AMELIORATION OF SOIL ACIDITY WITH LIME FOR SUSTAINABLE SOYBEAN PRODUCTION ON FERRALITIC SOILS OF UGANDA– A REVIEW

Abstract

Ferralitic soils are the dominant soil type constituting 33% of the soils in Uganda with a low to moderate inherent productive capacity and are predominantly found in the Central and Western regions of the country. They are highly weathered, acid infertile, have low nutrient reserves thus rendering them incapable of supplying phosphorus, potassium, calcium, magnesium and other mineral elements to support plant growth and increase yield. The degradation of these soils has necessitated decline in crop yields at a time population in the region is rapidly increasing. Despite the never-ending increased in human population and the importance of Agriculture to the households of the country, little or no research has been conducted on Ferralitic (Ferrasols) Acid Soils with the use of soil amendments such as lime to improve fertility for increase yield. Besides, the country's research programs rarely emphasized the use of soil fertility management strategies such as liming. Crop production on these soils is only a small fraction and are variable often less than half of those reported on research stations. This review paper focuses on the extent and effects, causes, challenges and opportunities associated with liming Ferralitic Acid soils and the effects on soil properties and crop yield as a management strategy to improve the productive capacity of these soils. Studies showed that detrimental effects of acid soils can be ameliorated through liming thus improving on the physiochemical properties to improve crop production and yield development. Future research is anticipated to develop soil lime fertility management requirements for these acid Ferralsols to meet the growing demand of food production for the over 70% households in the region depending directly or indirectly on agriculture production as a source of livelihood.

Comment [A1]: Recast. Confusing.

Key words: Ferralitic acid soil, liming, soil fertility, crop yield

Introduction

Ferraliticsoil also known as ferralsols are highly weathered and leached soils of the humid tropics enriched in Iron and aluminum. They are by nature characterized by strong acidity containing toxic levels of Al, Fe and Mn, low cation exchange capacity, low nutrient retention and low available phosphorus (Jaetzold*et al.*, 2012). In Uganda, about 33% of the soils are Ferralitic (Ferrasols), predominantly old, highly weathered with a low to moderate inherent productivity and has a pH below the critical value of soil pH 5.5 (NSER, 2016, Drake *et al.,* 2017). Many small-scale farmers across Uganda depend on these soils for sustaining their economic and social livelihoods. However, the productive capacity of these soils has shown an adverse effect on crop production. Example, soybean yields on these soils are often only a small fraction of the potential yields with average yields on smallholder farms in Central Uganda being 0.5t/ha, Northern Uganda 0.519t/ha and Eastern Uganda 0.321t/ha less than the potential yield of 2-3t/ha (Personal Communication, Uganda Martyrs University). Besides, new and high yielding varieties of Soybeans have continued to be released but the farmers' yield continue to be low averaging 1.5 tons per ha (Douglas, 2021). This is because the release of the new varieties has not been matched with their nutrient demand primarily due to the acidic nature of these soils predominantly found in every region of the country.

The low crop production on these soils is attributed to many management problems among which is soil acidity. Notably, acid soil is a key problem contributing towards reduced agricultural productivity worldwide (Marschner, 2012). According to the Ministry of Agriculture, Animal Industry & Fisheries of Uganda, about 46% of Uganda's soils are degraded and 10% is very degraded. Besides, about 65% of the agricultural soils in SSA are degraded due to poor management practices, which induce declines in soil biological, chemical and physical quality and the reduced capacity of these soils to support crop production and provide other ecosystem services (Zingore*et al.,* 2015). Long-term solutions such as approaches that build organic matter (OM) and organic nutrient pools in addition to inorganic fertilizer applications will likely be an essential component to achieving sustainable soil fertility in Uganda (Vanlauwe*et al.,* 2010, 2014, 2015) with lime and inoculants being an effective amendment for improving soil fertility, increase microbial activity, and generally improve crop yield (Nekesa*et al*., 2011).

Furthermore, most of the farmers in Uganda are resource limited and their population continues to grow exponentially which puts more pressure and constraints on agricultural land through continuous cultivation resulting to nutrient mining and soil acidification. Although enhancing fertility management in acid soils is crucial to ameliorating and replenishing loss nutrients, it is reported that many small-scale farmers in Uganda do not prioritize soil chemical testing which is key to correcting the detrimental effects of nutrient depleted soils. Adoption of generated research findings such as liming strategies are also low among farmers in SSA.

