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KALRO Kenya Agricultural & Livestock Research Organization

THE KENYA CEREALS ENHANCEMENT PROGRAMME – CLIMATE RESILIENT AGRICULTURAL LIVELIHOODS

(KCEP-CRAL)

INTEGRATED SOIL FERTILITY AND WATER MANAGEMENT EXTENSION MANUAL

SUPPORTED BY FUNDS FROM EU

APRIL 2021

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Disclaimer

The information presented in this manual is for advisory use only. Readers using the manual should verify details that relate to their agro-climatic zones from their area agricultural extension officers.

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We also thank the researchers, farmers and stakeholders who participated in the project for their support in setting up trials, collecting and processing the data and thus generating large amounts of knowledge and information that KCEP-CRAL has packaged and shared through scientific papers, in seminars and in reports among others. The support of technical officers, laboratory personnel, administrative and support staff is also appreciated as it contributed to the success that the project achieved.

FOREWORD

Kenya Agricultural and Livestock Research Organization (KALRO) is one of the key partners in the Kenya Cereals Enhancement Programme - Climate Resilient Agricultural Livelihoods Window (KCEP-CRAL) Programme funded by the European Union (EU) and implemented by the International Fund for Agricultural Development (IFAD). KALRO participation in this programme is based on proven experience and expertise in agricultural research. Within the programme, KALRO handles the research component, conducting on station and on farm trials, develops farmer recommendations together with training materials for extension staff and service providers and conducts the training. The implementation of KCEP-CRAL is in thirteen (13) counties namely Nakuru, Nandi, Trans Nzoia, Kakamega, Bungoma, Kitui, Tharaka-Nithi, Embu, Machakos, Makueni, Taita Taveta, Kwale and Kilifi.

KCEP-CRAL focuses on the three leading rain-fed cereals (maize, sorghum and millet) and associated pulses (beans, green grams, cowpeas and pigeon peas). The programme's overall objective is to contribute to the reduction of rural poverty and food insecurity of smallholder farmers.

Through this manual, the programme will provide a comprehensive guide to extension officers, service providers and lead farmers on how to successfully produce cereals and pulses in Kenya. The manual is a useful training and reference material for extension officers and other stakeholders seeking to enhance the capacity of farmers, increase commercialization for food security and promote gender inclusion and participation along the commodity value chains.

Initial lessons learnt in this project indicate that enhancing the capacity of the extension staff and service providers has improved uptake of new technologies for dry land farming. It has opened up more land for farming through use of conservation agriculture in areas that hitherto were not under agriculture. Besides easing the pressure on previously arable land, farmers in the project areas have been trained to use alternative disease and pest management regimes using Integrated Disease and Pest Management and Push pull technologies for persistent pests of economic importance.

On behalf of KALRO, I am grateful to the European Union for supporting this project through the IFAD and KCEP-CRAL of the Ministry of Agriculture, Livestock, Fisheries and Cooperatives (MoALF&C). I also appreciate the excellent coordination of the whole process by the KCEP-CRAL Secretariat led by Dr Anthony O. Esilaba, MoALF&C and other partners, scientists in participating centres, Knowledge, Information and Outreach Unit team and secretarial staff. It is my hope and desire that in using this manual, the expectations of all stakeholders will be met.

Eliud K. Kireger (PhD , OGW)

DIRECTOR GENERAL, KALRO

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ABBREVIATIONS AND ACRONYMS

AEC	Anion exchange capacity
CEC	Cation Exchange Capacity
EU	European Union
IFAD	International Fund for Agricultural Development
ISFM	Integrated Soil Fertility Management
KALRO	Kenya Agriculture and Livestock Research Organization
KCEP-CRAL	Kenya Cereals Enhancement Programme - Climate Resilient Agri cultural Livelihoods Window
MoALF&C	Ministry of Agriculture, Livestock, Fisheries and Cooperatives
ToTs	Training of Trainers'

1 INTRODUCTION

Our food is part of a global chain of production and distribution, which impacts our health, environment, and economy. Soils are at the base of our food production. It is estimated that 95% of the food for the more than 7 billion people is directly or indirectly produced on our soils. Food availability is however, unevenly distributed and about one billion people in developing world are structurally underfed due to social, economic, political factors, climate change as well as biophysical factors such as land degradation and, land and water resources competition. Projections indicate that the world's population will increase by 2 billion in the next 30 years, from 7.7 billion currently to 9.7 billion people in 2050. To meet this increase food biophysical, socio-economic availability and productive capacity must be improved. Of crucial in this regard is the capacity of land users worldwide to manage their soils sustainably and productively.

Judicious soil management is important in ending extreme hunger, achieving food security, improved nutrition, livelihoods as well human and environmental health. Partly; nutritious and quality food and animal fodder can only be produced from healthy soils. These soils also promote adequate healthy water resources leading to healthy landscapes and environments. Continuous restoration, maintenance and improvement of productive capacity soils are essential aspect of farm lands.

Healthy soils are fertile and have the ability to provide all required nutrients in right proportions and forms for all plant needs to maturity. Soils that meet these criteria possess balanced physical, chemical and biological factors. Human beings however, disrupt the balance through their day to day activities that lead to land and soil degradation.

Agricultural sector is a major contributor to land and soil degradation through unsustainable agricultural practices, overgrazing of rangelands, mono-cropping, excessive tillage, and low usage of fallow without appropriate replenishment of soil nutrients The diversity in the nature of the degradation causes and forms in different enterprises, landscapes and land use practices calls for varied management methods in managing land sustainably. Empowerment of stakeholders, trainers and farmer's knowledge base are vital ingredients in this complex mix.

This manual is aimed at empowering farmers, extension staff, researchers and other stakeholders with the necessary skills, information and knowledge on sustainable land use while conserving the soil ecosystems. It is envisaged that through this manual, farmers and field officers will deepen their understanding of our soils, enabling them to make site specific independent management and conservation decisions that promotes soil fertility leading to health soils that will promote increased food production, food security, human and environmental health in Kenya and beyond.

2 SOIL AND ITS COMPOSITION

2.1 Definition of soil

Soil is the media for plant growth. It consists of mineral or organic components, water, air / gases and organisms which support plant growth. It is the main source of nutrients for plants, animal and human life.

2.2 Role of soil in crop production and environment

In addition to providing essential nutrients to plants, soils also play other important roles in the ecosystem like:

- Provision of habitat for a wide variety of organisms,
- Recycling of systems through decomposition,
- Assimilation and mineralization of all substances,
- Carbon sequestration, and
- Detoxification of toxic substances on the lands surface.

Soils also influence hydrological cycle and clay, sand, limestone, gravel are used in engineering or construction.

2.3 Composition of Soil

All soils are made up of four main components, namely:

a) Solids (Mineral/Organic components)

b) Water (Soil solution)

c) Soil air (gases like CO_2, O_2, H_2 etc.)

d) Biota (Macro organisms, Microorganisms, lower plants and plant roots)

2.3.1 Solids

Composed of the inorganic and organic portions of the soil.

Inorganic Portion

The inorganic portion is made up of small rock fragments and minerals depending on weathering process. Primary and secondary minerals are the two types of minerals that constitute the inorganic matter. Primary minerals come from cooling of molten magma while secondary minerals are derived from weathered primary minerals.

Organic portion

The organic matter portion is made up of accumulation of partially disintegrated and decomposed plant and animal residues and organic compounds synthesised by the soil microorganisms as they decay. It normally ranges from 1-5%. However, because these materials are continually being broken down and re-synthesized by soil microorganisms, regular maintenance by addition of plant/animal residues, which are the sources for organic constituents is important.

2.3.2 Soil water

Generally, 40-50% of the bulk volume of the soil body is occupied by soil pores, which may be completely or partially filled with water. Soil water acts as a reservoir for supplying water to plants for their growth. It keeps the soluble salts in solution, which act as plant nutrients. The soil pores hold water and when all the pores are filled with water, the soil is said to be saturated or waterlogged. The amount of water that can be held by the soil depends on the size of the pore spaces. Soils with large particles have larger pores and do not hold a lot of water compared to soils with small sized particles.

2.3.3 Soil air

Soil air occupies the pore spaces. Its content and composition differs from place to place within a given soil depending on the particle sizes and water content in the soils. Most of the gases found in the atmosphere are found in the soil. Comparing atmospheric air and soil air, soil air has higher moisture content, sometimes it reaches 100% (in terms of relative humidity) and it has carbon-dioxide hundred times higher than atmospheric air. But oxygen content is less and decreases even up to 5% or even less than that. The gases in the soil are utilized by the plant roots and other living organisms within the soil.

2.3.4 Microbes

Microbes make up a very small part of the soil on weight basis, but they are the very active portion. Some of them are visible to the naked eye (roots of higher plants and macro-flora such as earthworms, termites) and some are microscopic (bacteria, fungi, actinomycetes). A single gram of soil may easily contain hundreds of millions of life bacterial cells, a million fungal spores, and a host of other microbes such as algae and protozoa. The microbes are a key component of a soil's ability to breakdown and recycle waste into useful products.

2.4 Soil Properties

2.4.1 Physical Properties

Soil physical properties includes: Horizonation/layering, colour, texture, structure, consistence, bulk density and porosity.

2.4.1.1 Horizonation/Layering

This refers to the different layers that make a soil profile. The layers indicate the degree of soil development. Well-developed soils are deep and contains a good number of the horizons (O, A, B, E, C, R) while shallow soils have few horizons. Horizonation is very important when choosing where to establish shallow or deep rooted crops.

2.4.1.2 Soil Colour

Colour is used as an indirect measure of the other soil properties. It can be defined visually or quantitatively using Munsel colour charts. Soil colour can be used as a physical indicator of some soil attributes. Example: dark or black colour especially on the surface soils may represent accumulation of humified organic matter contents. Yellow, brown and red coloured soils may represent well drained and well aerated B/C horizon, while white or light colour above B-H may be an indication of E-H. Additionally, light or grey colour occurring below B-H can an indication of accumulation of $CaCO_3$.

2.4.1.3 Soil Texture

Soil texture is the relative proportion of sand, silt and clay that makes up the mineral component of the soil. Collectively, the soil separates of sand, silt and clay are called the "fine-earth fraction" (Table 1) and represents inorganic soil particles less than 2mm in diameter. Inorganic soil particles 2mm and larger are called rock fragments or non-soil.

Table 1: Soil size ranges

Particle diameter (mm)	Textural class
≤ 0.002mm	Clay
0.002-0.05mm	Silt
0.05-2.0mm	Sand

Texture is an important characteristic because it influences drainage, erosion, runoff, leaching and nutrient retention. It also influences soil chemical properties. Example: fine grained particle fraction increases surface area hence increasing chemical activities. Hence, soils with large internal surface area such as clay are more chemically active than soils with low surface area such as sand because soils with large surface area have a greater charge per unit volume hence the capacity to hold water or nutrients is higher. Application of organic matter is important because it improves water and nutrient holding capacity of clay and sand soils leading to improved fertility levels.

2.4.1.4 Soil Structure

It refers to combination or arrangement of primary soil particles to form secondary patches or aggregates or peds. Peds are naturally occurring structures while clods are manmade structures such as chunks left after ploughing or hardpan.

Structures are classified into different classes depending on shape. They include, granular, angular, prismatic, platy, and blocky among others. Knowledge of the different structures is important because it provides an understanding of the nutrient holding capacity of a given soil, water retention and transmission of fluids, soil aeration status, soil thermal properties and expected germination patterns, root growth and development.

2.4.2 Chemical Properties

2.4.2.1 Soil Reaction (pH)

Soil pH, which is also called soil reaction, is defined as a measure of the active hydrogen ion (H+) concentration in soils. It is an indication of the acidity or alkalinity of soil. The pH scale range from 0-14, with values below 7.0 being acidic and values above 7.0 being alkaline. A pH value of 7 is considered neutral. A pH range of 6 to 6.8 is ideal for most crops because it coincides with optimum solubility of the most important plant nutrients, which makes most important nutrients available for crops and soil organisms' uptake for optimal growth and yields (Figure 1).

The pH of a particular soil is determined by the parent material, vegetation, climate and farming management practices. Some rocks produce soils that are acidic in nature; Some vegetation produce organic acids which contributes to lowering soil pH; Wet climate leads to washing away of bases hence domination of Hydrogen ions in the soils that makes them more acidic; and some acid fertilizers makes soil more acidic while liming or organic matter application neutralizes soil acidity.

