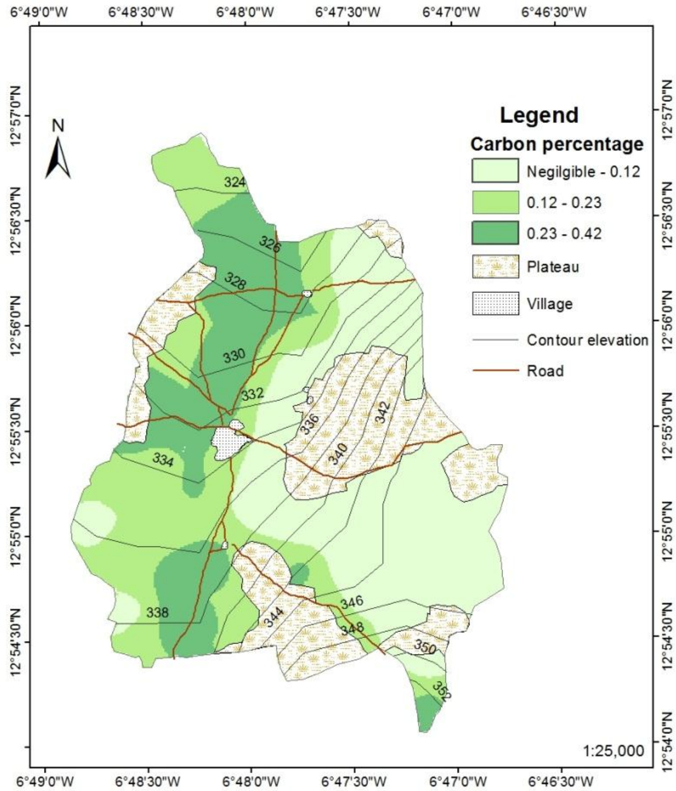

Figure 3.17: Spatial distribution of soil organic carbon at Siguidolo

There is the need to search for local leguminous plants which produce large quantities of biomass but not eaten by livestock for possible inclusion in smallholder farming systems.

Spatial distribution of soil total nitrogen

The different levels and distribution of total nitrogen in 2013 are presented in Figure 3.18. The percentage of total nitrogen content was very low. It ranged from negligible to 0.03%. The 3 classes, negligible to 0.01%; 0.01 to 0.02% and 0.02 to 0.03% occupied 36.78%); 27.05% and 36.20%) of the arable area, respectively.

Nitrogen usually has a greater effect on crop growth, crop quality and yield. The low nitrogen content would therefore affect plant growth and yield. The very low levels (0.01-0.03%) of N are not surprising considering its close association with SOM, which was also very low. The general high hydraulic conductivity of sandy soils could cause leaching of Nitrogen. The situation is exacerbated by the intensive cropping without replenishing the depleted nutrients. Intervention in the area should be directed to enhance soil nitrogen to the adequate level of 1.2% (LSEP, 2008) or to 0.13 to 0.23 (Soil Testing Guide)

Spatial distribution of available phosphorus

The spatial distribution of available phosphorus of the topsoil is presented in Figure 3.19. The available phosphorus ranged from 2.22 to 5.51 mg/kg. These were categorized into 2.22-3.39 mg/kg on 256.7 ha (29.03%), 3.39-4.26 mg/kg on 464.97 ha (52.37%) and 4.26 - 5.51 mg/kg on 164.43 ha (18.60%) of the arable land.

Available phosphorus was similarly very low with values ranging from 2.2 to 5.5 mg kg^{-1} compared to the critical level of ≤ 7 mg kg^{-1}(LSEP, 2008). The low level of organic matter, the very strongly to strongly acidic conditions and uptake without replenishment may account for the low level of P in the soils of the study site.

Spatial distribution of exchangeable potassium

Potassium levels and their spatial distribution are presented in Figure 3.20. The soil K status varied from 0.01 to 0.07cmolc kg^{-1}. The three classes for mapping were 0.01-0.02 cmolc kg^{-1}, 0.02 to 0.04 cmolc kg^{-1} and 0.04 to 0.07 cmolc kg^{-1} covering 67.09%, 26.82% and 6.09% of the study area respectively. For the same underlying reasons of very low organic matter, the sandy soils, with low clay content, high hydraulic conductivity and nutrient losses through leaching and erosion without replenishment, the K levels of the soil were also low.

Soil fertility map

The superimposition of carbon, total nitrogen, available phosphorus and potassium generated a soil fertility status map of the study area (Figure 3.21). The area was delineated into three soil fertility classes namely low, very low and extremely low. Their respective percentage of coverage were 4.81%, 79.93% and 15.26%.