Uganda has one of the highest soil nutrient depletion rates in the world with the lowest inorganic fertilizer application of 1.8Kg/ha (Douglas, 2021). World Bank calculated that the value of replacing these depleted soil nutrients could be 20% of the average rural household income (Douglas, 2021).Liming can however shift these nutrient depleted soils toward nearly neutral levels and improve on the availability of mineral nutrients to enhance plant growth (Holland *et al.,* 2018) thereby aiding farmers save on the cost of purchasing inorganic mineral fertilizers as recommended by the World Bank. When soil pH is lowered than the optimal pH 5.5, it reduces the solubility of nutrients needed for plant growth and usually leads to Al^{3+} and Mn^{2+} toxicity plus deficiency in N, P, K, Mg, Ca, and various micronutrients (Marschner, 2012). Acidic soils limit or reduce crop production primarily by impairing root growth thereby reducing nutrient and water uptake (Marschner, 2012). The most recognized effect of soil acidity is observed in plant roots since exchangeable Al^{3+} impairs the development of the root system and interferes with P, Ca and Mg absorption and movement by plants (Cyamweshi*et al.,* 2014). Soil pH is known to influence a variety of soil characteristics needed by plants for healthy growth and development (e.g., resistance against diseases, root system, soil microbial activities, availability of nutrients, and rate of photosynthesis), resulting in projected[?]harvests (Li *et al.,* 2019). There is limited understanding of the associated problems and management strategies ameliorating acidic soils' conditions in Uganda. Besides, Athanase*et al.* (2013) attributed the lack of awareness, lack of appropriate lime recommendations, limited studies done and unknown agricultural lime quality as some of the problems associated with liming practices for crop production in SSA. There is also limited literature on the performance of different crop species on the different soil types in Uganda when lime is applied. Numerous studies have been carried out globally to establish the effects of application of different limestone application for ameliorating acid soils. In Uganda, there have been numerous studies carried out to determine the effects of lime and manure on crop production. However, determination of appropriate lime requirements for these acid and infertile ferralitic soils affecting crop production and yield development are yet to be established. Besides, many small-scale farmers across Uganda depend on these soils for sustaining themselves. A perception survey involving farmers was carried out in the Northern and Eastern regions of Uganda to determine the fertility status of farmers' fields, that is; good, medium and poor (Tanyima, 2015). The perception survey showed that soil fertility status in Northern Uganda was medium while Eastern Uganda was poor with yield below those cultivated in northern Uganda. The perceptions of these farmers could be attributed to the knowledge gaps that still exist about the state of soil fertility in the region. It could also be that research programs in the country had not placed emphasis on the identification, distribution and characterization of acid ferralsols to determine fertility management strategies such as liming. The gap in experience could be learned from other countries that have successfully worked to mitigate the challenges associated with strongly acidic soils. For instance, numerous studies have shown the experience of the Cerrado region in Brazil which saw the conversion of large areas of acidified soils to productive use through an integrated solution could be integrated and adopted in Uganda. Brazil has been able to develop over 60 million ha of the Cerrado region with crops and improved pasture with the implementation of appropriate technologies and inputs, infrastructure, and policy support (Klink, 2014). This review paper attempts to capture the many lessons learned in other countries about the management of acidic soils and how those best practices could be integrated into the Uganda context. The objective of this review paper therefore is to generally understand the extent, effects and characteristics, their distribution, causes, challenges and opportunities associated with liming Ferralitic Acid soils and the effects on soil properties and crop yields as a management strategy to improve production and increase yield at all levels.

Characteristics, extent and distribution of Ferralitic Acid Soils

Acidic soils belong to Ferralsols and Acrisols and to a smaller extent the Plinthisols, Alisols and Nitisols (IUSS Working Group WRB, 2015). Acrisols covered 87.8 million ha or 2.9% and Ferralsols about 312.4 million ha or 10.3% of the total land area of Africa (Tully et al. 2015). The chemical fertility of ferralsols is poor; weatherable minerals are scarce or absent, and cation retention by the mineral soil fraction is weak (Fungo et al., 2011).

Approximately, 50% of the world's arable soils are acidic and are subjected to the effects of aluminum (Al), iron (Fe), and manganese (Mn) toxicity of which the tropics and subtropics account for 60% (Kochian et al. 2015). In fact, Al^{3+} toxicity has been reported in 67% of the world's acidic soils (Lin et al. 2012), and is considered the third most element after oxygen and silicon, and forms approximately 7% of the total solid matter in soils (Frankowski, 2016) with soil acidity expanding widely in areas across Sub Saharan Africa (SSA). Major areas affected by these acid soils include East and Central Africa (Uganda, Kenya, Tanzania, Ethiopia, Rwanda, Brundi, Malawi, Central African Republic, Democratic republic of Congo), West Africa (Ghana, Nigeria, Ivory Coast, Liberia, Sierra Leone, Guinea) and Southern Africa (south Africa, Zimbabwe, Mozambique)(Leenaars*et al.* 2014). For instance, highly weathered, poorly fertile soils are predominant in central Uganda, where years of continuous cropping, erosion and poor soil management have contributed to soil acidification thus constraining average farm sizes to about 0.8 to 1.2 hectares per household in many farming communities with subsistence farming being unavoidable (Bulyaba et al., 2020; FAO, 2015). Furthermore, study done by Woniala and Nyombi (2013) in Eastern Uganda showed low pH (5.2) and low phosphorus availability across farmers' fields suggesting the use of lime as a management requirement. The low fertility status of these soils due to soil acidification among others, is overly affecting the productive capacity of crop production as yield on farmers' fields remained at an all-time low. Despite recommendations by researchers, relevant stakeholders in the sector are yet to institute measures on Improve Acid soil Management Practices (IASMP) to begin addressing the concerning problems. It is well documented that as soil pH declines, so does the supply of several essential plant nutrients, including calcium, magnesium and phosphorus (Goulding, 2016; Miller, 2016; USDA-NRCS, 2019). In many soils, this decline occurs alongside an undesirable increase in aluminum to levels toxic to plants (Harter, 2007; Miller, 2016). Besides, acidic soils such as Ferralsols contain toxic levels of Al and Mn, which have low availability of nutrients (IUSS Working Group WRB 2015). The low nutrient content of these Ferralsols is due to the predominance of 1:1 clay mineral, and Fe and Al oxides in the fraction (de Sant-Anna et al. 2017).