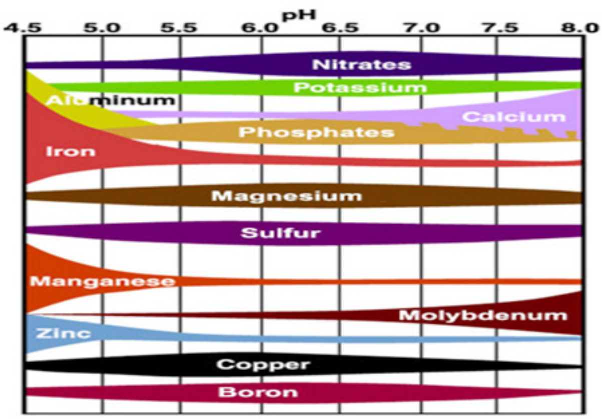


Figure 1: Soil pH range

2.4.2.2 Cation Exchange Capacity (CEC)

Some plant nutrients and metals exist as positively charged ions, or "cations", in the soil environment. Among the more common cations found in soils are hydrogen (H^+), aluminium (Al^{3+}), calcium (Ca^{2+}, magnesium (Mg^{2+}), and potassium (K^+). Clay and organic matter particles are predominantly negatively charged (anions), and have the ability to hold cations from being "leached" or washed away. The ability of soil to retain enough cations within the soil solution or exchange complex at a given pH range is, therefore, referred to as Cation exchange Capacity (CEC). In general, the greater the clay and organic matter content, the greater the CEC. Sandy (coarse) soils usually have a low CEC compared to clay soils. Apart from retaining soil nutrients for uptake, CEC is important in adsorption of contaminants and wastewater treatment in soils. In summary, fertile soils have high CEC and poor soils have low CEC levels.

2.4.2.3 Anion Exchange in Soil

Anion exchange capacity (AEC) refers to the ability of soil to retain adequate anions within the soil solution or exchange complex for plants and soil microbes' uptake. Anions are negatively charged ions of minerals present in soil colloid. They include: nitrates (NO_3^-), chlorides (Cl^-), sulphates (SO_4^-), and orthophosphates ($H_2P0_4^-$). Because the exchange of anions within soils is carried out by the silicate clay minerals and organic colloidal materials, different soil types have different anion exchange rates. For example, sandy soils have lower AEC compared to clay soils. Most soils with low AEC have low soil fertility levels and can be improved by application of organic amendments.

2.4.2.4 Buffering Capacity of Soil

Buffering capacity is the capacity of a soil to resist the changes in soil pH. The buffering capacity of the soil can be explained by the equilibrium that occurs between active and reserve acidities of soils. Active acidity refers to acidity found in soil solution and can be easily controlled through liming while reserve acidity refers to acidity found within the soil colloid and not ease to control. The buffering action of the soil is directly governed by the amount and nature of clay and organic matter or humus colloids present. It is also partly influenced by presence of large quantities of weak acids and their salts in the soil. The materials which impart buffering capacity to the soil are called buffering agents. The strongest buffering agents in the soil are clay and humus or organic matter.

It should be noted that buffering capacity of the soil is both desirable and undesirable depending on the state of soil reaction. It is a highly desirable in neutral or near neutral soil as it establishes soil pH and protects the plants and microorganisms from direct adverse and injurious effects of sudden change in soil reaction. On the other hand, it is not desirable in acidic or extremely alkaline soils because the greater the buffering capacity of the soils, the larger the amount of amendment such as lime to correct the acidity or alkalinity.

2.4.3 Biological Properties

Soil contains a wide range of soil organisms (fauna and flora). These organisms are classified as microorganisms, macroorganisms and plant roots.

Microorganisms are the smallest organisms (< 0.1mm in diameter). They are extremely abundant and diverse within soils and they include: bacteria, fungi, algae, yeast, actinomycetes, among others. Most of these microorganisms are able to decompose any existing natural material. Bacteria and Fungi are, however, of great importance in agricultural soils.

Although some soil bacteria and fungi are pathogenic, beneficial bacteria plays an important role in organic matter decomposition, biological nitrogen fixation and soil aggregation through production of sticky substances that bind soil particles together leading to improved water infiltration and holding capacity. Beneficial soil fungi on the other hand help in organic matter decomposition while mycorrhizal fungi form large surface area for nutrients and water uptake in deficient soils.

Macro organisms consist of organisms with a diameter greater than 0.1mm diameter. They include mites, nematodes, protozoa, earthworms, termites, ants. Through their activities in the soil, the organisms' breakdown organic materials, carry them from one place to another and aid the decomposition process to give humus leading to improved soil structure, enhanced soil carbon sequestration, nutrient recycling, soil fertility maintenance and good crop production.

2.5 Soil Health

A healthy soil is a soil that has the capacity to sustain soil biodiversity while maintaining water and air quality and supporting human health and habitation. The soil should have a good soil tilth, sufficient depth, good water storage, good drainage, sufficient supply of nutrients, small population of plant pathogens and insect pests, large population of beneficial organisms, low weed pressure, free from chemicals and toxins that may harm crops, resistant to degradation and resilient when unfavourable conditions occur. Some of the attributes that constraint soil health includes: soil compaction, poor aggregation, weed pressure, high pathogen pressure, low water and nutrient retention, salinity and sodicity, heavy metal contamination among others.

3 PLANT NUTRIENTS, DEFICIENCIES AND TOXICITIES SYMPTOMS

3.1 Plant Nutrients

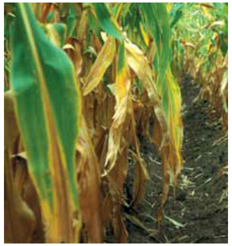
Soil fertility is the capacity of soil to produce crops of economic value and maintain soil health for future use. Soil is fertile when it contains all the required nutrients in right proportion and available forms for proper plant uptake and growth (Table 2). Plants need 16 elements for their optimal growth and completion of life cycle. The 17 elements are: Carbon (C), Hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (Bo), molybdenum (Mo), and chlorine (Cl).

Table 2: Classification of the 17 nutrients and where plants source them

Class	Nutrient	Source
Basic	C,H,O	Air and Water
Macro	N, P, K, Ca, Mg, S	Soil
Micro	Fe, Mn, Zn, Cu, B, Mo & CI	Soil

Plants obtain the basic elements from either air or water while the macro and micronutrients are obtained from soil through applied fertilizers. Macro nutrients are divided into primary and secondary nutrients. The primary nutrients are required by plants in large amounts and they include: N, P, K while the secondary nutrients are required in lesser amounts than primary minerals and they include calcium, magnesium and sulphur. The micronutrients are required by plants in small amounts but a considerable amount must be available for optimal crop growth and productivity. Table 3 shows the functions of each element in plants, their sources and deficiency and toxicity symptoms.

Table 3: Essential Soil Nutrients and their Management

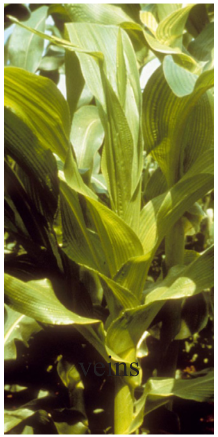
Nutrient	Functions	Deficiency symptoms	Toxicity symptoms	Nutrient sources	Notes
Nitrogen	• Protein and chlorophyll formation • Photosynthesis vigorous growth • Deep green colour	Yellowing of lower leaves from midrib 	• Excessively vegetative, delayed flowering and fruiting, • Tender succulent plants • Lodging susceptibility	Urea, CAN, AS, DAP, NPK, Mavuno, Farmyard manure, compost, green manure, BNF	Split applied at planting and 2-4 weeks after germination. BNF is used in relay and intercropping systems
Phosphorus	Energy storage/ transfer, root growth, seed and fruit formation, protein synthesis, photosynthesis	Reddish-purple colouration from margin to midrib 	• Leaf edges of the upper leaves brown or scotched • Death of growing points of upper leaves	DAP, TSP, SSP, NPK, Mavuno, Rock phosphate, farmyard manure, compost, green manure	• Applied during planting to enhance root system development • Soils with inherent pH values between 6 and 7.5 are ideal for P availability (Crop response to P application) while pH values below 5.5 and between 7.5 and 8.5 limits P availability to crops due to P fixation by Aluminium, Iron or Calcium which are usually associated with the soil parent materials. • P availability is controlled by three primary factors: Soil pH, amount of organic matter and proper placement of P fertilizer

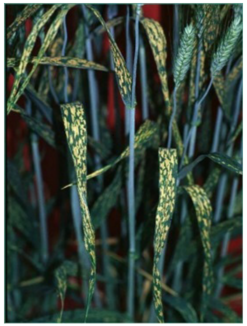
Nutrient	Functions	Deficiency symptoms	Toxicity symptoms	Nutrient sources	Notes
Potassium	Photosynthesis, carbohydrate transport, water regulation, protein synthesis	Interveinal chlorosis or bronzing from the edges leading to firing or scorched edges. 		Muriate of potash (KCL), Potassium sulphate (K2SO4), Potassium nitrate (KNO3), potassium magnesium sulphate (KMgSO4)	• Applied at planting • When K is limiting it limits the availability of N and P • Cation exchange capacity is the key determinant of the amount of K available for plant uptake. • It is difficult to build soil potassium levels especially in soils with high percentage clay. In clay soils K is bound becoming unavailable for plant uptake. • Plants can take up more K without increase in crop yield (luxury consumption). • Therefore it wise to apply only the needed amount to meet the yield gaol for the season. • High rates of potassium enable efficient use of N and P leading to better early vegetative growth and higher grain/straw growth.

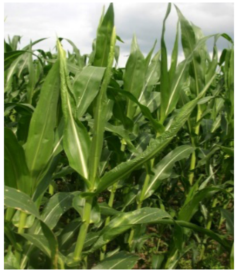
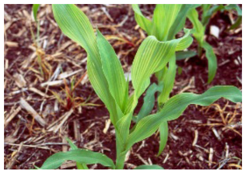
Nutrient	Functions	Deficiency symptoms	Toxicity symptoms	Nutrient sources	Notes
Magnesium	Protein synthesis, Photosynthesis, seed formation	Interveinal chlorosis with thin red or purple colour in lower leaves from the margin. 	Brown spots on leaf veins. Necrosis starting at the tips and margins. Leaf crinkling.	Dolomitic ($MgCO_3$. $CaCO_3$) lime, magesite ($MgCO_3$), magnesium sulphate ($MgSO_4.7H_2O$), Kieserite ($MgSO_4$. H_2O), Kainite ($MgSO_4$. $KCl.3H_2O$), Magnesium chloride ($MgCl_2$), Magnesium nitrate ($Mg(NO_3)_2.6H_2O$), Magnesium oxide MgO	• Applied at planting • Magnesium deficiencies are common in low pH soils, and sandy soils where Al dominates cation exchange sites. High exchangeable concentration can have an adverse effect on Mg availability for plants. The competition between these two cation for root uptake is the primary cause. • The pathways for Mg loss include crop removal, leaching losses, erosional loss

Nutrient	Functions	Deficiency symptoms	Toxicity symptoms	Nutrient sources	Notes
Calcium	Cell wall structure	• Malformed young leaves and abnormal terminal growth. • Blossom endrotend rot in vegetables 	Toxicity symptoms have not been reported for crops under field conditions	CAN, gypsum, Calcium oxide, calcium hydroxide, $CaCO_3$, $CaHCO_3$, Limestone, Calcium nitrate	• Applied at planting • Mostly likely to occur in acid, sandy soils by which Ca has been leached by rain or irrigation water. It may also occurs in strongly acid peats. Calcium deficiency is not likely in crops when soils are properly limed. As soils become more acidic crop growth is often restricted by toxic soil concentrations of Al or Mn and not Ca shortage. Soil testing and good liming program are the best management practices to prevent these problems. • Balance the nutrition program by keeping Ca, K and Mg available in balanced supply. • An over-abundance of one can lead to shortage or uptake (antagonism) of another. Also apply Ca for specific functions e.g. Ca applied when peanuts begin to set pods can improve seed development.

Nutrient	Functions	Deficiency symptoms	Toxicity symptoms	Nutrient sources	Notes
Copper	• Chlorophyll and seed formation, protein synthesis. • Improves fertility • Good cob development Improves yield • Brings harvest date forward	• Yellowing of upper leaves between leaf veins • The youngest leaves show yellow interveinal discoloration as they come out of the whorl. Mainly the basal part of the leaf is uniformly yellow-green. 	Chlorosis and necrosis of older leaves. Inhibition of root elongation.		

