Integrated Soil Fertility Management in Zambia

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AGRA Growing Africa's Agriculture

The Zambia Soil Health Consortium

Preface

A holistic approach to managing soils for agricultural use is being promoted as a strategy to improve soil productivity and attain sustainable agricultural production. A key component of this approach is soil health, which takes into account the soil biological, chemical and physical characteristics, in order to optimize returns to capital, labour and other investments. The concept of soil health is relatively new and necessary for sustainable agricultural production.

This booklet attempts to give a broad overview of some of the main problems farmers face in managing soils for crop production in Zambia. It also provides information on Integrated Soil Fertility Management (ISFM) and gives recommendations on practices that have been proven to address some of the challenges.

In the first chapter, the booklet gives a brief description of the physical environmental conditions in Zambia that affect crop production. These include a brief description of land available for crop production, the climatic conditions that influence crop production, the dominant types of soils in the country. It ends with a summary of the current national agricultural policy and the major institutions involved in agricultural research.

The second chapter defines the term Integrated Soil Fertility Management and the main problems identified to be adversely affecting the health of soils in Zambia. The problems are broadly classified into three groups of (i) physical factors (ii) chemical factors and (iii) biological factors. Within each of these broad classes, specific and important problems have been identified and strategies that can be used to address them provided. This chapter also gives a general picture of the current status of soil constraints and management practices employed in the country to address the limitations. The authors have summarized the key challenges for improving the productivity of soils in Zambia for crop production.

The third chapter reminds readers that while a number of technologies, products and practices are available, not all may be suitable for every farmer and region. For instance, the suitability of seeds or crop varieties grown may vary with climatic conditions. Therefore, the promotion of farming practices and technologies has to be done with full consideration of the farmers' local conditions and circumstances. These include the physical environmental conditions such as climate and soil types, as well as the social and economic status of the farmer. There is no one size-fits-all solution that all farmers can adopt, but in any given location, farmers should be able to choose what works best for them from a basket of options of sound best management practices.

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List of Abbreviations

AGRA	Alliance for a Green Revolution in Africa
CA	Conservation Agriculture
CBU	Copperbelt University
CSO	Central Statistics Office
CSPR	Civil Society for Poverty Reduction
DAP	Di-ammonium Phosphate
FAO	Food and Agriculture Organization
GART	Golden Valley Agricultural Research Trust
IPNI	International Plant Nutrition Institute
IAPRI	Indaba Agricultural Policy Research Institute
ISFM	Integrated Soil Fertility Management
KATC	Kasisi Agricultural Training Centre
MRI	Maize Research Institute
MU	Mulungushi University
NACP	National Agricultural and Cooperative Policy
NAP	National Agricultural Policy
SEEDCO	Seed Company of Zambia
SSF	Small Scale Farmer
UNZA	University of Zambia
ZAMSEED	Zambia Seed Company
ZARI	Zambia Agricultural Research Institute
ZSHC	Zambia Soil Health Consortium

1. Background

Crop production in Zambia is predominantly rain-fed. Presently, 58% of the country's 752,000 km^2 of land area is considered suitable for agriculture. Of this, about 423,000 hectares can be brought under irrigation. However, only about 14% of the arable land is currently under cultivation and only about 50,000 hectares or 12 % of the potentially arable land is under irrigation. One of the reasons for the low exploitation of the available arable land is that the Zambian agricultural sector is dominated by small scale farmers who own very small pieces of land. Furthermore, most small scale farmers are resource-poor and as such cannot afford to invest in irrigation.

1.1 Zambia agro-ecological regions

Zambia is divided into three agro-ecological regions mainly based on the annual rainfall (Veldkamp et al, 1984). Region I receives the lowest annual rainfall with a mean of less than 800mm, region II receives intermediate rainfall with a mean of between 800 and 1000mm, while region III receives the highest annual rainfall of more than 1000mm.

The nature of the soils in the different agro-ecological regions is largely influenced by the amount of rainfall and the nature of the parent materials from which the soils are formed. Region I is characterized by soils that are slightly weathered and slightly leached. The soils of region II are moderately weathered and moderately leached while those of region III are highly weathered and highly leached. Due to this, the soils of region I are generally more fertile than those of regions II and III, with region III having the least fertile soils. Below are the typical characteristics of the three agro-ecological regions:

Region I

This is commonly classified as the low rainfall region of Zambia. It covers valleys in the South and South-Eastern margin of the country. It has a mean annual rainfall of less than 800mm. The rainfall is usually erratic and often of high intensity. Long dry spells and moisture stress are common limitations to crop production in this region. The region has the shortest length of cropping season, ranging between 60-90 days.

The dominant soils in the valley areas of region I are slightly acid to alkaline and generally have higher levels of fertility than soils of plateau areas. Apart from inadequate rainfall, induced soil acidity is also a dominant constraint to crop production in this region.

Region II

This region is commonly classified as the medium rainfall region of Zambia. It forms a central band stretching from the Western border to the Eastern border of the country. The region is characterized by a mean annual rainfall of between 800 and 1000mm, and has a rain-fed cropping season of 90-150 days.

Region II is subdivided into two sub-regions, namely IIa and IIb. Region IIb comprises of the Kalahari sand plateau and the Zambezi flood plains in Western Province. Whereas IIa comprises of the sandveld plateau of Central, Eastern, Lusaka and Southern Provinces. The dominant soils are sandy, acidic, have low nutrient reserves and poor water retention capacity. These soils are prone to leaching of nutrients after heavy rainfall and to water stress during dry spells because of their limited ability to retain nutrients and water. Sub-region IIb includes other portions of region II not covered by the Kalahari sands. The dominant soils include Sandveld soils which are moderately leached, medium to strongly acid with sandy top soils overlying loamy subsoil. They also include portions of moderately weathered, moderate to slightly acidic red to strong brown soils derived from limestone. In low lying areas or flood plains, there may be slightly acidic to neutral heavy dark cracking clays.

The combination of the moderately fertile soils with medium rainfall and a moderately long growing season makes sub-region IIb the most productive region of Zambia for most arable crops particularly maize, wheat, soya beans, groundnuts and tobacco.

Region III

This is classified as the high rainfall region of Zambia. It covers the Northern region of the country and is characterized by a mean annual rainfall of more than 1,000 mm. Region III has the longest rain-fed cropping season of 140-200 days.

As a result of the high rainfall received in this region, soils are highly weathered and highly leached. The high rate of leaching has left the soils acidic and depleted of nutrients hence making them inherently infertile and generally strongly acidic. Because of the low nutrient levels and high levels of acidity, the productivity of the soils of region III is generally lower than that of soils of regions I and II.

There are different farming practices and techniques that farmers have adopted to mitigate the different limitations to crop production faced in the different agro-ecological regions. For instance, the use of conservation basins which serve as water harvesting structures is predominant in regions I and II where the annual rainfall is low. In region IIa where the soils are very sandy, farmers use kraal shifting, an indigenous practice which involves confining a herd of cattle on a small piece of land for three to four days. This practice ensures that enough organic matter is incorporated in the soil thereby improving soil physical, chemical and biological characteristics and hence imparting the soil with good attributes for crop production. Another example of farmer adaptation to factors limiting crop production is seen in the northern part of the country where soils are very acidic. Here, farmers address the acidity problem by using the ash produced through practices such as the Chitemene also known as the slash-and-burn.

The agro-ecological regions of Zambia are presented in Figure 1. Table 1 presents a summary of the major soils in the agro-ecological regions as well as the main limitations to crop production.