Causes and effects of acid soils

Heavy rainfall influenced by leaching is the main cause for the removal of basic cations (Ca^{2+}, K^{+} and Mg^{2+}) with the replacement of acidic cations (H^{+} and Al^{3+}) over a long period of time. This can exacerbate soil acidity by leaving the toxic and insoluble compounds of Al and Fe remaining in soils (Zhang et al., 2016). The nature of these compounds is acidic and its oxides and hydroxides react with water and release hydrogen (H^{+}) ions in soil solution thus rendering them acidic (Slattery and Hollier, 2002). As the soil gets gradually depleted of its exchangeable bases through constant leaching, it gets de-saturated and becomes increasingly acid (Lesch et al., 2012). Rainfall is most effective in causing soils to become acidic if a lot of water moves through the soil profile that accelerates the leaching of bases (Desalegn et al., 2020). In productive agricultural systems, the most important source of soil acidity is the application of chemical fertilizer based on ammonium N (Goulding, 2016). Added to soil, N-fertilizer is nitrified (Goulding, 2016), and if the resulting NO_3^- isn't taken up by the crops, it gets leached causing acidification (Goulding, 2016). Also, application of acidifying fertilizers such as diammonium phosphate, which is used to improve the deficiencies of phosphorous has become a noticeable cause to increase soil acidity (Mosissa, 2018). Different soil adoption management practices such as application of lime and other organic matter to agricultural acid soils has been widely adopted as an amelioration strategy for many years to improving crop productivity (Bambara and Ndakidemi, 2010). However, lime is rarely used in wide areas of agricultural land in Uganda. Limited knowledge on the use of lime and the inability of research programs to begin prioritizing the use of lime by farmers as one of the key requirements for ameliorating acidic soils have left most of the soils challenged across the farming systems in Uganda. Acid deposition can potentially alter the biogeochemistry of ecosystems, acidify soils, reduce the availability of some nutrients, aggravate aluminum, decrease root growth, contribute to low yield and crop quality, influence manganese toxicity, regulate crop diversity and adversely affects ecosystem structures and functions (Goulding, 2016). Liming can however shift acid soils toward nearly neutral levels and improve the availability of Ca^{2+} or Mg^{2+} concentrations and other plant minerals which are essential to plant growth hence neutralizes the toxicity effects of H^{+}, Al^{3+} and Mn^{+2} (Holland *et al.,* 2018; Ronner*et al.,* 2016). [Too long paras, consider splitting.]

Parent materials (rocks types) from which soils are formed is also a determining factor for acidity. Parent materials containing excess of quartz or silica as compared to their content of basic materials or basic elements are categorized as acid rocks; for example, granite and rhyolite. Soils that develop from weathered granite are likely to be more acidic than those developed from shale or limestone (Loganathan et al., 2012). For instance, soils developed from sand stones are poor sandy soils and are chemically inert whereas the inherent soil fertility developed over basic parent materials is relatively high. Humus materials in soils occur as a result of microbiological decomposition of organic matter and contain different functional groups like carboxylic (-COOH), phenolic (-OH) etc. which are capable of attracting and dissociating hydrogen ions (Amsalu and Beyene, 2020). Studies have shown that, decaying organic matter produces H^+ which is also responsible for acidity. During the process of decaying, carbon dioxide (CO_2) is produced which reacts with water in the soil to form a weak acid called carbonic acid. This is the same acid that develops when CO_2 in the atmosphere reacts with rain to form acid rain naturally affecting agricultural soils.

