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Review article

A review of the Current State of Soil Infertility and Management Options in Kenya: The Case of Maize Growing Regions

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Abstract

Inappropriate soil fertility management has caused fertility to decline considerably over the years leading to low maize yields despite the growing human population with high food demand in Kenya. Despite high nutrient mining, fertilizer use and adoption of soil fertility improvement practices have remained low among maize farmers in the country. At the current yield levels, maize crops extract over 40, 8, 40.6, and 5.4 kg of N, P, K, and S per growing season, respectively. These extracted nutrients must be replaced to avoid nutrient depletion. Maize crop response to secondary macronutrients (S, Ca, and Mg) and micronutrients (Zn and B) is evidenced, signifying that these nutrients have also reached critical levels in Kenya soils. The rate of replenishing these lost nutrients is still low, farmers apply an average of 43.25 kg of fertilizer per hectare per season. The situation is worsened further by increasing soil acidity- currently below pH 5.5 in most maize-growing regions. Poor agronomic practices applied by farmers directly reduce yields and facilitate other factors leading to nutrient losses. For example, farmers across the country recycle seeds, apply low fertility rates, and rarely keep their fields weed-free. These practices lower the capacity of the crops to tolerate the impact of other production constraints including infertility.

To realize yield improvement and return on investments, farmers must adapt and adopt crucial practices under integrated soil fertility management. Managing soil acidity should be the first approach to unlocking fixed nutrients. Fertilizer application should follow the right rate, right source, right time, and right placement approach. Also, improved cropping systems such as maize-legume rotation and intercropping should be considered for sustainable soil fertility management and crop production.

Keywords: Agronomic practices, ISFM, fertilizer application, maize production, soil infertility, soil acidity.

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INTRODUCTION

Maize (*Zea mays* L.) is the most important staple food crop in Kenya. The crop feeds over 85% of the population with daily consumption per capita of 400 g (Stanley & Nderitu, 2011). Besides being a key source of food, the nationwide production provides direct and indirect employment opportunities to over 90% of the farming families. It is a source of raw material in the livestock sector- used as animal feeds (silage, brans, and cakes). Maize is also a crucial raw material in the food processing industry, where it is used in the production of cooking oil, cakes, and flour.

In Kenya, maize is grown in nearly all agro-ecological zones, with more than half of household land dedicated to its production every season. It is estimated that about 75% and 25% of Kenya's total production is done by small-scale and large-scale maize farmers, respectively (Kang'ethe, 2011). Rift Valley is the leading producing zone, with Trans Nzoi, Kericho, Nakuru, Nandi, Uasin Gishu, and Nakuru counties cumulatively account for about 95% of the total marketed maize in Kenya (Wangia *et al.*, 2002). Other important maize producing regions include Western, Nyanza, Eastern, and Central Provinces (Figure 1). Nationally, total area harvested and grain production have upward trends while the yields are relatively constant (Figure 2). Lack of uniformity in production practices and relatively flat yield trend across the country could be because of ever-varying socio-economic, edaphic, and climatic differences. These factors have led to the adoption of a wide range of production practices, most of which are sub-optimum. These sub-optimal practices in turn have led to low yields below 2 tons per hectare in farmers' fields compared to over 5 tons per hectare under well-managed systems (Otieno *et al.*, 2020). Ironically, this low yield is recorded when various initiatives like distributing subsidized fertilizers, seeds, farm input loans, and extensional services are launched by the government, Non-Governmental Organizations, and private sectors across the country. The low productivity and high consumption have always put the country in an awkward food security situation as the national food security is described based on maize availability and sufficiency in meeting household food demands. The observed expansion of land under maize is expected to continue because of the ever-increasing population, with an estimated growth rate of 2.5% per annum (World Bank, 2018).

Therefore, this research aimed to assess soil infertility and potential management practices and technologies for the impacted zones. This research is crucial as it builds on the existing information and provides up-to-date soil fertility status for future research and recommendations. This work reviewed several publications under soil fertility management and maize production themes across the country.