Nutrient	Functions	Deficiency symptoms	Toxicity symptoms	Nutrient sources	Notes
Iron	• Photosynthesis and respiration. • Participates in oxidation reduction reaction of nitrates • Sulphates and nitrogen fixation	Yellowing of upper leaves between leaf veins 	Bronzing and purple discolouration of leaves in other crops		
Manganese	• Is a component of enzymes and is also involved in photosynthesis and root growth. • It is involved in nitrogen metabolism and assimilation.	Yellowing of upper leaves between leaf  	Chlorosis, or blotchy leaf tissue due to insufficient chlorophyll synthesis. Growth rate will slow and vigour will decline. Leaf edges and tips also become chlorotic, which leads to the death of the leaf. Young leaves may become cupped and crinkled.	Manganese sulphate ($MnSO_4.3H_2O$), Manganese chloride ($MnCl_2$, Manganese carbonate ($MnCO_3$), Manganese oxide (MnO_2, anganese oxide (MnO), Manganese chelate (Mn EDTA)	• Applied as foliar • Deficiencies occurs in high pH (alkaline soils) • Deficiencies may also be problematic in high organic matter soils such as peats that favour formation of unavailable Mn chelates. • The high levels of Cu, Fe, or Zn may reduce Mn uptake

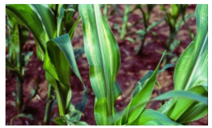
Nutrient	Functions	Deficiency symptoms	Toxicity symptoms	Nutrient sources	Notes
Chlorine	• Stimulates photosynthesis, osmoregulation and disease suppression • Increases cell osmotic pressure and water content of the plant tissue	• Chlorosis of younger leaves and wilting of the plant • Deficiency seldom occurs because chlorine is found in atmosphere and water  Wheat	Premature yellowing of young lower leaves, burning of leave margins and tips, plants will easily wilt leaf abscission will occur primarily for woody plants		

Nutrient	Functions	Deficiency symptoms	Toxicity symptoms	Nutrient sources	Notes
Boron	Development/ growth of new cells.	Death of growing points of upper leaves 	Chlorosis and necrosis of leaf tips and margins.		
Sulphur	• Synthesis of chlorophyll, photosynthesis, oil formation in seeds. • Crops with high nitrogen requirement must have adequate sulphur to optimize nitrogen utilization.	vf  	• Leaf size will be reduced and overall growth will be stunted. • Leaves yellowing or scorched at edges.	SSP, Potassium sulphate, Mavuno, Farmyard manure, compost, green manure, atmospheric deposition, gypsum, ammonium sulphate, Kieserite, Thiosulfates	• Applied at planting • Elemental sulphur is applied well in advance crop demand since a lag period of bacterial oxidation and conversion to sulphate is involved. • It may be subject to leaching losses similar to nitrate • There are no adverse environmental impacts associated with typical concentrations of sulphate in water.

Nutrient	Functions	Deficiency symptoms	Toxicity symptoms	Nutrient sources	Notes
Molybdenum	• Nitrogen fixation and assimilation • Necessary component of two major enzymes in plant –nitrate reductase and nitrogenise which are required for normal assimilation of nitrogen • Required by some microorganisms for nitrogen fixation in the soil	• Resemble those of nitrogen because the function of Mo is to assimilate nitrogen in the plant • Older and middle leaves become chlorotic and the leaf margins roll inwards • In contrast to N deficiency, necrotic spots appear at the leaf margins because of nitrate accumulation • Deficient plant are stunted and flower formation may be restricted • Mo deficiency can be common in N-fixing legumes	• Most plants are quite tolerant to high Mo concentrations. There is no record of Mo toxicity under field condition • In the greenhouse studies tomato leaves turned golden yellow • Animals fed on high Mo may need supplemental Cu to counteract the Mo		

Nutrient	Functions	Deficiency symptoms	Toxicity symptoms	Nutrient sources	Notes
		 Cucurbit plant  Cucurbit leaves			

Nutrient	Functions	Deficiency symptoms	Toxicity symptoms	Nutrient sources	Notes
Zinc	• Aids plant growth hormones and enzyme systems • Necessary for chlorophyll formation • Necessary for carbohydrate formation • Necessary for starch formation • It aids in seed formation and maturation • Protein synthesis	• Interveinal chlorosis occurs on younger leaves similar to Fe deficiency however, Zn deficiency is more defined appearing as banding at the basal part of the leaf whereas Fe deficiency result in interveinal chlorosis along the entire length of a leaf • In vegetable crop colour change appears in the younger leaves first, the new leaves are usually abnormally small, mottled and chlorotic	• Excessive Zn levels may occur on extremely acidic soils (<pH 5) • A general guide for Zn concentration in mature leaf tissue is as follow: deficient <20 ppm, sufficient 25-150 ppm, Toxic to excessive toxic 300 ppm or more • Soybean and most small grains fall between maize and edible beans in the Zn tolerant.	• Parent material, atmospheric deposition, Zinc sulphate, Zinc carbonate, zinc oxide, Zinc nitrate, Zinc chloride. Farmyard manure, compost, green manure • Zinc sulphate is the most commonly used source in the world.	• Inorganic: Applied as foliar • Organic: applied at planting • The total Zn content of a soil is depended on the geological composition of the parent material. • The Zn that is available for plants is that which is in a salt solution or absorbed in labile form. • The factors controlling Zn availability include: the total Zn content, pH organic matter content, clay content, calcium carbonate content and soil moisture status, and concentration of macro-nutrients especially phosphorus.

Nutrient	Functions	Deficiency symptoms	Toxicity symptoms	Nutrient sources	Notes
		• In citrus, irregular interveinal chlorosis occurs with small, pointed, mottled leaves. Fruit formation is significantly reduced • In legumes, stunted growth with interveinal chlorosis appears on the older, lower leaves. Dead tissues drops out of the chlorotic spots	Vegetable crops are highly sensitive to high Zn levels while grasses tolerate high levels of available soil Zn  		• The soils that are commonly associated with Zn deficiency are: sandy soils, strongly weathered tropical soils, saline and sodic soils, Vertisols and Gleysols. • Zn deficiency is likely to show up in the following crops: avocados, citrus, oil palm, banana, dry beans, maize, peas, rice, wheat, and sugarcane

3.2 Soil Fertility Indicators

Farmers use indigenous knowledge to judge poor versus fertile soils. Some of the local or traditional indicators for soil fertility include: soil colour, type of weeds and soil physical properties. Dark coloured soils indicate fertile soils due to presence of organic matter or humus. Some weed species are associated with either low or high soil fertility levels (Figure 2). For example: the grassy weed called poverty grass (*Rhynchely trumrepens*) occurs in very infertile soils while wondering jew, blackjack, macdolnaldi weed, Commelina species and Amaranthus, thorn apple, and back night shade species are associated with fertile soils. Presence of soil fauna such as earthworms is also associated with presence of decomposing organic matter, which leads to fertile soils.

Wandering jew *(Commelina benghalensis)*- **indicator for fertile soil**

Thorn apple *(Datura stramonium)* - **indicator for fertile soil**

Black jack *(Bidens pilosa)*- **indicator for fertile soil**

Mexican marigold *(Tagetes minuta)*- Poverty grass- **indicator for infertile soil**

Figure 2: Crops used as fertility indicators

Scientific way of determining soil fertility is by use of soil physical, chemical and biological properties. It analyses soil depth, texture, structure, consistence, bulk density, porosity, reaction, and cation exchange capacity, anion exchange capacity, buffering capacity, the various soil organism's quantities and their relationships. This is done through soil sampling and analysis.

4 SOIL SAMPLING AND ANALYSIS

4.1 Introduction

Soil sampling is a systematic collection of soil samples in a farm for analysis. Soil analysis is the chemical, physical or microbiological technique that estimates the availability of essential nutrients and organisms in the soil for plant growth and predicting the nutrient requirement of crops. Soil contamination and presence of toxic elements is also determined through soil analysis. The basic soil tests involve the determination of components that are of significance to crop growth such as pH, phosphorus, calcium, potassium, magnesium, sodium, cation exchange capacity, base saturation and bulk density. The test methods used in nutrients determination in soils and plant tissue correlate the relationships between the quantity and mineral form of the essential elements present in the soil and plant. This enables the grower to know what is needed to ensure the condition of the soil is suitable for crop reach its genetic yield potential. The soil and plant tissue tests are the most reliable method for identifying and confirming nutrient deficiencies.

4.1.1 Importance of soil sampling and testing

Soil testing is important for the following reasons.

- To establish baseline soil nutrient status.
- To measure changes in soil nutrient status over time.
- To assess the overall nutrient status of different soil types essential for crop growth and development.
- To predict nutrient deficiencies in current or succeeding crops.
- Establish fertilizer application recommendations/effectiveness (types and rates). This helps to avoid excessive nutrient application or accumulation of soluble salts.
- To assess nutrients removed in crop residues.
- To monitor the soil pH (acidity and alkalinity) and organic matter content.
- For soil biological characterization.
- For soil physical characteristic evaluation (soil physical characteristics are crucial determinants of the plant rooting pattern.

4.1.2 What to consider when undertaking soil sampling

When carrying out soil sampling, it is important to ensure that the samples are representative of the farm or area situation. It is important to always take separate soil samples where farm features differ because they have an effect on soil fertility. Features associated with soil fertility variability in the farm include:

- Topography (slope length or gradient, rocky outcrops)
- Soil types (texture, colour)
- Land degradation intensities (erosion sites, vegetation cover and type)
- Land-use history or distance from the homestead and livestock facilities.

4.1.3 Sampling tools and accessories

In general tools and accessories for soil sampling depends on the purpose and conditions of the soil. The most commonly used tools and accessories are:

a) Soil auger (spade or panga)
b) Trowel/strong rod for mixing soil
c) A clean bucket or any clean container
d) Markers for labelling
e) Soil sampling information sheet
f) Soil sampling bags/Clean plastic containers
g) Cooler box
h) Core rings
i) Tape measure/ruler
j) Knife/sample divider
k) Data sheet/note book
l) GPS
m) Scoopers
n) Sampling probe/core.

4.1.4 Selection of a sampling unit

In selecting the sampling unit start by a visual survey of the field. Traverse the field, note any variations in slope, soil colour and texture, management and cropping pattern, and demarcate the field into uniform portions, each of which must be sampled separately. The more the number of samples per sampling area the better the representativeness. The unit of sampling is a compromise between the expenditure, labour and time on one hand and precision on the other.

Avoid sampling in small areas where the conditions are different from the rest of the field (former manure piles, fertilizer bands or fence lines). These can be spotted by observing the plant vigour.

4.1.5 Sampling strategy

In Kenya 9 core samples were found to be adequate for fields of about 0.5 ha to detect differences in nutrient status of soils in many parts of the country (Okalebo *et. al*., 1992).

The number of cores to be taken depends on variation of the soil characteristics. The number of samples that are ultimately taken should be a good compromise between the desired expenditure, labour and time on one hand and desired level of precision on the other. A zigzag path soil sampling pattern is currently widely used and accepted across most regions in sub-Saharan Africa (Figure 3).

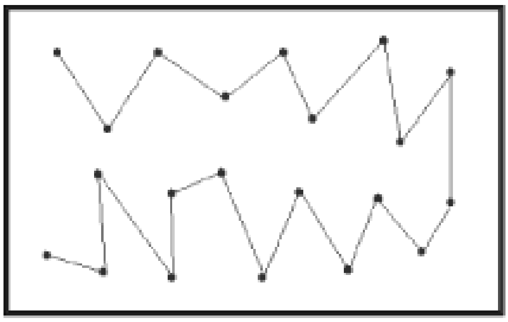


Figure 3: Zigzag path soil sampling

Source: Gelderman et al., 2006. Random

In this model, samples are taken along a zigzag path forming a letter "W" on flat fields. In fields that have a rectangular shape, cores may be taken along a transect formed diagonally between the two sides of the field. In other cases where fields are uniform in topography cores are made on randomized quadrants (Figure 4).

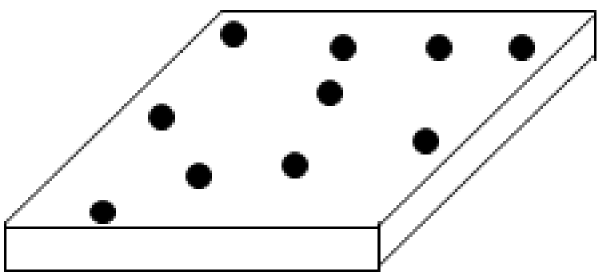


Figure 4: Random sampling in a relatively flat and uniform field

For fields that vary in topographical features, a multistage sampling strategy using topographical stratification may be adopted (Figure 5).