Effects of soil acidity on crop production

Crop plants need 17 kinds of nutrients to complete their life cycle, of that, 14 nutrients should be present in the soil in adequate quantity and proportion for healthy plant growth (Fageria et al., 2009). However, the availability of these nutrients is influenced by chemical reactions like acidity or alkalinity in the soil. In general, soil acidity elevates aluminum (Al^{3+}) concentration within the soil solution to a level toxic to plants (Alvarez et al., 2020), limits the availability of essential plant nutrients, and restricts crop performance (Laekemariam and Kibret, 2021). This would imply that soil acidity and its associated low nutrient availability are among the major constraints toward attaining sustainable crop production and achieving food security. In 2015, the ~~United Nations~~ Food and Agriculture Organization (~~UN~~FAO) Intergovernmental Technical Panel on Soils (ITPS) reported ten main soil threats globally among which are soil acidification, soil contamination, loss of soil biodiversity, soil salinization etc. Healthy soil is fundamental towards increasing food production and achieving food security, but the challenge is due to soil acidity (Hollande *et al.*, 2018). When soil pH is < 5.5, it affects the growth of crops due to high concentration of aluminum (Al) and manganese (Mn), and deficiency of phosphorus (P), nitrogen (N), sulfur

(S) and other mineral nutrients (Abreha, 2013). Soil acidity has also been affecting large-scale farms by reducing yield and quality of cash crops such as coffee, tea, pineapple, oil palm, rubber and sisal, which are important sources of foreign exchange for several African economies (Vlek et al. 2010). Studies have shown that excess Al^{3+} primarily injures the root apex and inhibits root elongation of agricultural crops. This poor root growth affects water uptake by plants at all levels. Generally, soil acidification has become a global threat towards future agriculture production and achieving food security in SSA. This has created a monumental reduction in farm size and yield output across the region with farmers being subjected to subsistence or peasant farming. Solubility of nutrients in these soils are greatly affected and usually leads to Al^{3+} and Mn^{2+} toxicity plus deficiency in N, P, K, Mg, Ca, and various micronutrients (Marschner, 2012). Successful crop production on these soils will however require both macro and micronutrients in forms that will support growth.

Beneficial effects of liming acid soils

One of the major effects of limed acid soils is an increase in yield output. However, chemical characterization of soil properties is key to necessitating the application of lime for effective management slurring[?]sustainable crop production. Liming has shown a synergistic interaction with applied nutrients (through fertilizers) and increased the nutrient uptake by plants by suitably changing soil chemical and physical properties (Chintala, 2012). These changes in soil characteristics depend on the interaction of numerous other factors, including climate, soil type, and intrinsic soil properties (Anikwe and Ibudialo, 2016). Adding liming materials helps to reduce soil acidity by neutralizing acid reactions in the soil. Lime has been found to enhance microbial activity, change the makeup of the microbial community, and increase the population of acid-sensitive microorganisms and soil respiration when soil acidity restricts microbial development (Goulding, 2016). Liming material is capable of altering numerous geochemical and biological properties of soil, and provides a variety of benefits (Li *et al.,* 2019). For example, it reduces soil acidity, solubilization of hazardous elements, namely aluminum (Al) and manganese (Mn). Besides, it aids in the rise of calcium (Ca) and magnesium (Mg) levels and the availability of phosphorus (P) and molybdenum (Mo), which plays a crucial role in plant healthy development (Costa and Crusciol, 2016). [Maybe some of these reactions could be shown by chemical equations?]

Furthermore, it encourages the proliferation of microorganisms already present in the soil and facilitates the formation of a more extensive root system, increases the plants' ability to absorb water and nutrients from the soil (Li *et al.,* 2019). Liming enhances a conducive environment for leguminous plants and associated microorganisms and increases the availability of plant nutrients by raising the pH and precipitating the exchangeable aluminum (Kisinyo*et al.,* 2015). Liming is essential in providing optimum conditions for biological activities that includes nitrogen-fixation, mineralization of nitrogen, phosphorus and sulfur in soils which improves soil conditions for plant growth especially for soybean by increasing grain yield, dry mass of the shoot, number of pods per plant and soil quality (Goulding, 2016). According to Horben*et al.* (2011), nitrogen is a critical limiting element for plant growth and is key to agriculture development (Korir*et al.,* 2017). On the other hand, legume growth can be limited under low nutrient availability partly because of the scarcity of N or other nutrients which may decrease plant photosynthetic capacity and reduce BNF capacity (Vitousek*et al.,* 2013). Several studies have shown the beneficial effects of liming acid soils on crop yields. Study done by Abubakari (2016) showed that soybean grown in lime-amended acid soils significantly increased nodule number, nodule volume and nodule dry weight per plant as compared to the un-limed treatment in legume crops. Besides, Temesgen et al. (2017) reported the positive effect of lime application on acid soil resulting to an increase in barley grain yield during the first trail[trial?] unlike to the final year. The study showed that yield reduction in the final year was as a result of re-acidification of the soil. In Croatia, Andric et al. (2012) also reported increased soybean yield by 44% as a result of lime application over the control/unlimed treatments. Workneh et al. (2013) reported significant increase in straw yield of soybean by 16.3%, due to soil liming at the rate of 2.6 t ha-1. Moreover, Workneh et al. (2013) reported that the application of lime produced the highest nodule number, nodule volume and nodule dry weight per plants. These authors also reported, the highest number of pods per plant (39.40) was produced when the crop was grown under limed soil. At the same time, Achalu et al. (2012) reported an increased in Plant height, fresh biomass, dry biomass, grain yields, harvest index and P-uptake of barley in limed acid soils. These increments in plant growth, yield and yield components are as a result of an increase in soil fertility and the reduction of the toxic concentration of acidic cations in these acid soils. These studies showed significant influenced of applied lime to acid soils for sustainable crop production. It is good to note that liming is the most commonly utilized long-term technique of soil acidity amelioration, and its effectiveness has been thoroughly established in the literature (Junior *et al.,* 2020). It is the least expensive and widely used alkali in agriculture since limestone deposits are extensively available globally, and a large percentage of the population has easy access to this material (Ferreira *et al.,* 2019).