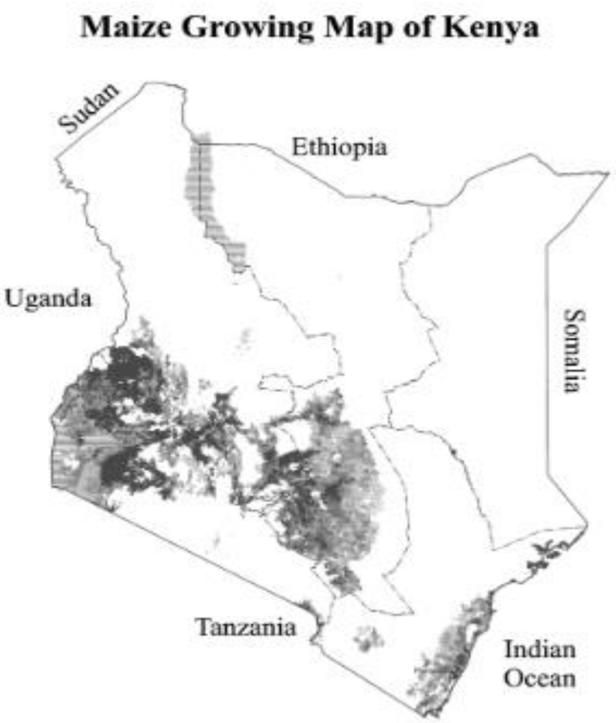

Figure 1. Important maize growing areas across Kenya. These areas are given in dark shadings- the darker the region, the high the production.

Source: Muhammad and Underwood (2004).

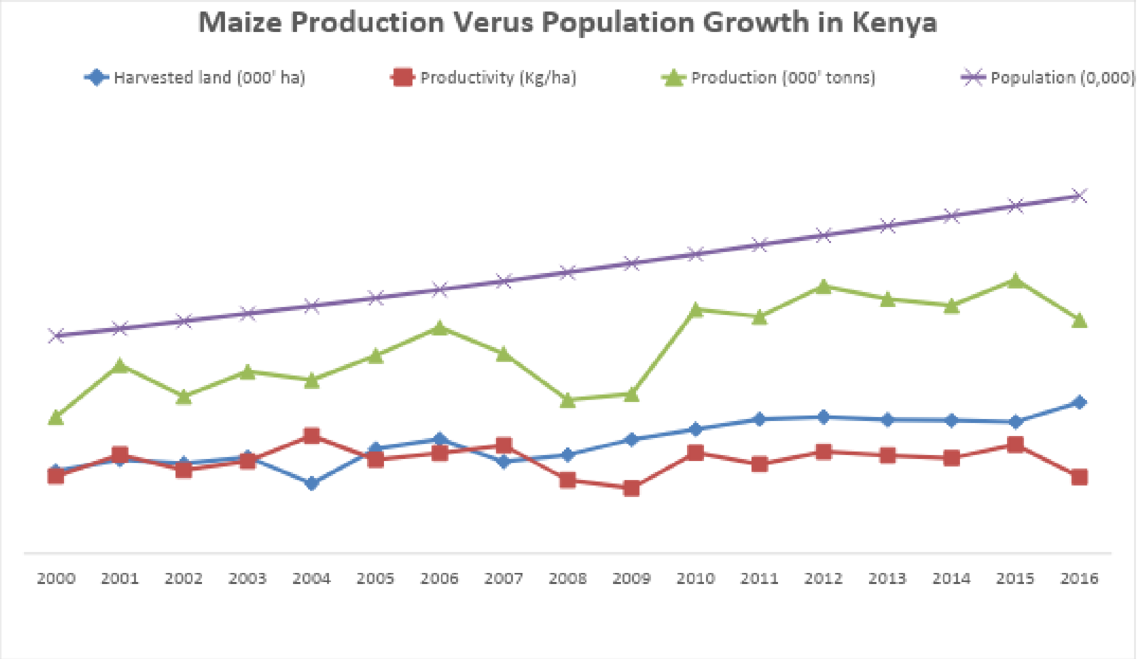

Figure 2. Summary of maize production trend in harvested area, production, and yield from 2000 to 2016. Adapted from FAOSTAT (2018); World Bank (2018).