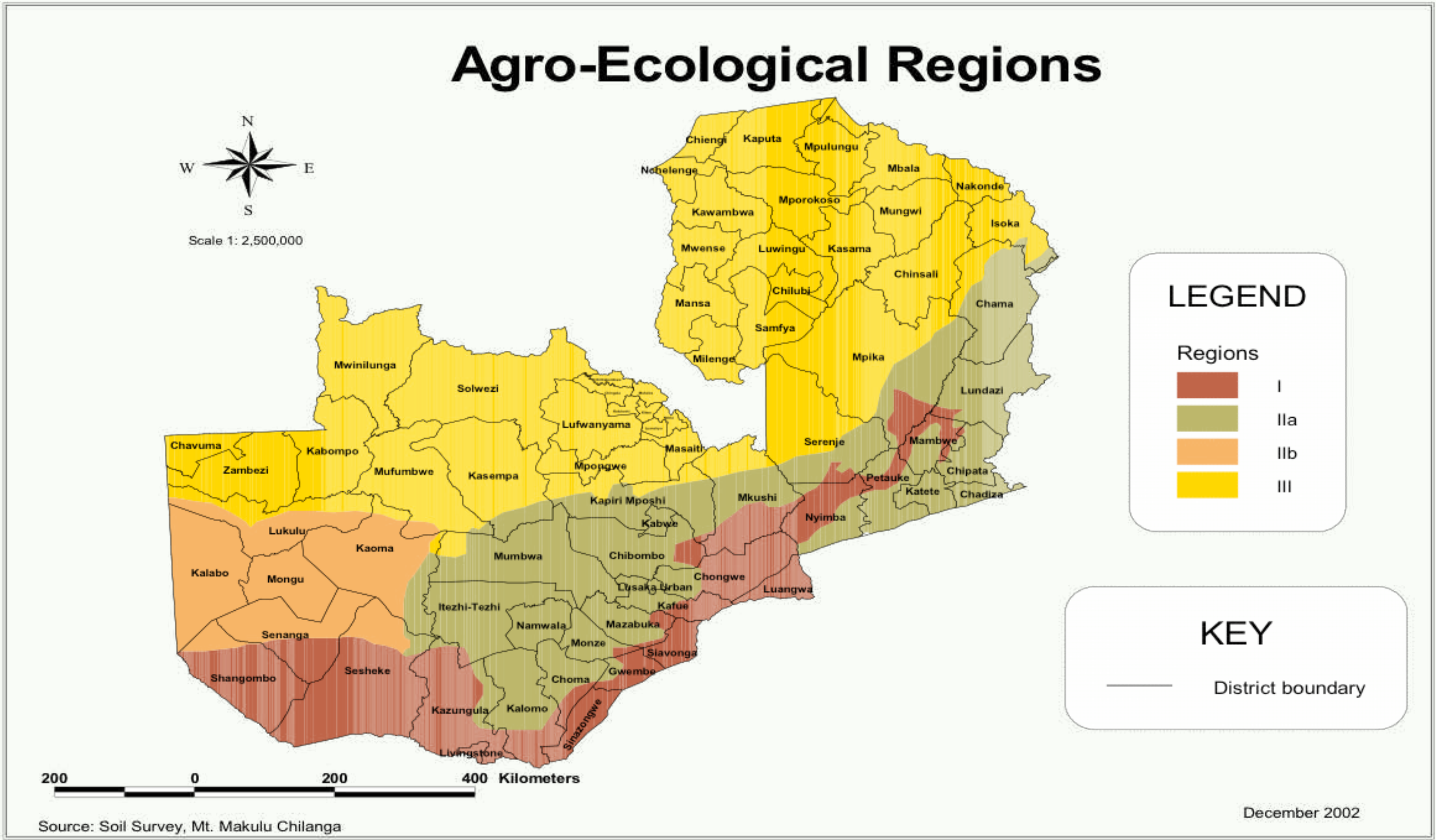


Figure 1: Agro-ecological map of Zambia

Table 1: Soils in Agro-ecological Zones and their Limitations to Crop Production

	General Description of Soils	Limitations to Crop Production
Region I	Loamy and clay with coarse to fine tops	Slightly acidic to alkaline. Minor fertility limitations
	Reddish coarse sandy soils	Low pH, available water & nutrient capacity reserve
	Poorly drained sandy soils	Severe wetness, acidic & low fertility
	Shallow & gravel soils in rolling to hilly areas including escarpment zones	Limited depth & unsuitable for cultivation
Region II	Moderately leached clayey to loamy soils	Low nutrient reserves & water holding capacity
	Slightly leached clayey soils	Slight to moderate acidity. Difficult to work due to heavy textured soils.
	Coarse sandy loams in large valleys	Imperfectly to poorly drained. Limitations due to wetness
	Sandy soils from Kalahari sand	Medium to strong acidity, coarse textured top soil, low water holding capacity and nutrient reserves
Region III	Red to brown clayey loamy soils	Very strong acidity and strongly leached
	Shallow and gravel soils in rolling hilly areas	Limited depth
	Clayey soils, red in color	Moderately to strongly leached. Fewer limitations
	Poorly to very poorly drained flood plain soils	Variable texture and acidity
	Coarse sandy soils in pan on Kalahari sand	Very strong acidity

Compiled from Bunyolo etal 1995

1.2 Background of Zambia agricultural sector

Agriculture accounts for about 18 – 20 percent of the Gross Domestic Product (GDP) and provides the livelihood for more than 50 percent of the Zambian population. In spite of the important role that the sector plays in the country's economy, the agricultural production has remained low (CSPR, 2000) thereby negatively affecting food and nutritional security especially among the rural poor communities.

Plate 1: The role of agriculture in reducing poverty in Zambia:

* It provides a livelihood for more than half of the population, including the rural poor, who constitute 83% of the Zambian population living in poverty (CSO, 1998; NACP, 2003);
* The agricultural sector absorbs 67% of the labour force and is the main source of income for rural women who constitute 65% of the rural population (NACP, 2003);
* Agriculture in Zambia generates between 18 and 20% of the GDP;
* Agricultural growth benefits the poor most: a 1% increase in agricultural yield reduces the percentage of people living on less than 1$ per day between 0.6 - 1.2% (DFID, 2003).

Note: Adapted from Agriculture and Poverty Reduction: Unlocking the Potential (DFID, 2003).

The major crops grown in the country are maize (*Zea mays*), sunflower (*Helianthus annus*), soybeans (*Glycine max*), groundnuts (*Arachis hypogeae*), sorghum (*Sorghum bicolor*), cotton (*Gossypium hirsutum*), common beans (*Phaseolus vulgaris*), cowpea (*Vigna unguiculata*), sugarcane (*Saccharum officinarum*), fingermillet (*Eleusine coracana*) and bulbrush millet (*Pennisetum glaucum*) rice (*Oryza sativa*), sweet potato (*Ipomoea batatas*), cassava (*Manihot esculenta*), tobacco (*Nicotiana tabacum*) barley (*Hordeum Vulgare*) wheat (*Triticum aestivum*).

Commercial farmers largely grow wheat, soya beans, and many other cash crops whilst small scale farmers grow a variety of crops including groundnut, maize, sorghum, rice, common beans and cassava for household food security. Medium scale farmers grow different crops for both household consumption and for sale. Crops grown include maize, cotton, soya beans, etc. Table 2 shows the major crops grown in each of the three agro-ecological regions of Zambia.

There is a long history of mono-cropping and inappropriate inorganic fertilizer use in Zambia. This has led to land degradation and consequently lower soil productivity.

Taking maize for example, which is the main staple food crop as an indicator crop, the national yield average has declined from 2.5 tons/ha in 1964 to 1.5 tons/ha in 2013 (FAO, 2013). Using the same varieties/hybrids, yields of a well managed maize crop, especially in research stations and on commercial farms average 6 to 8 tons/ha. The factors driving widening of the gap and the challenges to addressing them form the key thrust of agricultural research in Zambia.

The majority of the small-scale farmers till their land by use of hand-hoe. Animal draught power is popular in the Southern, Eastern, Western and parts of Central provinces. The use of tractors is predominantly by commercial farmers who form only 1% of the farming population.

Table 2: List of ten priority crops grown in each agro-ecological zone

Region I	Region II	Region III
Maize	Cotton	Sorghum
Groundnuts	Groundnuts	Beans
Cotton	Paprika	Coffee
Vegetables	Maize	Cassava
Sorghum	Wheat	Rice
Cowpeas	Sweet Potato	Soya beans
Pearl Millet	Sorghum	Groundnuts
Citrus	Sunflower	Finger Millet
Sunflower	Soya beans	Sweet Potato
Banana	Castor	Maize
Sweet Potato	Banana	Sunflower

Source: www.erails.net/zm/kms-zambia/kms-zambia/agro-ecological-zones/

1.3 The Agricultural Policy Framework

Zambia has a 10 year (2004-2015) National Agricultural Policy (NAP) in place. The overall objective of this policy is to facilitate and support the development of a sustainable and competitive agricultural sector (NAP, 2004). Some specific policy objectives are i) to increase productivity through improved seed varieties and better research/extension linkages; and ii) to increase the use of better and sustainable farming practices including conservation farming and low-input agriculture as focal point for investment.

The two aspects highlighted above form key pillars of Integrated Soil Fertility Management (ISFM). It is, however, worth noting that there is no outright policy in Zambia that specifically targets ISFM. However, Conservation Agriculture (CA) has been identified and is being recommended as an important farming practice to be adopted by farmers. As practiced in Zambia, CA entails minimum tillage, retention of crop residues on land, crop rotation with legumes and agro-forestry. In most cases, adoption of CA is partial as farmers normally choose one or two practices that suit their circumstances.

1.4 Research and Development

There is a wide range of national, regional and international agencies that have been conducting agricultural research in Zambia. The main ones are public institutions such as the Zambia Agriculture Research Institute (ZARI); Non-Profit Public-Private Partnership Organizations such the Golden Valley Agricultural Research Trust (GART); privately owned research institutions such as the Maize Research Institute (MRI), Zambia Seed Company (ZAMSEED), Seed Company of Zambia (SEEDCO) and public educational institutions such as the University of Zambia, Copperbelt University and Mulungushi University. A lot of work has been done on issues related to soils and crops in the three agro-ecological regions of Zambia. Most of this work has mainly focused on generating technologies for use by small-scale famers. These technologies include improved seed varieties and several crop and soil management options which are more adapted to specific constraints in the different agro-environments such as drought, low soil fertility and acidic soil conditions.

In spite of all this work, agricultural production and productivity among small-scale famers has remained low. This is partly due to the fact that these technologies are not packaged and promoted in a holistic manner. For instance, some sectors are only concerned with the promotion of chemical fertilizers while others only dwell on organic sources of plant nutrients as a way of building-up and maintaining soil fertility. The often conflicting messages on appropriate technologies confuse farmers, extension workers and policy makers, leading to either inappropriate use or non-adoption of improved agricultural technologies. However, agricultural production and productivity is best enhanced by an integration of several technologies including organic and inorganic inputs that interact to produce a healthy soil and enhance efficient uptake of nutrients by crops. Appropriate seed varieties and soil moisture are also required to optimize use of available nutrients and boost crop yields.