Liming materials influencing soil acidity and crop performance

Lime in a broad sense is any material containing calcium (Ca^{2+}) or magnesium (Mg^{2+}) that tends to neutralize soil acidity by making soluble nutrients insoluble for plant uptake. Liming materials include $CaCO_3$, $CaMg(CO_3)_2$, $Ca(OH)_2$, CaO etc. which vary according to their degree of fineness and neutralizing capacity (TSO, 2010). Addition of lime to acid soils, supplies Ca^{2+} and Mg^{2+} ions and displaces H^+, Fe^{2+}, Al^{3+}, Mn^{4+} and Cu^{2+} ions from the soil adsorption sites resulting into an increase in soil pH (Andric *et al*., 2012) which directly improves microbial activity and increased crop production (Badole*et al.,* 2015). Application of lime significantly increased root and shoot yields in acid soils in Nigeria (Anetor and Akinrinde, 2006) and, grain yields of soybean in Brazil (Caires*et al.,* 2008). Similarly in Croatia, Andric *et al.* (2012), reported increased soybean yield by 44% as a result of lime application in acid soils. Moreover, Nekesa*et al.* (2011) in Western Kenya also found positive response of soybean grain yield to lime application either alone or in combination with P fertilizer.

Determination of soil acidity and amount of lime requirement is associated not only to the soil pH but also to the buffer or CEC (Nelson and Su, 2010). Lime neutralizes both active acidity and some reserve acidity. As active acidity is neutralized by lime, reserve acidity is released into the soil solution, hence preserving active acidity or pH (Abu, 2021). The ability of a soil to tolerate variations in pH is referred to as buffering capacity, and it is mostly determined by reserve acidity (Abu, 2021). In a strongly buffered soil, more lime is required to counteract acidity than in a less buffered soil. Furthermore, the amount of lime required to raise soil pH is dictated by the type of lime used, the history of land use, and the initial pH prior to lime application (Abu, 2021). Several studies showed that lime frequently increases effective crop rooting depth by lowering Al toxicity in acidic soils and allowed the crop to explore a larger soil volume for nutrients and water uptake. In Ethiopia, the effects of liming on agricultural output have been researched for a variety of crops whereas yields for different crops increased by applying lime above the control (no liming) ranges from 2.8-4.5, 3.01-3.09, 2.01- 2.55, 1.6-3.3, 1.9-2.6, and 2.1-2.5 t ha-1 for barley, maize, malt barley, fababean, common bean, and soybean (Abu, 2021). Similarly, studies done in Kenya, showed positive effects of liming on soybean yield (Keino et al., 2015). Overliming have however been reported to increase deficiencies of micronutrients such as Zn, Cu and Mn while under liming is not effective in ameliorating the deleterious effects of acidity (Sanchez, 2019). It is therefore prudent to acknowledge the pH of the affected soils before making ~~an inform~~ decision on liming requirement to ameliorate the associated problems. Amendment of lime on soil has been noted to improve soil structure, porosity, aggregation, bulk density and water transmissivity (Cahn et al., 2017). According to Erkki and Hedlund (2016), lime stabilizes organic matter content through enhanced nutrients mineralization. Among the nutrients stimulated and made available in the soil include: N, P, K, Ca and Mg. Additionally, Al and Mn solubility or their toxicities in soil including Al and H exchange are reduced (Adeli et al., 2017) and this boosts CEC activity. It is also true that the response of a particular crop to lime treated varied from site to site. Proper measures are required to ensure the effective use of lime on acid soil for improve crop growth and yield development. [Are the complexities of LR determination not worth mentioning here?]

Comment [A2]: Overliming is a sensitive subject here, needing a para of its own.