CHARACTERISTIC OF MAIZE FARMING IN KENYA

Maize production practices vary across the regions depending on the climatic and socio-economic characteristics of the farmers. The land under maize has increased and is projected to continue (Kang'ethe, 2011). This trend could be due to farmers clearing more land under forest cover or reducing land under other crops for more maize production. Clearing of land has significant negative impacts on soil productivity; cleared land is prone to soil erosion, high soil carbon degradation, and interference with soil microbes.

The methods of land preparation depend on the system (conventional tilling and no-tilling systems) used. Adoption of no-till system is common with the large scale farmers who are financially stable while small scale farmers practice conventional tilling system. Under the conventional tilling system, farmers use hand-held tools like jembe (on plots less than 0.5 ha), ox-drawn plows, and tractor-drawn plows (on fields above 0.5 ha). On the other hand, no-till farmers use herbicides. The use of farm inputs like fertilizers is inconsistent throughout the country. The inconsistency is due to agro-ecological zones, land ownerships, land sizes, education background, exposure to modern production technologies, and farmers' financial capability. According to Mathenge (2009), fertilizer rates as low as 2.1 kg per acre (in Coastal Lowlands) to as high as 84.4 kg/acre (in high potential zones) are applied by maize farmers in Kenya. Maize is commonly intercropped with legumes (like green and black gram, soybean, cowpea, and dry bean) and root and tuber crops (like cassava, sweet potato, and Irish potato).

HIGH ACIDITY AS A SOIL INFERTILITY INDICATOR

Soil acidity is an essential aspect of the edaphic factor that constrains production of any crop. Soil acidity affects the availability of critical crop nutrients, growth of plant roots, and yields (Yamoah *et al.*, 1996). According to One Acre Fund (2014), addressing soil acidity alone through lime application could increase maize yields by at least 14% in Kenya. There are several causes of soil acidity. With no human influence, soils may become acidic because of nature- the mineral composition of the parent rock that formed the soil. In Kenya, this accounts for about 20% of soil acidity (FURP, 1987). For instance, the main soil types of western Kenya (Ferralsols and Acrisols) are acidic by nature (Musandu & Njul, 1999; Kanyanjua *et al.*, 2002). Present studies have reported an increasing soil acidity across maize-producing regions in Kenya (Figure 3). These regions are also characterized by high rainfall that could be accelerating the leaching of most of the cations, such as Ca^{2+} and Mg^{2+} (Day & Ludeke, 1993; Kalkhoran *et al.*, 2019). The washing away of mobile nutrient cations means that the highly adsorbed H^+, Al^{3+}, Mn^{2+}, and $Fe^{2+/3+}$ ions are left on the soil colloids to cause soil acidity (Otieno *et al.*, 2018). Also, the traditional usage of ammonium-based fertilizers such as Di-ammonium phosphate (DAP), calcium ammonium nitrate (CAN), and high N urea fertilizers in maize production could have aggravated the situation below tolerable levels. According to the latest research work by Oseko and Dienya (2015), DAP is the most consumed inorganic fertilizer followed by urea, then CAN in Kenya. In a long-term study, Lungu (2008) found that urea application resulted in soil acidification and decreased exchangeable bases in the soil. The use of DAP, CAN, and AS fertilizers has also been linked with increased H^+ concentrations leading to soil acidification (Bolan & Hedley, 2003). This acidification process confirms the currently low soil pH (below 5.5) levels reported in Kenya. In Western Kenya, soil pH range from 4.1 to 4.8 (Kisonyo *et al.*, 2014; Otieno *et al.*, 2018; Otieno, 2019); in East and West Highlands of Rift Valley, soil pH range from 4.0 to 4.9 (Kisonyo *et al.*, 2013); in Central Highlands, soil pH range from 4.8 to 5.4 (Verde *et al.*, 2013); and in South Western, soil pH range from 4.5 to 5.4 (Ademba *et al.*, 2015). The nationwide soil analysis report has shown that all maize-producing regions have over 50% of their soils with pH below 5.5 (Ministry of Agriculture, Livestock and Fisheries, 2014).