2. Principles And Practices Of Integrated Soil Fertility Management (ISFM) In The Zambian Context

Integrated Soil Fertility Management (ISFM) is defined as 'a set of soil fertility management practices that include the use of fertilizers, organic inputs and improved germplasm, combined with the knowledge on how to adapt these practices to local conditions aiming at optimizing agronomic use efficiency of the applied nutrients and improving crop productivity'. All inputs need to be managed following sound agronomic and economic principles (Vanlauwe et al., 2010).

This definition of ISFM has been adopted in Zambia with a slight modification, where the term improved germplasm has been replaced with 'appropriate germplasm'. The Zambia Soil Health Consortium has acknowledged that there are a number of soil management practices that farmers in the country use to address a number of soil health problems

Plate 2: Sound agronomic principles include use of appropriate varieties, appropriate land preparation, spacing, planting dates and practices, timely weeding, appropriate pest and disease management practices, proper rotation and intercropping practices, use of appropriate water harvesting techniques and adapting all these to local conditions.

Sound economic practices refer to practices that enhance the profitability of the agricultural business by maximizing returns per unit input

The Consortium identified a number of soil-related factors that adversely affect the health of the soil which were conveniently grouped into three classes: (i) those related to the chemical properties of the soil; (ii) those related to the physical properties of the soil; and (iii) those related to the biological properties of the soil. Factors that affect the health of soil in each of the above three classes have been identified, and practices that farmers employ to address problems caused by each of these factors have also been identified and listed. In a few cases, some innovative practices that are either still under-going research or are in the early stages of promotion have also been suggested as alternative measures that can be used to deal with different soil health problems. This is mainly based on expert knowledge and an understanding of the existing agro-ecosystems.

2.1 Managing the chemical health of soil for crop production

The problems related to the chemical fertility of the soils are summarized in Figure 10. Among the prominent ones are:

1. The constrained ability or inability of the soil to supply nutrients to the crops
2. The constrained ability or inability of the soil to retain nutrients
3. Soil acidity
4. Soil alkalinity
5. Soil salinity

2.1.1 Practices to enhance supply of nutrients to crops

The limited ability of the soil to supply adequate nutrients to crops is a countrywide problem that requires urgent attention. There are a number of practices that farmers use to address this problem. These include:

i. The use of chemical fertilizers whereas chemical fertilizers offer an instant solution to the issue of limited nutrient supply, it should be emphasized that their injudicious use might lead to negative effects on the soil. For instance the excessive use of nitrogenous fertilizers, especially urea, has an acidifying effect on the soil and the high N content in the fertilizer could lead to rapid microbial decomposition of soil organic matter.

ii. The use of organic fertilizers such as animal manures, green manures or cover crops as shown in Figure 2, nitrogen fixing agro-forestry tree species and compost as illustrated in Figures 3 and 4. These materials have an advantage over chemical fertilizers in that they are less expensive as farmers can access them locally and at a low cost, and have the potential not only to supply nutrients, but also improve the soil physical and chemical properties. However, there are two major short comings associated with organic fertilizers. These are: i) The nutrient release pattern of organic resources does not match with crop requirement phases and ii) The nutrient contents of most of these organic inputs tend to be very low and as a result very large quantities of up to 20 tons/ha are required to meet crop nutrient demand. The large quantities required creates logistical challenges of moving these resources, incorporating them and sourcing for sufficient quantities.

iii. Crop rotation: include use of leguminous crops and agro-forestry species that are deep-rooted to break the hard pan, fix nitrogen, capture and recycle leached nutrients from deeper soil horizons.

iv. Intercropping of crops with different root and leaf architecture and requirements of nutrients, water and sunlight to enhance the interactions among the inter-planted crops through nitrogen fixation and water management . Intercropping also helps to break the cycles of diseases, weeds and pests.

v. Combination of chemical and organic fertilizers – this is the best option for enhancing the nutrient supply to crops. All the shortcomings associated with the sole use of either chemical fertilizers or organic inputs are addressed by combining the two practices.

Figure 2: A green manure crop of velvet beans (Mucuna spp) (courtesy of KATC)

Figure 3: Large-scale compost making process (courtesy of KATC)

Figure 4: Small-scale compost making process (courtesy of KATC)

Figure 5: Maize inter-cropped with black sunnhemp (courtesy of KATC*)*

Figure 6: Sorghum inter-cropped with pumpkin (Courtesy of KATC)

2.1.2 Practices to improve nutrient retention

The following are practices that are used to address the problem of the limited ability of certain soils to retain nutrients:

i. Application of organic fertilizers such as animal wastes and compost. For quick results, the organic materials should preferably be partially to highly decomposed, relatively stable organic materials as these have a high cation exchange capacity. High cation exchange capacity promotes better soil nutrient retention.

ii. Conservation Agriculture: This includes retention of crop residues in the field, no-burning, minimum tillage, the use of green manures and cover crops. Conservation tillage reduces nutrient and carbon losses through leaching, erosion and decomposition and burning.

iii. The use of Biochar: Biochar is charred organic material produced by incomplete burning of organic residues in an environment with limited supply of oxygen (see Fig 7). Biochar has a relatively high specific surface area and has the capacity to retain nutrients such as potassium, nitrogen (present as ammonium), calcium and magnesium against leaching. Biochar is also rich in carbon, a key requirement for structurally stable and healthy soils.

Figure 7: *Application of biochar in planting basins (Courtesy of UNZA)*

Plate 3: Effect of biochar on yield of maize grain

A study was conducted by the Golden Valley Agricultural Research Trust (GART) in Chisamba (Region II), Batoka (Region II) and Magoye (Region I) to evaluate the agronomic effectiveness of two types of biochar: charcoal dust and charred maize cobs on the performance of maize grain yields.

The results showed that addition of biochar at rates of 3965kg/ha with normal fertilization increased yields by 16%, 88% and 48% at Chisamba, Magoye and Batoka respectively over the controls. These results were largely attributed to the ability of the biochar to neutralize soil acidity and increase nutrient and water retention capacity. This was especially evident at Magoye and Batoka where the soils were acidic. The biochar from the maize cobs increased the yield of the maize grain to a greater extent than charcoal dust due to its ability to release nutrient with more ease than charcoal dust.

Excerpt from the GART Year Book, 2011.

2.1.3 Practices for managing acid soils

Soil acidity is particularly a more serious problem limiting productivity of most Zambian soils. It is estimated that over 30% of agricultural soils in Zambia are acidic with pH ranging from 4 to 6.9. Acidity is particularly a more serious problem in the high rainfall region or agro-ecological region III. Acid soils also occur, to some extent, in other regions of the country. Figure 8 below shows the soil reaction map of Zambia. There are several causes of soil acidity which include natural and induced. Among the natural causes of acidity are (i) high rates of weathering and leaching associated with high levels of rainfall and (ii) dominance of parent materials with low levels of basic ions such as calcium, magnesium and potassium. Soils derived from rocks with low levels of such elements such as granite tend to become acidic more rapidly than soils enriched with these ions. The induced causes of acidity include:

i. The prolonged indiscriminate use of nitrogenous fertilizers e.g. DAP,
ii. Mining of basic nutrients by crops
iii. Release of H- by plants during growth and,
iv. Decomposition of organic matter.

Practices to address the problem of acidic soils include:

i. **Use of agricultural lime** - there are two main types of Agricultural lime is used to make the soil less acidic and should be applied if the soil pH is less than 5.5". lime recommended in Zambia. These are dolomitic lime and calcitic lime. **Agricultural** lime is used to make the soil less acidic and should be applied if the soil pH is less than 5.5. Lime benefits the soil by adding calcium (a plant nutrient) and by neutralizing soil acidity arising from excess hydrogen, aluminum or manganese in the soil solution. Recommendations on the type of lime to use should be based on the type of lime available in the area and in some cases the need to maintain an adequate ratio of calcium to magnesium in the soil. Lime application rates should be based on the soil types and soil test information. Lime can either be applied in split application or single doses. Split applications have an advantage over single large dose applications in that there is a reduced chance of over-liming. More labour is however required for split application.