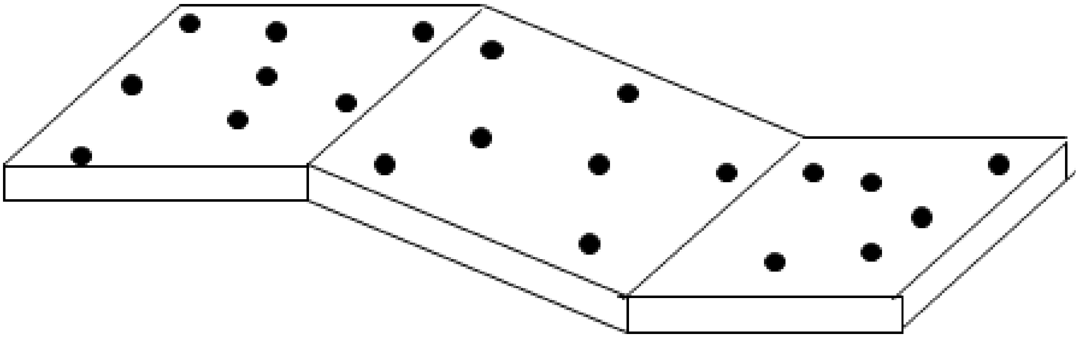


Figure 5: Multistage sampling following stratification with topography

4.1.6 Sampling for within-farm variability

Smallholder farmers in Kenya are known to apply nutrients inconsistently within the farm. For example farmers apply manure to fields close to homestead because it is bulky while fertilizer applications are made further afield. The goal for within-farm sampling is to determine the nutrient, salt, and pH variability of fields within a farm. Once this is determined, the nutrients are mapped and fertilizer and/or lime are variably applied field-wise. This is used mainly for specific field recommendations.

4.1.7 Grid sampling

Use a grid system where the field history is unknown (Figure 6), the non-mobile nutrients (P, K, Zn) are of primary importance and are high either from past fertilization or manure applications, where small fields have been merged into one or more large fields, or where year to year variability in non-mobile nutrient tests are high.

The field is divided into rectangular grids and a sample is taken from each grid. Each grid sample is usually a composite of 6 to 8 cores. In some procedures the cores may be taken in a “point,” usually from a circle of 6 to 8 feet around the point located in the grid of interest. If this system is used the points should be staggered in the grid as one goes from one grid to the next. This can be combined with inclusion of GPS coordinates that supports mapping of the field characteristics. Because of past management practices “streaks” of higher nutrient concentrations can often be found from one end of the field to the other. Staggering the point samples can avoid bias in the soil tests.

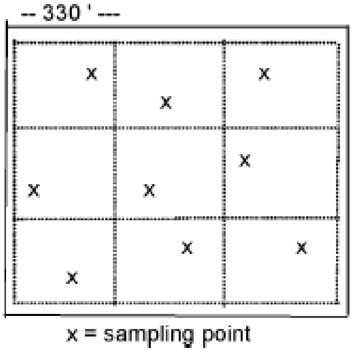


***Figure 6*: Grid soil sampling**

Source: Gelderman et al., 2006

4.1.8 Sampling by landscape/topography

This is one of the oldest procedures. The fields are divided into variable nutrient zones and sampling done by visual landscape differences (Figure 7). For instance, uplands may be sampled as one sample, slopes another, and bottom ground another.

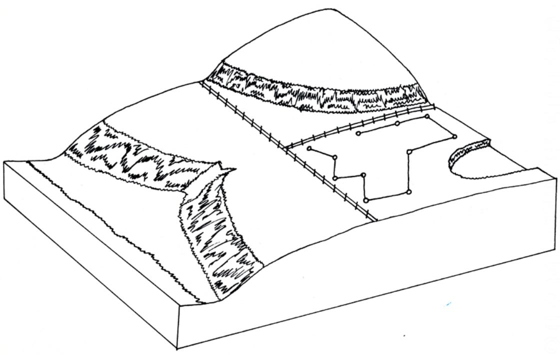


Figure 7: Landscape/topography soil sampling

Source: Gelderman et al., 2006

4.1.9 Sampling procedure

i. Divide the field into different homogenous units based on the visual observation and farmer's experience. Remove the surface litter at the sampling spot (Figure 8).

ii. Drive the auger to and the required depth and draw the soil sample. If auger is not available, make a 'V' shaped cut in the sampling spot using spade.

iii. Collect at least 10 to 15 samples from each sampling unit and place in a bucket or tray.

iv. Remove thick slices of soil from top to bottom of exposed face of the 'V' shaped cut and place in a clean container. Mix the samples thoroughly and remove foreign materials like roots, stones, pebbles and gravels.

v. Reduce the bulk to about half kilogram by quartering or compartmentalization. Quartering is done by dividing the thoroughly mixed sample into four equal parts. The two opposite quarters are discarded and the remaining two quarters are remixed and the process repeated until the desired sample size is obtained. Collect the sample in a clean cloth, brown paper bag or polythene bag.

vi. Label the bag with information like name of the farmer, location of the farm, survey number, previous crop grown, present crop, crop to be grown in the next season, date of collection, name of the sampler *etc*.

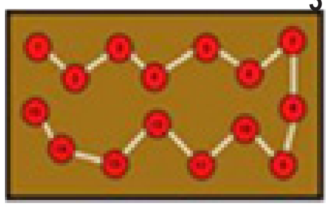
1 	2  or  **Sample to a depth of 0-20 cm for shallow and > 20 cm for deep rooted crops**	3  **Take soil from at least 10 places in each field**
Label the bag: 4 • **Name of the farmer** • **Sampling date** • **Location/GPS** • **Sampling depth** • **Analysis required** • **Previous crop** • **Crop to be planted** **Insert a similar tag in the sampling bag**	5  **Put about 500 g (1/2 kg) of the composite soil in a sampling bag**	6  **Mix the soil thoroughly to get a composite sample**

Figure 8: Soil sampling steps

NB: It is important to collect samples from all the spots marked for one sampling unit.

As precautionary measures: Soil samples should never be kept in the store along with chemical materials and detergents that could potentially contaminate the samples. The store for the samples should be kept dry.

4.1.10 Sampling depth

The appropriate sampling depth is best determined by the intended type of analysis and crop to be grown. For microbial analysis, the top soil can be sampled up to 10 cm depth because this is the horizon where most microbial activity takes place. For chemical/soil nutrient status analysis a reference to top soil is 0-20 cm depth because this is regarded as the rooting depth for most of the annual crops. For soil physical characteristics the sampling depth may vary depending on the intended use of the soil physical data.

4.1.11 Frequency of Sampling

New land soil sampling is done yearly for first few years until one understands the soil they are working with. On cultivated land, sampling is done every 2-3 years, unless there are concerns for environmental problems. Samples are taken at least one month before the onset of rains to provide enough time for analysis and amendment application.

4.1.12 Soil Sample Processing

Most of the soil test methods require that soils are dried to a constant weight. However, certain tests like inorganic-N (Nitrate-N and Ammonium-N) are done on wet soils. For the latter type of tests the soils are packed in cooler boxes to reduce microbial transformation and losses of N through various N-loss pathways like volatilization. To prepare samples for N analysis samples are sorted to remove the rocks, roots and other foreign materials. They are crushed to break the larger particles and sieved to pass through 2 mm sieve.

4.1.13 Soil Analysis Reports

A soil analysis report is provided after the soil has been analysed in a laboratory. Soil test reports contain the following:

- Values that indicate the available plant nutrient levels (low, moderate and high fertility) in the soil (Table 4 and 5).
- A summary of fertility levels for soils from a given farm (Table 5).
- Information on whether the minerals are adequate for optimum growth of a particular crop intended to be grown in the field or require replenishment through certain soil fertility management methods. Soil fertility management and nutrient replenishment recommendations are based on the analysis report and the intended crop to be grown. Nutrients replenishment is mainly through application of fertilizers. The type of fertilizer to be used is based on the particular nutrients that are not adequate in the soil. Crops grown in soils with low fertility levels have greater response to fertilizer application than soils with high fertility levels (Table 6).

4.1.14 Interpretation of Soil Analysis Results

Table 4: Guidelines to interpretation of soil chemical analysis results (Critical levels)

Soil pH levels

Range	Ratings	Interpretations
> 8.5	Very high	Alkaline soils
7.0-8.5	High	Alkaline to neutral
5.5-7.0	Medium	Acid to neutral
<5.5	Low	Acid soils

Adopted from Okalebo et al (2002)

Table 5: Guidelines on interpretation of soil N and C

Nutrient	Value	Rating
Organic C%	>3.0 1.5-3.0 0.5-1.5 <0.5	High Moderate Low Very low
Total N %	>0.25 0.12-0.25 0.05-0.12 <0.05	High Moderate Low Very low

Adopted from Okalebo et al (2002)

Table 6: Interpreting of exchangeable cation levels in soils

Rating	K(mg kg^{-1})	Mg (mg kg^{-1})	Ca (mg kg^{-1})
Very high	>300	>180	>2400
High	175-300	80-180	1600-2400
Medium	50-175	40-80	1000-1600
Low	50-100	20-40	500-1000
Very low	<50	<20	<500

Adopted from Okalebo et al (2002)

4.1.14.1 Plant tissue sampling for analysis

Plant tissue analysis is the laboratory examination of the nutrient concentration of a part of a plant at some point in time. Plant tissue analysis is a very important tool in the diagnosis of nutritional problems of plants. However, the results are dependent on many factors and therefore it is important to conduct other tests such as soil analysis, in order to give appropriate fertilizer recommendations.

4.1.14.2 Importance of plant tissue analysis

Plant tissue analysis is used to:

- Monitor the nutrient status (plant nutrient uptake) of the plant and therefore acts as a basis for nutrient recommendations for the crop.
- Detect nutritional problems of the plant prior to visual manifestation.
- Diagnose suspected nutrient problems overall health of the plant.

4.1.14.3 Plant sample collection

Samples for analysis should represent the general population of the plants. Timing of the sampling (plant physiological stage) is important.

While sampling considers:

- **The part of the plant sampled:** Samples should be taken from the same parts of the plant. It is critical to get the right plant part at the right growth stage. Generally, use the most recently matured fully developed leaf for more mature plants. For young plants, you can generally use the entire plant. For high-value crops, the petiole is used.
- **Timing of sample collection:** This depends on the phonological stage of the plant. The correct time to sample varies by crop. Always collect tissue samples from plants which are at the same physiological stage. For most plants, the appropriate time for sampling is prior to or during early reproductive (flowering) stage. It is important to remember that nutrient contents from tissues of plants that are too young undergo rapid changes while very old plant tissues are also not a good representative. Sampling can also be done whenever you suspect a plant growth problem (slow growth, unusual colour) related to nutrition or general health.

4.1.14.4 Number of samples collected

The appropriate number and location of samples needed depends on the variations in the plants and field. Plant analysis results of adjacent plants may vary considerably, even if the plants were fertilized at the same fertilizer rates.

4.1.14.5 Interpretation of results

The nutrient content of the plant is expressed on a dry weight basis. Macronutrients N, P, K, Ca, Mg and S are usually expressed as percentage or as g kg^{-1} and the micronutrients as either mg kg^{-1} (=ppm) or microgram/ gram. The amounts are expressed as deficient, marginal, adequate/optimal, high and toxic depending on individual crop requirements (Table 7).

Table 7: Table: Plant Nutrient status category terminology

Nutrient Status Category	Definition
Deficient	• Concentration of a nutrient associated with visible deficiency symptoms • Deficiencies severely reduce growth and production
Critical value or range (marginal)	• Concentration of a nutrient below which production is adversely affected • Producers should strive to keep all nutrient levels above their critical value or critical range
Sufficient range (adequate/normal/ optimal)	• Concentration of a nutrient that is optimal for plant growth and production • If all nutrient concentrations for a crop are within each nutrient's sufficiency range, nutrient status should not be considered a limiting factor for crop production
High	• Concentration of a nutrient that is greater than needed for optimal growth • In some crops, this level of nutrients may be associated with undesirable quality or vigor
Toxic (excessive)	• Concentration of a nutrient, greater than optimal, that is associated with reduced growth and production • This is usually observed only for minor nutrients

Adopted from: Plant Analysis: An Interpretation Manual

4.1.15 General Fertilizer Recommendations

Once the soil fertility level is determined through analysis, it is followed by fertilizer recommendations to bring the soil into productivity. This determines how much of soil nutrients that needs to be replenished. Other soil amendments like liming may be recommended depending on the soil status. Different crops require different levels of fertilizers.