The formation of complex compounds between Al^{3+}, $Mn^{2+/4+}$, or $Fe^{2+/3+}$ ions and plant available forms of phosphorus, potassium, calcium, magnesium, and zinc make these nutrients unavailable for plant uptake (Otieno *et al.*, 2018). At pH below 5.5, most soil micronutrients become highly soluble, leading to high concentrations toxic for maize growth. For instance, aluminum ions concentration rises as the solubility increases at pH below 5.5. The increased solubility adds to the already high Al concentrations (between 20 and 45%) reported across the country (Gudu *et al.*, 2005). At levels above 2ppm, Al becomes toxic to maize and retard growth and lower yield (Panda *et al.*, 2009).

Also, very low pH hinders the survival of topsoil fauna. These faunas are crucial in improving soil health through the decomposition and mineralization of organic matter and biological nitrogen fixation process (Higashida & Takao, 1986). The desirable soil pH for maize production is between 5.5 and 7 (Espinoza & Ross, 2003). By comparing this optimum range with the reported pH values in Kenya, it is evident that all zones are increasingly becoming unfit for maize production if left un-amended.

An attempt to improve soil conditions by lowering this pH has never been very successful across the country. Although several organizations, including One Acre Fund, have tried to distribute pH ameliorants like lime at low prices, the adoption is still not significant. Factors such as illiteracy and lack of agricultural extension services, among others, could be cited as the reasons behind such low adoption. Moreover, lime acts very slowly and farmers are impatient when it comes to waiting for an impact.

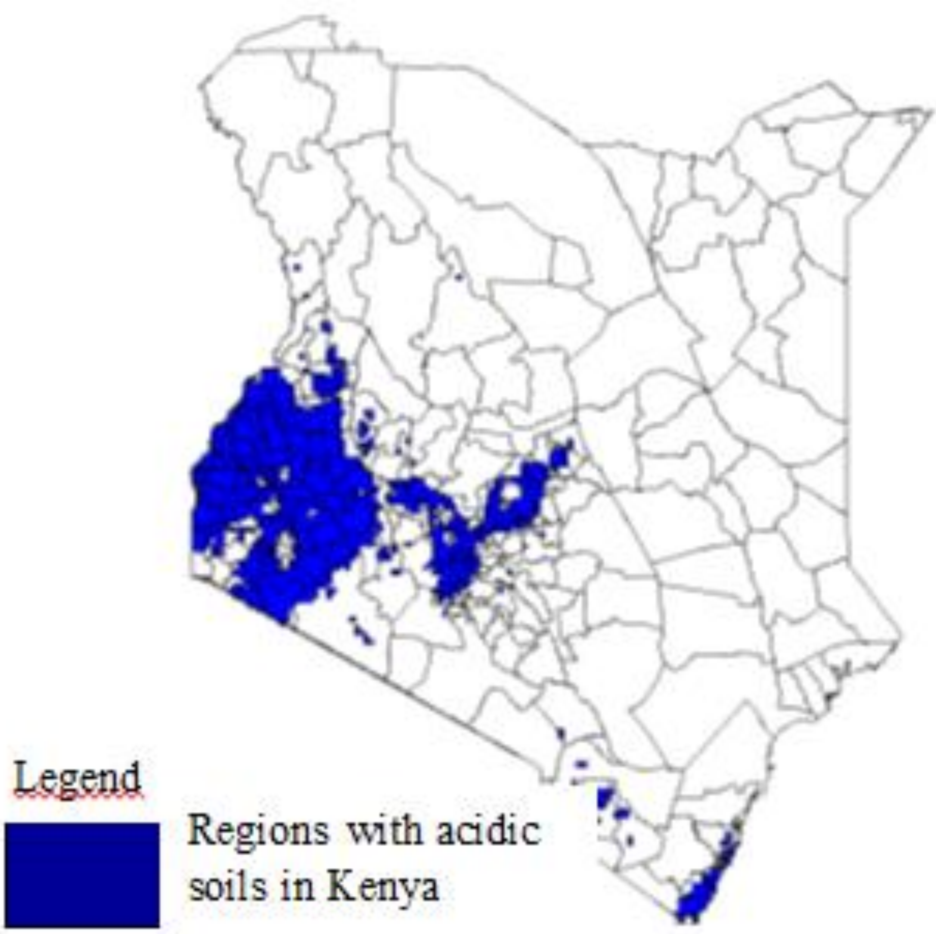

Figure 3. Distribution of acidic soils across maize-producing zones in Kenya. Source: Kanyanjua *et al.* (2002).