NB: Excess aluminum in the subsoil may restrict root growth into the depth of the soil and thereby restrict plant access to water and nutrients.

ii. Use of partially or completely decomposed organic materials:

Organic materials have the potential to acidify the soil as they decompose. Therefore, materials to be used for addressing soil acidity should preferably be partially or fully decomposed. Good examples of preferable materials include the compost and worm casts.

iii. Use of biochar:

This practice is still relatively new in Zambia and is still under research. In some places where soils are acidic and have low nutrient retention capacity, biochar has shown very positive results. This is a technology worth exploiting.

iv. Use of ash:

The use of wood ash is a common traditional farming practice in Zambia especially in the high rainfall region where the slash and burn system locally known as the "Chitemene System" is practiced. In the absence of lime, wood ash presents a good alternative for small-scale farmers to address soil acidity problems. The danger however, is that this is an extensive farming system, based on shifting cultivation, and is therefore not sustainable under the increasing population and dwindling land resources. A cut forest takes up to 25 years to regenerate. The burning of plant materials could also result in loss of other important nutrients contained in the plant

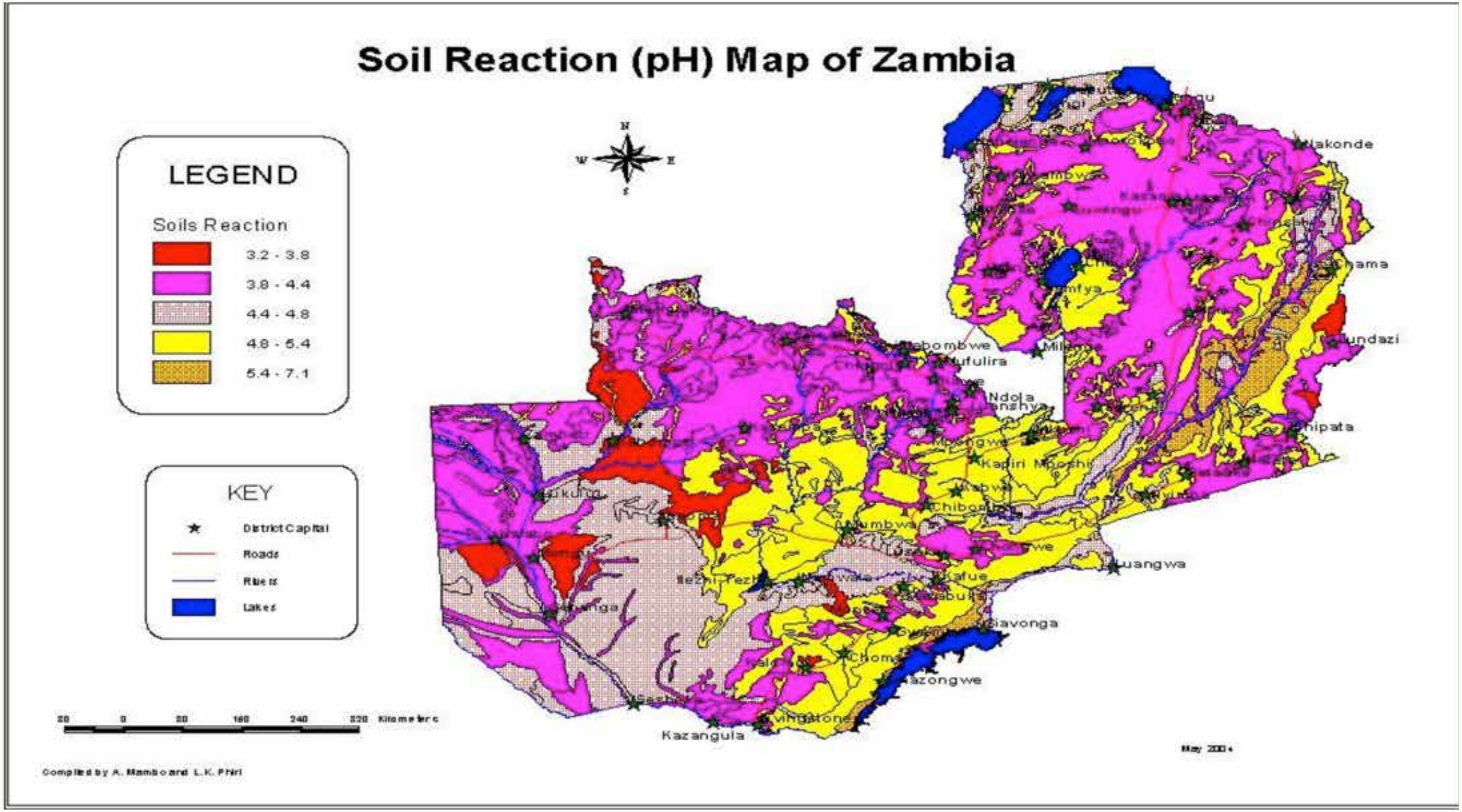


Figure 8: Soil reaction map (pH) map of Zambia

2.1.4 Practices for the management of soil alkalinity

The water present in the soil contains a number of substances that readily dissolve in water, including salts. During the formation of soils, minerals and rocks are weathered or broken down by chemical (dissolution by water and acid in the soil), physical (abrasion, thawing and freezing) and biological (activity of macro and micro-organisms) factors. The elements in the rocks and minerals are released into the soil water or soil solution. Some of the dissolved substances in the water exist as charged particles that may carry a positive or negative charge (ions). Positively charged ions are called cations while negatively charged ions are called anions. The common cations found in the soil solution include calcium, magnesium, sodium and potassium, while the common anions include carbonates, bicarbonates, sulphates, chlorides, nitrates and phosphates. Water itself always splits into hydrogen ions and hydroxyl ions.

When a soil solution contains more hydroxyl ions (OH-) than hydrogen ions (H+), it is said to be alkaline. Alkalinity develops when a soil accumulates ions that react with H+ present in solution, leading to a reduction in the concentration of H+ in solution. Ions such as carbonates and bicarbonates commonly react with H+ in the soil, causing the soils to become alkaline. Introduction of water containing high levels of bicarbonates and carbonates, such as during irrigation with groundwater obtained from aquifers rich in limestone can significantly increase the alkalinity of the soil. Seepage of groundwater containing carbonates and bicarbonates from locations of higher ground positions of the landscape can also introduce alkalinity to soils in lower lying regions. Another source of alkalinity is the ions released during the natural weathering in soils, especially in areas with low rainfall. The bases released from the weathering process are not removed from the soil but accumulate with time because there is little or no water to remove them from the soil through leaching therefore with time, the soils become alkaline.

Alkaline soils are, therefore, more likely to occur in low-lying areas, especially in dry environments, or semi-arid to arid conditions where the soils are dry for a significant period of the year. In upland areas, alkaline soils are more likely to occur where irrigation is practiced, especially where groundwater is used to irrigate the fields. Evaporation of water from such soils leaves salts on the soil surface.

Alkaline soil conditions are unfavourable for crop production because they tend to cause some plant nutrients to precipitate into insoluble compounds. This leads to the development of some nutrients especially the micronutrients such as iron, zinc and copper that belong to the metallic group of elements such as iron, zinc, and copper. In alkaline soils, other nutrients such as phosphorus become strongly bound to elements such as calcium which commonly accumulate in these soils. In general, metallic plant nutrient elements tend to become insoluble in alkaline soil and their availability to plants is reduced.

In Zambia, alkaline soils are more prevalent in Agro-ecological regions I and II or the low and medium rainfall regions. They are however most prevalent in region I, especially in the valley areas such as the Luangwa and Zambezi. Alkaline soils are generally rare in region III or the high rainfall region of Zambia where the high rainfall promotes rapid leaching of ions, thereby reducing chances of the formation of alkaline soil conditions. In areas where soils have become alkaline or are naturally alkaline, and where farmers can afford to purchase chemical fertilizers, one of the most effective practices is to use acidifying nitrogenous fertilizers. In general, all nitrogen fertilizers containing nitrogen in forms other than nitrate (NO^{3-}) have the potential of acidifying the soil. This occurs during the process of converting the nitrogen from the form present in the fertilizer to the nitrate form. This natural process is called nitrification and is carried out by soil microorganisms in well-aerated soils. For every unit of nitrogen converted to nitrate, two units of hydrogen ions or acid are produced. The acid produced during the nitrification process in the soil neutralizes or reduces the levels of alkalinity.

Among the commonly used nitrogenous fertilizers, ammonium sulphate probably has the highest capacity to produce acid in the soils through nitrification. For this reason the use of ammonium sulphate is recommended as an effective method of controlling alkalinity. In the absence of ammonium sulphate, other nitrogenous fertilizers such as ammonium nitrate and urea can be used. They also acidify the soil, although to a lesser extent than ammonium sulphate. The other alternative materials include powdered elemental sulphur or aluminium sulphate, iron sulphate and pyrite depending on their availability and cost.

2.1.5 Management of soil salinity and sodicity

As mentioned earlier, the soil solution contains dissolved substances, which include a number of salts. In some soils, the concentrations of dissolved salts can reach high levels that can interfere with the normal growth and development of plants. Soils that contain high levels of water soluble salts to the extent that the salts adversely affect plant growth are said to be saline. The effects of the soluble salts on crop growth can be direct or indirect. High salt concentrations in the soil reduce the availability of water to plants. Plants use more energy to obtain water from a salty solution than from water containing little or no salts. Some of the dissolved salts can also be toxic to plants. For instance, high levels of boron and chloride in the soil solution are known to be toxic to plants. Uptake of salts by plants to levels exceeding the tolerance of the plant can result to such plant injury as leaf burn or drying of leaf tissue.

Many soils containing high levels of salts often also contain high levels of dissolved sodium ions. Sodium ions disperse soil particles and interfere with the development of stable soil aggregates. High levels of sodium tend to make soil particles more susceptible to puddling, water logging and erosion especially on steep slopes. Soils with high levels of sodium tend to be very prone to gully erosion (Figure 9) and poor aeration due to the clogging of pore spaces by dispersed soil particles and do not provide a suitable environment for root development. Salt-affected soils which have poor physical properties as a result of the presence of high levels of sodium are termed as sodic, whilst soils with high salt concentration are called saline soils. Saline soils can be sodic (saline-sodic) or non-sodic. Because of the high concentration of salts, both saline and saline-sodic soils have better structures than sodic soils.