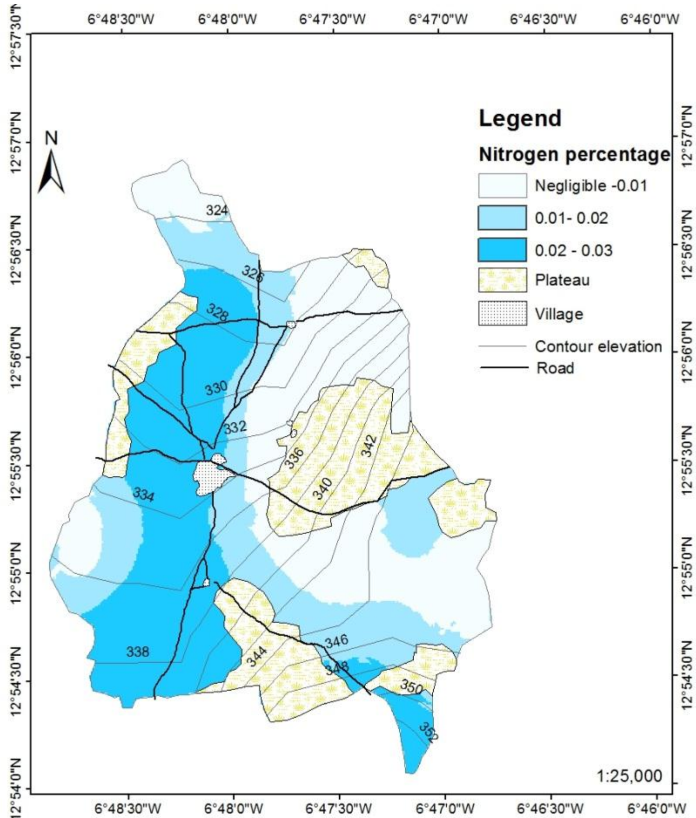

Figure 3.18: Spatial distribution of total nitrogen at Siguidolo in 2013

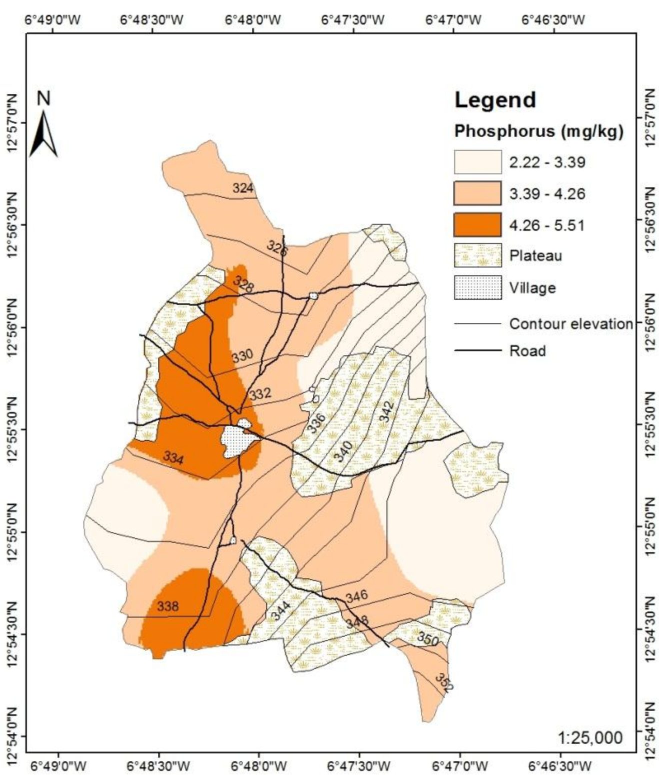

Figure 3.19 Spatial distribution of available phosphorus at Siguidolo in 2013

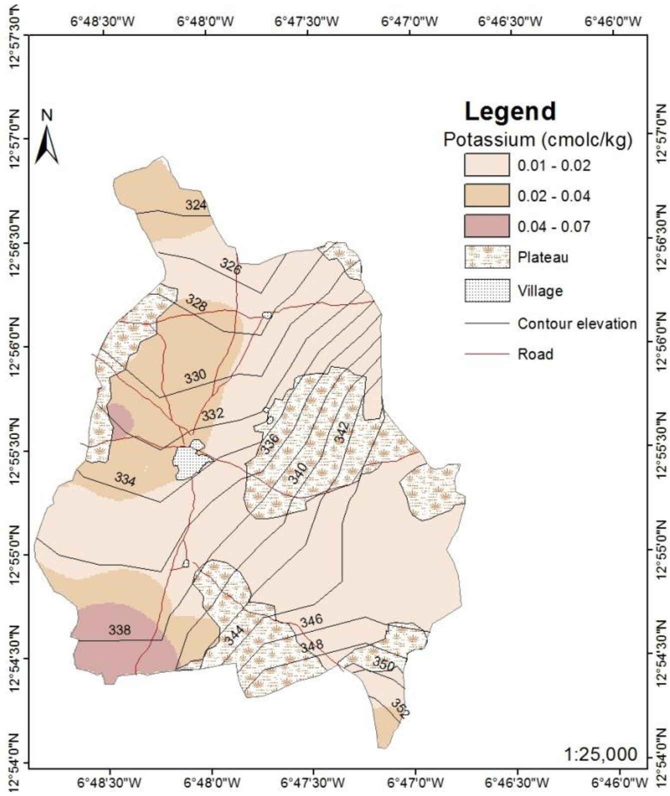

Figure 3.20: Spatial distribution of exchangeable potassium at Siguidolo in 2013

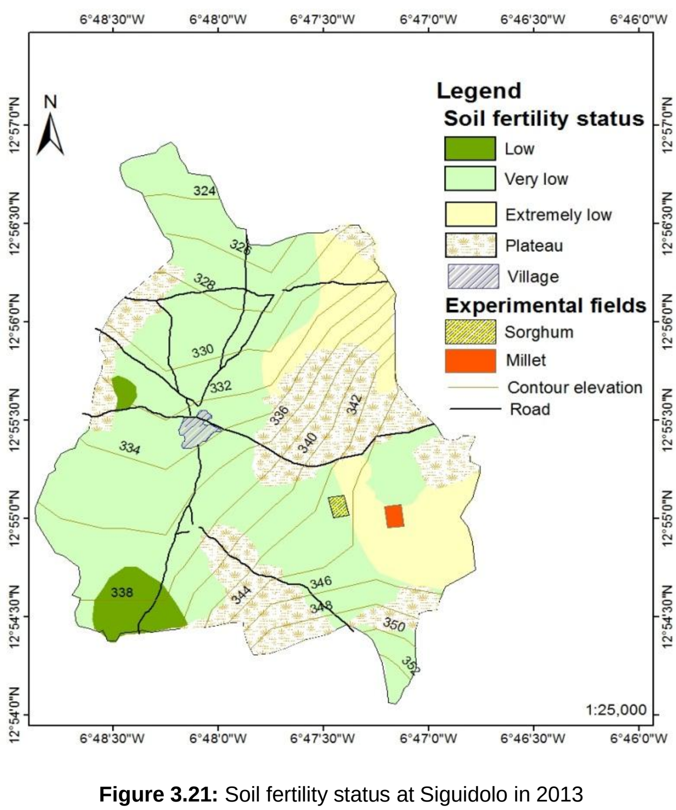

Figure 3.21: Soil fertility status at Siguidolo in 2013

The overlay of N, P, K and C maps produced a generalized soil fertility map with low level of fertility. The fertility status of greater part of the area was very low. This is indicative of the very low levels of nutrients recorded in the soils of the area. Sustainable crop production in the Siguidolo area can be achieved only through the development and implementation of integrated soil fertility management strategies. Of prime importance is the soil acidity problem, which is a major constraint to nutrient availability and uptake with resultant decreases in crop yields.

In this regard, integrated nutrient management involving the combined use of mineral fertilizers and organic amendments offer better soil fertility replenishment opportunities (Swift, 1997; Traore, 2003)

Sound soil fertility management, as recommended by Quansah (2000), should therefore use available livestock and poultry manure and crop residues wherever practical, taking appropriate nutrient credit for these materials and using mineral fertilizers to balance the crops nutritional requirements for realistic yield goals.

This will require a set of accompanying soil conservation and water utilization technologies. These include ridge and furrow system, tied-ridging, circular contour bunds, zai, cereal and legume rotations and residue management. The current practice of ridging for water harvesting, use