NUTRIENT MINING AND LOW FERTILIZER USE AS A SOIL INFERTILITY INDICATOR

Soil fertility is crucial in crop production, and every species has specific critical thresholds. When the fertility level is below the required threshold, crops show deficiency symptoms, and yields are depressed. The variation in soil fertility levels is mainly due to uninformed farm management practices leading to negative nutrient balances. On average, soil nutrient depletion rates of more than 40 kg N, 6.6 kg P, and 33.2 kg K per hectare per year have been estimated over two decades ago in Kenya (Smaling *et al.*, 1997). These rates could be higher now. Among other factors, climatic, edaphic, crop, and farming practices are the leading causes of such high nutrient losses. Crops have different levels of nutrient demand and rates of extraction. Nutrient extraction by cereals like maize is higher than some cash crops (Argwings-Kodhek *et al.*, 1998). The quantities of nutrients extracted by plants at any given time depend on crop species, stage of growth, and season (Espinoza & Ross, 2003). Using the Nutrient Removal

Calculator developed by the International Plant Nutrition Institute (IPNI), for every one ton of grain produced, maize crops extract, respectively, 20, 4, 20.3, and 2.7 kilograms of N, P, K, and S nutrients from the soil. Assuming an average yield of 2 t ha^{-1}, over 40 kg N, 8 kg P, 40.6 kg K, and 5.4 kg S are lost every season of maize production. In Western parts of Kenya, where maize is grown twice a year (in the short and long rainy seasons), farmers could be losing twice as much nutrients annually. These nutrients are not returned to the fields, as crop residues are always burnt or fed to livestock (Valbuena *et al.,* 2012). The manures from these animals are also not returned to the crop fields to replace the lost nutrients.

Soil erosion is another process that leads to nutrient losses in Kenya. Soil water erosion rate is high and prevalent in high altitude and mountainous regions that receive high rainfall. Soil erosion process is the primary cause of P loss from the soil. This is because P is strongly adsorbed onto soil particles causing little or no leaching. The amount of any nutrient lost is expressed as a concentration in water or sediments. This concentration varies depending on the tillage method, soil surface cover level by vegetation and crop residues, soil type, intensity of rain, slope, amount, and time of fertilizers application (Gascho *et al.*, 1998; Schick *et al.*, 2000; Bertol *et al.*, 2003). Adoption of soil conservation measures like reduced tillage, contour plowing and planting, mulching, and cover-cropping in areas prone to erosion is low (Otieno *et al.*, 2017). Meaning, farmers could be experiencing high nutrient losses and imbalances in such areas.

Nutrient loss through leaching is also significant under the current conventional tillage system practiced by maize farmers. The rate and amount of nutrients lost through leaching largely depend on soil type and climate- rainfall (Lehmann & Schroth, 2003). Oliveira *et al.* (2002) reported that leaching could cause losses of about 4.5 kg N, 13 kg K+, 320 kg Ca^{2+}, and 80 kg Mg^{2+} per hectare within 11 months of fertilizer application from sandy soil. Areas that are humid and receive heavy rainfall (for example, Rift Valley, parts of Western and Highlands of Central and Nyanza) are likely to have higher leaching rates than low potential areas with less rainfall (for example, Coastal region). Because heavy rains saturate the soil pores rapidly, causing continuous downward and lateral water and dissolved nutrients movement within the soil profile. The soil type also plays a crucial role in nutrient leaching through its texture and cationic and anionic exchange capacities (Salcedo *et al.*, 1988). In Kenya, the dominant soil types found in the high potential areas include Ferralsols, Nitisols, Acrisols, and Phaeozems (Figure 4). These soil types are weathered and heavily leached and poor chemically (Muchena & Gachene, 1988; Omuto, 2013). Hence, high rates of leaching of nutrients.