In Zambia, saline soils are not very widespread. They generally occur in low lying areas of the medium to low rainfall regions and are typically common in the valley regions. In their natural setting they are often associated with the Mopane vegetation. Areas with salt affected soils, both saline and sodic soils are generally considered to be moderately to marginally suitable for sustainable crop production. Such areas are often avoided for crop production in preference to alternative areas with better soils. Salinity can also be caused by farming practices, especially irrigation. When poor quality irrigation water is applied to a field, salts are introduced. In addition, the excess water that drains from locations in higher positions of the landscape flows and carries salts from the upland areas and deposits them in lower lying areas. In the lower lying areas, evaporation of this water from the soil surface leads to the accumulation of the salts present in the water on the surface of the soils. The accumulation of these salts can lead to the development of saline soil conditions.

In areas where soils accumulate soluble salts, it is necessary to remove these salts by draining the soils. Where irrigation is practiced, water applied to the field should include a slight excess over what is required by the crop to leach the salts out of the soils. To ensure that the salts are leached out of the soil and removed from the field, there should be adequate drainage. In heavy clay soils that are usually not very permeable organic residues can be incorporated into the soil to improve permeability.

In addition, open drains can be constructed to ensure that the water is drained from the fields and the water table is not close to the surface. Under natural conditions, salts are removed from the field by rain water during the rainy season. Rain water contains no salts, so it has a huge capacity to dissolve and wash out salts from the soil.

In cases where it may not be feasible to remove the excess salts, it is advisable to avoid cultivating such areas. The soils can be used for growing salt-tolerant crops, pastures or left for non-agricultural uses such as recreation. Alternatively, appropriate crops that are tolerant to saline soils may be recommended for such areas. Soil sodicity is not a common problem in Zambia. However, where sodicity problems have been identified, the use of gypsum in combination with good quality irrigation water with low salt content is recommended. Gypsum is a good source of soluble calcium that aggregates the soil while sodium is removed as soluble sodium sulphate.

Figure 9: Gully erosion on salt-affected soils with high levels of sodium.
(Courtesy of UNZA)

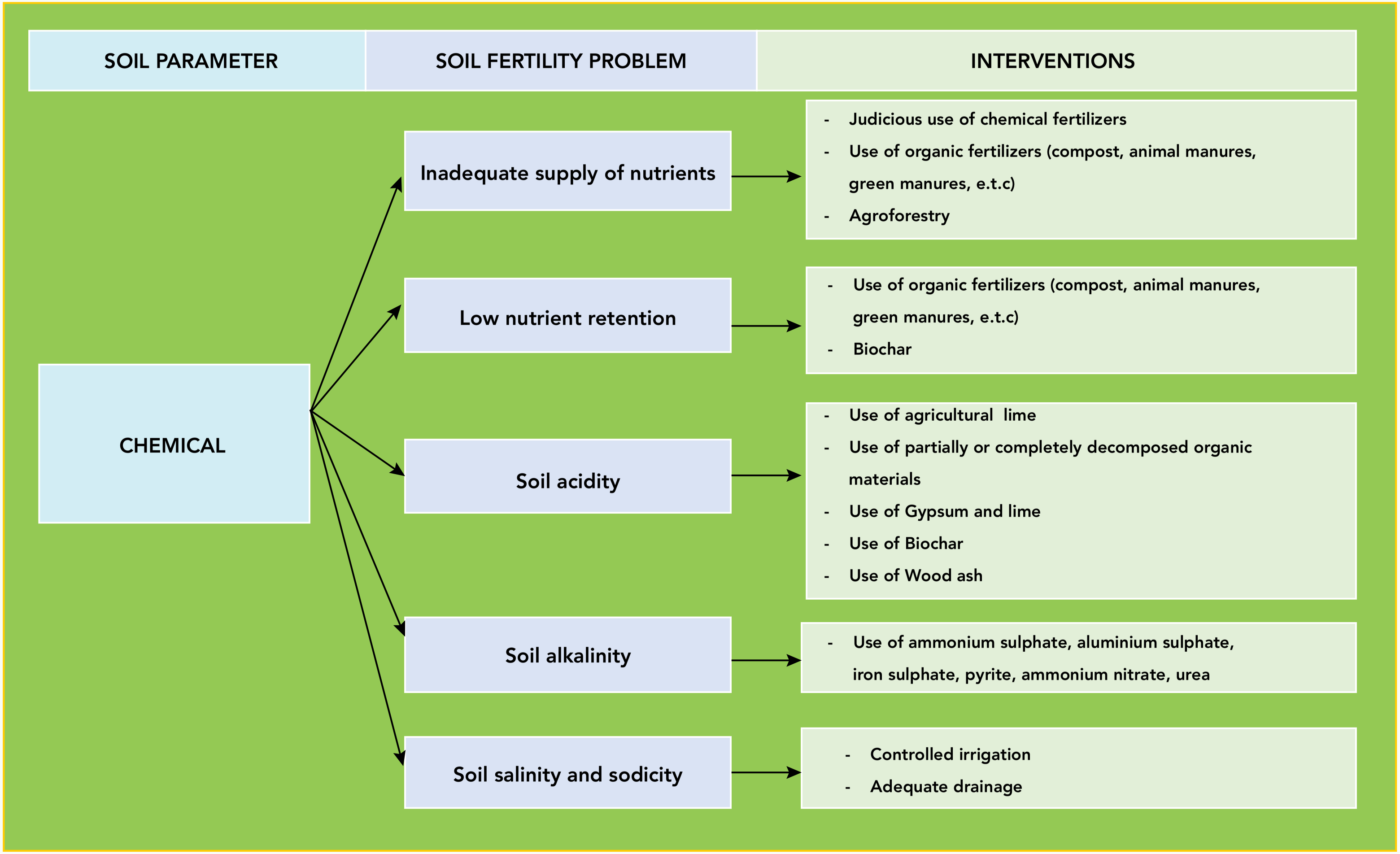


Figure 10: Summary of problems of chemical soil health and related intervention

2.2 Managing the physical health of soil for crop production

In addition to providing adequate nutrients for plant growth and being free of chemical conditions that may limit crop growth, a healthy soil should also be able to provide adequate water, aeration and mechanical support to the crop. In addition, the soil should be well protected from erosion and provide optimal temperatures for optimal growth and development of plants.

2.2.1 Practices for addressing the problem of poor soil structure

One of the properties of the soil that affects its physical suitability for crop production is its structure. The structure refers to the arrangement of the soil particles into aggregates. Soils with well aggregated structures generally tend to better retain and supply water and nutrients to plants. They are also easier to till and are less prone to compaction than soils with a poor soil structure. A number of undesirable physical conditions that adversely affect the use of soils for crop production are related to the structure of soils as shown in Figure 11. Among the undesirable effects of poor physical soil conditions that negatively impact on the productivity of soils are the following:

i. Inadequate aeration
ii. Inadequate moisture retention
iii. Inadequate drainage
iv. Poor workability
v. Soil compaction
vi. Soil erosion

Figure 11: Land degradation as a result of soil erosion (Courtesy of UNZA)

A soil with a good structure consists of aggregates that have a good distribution of both small and large pores. The pores allow for the entry and movement of water and air into the soil. The small pores are important for the retention of water, while the large pores are important for the movement of air and water in the soil profile. Large pores allow water to easily move or percolate through the soils when the soil is wet or saturated with water and reduces the chances of water stagnation especially after heavy rainfall. An ideal soil for crop production should have half of its total volume occupied by solid particles and the other half occupied by pores. Half of the pore spaces should be occupied by water and the other half by air (Figure 12). Although it may be rare to come across such an ideal soil, generally, the soils should have adequate pores to retain water and air.

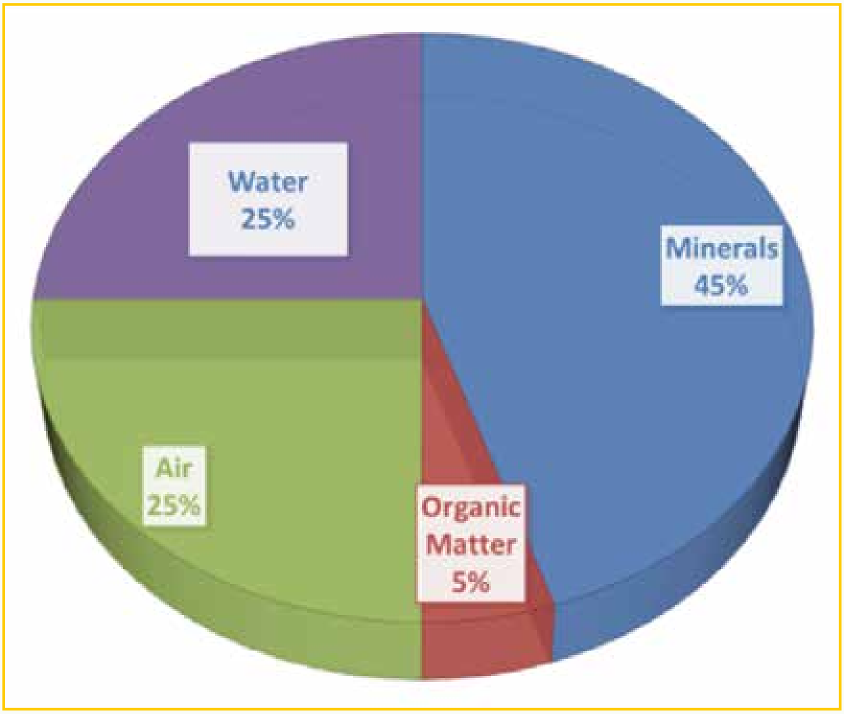


Figure 12: Ideal composition of a well aggregated soil

In order to ensure that soils have a good structure, there are a number of practices that need to be followed. Some of these practices contribute to the formation of soil aggregates that result in good soil structure while others prevent the deterioration of the existing structure. Below are some practices that are used to improve and maintain soil structure:

a. Addition of organic matter to the soil

Organic materials such as compost, animal manure and green manure when added to the soil are known to improve the structure of soils. The breakdown of fresh organic materials in the soil by microorganisms results in the formation of stable dark coloured organic material commonly known as humus. Humus serves as a cementing material in the formation of stable soil aggregates. The formation of stable aggregates improves the aeration, permeability and water retention of soils.

b. Retention of crop residues in the field

Crop residues left in the field eventually get converted into humus which improves the structure of soils. Figure 13 illustrates how soil structure can improve with the addition of organic matter. The burning of crop residues should be avoided as this will reduce the amount of materials that can be used to stabilize the structure of the soil.