4.1.15.1 Cereals

a) Millet

Most soils in millet production areas are deficient in essential macronutrients such as nitrogen (N) and phosphorus (P), which are essential for adequate crop growth. To correct these deficiencies, a wide range of organic and inorganic fertilizers are recommended. During planting, it is recommended to apply NPK (20:20:0 or 23:23:0) at a rate of one bag (50kgs) or DAP (18:46:0) 25 kg ha^{-1} per acre. Planting fertilizer is drilled along the planting furrow and thoroughly mixed with soil before seeds are planted. In soils with low fertility and in instances where rainfall continues beyond 30 days after planting, top dress with CAN at a rate of one bag (50Kgs) per acre when the crop in knee high (three weeks after germination). Application of farmyard manure at 5 tons per ha (2 tons $acre^{-1}$) is recommended. Fertilizer recommendations are listed in the Table 9.

b) Sorghum

Grain sorghum is well adapted to grow on many different soils throughout the country. However, it does best on deep, fertile, well-drained loamy soils and is more tolerant of shallow soil and droughty conditions. It can be grown successfully on clay, clay loam, or sandy loam soils. However, farmers should not expect soils that produce poor beans or poor maize crops to yield a bumper crop of grain sorghum. The best soils for other crops also produce the highest grain sorghum yields easily. During planting, it is recommended to apply NPK (20:20:0 or 23:23:0) at a rate of one bag (50kgs) or DAP (18:46:0) 25 kg ha^{-1} per acre. Planting fertilizer is drilled along the planting furrow and thoroughly mixed with soil before seeds are planted. In soils with low fertility and in instances where rainfall continues beyond 30 days after planting, top dress with CAN at a rate of one bag (50 Kgs) per acre when the crop in knee high (three weeks after germination). Application of farmyard manure at 5 tons per ha (2 tons $acre^{-1}$) is recommended. Fertilizer recommendations are listed in the Table 9.

c) Maize

Maize grows on a wide range of soils but performs best on well-drained, well aerated and deep soils containing adequate organic matter content and well supplied with available nutrients. High maize yields results in heavy removal of soil nutrients. This requires regular replenishment with soil nutrients to replace nutrients taken up after every harvest. For sustainable production, nutrients removed from the soil must always be applied within a growing period taking into consideration nutrient losses through harvested materials, leaching, volatilization, and erosion. For optimum production, factors such as soil moisture, temperature, pests and diseases, weed control, and soil chemical and physical conditions must be taken into consideration. Maize crop grows generally well in soils with a pH range of 5.0 to 8.0 with an optimum pH range for growth at 5.5 to 7.0. The pH outside this range usually makes certain elements more or less available, so toxicity or deficiency develops and growth rates of the crops is reduced. It is very important to maintain the pH as close to the optimum range as possible because below a soil pH of 5.0, aluminium and manganese toxicities may occur and deficiencies of P, Mg and Ca become common. At pH above 8.0, deficiencies of Fe, Mn, Zn and P tend to occur. For example if pH is lower than 6.0, P starts forming insoluble compounds with iron (Fe) and aluminum (Al) and if pH is higher than 7.5, P starts forming insoluble compounds with calcium (Ca) making it unavailable to the plants. Fertilizer recommendations are listed in the Table 8.

Tables 8 and 9 show fertilizer recommendations for cereals in Western, Eastern and Coastal regions.

Table 8: KCEP fertilizer recommendation rates for Western Kenya region

Choice	Maize		Maize/bean intercrop
	Planting	**Top dress**	**Planting**
Choice 1	NPK (23-23-0) 2 bags acre^{-1-}	Top-dress with CAN (26-0-0) 1.5 bag acre^{-1}	NPK (23-23-0) Extra 25 kg acre^{-1}
Choice 2	MEA Mazao (10-26-10 + 25% Ca and micronutrients) 2 bags acre^{-1}	Top dress CAN (26-0-0) 1 .5 bag acre^{-1}	MEA Mazao Extra 25 kg/ acre^{-1}
Choice 3	Mavuno Basal (10-26-10 + Ca and micronutrients) 2 bags acre^{-1}	Top-dress with Ma-vuno 1.5 bag acre^{-1}	Mavuno basal Extra 25 kg acre^{-1}

Table 9: KCEP fertilizer recommendation rates for Eastern and Coastal Kenya regions

Choice	Sorghum/Millet	
	Planting	**Top dress**
Choice 1	NPK (23-23-0) **1 bags acre^{-1}**	Top dress CAN (26-0-0) **1bag acre^{-1}**
Choice 2	MEA Mazao (10-26-10 + 25% Ca and micronutrients) **1bag acre^{-1}**	Top dress CAN (26-0-0) **1 bag acre^{-1}**
Choice 3	Mavuno Basal (10-26-10 + Ca and mi-cronutrients) **1bags acre^{-1}**	Mavuno top-dress **1 bag acre^{-1}**

4.1.15.2 : Fertilizer recommendations for production of pulses

a) Pigeon Peas

Although pigeon peas are a nitrogen fixing species, compound fertilizer is recommended at 20 kg P ha-1 and 8 kg N ha-1 (DAP 50 kg-bag/ha) (Table 10). Phosphorus is the most limiting factor for pigeon pea. Pigeon peas can fix up to 35kg ha N-1- by symbiosis by the mid pod filling stage. To enhance nitrogen fixation the seeds are inoculated with *Rhizobium during planting*. Pigeon pea is also used as a green manure.

b) Green grams

The best pH range is between 6.0 and 7.0. If it is below 6.0, lime should be added to raise pH to the desired level. For best results, lime should be applied one year prior to growing green grams and thoroughly incorporated. Fertilizer application is recommended based on soil analysis and availability of the soil nutrients. A compound fertilizer containing nitrogen, phosphorus (P) and potassium (K) at rate of 1 bag (50Kgs)/ acre is applied and incorporated into the soil before sowing. Manure can be also be applied before fertilizer or alone at 5 tons per ha or 2 tons per acre (100 wheel barrows per acre). The manure should applied in the planting lines and mixed with the soil just before rains starts.

c) Cowpeas

Cowpeas are adapted to a wide range of soils from sandy soil to well-drained clay soils. It does better in lighter soils that favour good root development. Cowpea does not tolerate excessively wet condition and have low tolerance to waterlogging. It requires a soil pH that range between 5, 6 to 6.5. Below pH 4.5, plant growth is impaired through limitation of development of the Rhizobium bacteria that are responsible for the nitrogen fixation. Same fertilizer recommendations like for pigeon peas applies.

d) Beans

They grow in soil with a pH range of 5.0 - 7.5. Below pH 4.5, plant growth is impaired through limitation of development of the Rhizobium bacteria that are responsible for the nitrogen fixation. The crop also performs poorly in compacted, alkaline or poorly drained soils. The use of 4-5 tons ha^{-1} of farmyard manure is highly recommended especially in areas where soils are low in organic matter content. Well-decomposed animal manure or compost should be applied under dry conditions, and then mixed with the topsoil. This should be done about one week prior to planting. It is usually better to give a good supply of animal manure or compost to the previous crop in the rotation, then the beans will not need any additional applications. Soil fertility may also be increased by growing green manure crops and ploughing them into the soil. Apply about 50 kg DAP or 100 kg NPK (23:23:0), or Mavuno per ha. The fertilizer should be thoroughly mixed with soil before covering the seed.

Table 10: Summaries of Fertilizer recommendations for pulses fertilizer recommendations

	Rate of application for pulses	
Fertilizer	Bags $acre^{-1}$	Kgs P ha^{-1}
DAP	1.0	20
Mea Mazao	1.5	20
Mavuno	1.5	20
17:17:17	2.3	20
23:23:0	2.0	20

5 SOIL DEGRADATION, ITS CAUSES AND MANANGEMENT

Soil degradation is the decline in soil quality because of improper land use activities such as inappropriate agricultural intensification and farming practices, intensive grazing and unsustainable urban or industrial expansion. It involves the decline of the soil's physical, chemical and biological quality. It can be the loss of organic matter, decline in soil fertility and structural condition, erosion, adverse changes in salinity, acidity or alkalinity, and the effects of toxic chemicals, pollutants or excessive flooding.

Soil degradation can impact directly on yield and yield quality, as well as the timing of tillage, planting and harvesting operations. This leads to gaps in continuity which can have a significant financial impact on growers and increase their reliance on imports to meet customer requirements. This, in turn, impacts on national food security, self-sufficiency and has social impacts due to uneven labour requirements and increased food prices.

Soil degradation may occur naturally, due to climate change or human activities.

5.1 Causes of soil degradation

5.1.1 Physical Factors

Physical factors such as rainfall, surface runoff, floods, wind erosion, tillage, and mass movements result in the loss of fertile top spoil thereby declining soil quality. These physical factors produce different types of soil erosion (mainly water and wind erosion) and soil detachment actions, and their resultant physical forces eventually changes the composition and structure of the soil by wearing away the soil's top layer as well as organic matter and hence decline in soil fertility and quality

a) Soil erosion

Soil erosion refers to the wearing away of a land's topsoil by the natural physical forces of water and wind or through forces associated with farming activities such as tillage. Soil erosion occurs through a number of ways. Two main channels, water and wind, are discussed below:

i) Water erosion

When soil particles are broken by raindrops, the fragments are washed into soil pores and prevent water from infiltrating the soil. This causes water to accumulate on the surface and increases runoff which carries the soil away. Well-structured soils are less prone to break up, and the impact of raindrops is minimized if the soil surface is protected by plant or litter cover. The vulnerability of soils to water erosion depends on:

- Rainfall intensity (erosivity)- High intensity rainfall creates serious risk as heavy drops on bare soil causes the soil surface to seal
- Nature of the soil (erodibility)- The percentage of clay in soils vary and hence its ability to withstand raindrop impact and erosion

- Slope length- Longer slopes tend to cause water running down the slope to becomes deeper and move faster washing the soil away
- Slope steepness- Steeper slopes increases water speed, which increases the power of water to break off and carry soil particles.

ii) Wind erosion

Bare soils with low or no vegetation are prone to wind erosion. Wind erosion is a significant problem in the arid and semi-arid grazing lands. It is most likely to occur when strong winds blow over light-textured soils that have been heavily grazed during drought periods. It contributes to scalding, a process that forms smooth, bare areas on impermeable subsoils. Sandy soils are vulnerable to wind erosion as the particles loosely hold together, have very low capacity to store moisture and are low in fertility. Eroded areas are difficult to re-vegetate due to lack of top soil, low permeability and saline surface. The channels result in various types of erosion.

Types of erosion

	
Sheet and rill erosion **Sheet erosion** occurs when a thin layer of topsoil is removed over a whole hillside paddock—and may not be readily noticed. **Rill erosion** occurs when runoff water forms small channels as it concentrates down a slope. These rills can be up to 0.3m deep. If they become any deeper than 0.3m they are referred to as gully erosion.	**Scalding** Scalding can occur when wind and water erosion removes the top soil and exposes saline or sodic soils.

 **Gully erosion** Occurs when runoff concentrates and flows strongly enough to detach and move soil particles. Gullies may develop in watercourses or other places where runoff concentrates. In cultivation or pastures, advanced rill erosion can develop into gully erosion.	 **Stream bank erosion** When clods of these soils are exposed to water, they readily break down into individual particles of sand, silt and clay which are easily removed as water moves through the subsoil. The major cause of stream bank erosion is the destruction of vegetation on river banks (by clearing, overgrazing, cultivation, vehicle traffic up and down banks or fire) and the removal of sand and gravel from the stream bed.

5.1.2 Biological Factors

Biological factors refer to the human and plant activities that tend to reduce the quality of soil. Some bacteria and fungi overgrowth in an area can highly impact the microbial activity of the soil through bio-chemical reactions, which reduces crop yield and the suitability of soil productivity capacity. The biological affect mainly lessens the microbial activity of the soil.

5.1.3 Chemical Factors

This is the reduction of soil nutrients due to alkalinity, acidity, water logging or removal of nutrients through crop harvests. The chemical factors are mainly alterations in the soil's chemical property that determine nutrient availability. They create undesirable changes in the essential soil chemical ingredients.

5.1.4 Deforestation

Removal of trees and crop cover exposes soil minerals to adverse weather effects. Vegetation cover primarily promotes the binding of the soil together and soil formation, hence when it is removed it considerably affects the capabilities of the soil such as aeration, water holding capacity, and biological activity.

5.1.5 Misuse or excessive use of fertilizers and chemicals

The excessive use and the misuse of pesticides and chemical fertilizers kill organisms that assist in binding the soil together. When fertilizers and other agricultural chemicals are not correctly used, they denature essential soil minerals. This gives rise to nutrient loss, destruction of the soil's biological activity and building up of toxicities.

5.1.6 Industrial and Mining activities

Industrial and mining activity destroys crop cover and releases various toxic chemicals such as heavy metals (mercury) into the soil thereby poisoning it and rendering it unproductive. It also releases toxic effluents and material wastes into the atmosphere, land, rivers, and ground water that eventually pollute the soil. Industrial and mining activities degrade the soil's physical, chemical and biological properties.

5.1.7 Improper cultivation practices

Improper tillage on agricultural lands breaks up soil into finer particles, which increase erosion rates. The decline of soil quality is accelerated by mechanization of agriculture that gives room for deep ploughing, reduction of plant cover, and formation of hardpan due to compaction. *Compaction* of *soil* is the compression of *soil* particles into a smaller volume, which reduces the size of pore space available for air and water. Other improper cultivation activities such as farming on steep slope and mono-cropping, row-cropping and surface irrigation wear away the natural composition of the soil and its fertility, and prevent soil from regenerating.

5.1.8 Urbanization

It removes the soil's vegetation cover, compacts soil during construction, and alters the drainage pattern. Most of the runoff and sediments from urban areas are polluted with oil, fuel, and other chemicals. Increased runoff from urban areas also causes a huge disturbance to adjacent water sheds by changing the rate and volume of water that flows through them.