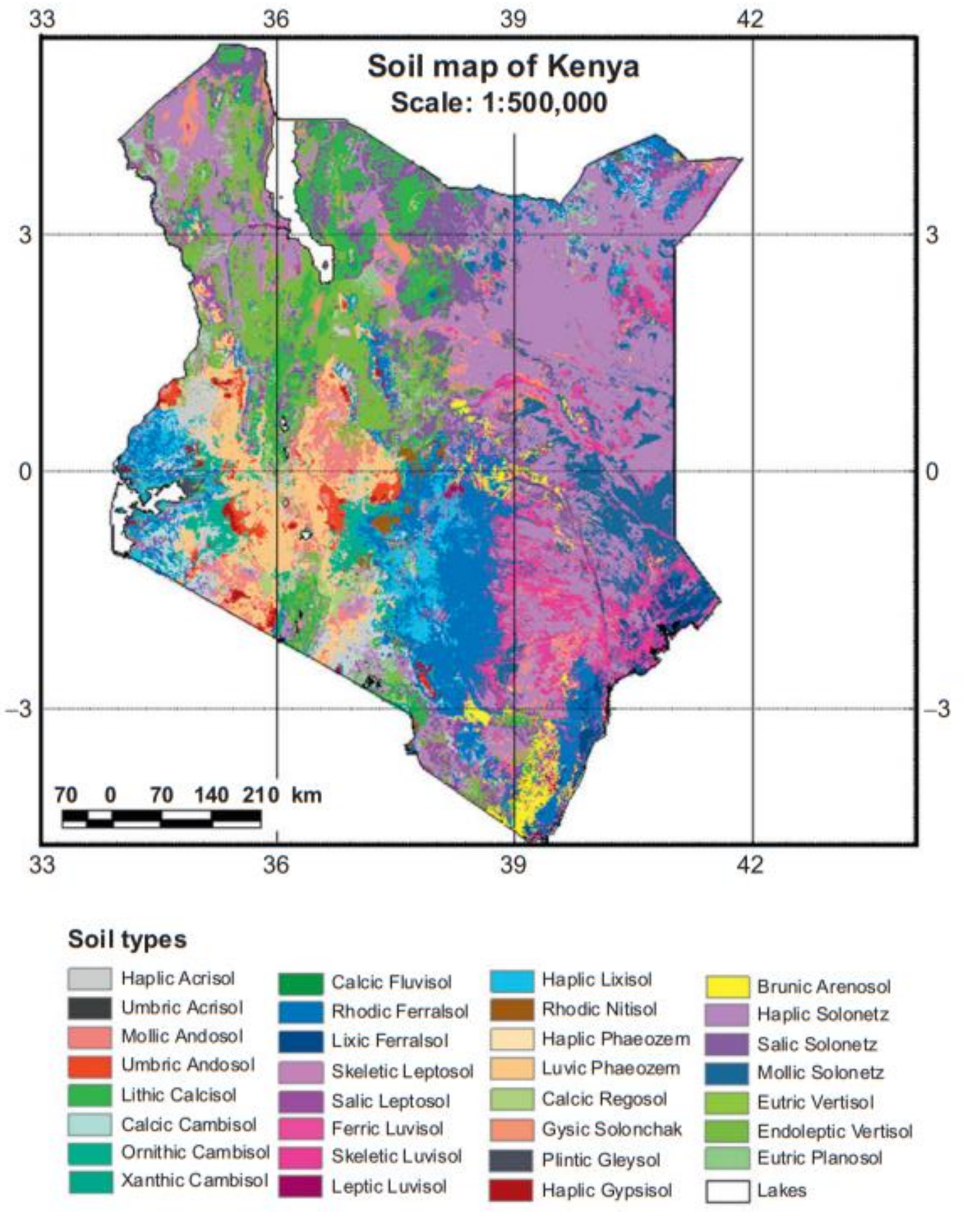

Figure 4. Soil map of Kenya, showing the distribution of soils prone to leaching of nutrients. Source: Omuto (2013).