Figure 13: Improvement in the structure of a loose sandy (right) soil by addition of organic matter (left) (Courtesy of Caritas Mongu)

It is therefore not recommended to burn crop residues unless it is absolutely necessary as in cases where residues may serve as potential source of pests and diseases.

c. Reduced or minimum tillage

Tillage practices that turn over the soil expose the organic matter present below the soil surface to higher temperatures and increased aeration which promotes a rapid decomposition of organic matter by soil micro-organisms. Tilled soils lose organic matter more rapidly than untilled soils, and are therefore prone to the degradation of soil structure. It is recommended to use minimum tillage when growing crops. This minimizes the deterioration of soil structure due to the loss of organic matter and due to compaction caused by traffic during tillage operations. A number of minimum or reduced tillage practices can be used. These include zero tillage or dibble planting, use of permanent planting basins, permanent ridges, and rip-lines (Figure 14, 15).

Figure 14: Minimum soil disturbances by preparing planting basins with mulch covering inter-row spaces (Courtesy of KATC)

Figure 15: Minimum soil disturbance by making rip-lines using the Magoye Ripper (Courtesy of KATC)

d) Timeliness of tillage operations

Compaction of soils is a common form of physical degradation of soils which occur when heavy equipment are used to till land. The time of tillage operations affects the structure of the soils. Cultivating soils when they are too wet or too dry leads to the deterioration of soil structure. It is, therefore, important that tillage operations are carried out at the correct time of the year when soils are moist enough to be tilled with minimum adverse effect on the soil structure.

e) Use of good quality water for irrigation

When soils are irrigated, it is important to ensure that the water is of good quality and not likely to adversely affect the physical and chemical properties of the soil. Water containing high levels of soluble sodium is not suitable for irrigation as it leads to the deterioration of the soil structure. Similarly, water with high levels of carbonates and bicarbonates is likely to make the irrigated soils alkaline. It is, therefore, important to test water for its suitability for irrigation before embarking on major irrigation projects.

2.2.2 Management of compacted soils

When soils on a farm are compacted, crops are not able to access water and nutrients present in the subsoil because the compacted soil layer restricts roots from penetrating to access water and nutrients from the subsoil. This may result in plants being more susceptible to water stress during dry spells. Compacted layers or hard pans also reduce entry of water and movement of air into the subsoil and make the affected soils prone to water logging and erosion especially after heavy rainfall. There are a number of practices that can be used to address the problem of soil compaction. They include:

i. Use of ox-drawn tillage implements such as the Magoye ripper or tractor drawn rippers to break the hardpan.
ii. Use of sub-soilers - Farmers that have access to sub-soilers can use them to break the hard layers that prevent roots from growing into the subsoil.
iii. Use of basins, though laborious can be effective in addressing problems of surface compaction.
iv. Crop rotation with deep-rooted crops alternating with shallow rooted crops can also be used to break the hardpan. Plants such as Gliricidia sepium, Cajanus Cajan and Sesbania sesban have roots that can penetrate and break hard pans.

2.2.3 Management of soil erosion

Soil erosion, commonly defined as the loss of soils from an area due to its detachment and transportation to other locations is a major form of physical degradation of the soils. There are many forms of erosion that occur in soils. The common ones include, sheet erosion, rill erosion and gully erosion, which are usually associated with the loss of soil from the field by moving water. There is also wind erosion which occurs when soil particles are carried from one area to another by wind. There are a number of practices that can be used to prevent or reduce soil erosion in farmer's fields. These include:

a. Use of soil covers - materials that can be used to cover the soil to prevent or reduce erosion include the use of mulches, growing of cover crops, green manures and inter- cropping within a field.
b. Contour ploughing - on sloping land, farmers can practice contour ploughing alongside structures such as contour ridges, contour ditches, stone lines, grass strips, etc. Within these structures, plants are grown and planted in rows across the slope of the land. The use of terraces, and planting of crops such as Vertiver grass and planting of bananas in gullies can also be employed as means of reducing soil loss from susceptible areas.
c. Wind breaks – planting certain plants such as some agroforestry species can serve as wind breaks that can reduce soil erosion by wind.

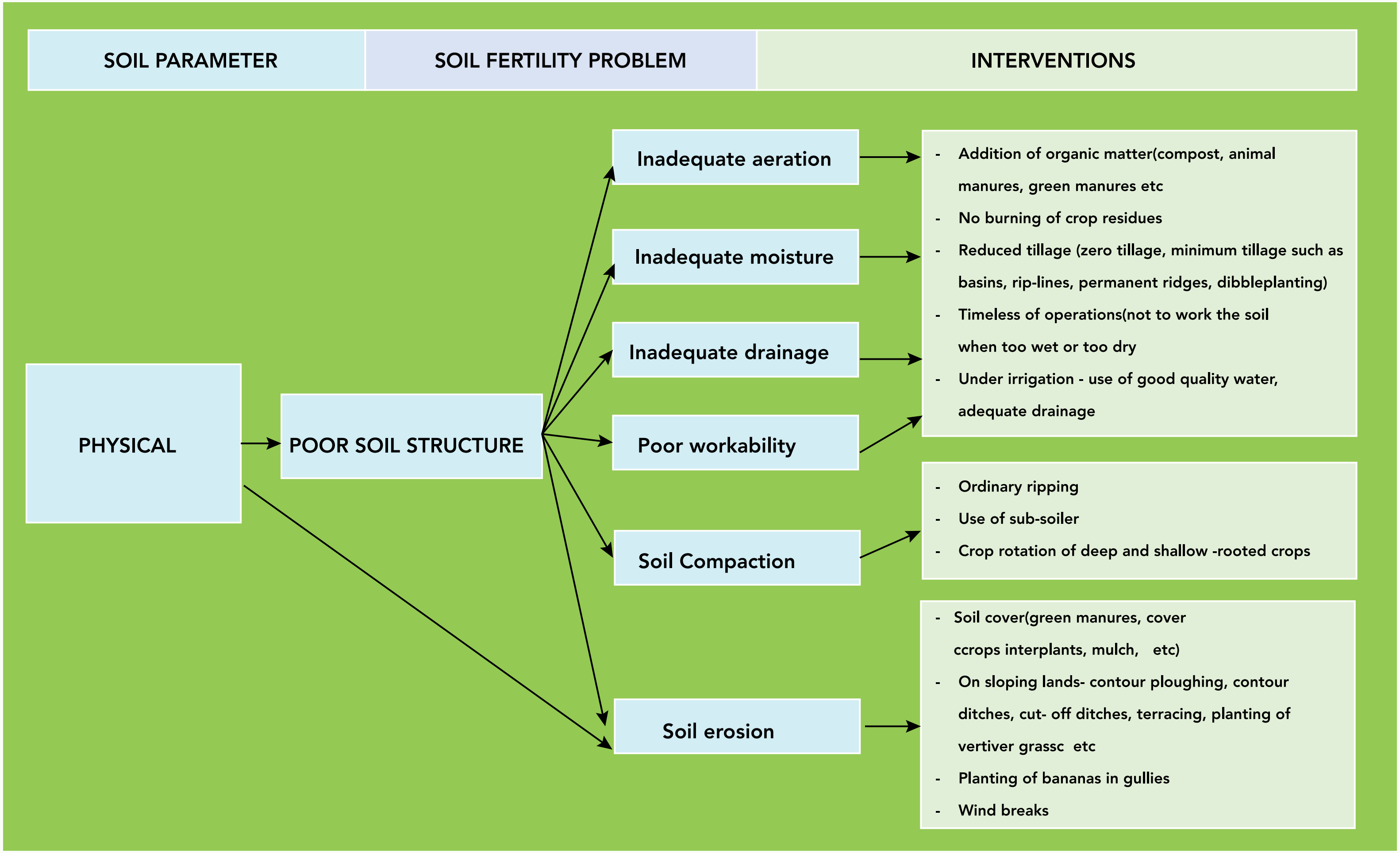


Figure 16: Summary of problems of physical soil health and related interventions

2.3 Managing the biological health of soil for crop production

The functioning of most agricultural ecosystems is largely governed by the soil microbial dynamics. The soil life is important for keeping agricultural soils healthy and productive. Soil is complex and includes living organisms that cannot be seen with the naked eyes, such as bacteria, fungi, actinomycetes, protozoa and nematodes often referred to as micro-organisms. It also contains larger living organisms that can be seen with the naked eyes, such as insects and earthworms often referred to as macro-organisms. This community of organisms is bound together in a food web that affects the soil's chemical and physical properties.