Conclusion

Soil acidity remains a major constrain to global food production. The significant reduction in crop yields due to the acidic nature of these agricultural land is adversely affecting the livelihoods of farmers across Sub Saharan Africa (SSA). These soils are low in available minerals required to successfully enable plants complete their life cycles. The detrimental effects of these soils have left farmers with no alternative but to shift from one area to another in search of arable land. These shifting practices are gradually affecting ecosystem services and impacting climate change. It is widely believed by farmers that soils across

Uganda are fertile; have the inherent ability to support plant growth, increase yield and do not need soil amendments such as lime. Besides, farmers are not aware of the increasing benefits associated with the use of lime. Up till now, soil research in Uganda has not placed more emphasis on the use of lime to reverse acidic soils. However, application of lime to acid soil should be considered an approach to optimize soil pH, create an enabling environment for increase soil bioavailability thus underscoring a healthy soil for crop production. The extent of soil acidification can as well be addressed through Integrated Soil Fertility Management Approach (ISFMA). The combine application of organic materials and lime will enhance a buildup process of nutrients accumulation with a high residual effect thereby reducing on the use of organic and inorganic fertilizers in successive farming seasons. More emphasis on the type of fertilizers used and the amount applied are also cardinal to the mitigation of soil acidification.

On the overall, adoption of improve soil management practices is key to the social and economic livelihoodsof the growing population that depends on these soils. Mitigating and reversing acid ferralsols across farmers' fields will require research, appropriate agronomic practices and improve crop varieties to generate information for use by farmers across the region.

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Soils of Uganda

(By NARO)

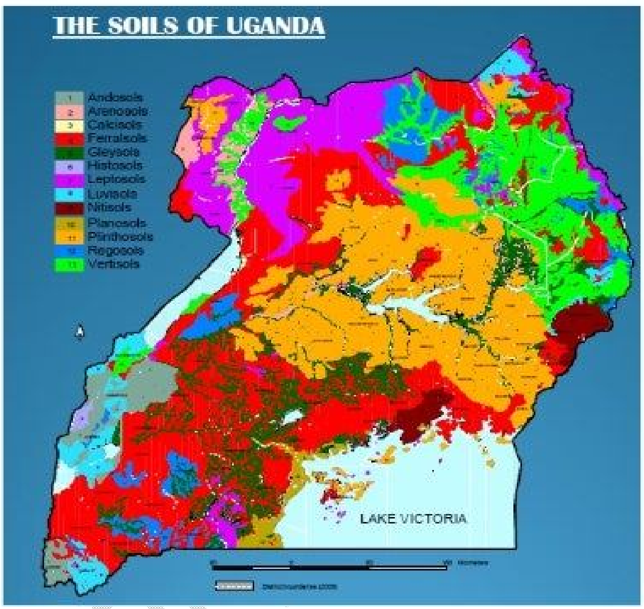

Figure 1: Major soil types of Uganda (NEMA, 2010, http://maps.nemaug.org/maps/ downloaded on 9/23/2022).

Each soil type has its own chemical properties suitable for different purposes. For instance, Ferrasols are highly weathered soils with low supply of nutrients, characterized by low pH and low available phosphorus. Calcisols on the other hand are soils characterized with high accumulation of $CaCO_3$ and have serious problems with trace elements deficiencies for elements such as Zn, Cu, Fe andMn