Another factor affecting the rate and amount of nutrients lost through leaching is the fertilizer type and rate applied (Camargo, 1989). Comparing organic versus mineral sources of nutrients, no clear direction as to which one is likely to lead to much leaching (Havlin *et al.*, 1999; Lehmann *et al.*, 1999). However, nutrients from inorganic sources are very soluble and immediately form solutions whenever applied in wet soils. Hence could be subjected to higher leaching than those from other organic sources. Leaching of nutrients from organic sources may not affect the Kenyan fields' nutrient balance since farmers rarely apply these organic sources. The mobility of a nutrient is also an important aspect that determines its rate of leaching. For instance, nitrate-based sources leach more than other forms of nitrogen due to the inability to get strongly adsorbed onto the soil particle surfaces in the topsoil (Lehmann & Schroth, 2003). Based on this, N losses from Kenyan farms could be high since commonly used fertilizers are nitrate-based- e.g. Diammonium phosphate (DAP) and Calcium ammonium nitrate (CAN) fertilizers. Mineralization flush is another way that significantly increases N and S leaching at the beginning of the rainy season (Birch, 1960; Havlin *et al.*, 1999). Mineralization flush is likely to occur in all farms across the country since it is a natural process. Leaching of K^+ is less compared to Ca^{2+} and Mg^{2+} (Lehmann & Schroth, 2003). On the other hand, Ca^{2+} leaches higher than Mg^{2+}, and this is because of the greater solubility of $Ca(OH)_2$ resulting from hydrolysis of CaO (Oliveira *et al.*, 2002). The rate and amount of nutrients leached are directly proportional to the quantities of fertilizer applied. In Kenya, farmers in high potential regions use higher fertilizer rates than their counterparts in low potential areas (Mathenge, 2009). Implying, leaching of nutrients is likely to be higher in the high potential areas (Rift Valley and Western) than in the low potential regions (Lake and Coastal lowland).

SOIL FERTILITY MANAGEMENT OPTIONS FOR MAIZE FARMERS IN KENYA

To improve yields, crop nutrient losses must be reduced to the minimum levels possible. Addressing nutrient deficiencies alone could close the maize yield gap to 50% of the attainable yield (Wopereis *et al.*, 2006; Mueller *et al.*, 2012). Therefore, addressing soil infertility is crucial in realizing increased maize production in Kenya. Restoration of already degraded soils requires effort and patience from maize farmers. The soil fertility restoration process involves the implementation of both short and long terms strategies. These strategies include improving soil conditions by applying soil amendments like lime and manure, applying appropriate fertilizer types, adopting long-term and sustainable soil fertility practices such as improved cropping systems and tillage practices, and using improved germplasm. All these are components of integrated soil fertility management (ISFM). Integrated soil fertility management is "a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm, combined with the knowledge on how to adapt these practices to local conditions, aimed at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity" (Vanlauwe *et al.*, 2010).

The first step in improving crop productivity is by restoring soil pH to levels suitable for crop production. Maize requires a pH range of 5.8-7.5 for better growth and efficient nutrient utilization. Lime and organic manure application are the main strategies in managing soil acidity. These ameliorants have different modes of action towards reducing soil acidity: Agricultural lime acts by neutralizing the acidity and precipitating H^+, Al^{3+}, Fe^{3+}, and Mn^{4+} ions, whereas organic manure acts by forming complex compounds with these cations (Otieno *et al.*, 2018). There are two types of liming materials available for maize farmers, depending on mineral compositions: calcitic lime- contains calcium (in the form of $CaCO_3$, $Ca(OH)_2$, or CaO) only; and dolomitic lime- contains magnesium carbonate ($MgCO_3$). The best way to determine the type and rate of lime required is through soil testing. The use of dolomitic lime is not as common as the calcitic type. However, it is commonly recommended for use in soils with low pH and deficient in Mg nutrients. The recommended rate and the effect of any agricultural lime product on soil pH are dependent on their neutralizing value, which is a combination of the purity (calcium carbonate equivalent) and the fineness of grind (particle size) (Murdock, 1997). Research on the use and effect of soil amendments is widespread across maize growing zones in Kenya: Otieno *et al.* (2018) found that the application of 5 t ha^{-1} of lime and 10 t ha^{-1} of cow manure significantly raised soil pH by up to 2.48 and 1.42 respectively, compared to control in Western Kenya. The effect was even higher when lime and manure were combined. In Central Kenya, Gitari *et al.* (2015) reported highest pH, maize height, biomass, and yield when supplied with either 12.5 t ha^{-1} of lime or 10 t ha^{-1} of goat manure. Other researchers have also reported these benefits across the country using varied application rates: 0.5-6 t ha^{-1} of lime in Western (Kisinyo *et al.*, 2014; One Acre Fund, 2014); 2 t ha^{-1} of lime in Rift Valley (Osundwa *et al.*, 2013); and 5-10 t ha^{-1} manure and 2 t ha^{-1} lime in Central (Verde *et al.*, 2013). These amendments are applied either through broadcasting or micro-dosing methods depending on plot size- large quantities on large farms are likely to be broadcasted, while small plots could easily be micro-dosed.