As much as the living organisms in soil have a direct effect on the chemical and physical soil properties, these soil properties in turn have an influence on the soil organisms. Several environmental factors and management practices affect the population and diversity of living organisms in the soil which may directly or indirectly affect the health and productivity of the soil. Land management practices such as tillage, use of chemical and organic fertilizers, pesticides and herbicides have an influence on the microbial biomass and diversity of the soil.

The following soil conditions and management practices are known to have an adverse effect on the soil biological health:

i. Inadequate aeration
ii. Inadequate moisture
iii. Inadequate drainage
iv. Lack of organic matter
v. Unfavourable chemical environment such as high levels of acidity, alkalinity
vi. Unfavourable soil temperatures
vii. Cropping systems e.g. mono-cropping
viii. Injudicious use of chemical fertilizers
ix. Excessive use of herbicides and pesticides

2.3.1 Practices to address problems of inadequate soil aeration, moisture and drainage

The biological health of the soil is directly related to the quantities and diversity of soil organisms. Like most other living organisms, soil organisms need sufficient oxygen and adequate moisture for their survival.

Soil moisture is one of the important factors influencing the microbial population, diversity and their activity in the soil. Soil moisture is useful to the organisms in two ways; it supplies the nutrients, hydrogen and oxygen to the organisms and serves as a solvent and carrier of other nutrients to the microorganisms. Under water-logged conditions, when oxygen becomes limiting, microbes that do not require oxygen become active while those that require oxygen get suppressed. In the absence of water in the soil, some of the microbes die due to dehydration while others may change into resting or dormant forms such as spores or cysts. Most of the microbes involved in key soil processes like mineralization and nitrification require oxygen to thrive and perform these functions. These functions are crucial for supply of nutrients to the soil in forms that are utilizable by plants.

Microbes utilize oxygen from soil air and in turn produce carbon dioxide. Under water-logged conditions, aeration is limited and may result in the accumulation of carbon dioxide which is toxic to microbes. The practices to address the problems associated with limited soil aeration, moisture and drainage include:

1. Addition of organic matter such as compost, animal manures, and green manures.
2. Retention of crop residues
3. Reduced tillage practices such as zero tillage i.e. dibble planting and minimum tillage practices like use of planting basins, rip-lines and permanent ridges
4. Timeliness of operations is important. Soils should not be worked on when they are either too wet or too dry
5. Use of good quality water for irrigation and adequate drainage.

2.3.2 Practices to address insufficient soil organic matter

Soil organic matter is a key indicator of soil health because it plays a role in a number of key functions such as the provision of nutrients and habitats for soil organisms; the provision of energy for biological processes; as well as contributing to the soil's resilience or ability of a soil to return to its initial state after a disturbance, such as after tillage.

The composition of organic material as expressed in terms of its percentage nitrogen (N) and carbon (C) or C: N ratio is a common measure of the quality of the material for microbial use. The C: N ratio of the material affects the activity, diversity and population of microorganisms in soil. Materials with a high C:N ratio or low content of nitrogen in relation to carbon take a longer time to decompose and release nitrogen and other nutrients to the soil.

The practices that are commonly used to build-up and maintain soil organic matter are listed below:

1. Use of organic fertilizers such as compost, animal manures and green manures.
2. Crop rotations that include legumes and cereals.
3. Use of mulch and cover crops
4. Minimum soil disturbance
5. Retention of crop residues
6. Use of agro-forestry practices such as improved fallows and alley cropping (refer to Figure 17).

Figure 17: Alley cropping of maize with *Gliricidia sepium*

2.3.3 Practices for addressing acidity or alkalinity with respect to biological soil health

Most soil organisms have an optimum pH range within which they function and thrive well. Generally, the activity of soil organisms is greatest when the soil pH is near neutral, but the optimum pH varies for different types of organisms. In general the numbers and activity of microbes are considerably lower in acid soils than in slightly acid to neutral soils. In very acidic and alkaline soil conditions, organic matter decomposition is significantly reduced and can even stop because of the low levels of microbial activity. Important soil processes such as nitrification, the release of nitrogen from decomposing materials, and nitrogen fixation, the conversion of nitrogen gas in the air into forms of nitrogen that plants can use, are also inhibited by low pH conditions.

The numbers and activity of bacteria decline as the levels of acidity in the soils increase, whereas fungi are generally adapted to a wide range of pH conditions or levels of acidity and alkalinity. The practices for addressing soil acidity include: application of lime, application of partially or completely decomposed organic materials, application of biochar and application of ash to acidic soils. On the other hand, the practices for managing alkalinity include: application of acidifying fertilizers. More detailed description of practices for managing acidic and alkaline soils are provided in sections 2.1.3 and 2.1.4 respectively.

2.3.4 Practices to address unfavorable soil temperatures with respect to the biological soil health

Temperature is an important factor in regulating the activity of soil organisms and shaping the soil organism community. Though soil organisms can tolerate extreme temperatures, the optimum temperature range at which they can grow and function actively is rather narrow.

Soil microorganisms are divided into three broad groups depending on the temperature range in which they can grow and function well. Microorganisms that grow at low temperatures of below 10°C are called psychrophiles or cold-loving organisms. Microorganisms that grow well in the temperature range of 20°C to 45°C are called mesophiles or organisms that like mild temperatures. Those that can tolerate high temperatures of above 45°C are called thermophiles. Most of the soil microorganisms grow well at temperatures ranging from 25 to 40°C and at an optimum temperature of 37°C.

True psychrophiles are almost absent in soil, and thermopiles though present in soil behave like mesophiles. True thermopiles are more abundant in decaying manure and compost heaps where high temperatures prevail.

Seasonal changes in soil temperature affect microbial population and activity. In the cold season when the soil temperature is low, the number and activity of microorganisms decline, and as the soil warms up in the hot season, there is an increase in the number and activity of microorganisms. In general, the population and activities of soil microorganisms are highest in the hot and wet season and lowest in the cold and dry season.The following are practices that can be used to improve soil temperatures and consequently increase the population and activity of soil organisms:

1. Adding organic materials such as compost, animal manures, and green manures to the soil. The organic matter in these materials has the ability to regulate and modify soil temperature.
2. Covering the soil using either dead or live mulch. Live mulch refers to crops grown to cover the soil surface which are also commonly referred to as cover crops.

3. Maintaining crop residues. Burning of crop residues results in a loss of organic matter and all benefits associated with organic matter. It may also kill the soil microorganisms.

4. Creating a suitable micro-climate by integrating agro-forestry into the farming system. Agro-forestry tree species provide a canopy cover which modifies environmental conditions under the canopy and makes soil temperatures favorable for microorganisms.

2.3.5 Addressing problems of mono-cropping with respect to biological soil health

The opening up of new land for agricultural activities normally disrupts the normal functioning of the ecosystem. A further imbalance in the ecosystem is created when the farming system relies heavily on mono-cropping. Mono-cropping reduces the diversity of soil organic matter, soil nutrients and consequently, the diversity of soil organisms. Repeated cultivation of the same crop year after year on the same piece of land decreases the diversity of materials available to sustain a healthy soil. This reduces the diversity of microorganisms as different species of soil microbes require different type of organic materials to survive. For instance, it is generally known that organic matter containing high amounts of lignin or woody materials tend to favor growth of fungi while organic materials that are easily decomposable and rich in nitrogen tend to favor the growth of bacteria.

The effect of having one or a few species of soil organisms dominating the soil is that it tends to create an imbalance in the microorganisms present in the soil. Mono-cropping with time also tends to promote the build-up of pests and diseases. Because mono-cropping provides the same type of organic matter to the soil microorganisms year after year, the soil environment becomes fragile or unable to support a wide range of beneficial organisms.

To address some of the problems cited above, farming practices such as crop rotation or inter-cropping different crop species such as legumes with cereals, usually tend to promote an increase in the numbers and diversity of microorganisms present in the soils as well as microbial activity.

2.3.6 Practices to address problems caused by injudicious use of chemical fertilizers

Chemical fertilizers have many advantages such as ease of application, quick release of nutrients, and supplying soil nutrients in exact required quantities. However, they could also have many adverse effects on the health of the soil when used in inappropriately. When used inappropriately many chemical fertilizers, especially those that supply nitrogen could acidify the soil, making it unfavorable for the survival of living organisms. Other fertilizers such as urea, when utilized by bacteria get converted to anhydrous ammonia and carbon dioxide. Anhydrous ammonia is highly toxic and kills soil organisms. Muriate of potash or potassium chloride (the form of potassium in D compound fertilizer) contains 50% potassium and 50% chloride. In the soil, the chloride combines with nitrate to form chlorine gas which kills soil organisms. Being salts, most chemical fertilizers have a high tendency to draw water to themselves, hence depriving the plant roots and soil organisms of water. In addition, most nitrogenous fertilizers tend to speed up the decomposition of organic matter by narrowing the C: N ratio. This leads to the rapid depletion of soil organic matter.