of household waste and mineral fertilizers, though lower than recommended rates, and the emerging millet/sorghum-groundnut/cowpea rotation intercrop in the study area should be fine-tuned into implementable and affordable package for the smallholder farmers. In contributing to this effort, the dynamics of the cropping systems in the study area was studied to show trends as a basis for recommending sustainable cropping systems within the biophysical and socio-economic circumstances of the farmers.

CONCLUSION RECOMMENDATION

The main purpose of this study was to use remote sensing and GIS as decision support tool for appropriate soil fertility management practices, a key factor for improving soil fertility and increase sorghum and millet yields on smallholder farms in Mali. The integration of remote sensing, GIS and conventional georeferenced field sampling facilitated the assessment and mapping of spatial distribution of the soils and their physical and chemical properties. These maps can be used as a guide for the development and implementation of adapted integrated soil fertility management strategies for sustainable crop production in the Siguidolo area.

The soils are generally sandy with sandy loam covering over 70% of the area. This is considered the “benchmark” soil of the study site. They are acidic, ranging from moderately to very strongly acidic. The inherent nutrient content and organic matter are generally very low. The remote sensing-GIS nexus can be further used to study and map the status of land degradation particularly when linked to erosion models, such as the Universal soil less Equation (USLE). Practices that enhance in-situ moisture storage, such as Zai and bunds need detailed studies to enhance crop productivity under rainfed farming.

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