5.1.9 Overgrazing

Overgrazing destroys surface crop cover and breaks down soil particles, increasing the rates of soil erosion. As a result, soil quality is greatly affected.

5.2 Effects of Soil Degradation

5.2.1 Land degradation

Soil quality decline is one of the main causes of land degradation and is considered to be responsible for 84% of the ever diminishing acreage. Year after year, huge acres of land lost due to soil erosion, contamination and pollution. About 40% of the world's agricultural land is severely diminished in quality because of erosion and the use of chemical fertilizers, which prevent land from regenerating. The decline in soil quality as a result of agricultural chemical fertilizers also further leads to water and land pollution thereby lowering the land's worth.

5.2.2 Drought and aridity

Drought and aridity are problems highly influenced and amplified by soil degradation. The contributing factors to soil quality decline such as overgrazing, poor tillage methods, and deforestation are also the leading causes of desertification characterized by droughts and arid conditions. Soil degradation may also bring about loss of biodiversity.

5.2.3 Loss of arable land

About 40% of the world's agricultural land is lost due to soil quality depreciation caused by agro-chemicals and soil erosion.

5.2.4 Increased flooding

Soil degradation takes away the soil's natural capability of holding water thus contributing to more cases of flooding.

5.2.5 Pollution and clogging of waterways

Most of the soil eroded from the land together with the chemical fertilizers and pesticides utilized in agricultural fields are discharged into waterways and streams. With time, the sedimentation process can clog waterways, resulting in water scarcity. The agricultural fertilizers and pesticides also damage marine and freshwater ecosystems and limits the domestic uses of the water for the populations that depend on them for survival.

5.3 Solutions of Soil Degradation

5.3.1 Reducing deforestation

With the reduction of deforestation, soil's ability to naturally regenerate can be restored. Governments, international organizations, and other environmental stakeholders need to ensure there are appropriate measures for making zero net deforestation a reality to inhibit soil degradation.

5.3.2 Land reclamation

To restore the lost soil mineral matter and organic content, it would require land reclamation. Land reclamation encompasses restoring the previous organic matter and soil's vital minerals. This include planting of vegetation such as trees, crops, and flowers over the affected soils, addition of plant residues to degraded soils and improving range management. Salinized soils can be restored by salt level correction and salinity control.

5.3.3 Preventing salinization

Prevention of salinization is far much cheaper than reclaiming salinized soils. Consequently, preventive actions such as reducing irrigation, planting salt tolerant crops, and improving irrigation efficiency will have high pay offs compared to reclamation projects which usually have high input and labour costs.

5.3.4 Conservation tillage

Proper tillage mechanisms is one of the most sustainable ways of avoiding soil quality decline. Conservation tillage aims at making very minimal changes to the soil's natural condition and, at the same time, improving the soil's productivity. It involves leaving the previous year's crop residue on the surface to shield the soil from erosion, planting cover crops, crop rotations, intercropping and avoiding extensive deep plowing.

5.3.5 Soil erosion control

The 3 main principles to control erosion are:

i. Use land according to its capability: the steeper slopes and shallower soils suitable for growing pastures, and the lower slopes and deeper soils suitable for growing crops.

ii. Protect the soil surface with some form of covers: Surface cover is a major factor to control erosion because it reduces the impact of raindrops falling on bare soils and wind removing soil particles. It also reduces the speed of water flowing over the land. Erosion risk is significantly reduced when there is more than 30% soil cover.

iii. Control runoff before it develops into an erosive force: Trees are often considered to be the universal answer to control soil erosion. Tree roots help prevent landslides on steep slopes and stream bank erosion

6 SOIL FERTILITYAND WATER MANAGEMENT

Soil management is the application of operations and practices that enhance soil health and performance. These practices may be broadly classified as soil fertility management by application of fertilizers, adoption of practices that enhance maximum soil moisture retention and minimum plant nutrient losses or loss of soil biodiversity.

Soil management is sustainable if the supporting, provisioning, regulating, and cultural services provided into the soil are maintained or enhanced without significantly impairing its functions

Sustainable soil management is fundamental to effective soil function, particularly in intensive production systems where optimal plant growth is required to deliver maximal crop yield and quality. In intensive cropping systems, when sustainable soil management is not practised, soil structural degradation in all forms is widespread and pervasive.

6.1 Soil Fertility Management

Soil Fertility Management (SFM) strategies centre on the combined use of mineral fertilizers, locally available soil amendments and organic matter to replenish lost soil nutrients. They include:

6.2 Integrated soil fertility management (ISFM)

This involves a set of agricultural practices and germplasm adapted to local conditions to maximize the efficiency of nutrient and water use and improve agricultural productivity. ISFM strategies are anchored on the combined use of mineral fertilizers and locally available soil amendments (such as lime and phosphate rock) and organic matter (crop residues, compost and green manure) to replace lost soil nutrients. This improves both soil quality and the efficiency of fertilizers and other agro-inputs. ISFM also promotes improved germplasm, agroforestry and the use of crop rotation and/or intercropping with legumes (a crop which also improves soil fertility).

Fertilizers supplement plants with the vital nutrients needed for optimal, healthy growth. There exist two major categories of fertilizers: organic and inorganic. Organic fertilizers are derived from naturally occurring substances, such as plant or animal byproducts and mineral rock, but inorganic fertilizers are synthetically manufactured. Organic fertilizers undergo little processing and include ingredients such as composts and manure, while inorganic fertilizers are synthetic and typically made from petroleum.

6.2.1 Organic fertilizers

The cementing agent that binds the soil particles together is the organic matter, which is found in organic fertilizers. It is both of animal and plant origin. Besides adding necessary nutrients to soil, organic fertilizers boost soil fertility status by improving all soil physical, chemical and biological properties which most plants rely on for healthy growth and development. They play the following roles in the soils:

i) Improves soil temperature regulation

ii) Improves soil aeration and reduces soil compaction.

iii) Improve infiltration rate

iv) Improves soil organisms population

v) Improves soil water and nutrient holding capacity.

Practices that increase organic matter in the soils include: crop rotations that contains high plants residues, leaving crop residues in the field, growing cover crops, use of low or no tillage systems, mulching, growing perennial forage crops, using optimum nutrient and water management strategies for healthy plants production with large number of residues and roots, growing cover crops and application of compost or manure.

Apart from insitu organic matter accumulation, there exists a wide range of locally available organic amendments. They include farmyard manure, green manure, compost manure, sewage/sludge and marine byproducts.

i) Farmyard Manure

Farm yard manure is made from livestock animals such as cattle, chickens, horses and sheep waste and their beddings. The amount of nutrient that manure provides and its subsequent availability to plants is influenced by a several factors:

- Nutrient contentof the animal feed
- Storage and handling procedures of the manure
- Amount and type of materials added to the manure
- Timing and method of application
- Properties of the soil
- Choice of crop.

ii) Legume /green manure

Green manure is made from crops that are generally grown for less than a growing season and are ploughed and incorporated in the soil before producing seeds. Examples of common green manure crops are: annual ryegrass, Sudan grass, tithonia and sesbania. Legumes are particularly beneficial since they are nitrogen fixing species and are a good source of nitrogen. A particular advantage of implementing a legume/green manure rotation into the soil/cropping system is the added source of organic matter. Green manures also improve soil structure by reducing bulk density.

iii) Sewage sludge

Sewage sludge consists of the solid products formed during sewage treatment. It is not uniform in mineral composition but generally, it contains between 1 to 3% total nitrogen

iv) Compost

Compost is made from decomposed plant matter such as vegetable peels, eggshells, coffee grounds and other organic scraps. Regardless of the source, compost provides soil with a well-balanced mix of nutrients, including nitrogen, phosphorus and potassium.

v) Manure

Manure comes from livestock animals such as cattle, chickens, horses and sheep, although bat and bird guano are also effective organic fertilizers. Like compost, manure also does double duty by adding essential nutrients to the soil as well as improving soil quality and its water-retention ability. Because manure can cause food-borne illness, use either composted manures or apply fresh manure well in advance.

vi) Marine Byproducts

Fish emulsion, fish scrap and seaweed extracts are important sources of soil nitrogen, phosphorus, and potassium. Fish emulsion, which is derived from partially decomposed ground fish, is an organic fertilizer that provides high levels of nitrogen to soil. Fish scrap is another marine byproduct and organic fertilizer that contains both nitrogen and phosphorus. Seaweed extracts provide nitrogen and potassium as well as trace elements to soil, and have a less intense odor than the fish derivatives.

vii) Meals

Meal supplements are agricultural byproducts from the meat and farming industries. Common examples of meals used as organic fertilizers include blood meal, which provides high levels of nitrogen and iron; bone meal, which is rich in both nitrogen and particularly phosphorus; and cottonseed meal, which contains all three macronutrients – nitrogen, phosphorus and potassium.

viii) Rock Minerals

Although mined rock minerals differ from other organic fertilizers in that they are not derived from a previously living organism, they are still considered organic fertilizers because they have not undergone extensive processing, and provide soil with nutrients vital to healthy plant growth and development. Common examples of mined rock mineral fertilizers include rock phosphate, greensand and sulfate of potash magnesia.

ix) Mulch

This can be derived from organic or inorganic materials. Organic mulch improve soil fertility through decomposition of the materials. Examples of organic mulches include grass clippings, shredded leaves and old hay. Annual applications of mulch, along with compost, improve soil’s ability to absorb nitrogen and other nutrients. Inorganic mulch contribute to soil fertility management through soil moisture retention and regulation of soil environment making it suitable for micro-organism action.

x) Inorganic fertilizers

Inorganic fertilizers come in single-nutrient or multi-nutrient formulas. Multi-nutrient formulas include compound and single fertilizers, which contain basic nutrients, such as nitrogen, phosphorus and potassium, as well as secondary and micronutrients such as calcium, magnesium, boron and manganese. The percentage of nitrogen, phosphorus and potassium contained in both complete and balanced fertilizers is indicated by three numbers on the package. For example, a 5-10-5 formula is a compound fertilizer, containing 5 percent nitrogen, 10 percent phosphorus and 5 percent potassium. Balanced fertilizers are those that contain equal nutrient amounts, such as a 10-10-10 formula.

6.2.2 Types of Inorganic Fertilizers

Inorganic fertilizers include slow-release formulas. These formulas contain larger molecules that are coated, helping them to break down slowly in the soil. A typical slow-release fertilizer releases nutrients over a period of 50 days to a year, reducing the chance of burning the plant or root system. Specially formulated inorganic fertilizers are those that are created for a specific type of plant. Specially formulated fertilizers are usually highly acidic and should be used only on the plants for which they are indicated.

6.2.3 Nitrogen Fertilizers

Inorganic nitrogen fertilizers come in many different forms, such as ammonium nitrate, potassium nitrate, calcium nitrate and urea. These fertilizers contain high levels of nitrogen, one of the most vital nutrients for plant growth. However, these inorganic fertilizers tend to increase the pH of the soil upon application, increasing the chances of burn and damage to seedlings. Others pull moisture from the air, making them difficult to apply and store.

6.2.4 Phosphorus Fertilizers

Inorganic phosphorus fertilizers such Superphosphates (single superphosphate, triple superphosphate) are forms of phosphorus fertilizer. These do not affect the pH of the soil upon application, while ammonium phosphates (Di-ammonium phosphate (DAP) and Mono ammonium phosphate (MAP)) come in water-soluble, granular forms.

6.2.5 Potassium Fertilizers

Inorganic potassium fertilizers include potassium sulfate and potassium nitrate, as well as muriate of potash, also known as potassium chloride. Muriate of potash is the most commonly used potassium fertilizer. In some cases, plants may be sensitive to chloride. If a plant is sensitive to chloride, potassium sulphate, also known as sulphate of potash, is a better choice, as it does not contain chloride. Potassium nitrate is easy to apply, because it does not pull moisture from the air, but it does slightly increase the pH of the soil upon application.

6.2.6 Fertilizer Application Methods

The method of applying fertilizers depends on the nature of crops, their nutrient needs and the soil.

Broadcast

Fertilizer is spread on the soil surface. It precedes tillage so that the fertilizer can be mixed with the soil this result in fairly uniform fertilizer applications. Both fluid and pelleted fertilizer may be broadcast. This provides the most uniform distribution of nutrients within a given soil volume. This method is suited particularly well to high rates of applied fertilizer. It is inefficient and may be wasteful.

Broadcasting of fertilizers is carried out at two stages

i). At the Time of Planting

Depending on the crop, broadcasting of the fertilizer is carried out prior to sowing/planting or just before the last ploughing and incorporated in the field.

Broadcasting of fertilizers at the time of planting is generally done under conditions:

a) When the soils are highly deficient in nitrogen and

b) When the previous crop has been exhaustive such as sugarcane, maize, etc.

ii) During Crop Growth Period

Broadcasting in standing crop is done mainly for nitrogenous fertilizers and mostly for close spaced crop like paddy rice and wheat. It is called top dressing. Muriate of potash is also applied as top dressing in some crops but this is not a general practice.