The application of chemical fertilizers provides an immediate strategy in dealing with soil infertility, as nutrients are instantly made available for crop growth. The use of fertilizer should follow the 4R nutrient stewardship concept. The 4R nutrient stewardship is the efficient and effective planning and management of plant nutrients; in a manner that improves the social, economic, and environmental performance of mineral and organic fertilizers (Bruulsema *et al.*, 2012).

Several research projects aimed at identifying deficient nutrients and maize response across various agro-ecological zones and soil types have been done in Kenya. A study carried out across major maize growing zones reported significantly higher response of nitrogen phosphorus and potassium in Nitisol; nitrogen in Phaeozem; nitrogen, phosphorus in Alisol; nitrogen and phosphorus in Acrisol; and nitrogen, phosphorus, and potassium in ferralsol (Smaling *et al.*, 1992; Mucheru-Muna *et al.* 2007; Ngome *et al.*, 2013; Njoroge *et al.*, 2018; Otieno, 2019). Response to secondary and micro-nutrients have also been reported in several studies (Njoroge *et al.*, 2018; Otieno *et al.*, 2020). A wide range of fertilizer application rates have been trialed and recommended for maize production across the country: 30-120 kg N, 30-100 kg P, 40-60 kg K, 26 kg S, 10-16 kg Ca, 10 kg Mg, 3-5 kg Zn, 5 kg B and 3 kg Cu

(Mugwe *et al.*, 2007; Ngome *et al.*, 2013; Njoroge *et al.*, 2018; Otieno, 2019; Otieno *et al.*, 2020). Despite showing responses, only N, P, and K nutrients applications have proved to be economical and should be prioritized (Otieno *et al.*, 2020). Research on secondary and trace elements should continue to enable timely monitoring and response to crop needs.

Also, the application of high-quality manure could have a similar impact as inorganic fertilizers. Kwabiah *et al.* (2003) found that the application of manure from *Tithonia* and *Croton* at 5 t ha^{-1} caused effects equivalent to 50 kg P + 120 kg N per hectare of inorganic fertilizers on maize in Western Kenya. In the same region, Achieng *et al.* (2010) reported a 4% more maize yield due to the application of 5 t farmyard manure than the combined application of 200 kg N+60 kg P+120 kg K+ 20 kg Mg+5kg B 5 kg per hectare. Highest maize yields of up to 5 t ha^{-1} due to the application of 30 and 60 kg N equivalent organic materials were also reported in Meru District in the Eastern Province of Kenya by Mucheru-Muna *et al.* (2007). Application of these organic sources improves soil SOM, pH, organic carbon, N, P, exchangeable K, Ca, Mg (Gao and Chang, 1996; Mucheru-Muna *et al.*, 2007).

Other ISFM practices with reported increase in maize productivity include maize-legume rotation and intercropping systems. Some of these legumes include common bean, cowpea, pigeon pea, *Crotalaria grahamiana,* soybean, groundnut, lima bean, lablab, velvet bean, crotalaria, and jack bean (Rao & Mathuva, 2000; Cheruiyot *et al.*, 2001; Bünemann *et al.*, 2004; Mucheru-Muna *et al.*, 2010; Ojiem *et al.*, 2014; Otieno *et al.*, 2019).

CONCLUSION

Evidence is showing that soil nutrient mining is higher than the rate of replenishment in Kenya. This condition has led to the current soil infertility affecting maize production across the country. The situation is aggravated by high acidity that fixes the nutrients that are already in low supply. The focus should be on adoption of integrated soil fertility management in order to avert the current condition. The use of inorganic fertilizers offers an immediate solution to soil infertility if done correctly. Application of fertilizer should follow 4R principles. To achieve high efficiency with the supplied nutrients, farmers must first improve their soil conditions by applying the recommended soil amendments like manure and lime. Also, agronomic practices such as better variety selection, drought management, weed control, pest, and disease management are essential and should be done properly.

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