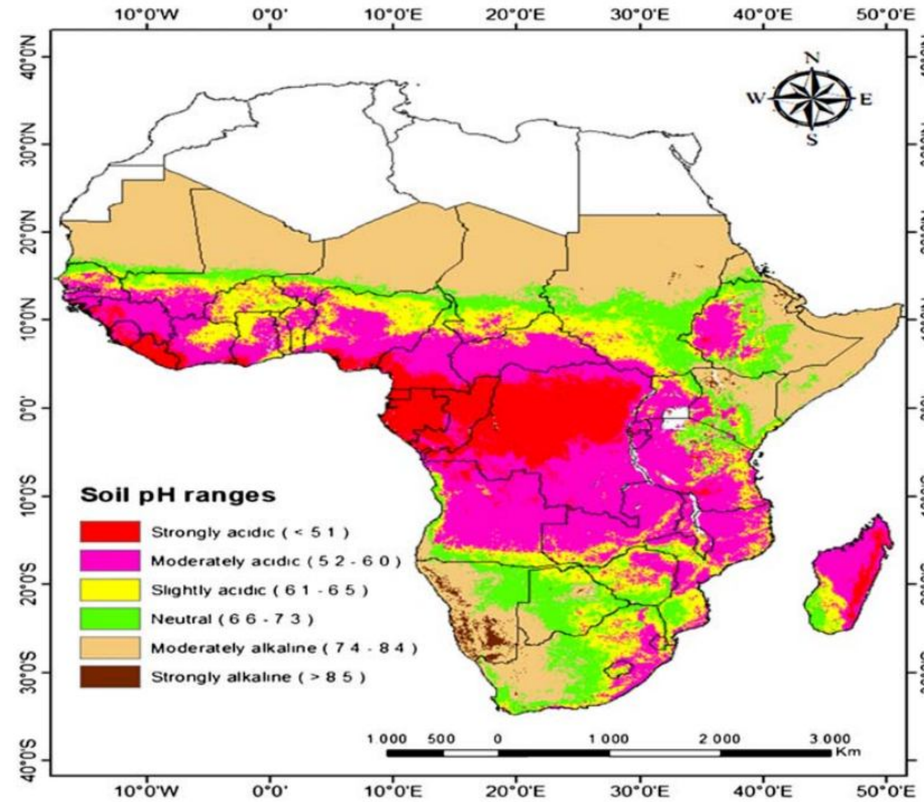

Figure 2: Extent and distribution of soil acidity in Sub-Saharan Africa (SSA) extracted from Horneck et al. (2011); Leenaars et al. (2014).

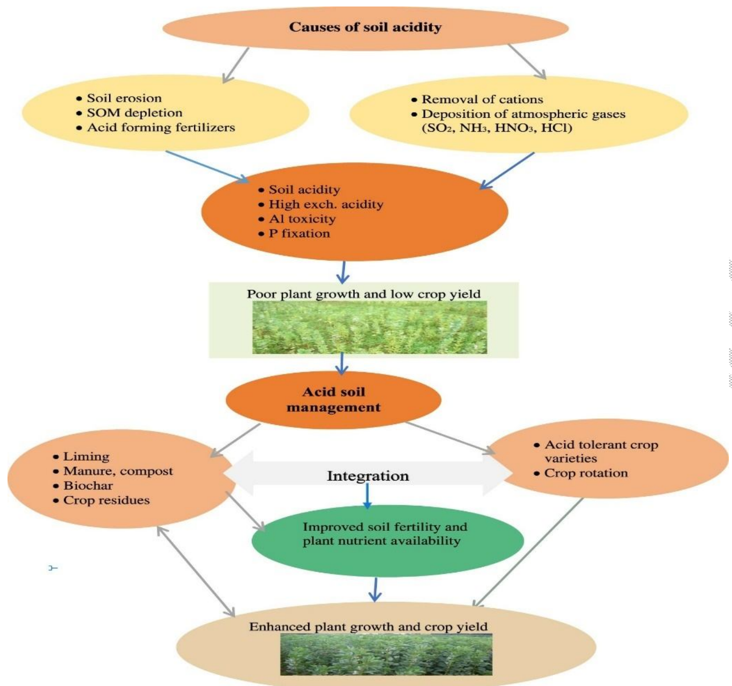

Figure 3: Causes of soil acidity Agegnehu et al.,(2021)

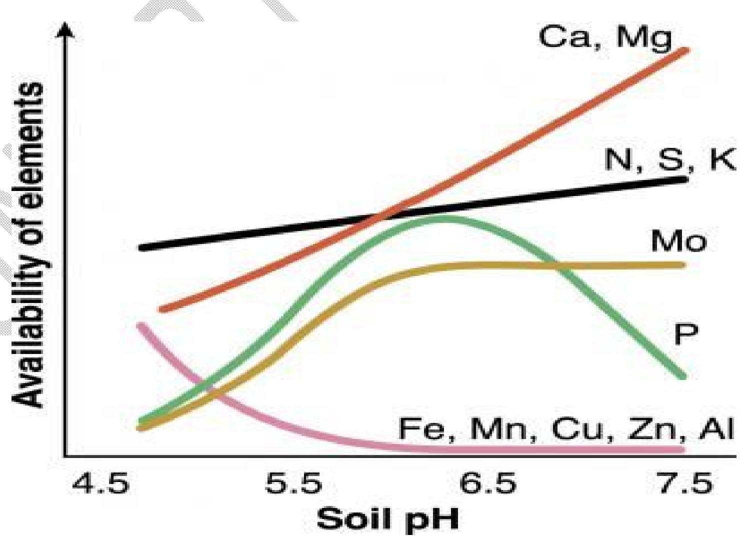

Figure 4: A representation of the relationship between soil pHCa and nutrient availability (Chris Gazey, 2018). In acidic soils, some nutrients may be insufficiently available for optimal plant growth and aluminum may become toxic.