Banding

Fertilizer is placed in a continuous band at the bottom of the furrow opened during ploughing. Each band is covered with soil after the application. In single band placement fertilizer is applied on one side of the planted row. Band applications of fertilizer concentrate nutrients within a specific soil volume. The goal of band applications is to limit the contact of the applied fertilizer with the soil. This application method is desirable when fertilizer reacts with soil to produce compounds that reduce its availability to the crop. It is an efficient way of supplying plants with nutrients.

Drill Application

Drill application refers to the drilling of fertilizer at sowing time. Drilling the fertilizer together with seed should be avoided as it may adversely affect the germination or the young plants may get damaged due to high or concentration of chemicals in the root zone. It is advisable in to use a separate attachment for seed and fertilizer drilling. This is one of the best methods for applying phosphatic (P) and potassium (K) fertilizers to closely spaced row planted crops like wheat, maize, etc. This method is also better for applying nitrogenous fertilizers. However, it is safer to drill only small quantities of fertilizers so that germination may not be adversely affected.

Foliar Application

Foliar application refers to the spraying fertilizer solution on foliage (leaves) of growing plants. Normally, these solutions are prepared in low concentration (2-3%) either to supply anyone plant nutrient or a combination of nutrients. It is most suitable form of topdressing in when there is inadequate soil moisture.

Starter Solutions

The use of liquid fertilizers as a means of fertilization has assumed considerable importance in foreign countries. Solutions of fertilizers, generally consisting of N, P_2O_5, and K_2O in the ratio of 1: 2: 1 and 1:1:2 are applied to young vegetable plants at the time of transplanting.

These solutions are known as 'Starter Solutions'. They are used in place of the watering that is usually given to help the plants to establish. Only a small amount of fertilizer is applied as a starter solution.

Irrigation Water/Fertigation

Fertilizers are allowed to dissolve in the irrigation stream. The nutrients are thus carried into the soil in solution. This save the application cost and allows the utilization of relatively inexpensive water.

Fertigation

Fertigation is the technique of supplying dissolved fertilizers to crops through an irrigation system. Intensification of agriculture by irrigation and enhanced use of fertilizers may generate pollution by increased levels of nutrients in underground and surface waters. Therefore, judicious management of plant nutrients available through different fertilizers need be catered. A higher efficiency is possible with the help of pressurized irrigation system is placed around the plant roots uniformly and allow for rapid uptake of nutrients by plants. Small application of soluble nutrients saves labour, reduces compaction in the field and thereby enhancing productivity.

Inorganic Fertilizer vs. Organic Fertilizer

Both organic and inorganic fertilizers provide plants with the nutrients needed to grow healthy and strong (Table 11). However, each contains different ingredients and supplies these nutrients in different ways. Organic fertilizers work over time to create a healthy growing environment, while inorganic fertilizers provide rapid nutrition. Determining which is better for crops depends largely on the needs of the crops and preferences of the farmer in terms of cost and environmental impact. Organic fertilizers are the environmentally friendly. Over use of Inorganic fertilizers cause pollution of ground water, stripping of soil nutrients, and plant and root burn if utilized improperly. The continual use of inorganic fertilizers reduces the soil's resistance to pests and diseases killing off the natural microbial activity.

Table 11: Comparison of organic and inorganic fertilizers

	Organic	Inorganic
Composition	- Contain only plant- or animal-based materials that are either a byproduct or end product of naturally occurring processes - Low in soil nutrients	-Mineral processed fertilizer -Supplement the soil with macronutrients needed in large amounts: nitrogen, phosphorous and potassium
Nutrient Availability	-Rely on soil organisms to break down organic matter -Release nutrients only when the soil is warm and moist -Nutrients are released slowly -Reduces the risk of nutrient leaching	-Provide this nutrition in plant-ready form -Nutrients may leach deeply into the soil and water table
Application	-Bulk application -Analysis needed to determine the amount of nutrients being applied	-Application is simple, easily mechanized -amount of a given element -Rate of application can be easily calculated -Expensive
Cost/availability	Locally available and relatively cheap	-Expensive
Environmental Impacts	-Organic materials are able to fully decompose. -Lower release of greenhouse gas	-Heavy applications can burn crop -Build up toxic salt concentrations in the soil, which can create chemical imbalances -High release of greenhouse gas

6.3 Soil Water Management

Conservation of soil and water resources is important for sustainability of agriculture and environment. The concept of soil conservation cannot be materialized without conserving and efficient use of water resources. Soil and water conservation can be carried out through tillage management or insitu water harvesting

6.3.1 Tillage management

Tillage is defined as the mechanical manipulation of the soil for the purpose of crop production affecting significantly the soil characteristics such as soil water conservation, soil temperature, infiltration and evapotranspiration processes. Tillage systems are sequences of operations that manipulate the soil in order to produce a crop. The ways in which these operations are implemented affect the physical and chemical properties of the soil, which in turn affect plant growth.

Tillage systems

Conservation Tillage

This is the tillage and planting system that covers 30 percent or more of the soil surface with crop residue, after planting, to reduce soil erosion by water. Where soil erosion by wind is the primary concern, conservation tillage is defined as any system that maintains at least 1,120 kilograms per hectare of flat, small grain residue equivalent on the surface throughout the critical wind erosion period. The tillage systems classified as conservation tillage are no-till, ridge-till, and mulch-till.

No-till - The soil is left undisturbed from harvest to planting except for nutrient injection. Planting or drilling is accomplished in a narrow seedbed or slot created by coulters, row cleaners, disk openers, in-row chisels, or roto-tillers. Weed control is accomplished primarily with herbicides. Cultivation may be used for emergency weed control.

Ridge-till - The soil is also left undisturbed from harvest to planting except for nutrient injection. Planting is completed in a seedbed prepared on ridges with sweeps, disk openers, coulters, or row cleaners. Residue is left on the surface between ridges. Weed control is accomplished with herbicides and/or cultivation. Ridges are rebuilt during cultivation.

Mulch-till - The soil is disturbed before planting and includes all conservation tillage practices other than no-till and ridge-till. Tillage tools such as chisels, field cultivators, disks, sweeps or blades are used. Weed control is accomplished with herbicides and/or cultivation. Two tillage practices that fall into this category are zone-till and strip-till. Both of these tillage practices involve tilling a strip into which seed and fertilizer are placed. Although these are popular terms in some areas, they are not official survey categories because they are considered modifications of no-till, mulch-till or “other tillage types.” Less than 25% row width disturbance is considered no-till. More than 25% row width disturbance would be considered mulch-till or “other tillage type,” depending on the amount of residue left after planting.

Reduced-till - Reduced-till systems leave 15-30 percent residue cover after planting or 560 to 1,120 kilograms per hectare of small grain residue equivalent throughout the critical wind erosion period.

Conventional-till - Conventional-till systems leave less than 15 percent residue cover after planting, or less than 560 kilograms per hectare of small grain residue equivalent throughout the critical wind erosion period. These systems generally involve plowing or some other form of intensive tillage.

There are other tillage systems that leave less than 30 percent crop residues but meet erosion control goals with or without other supporting conservation practices, such as strip cropping, contouring, terracing.

Effects of Tillage on Plants and Soils

Tillage systems affect soil properties such as temperature, moisture, bulk density, aggregation, organic matter content, and plant properties such as root density. Conservation tillage practices change many soil properties when implemented for a long term. Changes in soil properties change the way in which crops respond to fertilizer management practices.

6.3.2 Insitu water Harvesting

Cut-off drains

Cut-off drains are made across a slope for intercepting the surface runoff and carrying it safely to an outlet such as a canal or stream. Their main purpose is the protection of cultivated land, compounds, and roads from uncontrolled runoff, and to divert water from gully heads. It serves as both soil and water conservation method.

Retention ditches

These are made along the contours to capture and retain incoming runoff water and hold it until it seeps into the ground. They are alternate to cut-off drains when there is no channel to discharge the water nearby. Sometimes these are for water harvesting in semiarid areas.

Terracing

Terraces are constructed across the field slope for soil and water conservation purposes. They reduce soil and water through erosion from hilly or sloppy lands by collecting and storing surface runoff. Terraces also increase water retention and infiltration in the soil. They consist of channels and embankments of soil constructed along the contour. They can construction using stone bunds or strips of vegetation (live or dead).

Infiltration ditches

The structure used to harvest water from roads or other sources of runoff is infiltration ditches. They comprise dug along the contour, upslope from a crop field and a ditch of 0.7-1.5m deep. Water is blocked at the other end when it is diverted from the roadside into ditch and seep into soil after it is being trapped.

Water-retaining pits

Water-retaining pits allow runoff water to seep into soil after by trapping the water. The runoff normally occurs into a series of pits which are dug into ground. Banks around the pits are made by the soil from the pit. Excessive water carry from one pit to next by furrows. The amount of runoff determines the size of pit and its typical size is 2 m square and 1 m deep.

Broad beds and furrows

The runoff water is diverted into field furrows (30 cm wide and 30 cm deep) in a broad bed and furrow system. The lower end of field furrows is blocked. The water backs up into the head furrow after the filling of one furrow and flows into the next field furrow. Crops are grown on the broad bed furrows of about 170 cm wide between the fields.

Keeping plant residues on the field

Crop residues decreases evapotranspiration; soil temperature and moisture is also reduced as it provides shades by conserving soil moisture. Crop residues should be partially removed for fodder or fuel use and if possible, it should be left standing in the field after harvest. Those that are left standing act as wind breakers. To retain much of the plant residues in the field, the stubbles should be cut at high point in the plant during harvesting time. The soil loss and impact of raindrop also reduces by keeping crop residues in the field.

Choosing water conserving species

Too much high water utilizing crops like alfalfa cannot conserve water in the landscape. Generally, low biomass producing annual legumes like beans, cowpeas and green grams are the crops that transpire the least amount of water.

7 PROBLEMATIC SOILS AND THEIR MANAGEMENT

7.1 Introduction

Problematic or problem soils refer to soils that possess characteristics that make them uneconomical for the cultivation of crops without adopting proper reclamation measures. There are three major types of problem soils.

a) Physical problem soils

b) Chemical problem soils

c) Biological problem soils

7.2 Soils with Physical Problems for Agricultural Production

Physical problematic soils are soils whose physical properties have some limitations. They include: include: impermeable soils, soil surface crusting and sealing, subsoil hardpan, shallow soils, highly permeable soils, heavy clay soils and fluffy paddy soils

7.2.1 Slow Permeable Soils/Impermeable Soils

Slow permeable soils are soils with very high clay content. The clay content restricts infiltration rate and encourages runoff, erosion and nutrient removal from the top layers of soil. Such soils have very poor drainage, aeration and suffer from reducing conditions.

Impermeable soils can be managed adoption of the following practices:

i) Addition of organic matter such as farmyard manure (FYM), compost, composted coir pith and press mud improves physical properties leading to improved water retention capacity.

ii) Ridges and furrows within the farm provide adequate root zone aeration.

iii) Broad/cumbered beds reduce the amount of water retained in black clay soils during first days of rainfall. The beds should be formed either along the slope or across the slope with drainage furrows in between broad beds.

iv) Provision of open or subsurface drainage to reduce waterlogged conditions.

v) Huge quantity of sand /red soil application to change the texture

vi) Contour /compartmental bunding to increase the infiltration

vii) Application of soil conditioners like vermiculite to reduce runoff and erosion

7.2.2 Soil Surface Crusting and sealing

Soil sealing and hard setting or soil capping are common problems in most soils in sub humid and semi-arid tropics. Soil sealing refers to formation of a thin impermeable layer on dry soils due to impact of rain drops while surface crust refers to the formation of compact layer within a few millimeters to a few centimeters depth. The crusts are formed by either physical forces such as livestock trampling or traffic by agricultural machinery and other off roading vehicles or chemically by presence colloidal oxides of iron and aluminium that binds soil particles together in wet soils. Such soils may have the following problems:

a) Poor seed germination or retarded root growth

b) Poor infiltration rates and high runoff rates

c) Poor aeration within the rhizosphere

d) Poor biological nitrogen fixation due to poor nodule development in legumes.

Soils with surface seal or crusting problems can be managed by the following practices:

a) Application of organic matter to improve soil physical properties

b) Ploughing to break the seal and surface crust.

c) Scraping the surface soil by tooth harrow will be useful.

d) Bold grained seeds may be used for sowing on the crusted soils.

e) More number of seeds/hill may be adopted for small seeded crops.

f) Sprinkling water at periodical intervals may be done wherever possible.

g) Resistant crops like cowpea can be grown.

h) Lime or gypsum may be uniformly spread before ploughing in severely crusted soils.

7.2.3 Sub Soil Hard Pan

This refers to a compacted subsurface soil layer. The compact layer is formed by accumulation of clay below the surface causing the subsoil to be dense, difficult for roots and water to penetrate hence leading to reduced water and nutrient uptake and low crop yields. Such soils are also susceptible to soil erosion. Subsoil hard pan can be managed by the following practices:

a) Deep cultivation

Ploughing with chisel plough, at 50 cm interval in both the directions. Chiseling helps to break the hard pan in the sub soil besides it ploughs up to 45 cm depth.

b) Application of organic matter

Application of farm yard manure or compost or composted coir pith helps in improving the soil physical properties.

7.2.4 Shallow Soils

Shallow soils refer to soils with less than 50cm depth. Soils having a depth of 50-100cm are referred to as moderately deep soils while soils with a depth greater than 100cm are referred to as deep soils. Most shallow soils are found on high mountains and valleys and they basically occur in areas were soils are not well formed. Shallow soils have severe limitations to agricultural use. They restrict root elongation, spreading, water and nutrient holding capacity and crop uptake.

Shallow soils can be managed through: growing shallow rooted crops and frequent soil fertility or water management practices.

7.2.5 Highly permeable soils (sandy soils)

Sandy soils containing more than 70 per cent sand fractions are referred to as highly permeable. Such soils have poor nutrient and water retention capacity, very high hydraulic conductivity and infiltration rates. The soils normally lack the finer particles, poor organic matter and living organism population; have poor temperature regulation, weak aggregate stability and very poor soil structure. These soils have poor soil fertility and nutrients and water added are subject to loss through deep infiltration and doesn't benefit the target crops.

Sandy soils can be managed by adoption of the following practices:

a) Application of organic matter such as farmyard manure or compost or slurry to improve soil aggregation.

b) Crop rotation with green manure crops.

c) Frequent irrigation with low quality water.

d) Frequent split application of fertilizers.

e) Uniform ploughing.

f) Application of clay soil depending on availability of clay materials.

7.2.6 Heavy Clay Soils

Clay soils are soils whose particles are less than 0.002mm in diameter. These soils have poor permeability but their permeability differs with clay content. Most soils are classified as clay soils when they are made up of about 40% clay particles. An example of a heavy clay soil that is commonly found in Kenya is Vertisol.

Vertisols can be grouped into self-Mulching and crusty Vertisols types. Self-mulching Vertisols have fine surface soil structure during dry season and when they are ploughed after exposure to repeated wetting and drying, the clods disintegrate with ease. Crusty Vertisols on the other hand have a thin, hard crust during dry season and when ploughed, they produce large, hard clods that may persist for 2 to 3 years before they have crumbled enough to permit the preparation of a good seedbed.

Some heavy clay soils such as Vertisols are chemically rich and capable of sustaining continuous cropping. They do not necessarily require a rest period for recovery; because the pedoturbation continuously brings subsoil to the surface. Some nutrients like nitrogen, phosphorus, and micronutrients are however constantly deficient in such soils and requires replenishment. Potassium contents are variable and in semi-arid areas, free carbonate and gypsum accumulations are common.

The heavy clay soils have hard consistence when dry and very plastic and sticky when wet. The workability of the soils is often limited to very short periods of minimal water status. It is advisable to carry out tillage operations in dry season with heavy machinery. Mechanical tillage in wet seasons causes serious soil compaction due to the very low hydraulic conductivity in the soils.

Due to low structural stability, the soils are very susceptible to water erosion. Slopes above 5 per cent are not good and if used, it is advisable to use contour cultivation and ground cover. Terracing methods are supposed to be designed to allow enough surface drainage. It is advisable to make open drains in areas that experience high rainfall to avoid flooding problems.

7.3 Soils with unfavorable Chemical Properties for Agricultural Production

Soils with chemical problems include: acid soils and salt affected soils.

7.3.1 Acid soils

Soil with pH of less than 7 is generally referred to as acid soils. The acidity level however increases pH decrease from 7 towards zero with pH levels lower than 5.5 being strongly acidic and pH of less than 4.75 being extremely acidic.

Acidity in soils can be caused by mineralogy of parent material, organic matter accumulation, leaching of base cations (calcium, magnesium, potassium and sodium), and management practices such as continuous use of acid forming fertilizers, application of elemental sulphur which undergoes reactions forming sulphuric acid, tillage practices and soil pollution.

At pH levels less than 5.5 most micronutrients are abundant and soluble except molybdenum. Some of the abundant micronutrients are toxic to plant roots and soil microorganisms. Oxides and hydroxides of some micronutrients like aluminium (Al) and iron (Fe) form insoluble complexes with important nutrients like phosphorus hence making them unavailable for plant and microorganisms uptake. At pH less than 5.5, some base cations such as calcium and magnesium are also low, which adversely affects the base saturation levels.

Soil acidity can be managed by application of organic amendments such as manure. Organic matter is a strong buffering agent that buffers the soil against drastic changes in pH on top of replenishing soil nutrients. Application of pulverized limestone or dolomitic limestone (which has magnesium in addition to calcium carbonate that makes up regular lime) is one the fastest ways to increase soil’s pH or reduction of soil acidity. It should however be noted that liming materials should be added periodically depending on the nature and level of acidity in particular soils. Basic slag obtained from iron and steel industry can be substituted for lime because it contains 48-54%CaO and 3-4%MgO. Calcium ammonium phosphate fertilizers, citrate soluble phosphate fertilizers and potassium sulphate are suitable sources of N, P and K respectively in acidic soils.

7.3.2 Saline soils

Saline soils are non-sodic soils containing sufficient soluble salt to adversely affect the growth of most crop plants with a lower limit of electrical conductivity of the saturated extract (ECe) being 4 Deci Siemens / meter (dS/m), which is equivalent to a value of 4 mmhos/cm. These salts might originate from parent rock from which the soils were formed or from sea water in low lying areas along the coastal strip. A very common source of salts in irrigated soils is the irrigation water. Most irrigation waters contain some salts. After irrigation, the added water is used by the crop or evaporates directly from the soil then salt is left behind. If not removed, the salts accumulate over time in a process called salinization. Salty underground water may also contribute to salinity when water table rises. For example: irrigation without proper drainage may cause salty ground water to rise to upper layers thus supplying salts to the root zone. Very salty soils are sometimes recognizable by a white layer or dry salt on the soil surface.

The saline soil problems are caused by the accumulated soluble salts in the root zone. Presence of salts leads to alteration of osmotic potential of the soil solution. Consequently water intake by plants is restricted and thereby nutrients uptake by plants is also reduced. In this soil due to high salt levels microbial activity is reduced. Specific ion effects on plants are also seen due to toxicity of ions like chloride and sulphate.

Solution

The reclamation of saline soils involves basically the removal of salts from the root zone soil through the processes of leaching with water and drainage. Provision of lateral and main drainage channels of 60 cm deep and 45 cm wide and leaching of salts could reclaim the soils. Sub-surface drainage is an effective tool for lowering the water table, removal of excess salts and prevention of secondary salinization.

Irrigation of Saline Soils

Proportional mixing of good quality (if available) water with saline water and then using for irrigation reduces the effect of salinity. Alternate furrow irrigation favours growth of plant than flooding. Drip, sprinkler and pitcher irrigation have been found to be more efficient than the conventional flood irrigation method since relatively lesser amount of water is used under these improved methods.

Fertilizer Management for Saline soils

Addition of extra dose of nitrogen to the tune of 20-25% of recommended level will compensate the low availability of N in these soils. Addition of organic manures like, FYM, compost, etc. helps in reducing the ill effect of salinity due to release of organic acids produced during decomposition. Green manuring and or green leaf manuring also counteracts the effects of salinity.

7.3.3 Sodic soils

From agricultural standpoint, sodic soils are soils containing sufficient exchangeable sodium to adversely affect the growth of most crop plants. These soils have high levels of exchangeable sodium (Na) and low levels of total salts caused by natural presence of minerals producing sodium carbonate (Na_2CO_3) or sodium bi-carbonate ($NaHCO_3$) upon weathering. They are usually defined as containing an exchangeable sodium percentage greater than 15% and a pH of 8.2 or more. Extreme cases may have a pH of above 10.5. These soils tend to occur within arid to semiarid regions and are innately unstable, exhibiting poor physical and chemical properties, which impede water infiltration, water availability, and ultimately plant growth.

Sodic soils may impact plant growth by: a) sodium toxicity to sodium sensitive plants; b) Nutrient deficiencies or imbalances; c) High pH of > 8.0 and d) soil structure destruction or dispersion or flocculation of clay minerals.

Sodic soils can be reclaimed or managed using several approaches, they include:

a) Establishment of sodic tolerant crops

b) Application of organic manures

c) Application of chemical amendments such as soluble calcium salts (gypsum, calcium chloride), acids or acid forming substances (sulphuric acid, iron sulphate, aluminium sulphate, lime-sulphur, and pyrite) or calcium salts of low solubility like ground limestone. The compounds in the salts or acids reacts with the sodium carbonate (Na_2CO_3 or $NaHCO_3$) forming a leachable compound.

d) Agronomic management such as planting at the edge of hills, leaching, crop rotation among others.

7.3.4 Alkaline soils

Alkaline soils are clay soils with high pH, poor soil structure and low infiltration capacity. Often they have a hard calcareous layer at 0.5 to 1 meter depth.

Causes

The causes of alkaline soils are natural or can be man-made. Natural causes are the presence of minerals producing sodium carbonate (Na_2CO_3) or sodium bi-carbonate (NaHCO3) upon weathering.

Solution

Alkaline soils with solid CaCO3 can be reclaimed with grass cultures, organic compost, waste hair and feathers, organic garbage, etc. Ensuring the incorporation of much acidifying materials (inorganic or organic material) into the soil, and enhancing dissolved Ca in the field water by releasing CO_2 gas. Deep ploughing and incorporation of the calcareous subsoil into the topsoil also helps.

7.4 Soils with unfavourable biological Properties for Agricultural Production

Soils with unfavourable biological properties for agricultural production are soils whose biological properties have some limitations. These include soils with undesirable biological properties like low organic matter content and harmful macro and microorganisms. Bacterial wilt, Fusarium wilt and nematodes are some of the unfavourable biological soil pathogens.

Biological properties of soils-Soil organisms break down organic matter and while doing so make nutrients available for uptake by plants. The nutrients stored in the bodies of soil organisms prevent nutrient loss by leaching. Microbes also maintain soil structure while earthworms are important in bio-turbation in the soil.

Biological degradation of soil refers to the impairment or elimination of one or more “significant” populations of microorganisms in soil, often with a resulting change in biogeochemical processing within the associated ecosystem.

Management for maintenance of soil biology and nutrition

The aim of management should be to create balanced organic matter and mineral budgets. It should ensure that, over several years (a complete crop rotation), soil organic matter is not depleted and that nutrients added equal or exceed those removed by cropping or lost in various ways.

Various approaches to good management include:

- Selection/choice of appropriate crops and crop rotations and intercropping with several species that include legumes in rotation
- Cultural practices that include use of inorganic fertilizers to maintain a neutral nutrient budget, plant litter conservation, incorporation of animal manure and organic wastes, minimum tillage and appropriate biological pest and weed management

8 TAKE HOME MESSAGES

- Good soil fertility is important for crop sustainable production.
- Farmers should understand their soil fertility status to improve crop production.
- Framers can use indigenous soil knowledge systems to predict soil fertility in their farms.
- This should be complemented with the laboratory soil test reports.
- Symptoms of nutrient deficiencies in crops can often be confused with disease. It is important to confirm this with the soil fertility and plant tissue tests.
- Soil fertility degradation occurs in various forms in many farms. Regular soil testing is necessary to monitor such degradation for timely and necessary management.
- Identification and management of problematic soils is important for increased agricultural productivity.

9 FURTHER READING

African Organic Agriculture Training Manual (2012).Module 02 Soil Fertility Management. FiBL, Research Institute of Organic Agriculture, Switzerland. ISBN 978-3-03736-197-9

CAB (2012).Africa Soil Health Consortium Handbook for Integrated Soil Fertility Management. CAB International.

FAO (2000). Fertilizers and their use. A pocket guide for extension officers. Fourth Edition FAO, Rome.

Mangale *et al* (2015). Handbook for Integrated Soil Fertility Management: Extension Approaches and Guidelines in Kenya. Kenya Soil Health Consortium, KALRO, Kabete, Nairobi, Kenya.

Brady, C. N. and Weil, R. R. (2008).The Nature and Properties of Soils, 14th Ed; Pearson Prentice Hall, New Jersey. 975pp.

White, R.E. (1979). Introduction to the principles and practices of soil science. 2nd Ed; Blackwell Scientific Publications, Oxford London Edinburgh. 244pp.

Adams, F. (1984). Soil Acidity and Liming. 2nd Edn, American Society of Agronomy, Madison, U.S.A.

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