Table 1. Estimation of lime requirements for different soil pH ranges using BC method

pH ranges used in the curve	Curve slopes	BC (g/100 soil)	BC (kg ha^{-1})	Remark or recommendation on the use of BC values	Examples of lime rates to raise a given soil pH to target pH		
					pH ranges		Lime rate (kg ha^{-1})
					Initial	Target	
Estimation of BC values and lime rates (kg ha^{-1}) for soils with pH between 5.0 and 5.6 to raise the pH between 6.0 and 6.5							
5.17-6.12	31.61	0.0316	644	For soils with pH 5.0-5.6	5.2	6.0	530
5.17-6.4	24.87	0.0402	844	Acceptable, but less economical for one time use	5.2	6.4	1010
Estimation of BC values and lime rates (kg ha^{-1}) for soils with pH between 4.5 and 5.0 to raise the pH between 6.0 and 6.5							
4.65-6.0	11.21	0.0892	1873	For soils above pH 4.6	4.8	6.0	2250
4.65-6.30	8.26	0.1211	2544	Expensive	4.8	6.3	3820
4.63-5.61	12.24	0.0817	1716	Cheaper for one time use, maybe with insignificant yield reduction. The rate is not recommended for split or localized application.	4.8	5.6	1370
Estimation of BC values and lime rates (kg ha^{-1}) for soils with pH between 3.8 and 4.5 to raise the pH between 6.0 and 6.5							
4.27-5.24	16.24	0.0616	1293	Cheap for one time use; perhaps, with some level of yield penalty.	4.27	5.24	1254
4.27-5.61	13.48	0.0742	1557	Acceptable for one time use; perhaps with insignificant yield reduction.	4.27	5.6	2070
4.27-5.84	11.23	0.0891	1871	Moderately acceptable.	4.27	5.8	2940
4.27-6.03	9.27	0.1079	2265	Expensive to bring the pH from below 4.3–6.0.	4.27	6.0	3918

Source: Extracted from Huluka (2005) and Sikora and Moore (2008).

Table 2: Effect of lime and other soil fertility management practices on yield of selected crops and soil properties.

Crop	Treatment		Yield			
	Manure ($t\ ha^{-1}$)	Lime ($t\ ha^{-1}$)	($t\ ha^{-1}$)	% increase over control	Effect on soil properties and nutrient uptake	Source
Wheat	0-5.0	0.0–2.20	0.90–2.69	94–199		(Asrat et al. 2014)
Wheat		0–10	2.44-4.27	34–75	Liming improved soil pH and plant P uptake.	
	N/P/K ($kg\ ha^{-1}$)	**Lime ($t\ ha^{-1}$)**	**Yield ($t\ ha^{-1}$)**	**% increase over control**		
Tef	0-46/0-26/0	0.00–2.00	0.82–2.88	99–252	Liming increased soil pH from 5.38 to 6.17 and CEC from 14.8 to 20.7	(Abewa et al. 2014)
Soybean	18/20/0	0.00–3.75			Increased soil pH from 5.03 to 6.72, and reduced Al^{3+} from 0.68 to 0.36 cmol kg^{-1}	(Buni 2014)
Soybean	18/20/0	0.00–2.60	1.58–2.31	29–46	Increased nodule dry weight by 100%.	(Bekere et al. 2013)
Barley	50/0-30/0	0.00–2.20	2.54–4.56	52–81	Lime reduced Al^{3+} by 0.88–1.19 meq 100 g^{-1} soil, and raised soil pH by 0.48–1.1 units.	(Desalegn et al. 2017)
Barley	145/00/00	0.00–7.00	2.52–4.24	15–68	Lime increased pH in the surface 15 cm and reduced Al^{3+} only in the 0-5-cm layer.	(Tabitha et al. 2008)
Barley	41/20/0	0–4.5	1.28–1.83	4.0–41	Liming increased soil pH from 4.53 to 5.61 and reduced EA from 2.2 to 0.23 cmol kg^{-1}	(Beyene 1987)
Oats/soy bean	-	0.0–2.0	0.96–1.48	5–54	Liming reduced H^{+} and Al^{3+} contents to a depth of 0.60 m.	(da Costa and Crusciol 2016)
Maize	60/26/0	0–2.0	1.77–4.99	111–182	Liming increased soil pH from 4.92 to 5.46 and reduced EA from 0.25 to 0.10 cmol kg^{-1}.	(Opala et al. 2018)
Faba bean	18/20/0	0.0–5.0	0.81–1.47	45–53	Liming increased soil pH from 5.1 to 5.9 and reduced EA from 1.31 to 0.12 cmol kg^{-1}.	(Agegnehu et al. 2006)
Mucuna flagellipes	-	0.0–4.0	1.39–2.82	45–103	Liming increased soil pH from 4.3 to 6.1.	(Agba et al. 2017)
Potato	0/0/0/-110/40/100	0.0–3.5	10.03–30.67	59–332	Liming increased soil pH from 4.8 to 5.5.	(Haile and Boke 2009)
	NPK ($kg\ ha^{-1}$)	**FYM/compost ($t\ ha^{-1}$)**	**Yield ($t\ ha^{-1}$)**	**% increase over control**		
Wheat	23/10/0	0.0–8.0	1.2-2.9	68–129	Addition of FYM increased soil pH from 5.0 to 5.6, OC, N and P.	(Agegnehu et al. 2014)
Potato	0/0/0/-110/40/100	0–20	17–54	134–217		(Haile and Boke 2011)