To alleviate these problems, it is imperative that chemical fertilizers are used judiciously and in combination with different organic and inorganic soil amendments. **The 4R Nutrient Stewardship** approach provides guidelines on the best way to manage fertilizers. It consists of applying the **Right Source** of nutrients needed by a plant, at the **Right Rate** to supply the quantity needed by the plant, at the **Right Time** to be taken by the plant, and in the **Right Place** to be accessible by plant roots. Correct practice of the 4R management practices will result in increased crop yields and incomes, as well as prevention of soil nutrient depletion.

For nutrient management to be considered "right," it must support the goals of farmers. The farmer is the final decision-maker in selecting the practices suited to local soil, weather, cropping systems, as well as socio-economic conditions. Because these local conditions affect the decision on the practice selected, approaches for implementing 4R management practices should improve the capacity of farmers to adapt the right practices to their local conditions. Figure 18, demonstrates the importance of applying nutrients at the right rate.

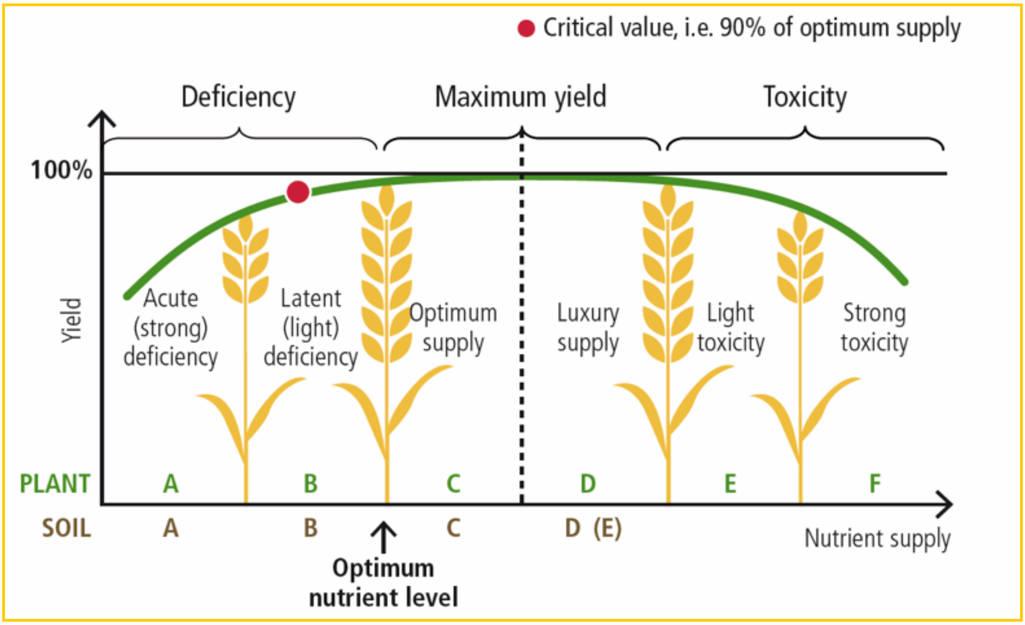


Figure 18: Effects of nutrient rate on wheat yield, showing potential deficiency and toxicity effects of not applying the right rates of nutrients (IFA World Fertilizer Use Manual, 1992)

2.3.7 Practices to address the excessive use of herbicides and pesticides with respect to the soil biological health

The most common pesticides include insecticides, fungicides, herbicides, rodenticides, nematicides, etc. Herbicides are pesticides used to kill unwanted plants. They are categorized into either selective or non-selective types. Selective herbicides kill specific targets while leaving the desired crops unharmed while non selective herbicides kill any plant material they come in contact with.

Though pesticides are beneficial, their inappropriate use can be counter-productive and threaten the long-term survival of major ecosystems by disrupting predator-prey relationships, loss of biodiversity, increase pest resistance and kill beneficial microorganisms. Some of these beneficial microorganisms are natural enemies of pests, while others are those involved in key processes which build and maintain soil fertility.

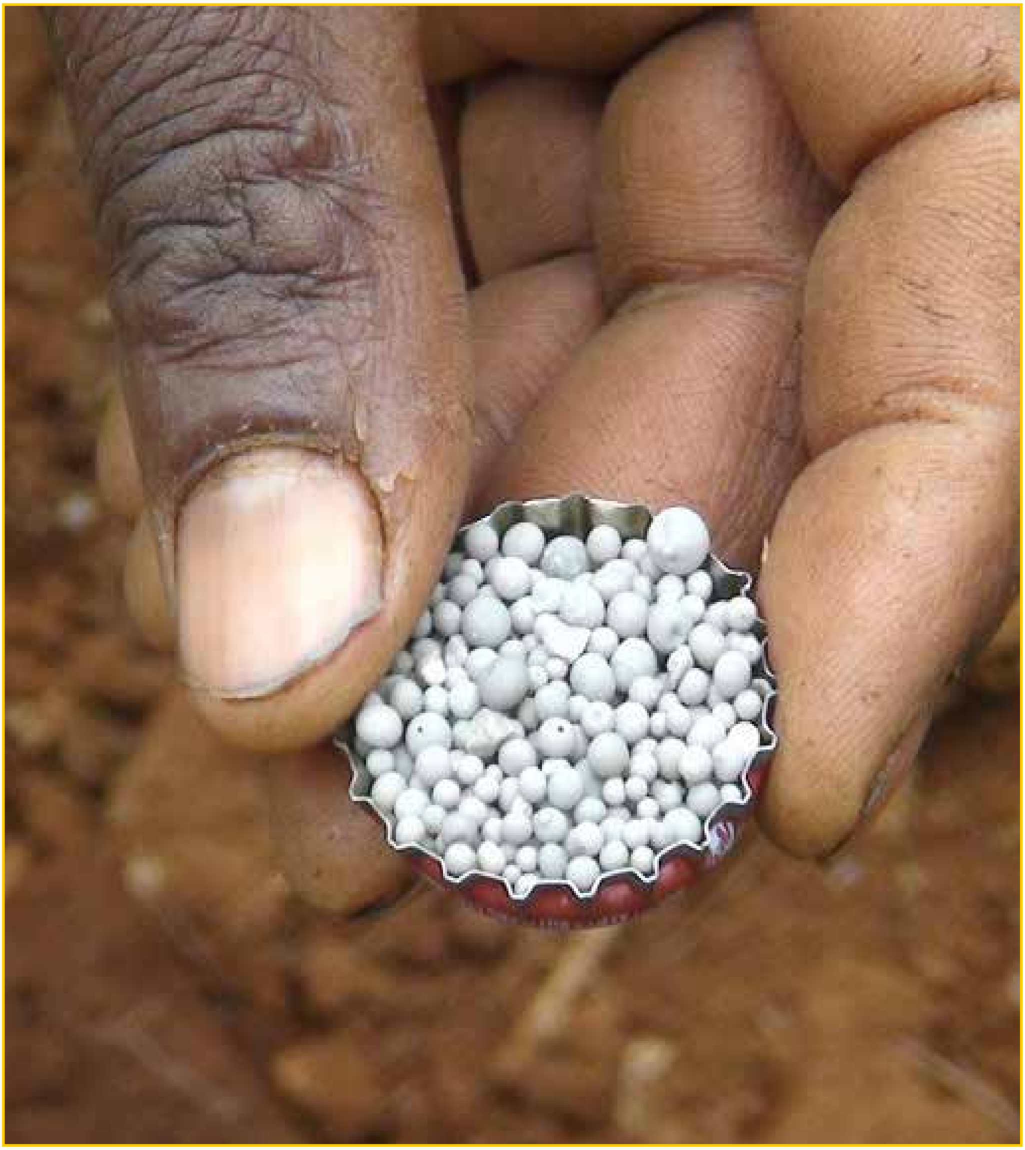
To address the above problems, pesticides should essentially be subject to safe and judicious use. This can be achieved by helping farmers understand the impact of different pesticides and herbicides on various soil functions. This will help farmers to minimize the negative impact of pesticides and herbicides on these functions. Farmers should stick to the recommended types of pesticide, application rates, frequency of application, and the soil and plant type in order to minimize the impact on soil biota and the various soil functions.

2.4 Fertilizer and Improved germplasm

The ISFM definition recommends that application of right sources of nutrients in an appropriate way to responsive soils combined with use of improved germplasm will enhance crop yield and improve the agronomic efficiency. The main package for achieving production gains on 'responsive fields' include:

(i) Use of disease-resistant and improved germplasm,
(ii) Adoption of crop and water management practices, and
(iii) Application of 4R Nutrient Stewardship – a science-based framework that focuses on applying the right fertilizer source at the right rate, at the right time, and in the right place. These 4R's provides an essentialbasis for optimizing the use of nutrients within an ISFM framework.

Improved varieties are better at nutrient uptake from the small amount of fertilizer that Zambian farmers can afford. It is estimated that all other factors held constant, quality seeds of high yielding varieties increases crop yield by 15-20%. In certain exceptional conditions this increase could be 30 to 60%. The yield level of quality high yielding seeds could be reduced by more than 80% by the limitations in soil nutrients and moisture.



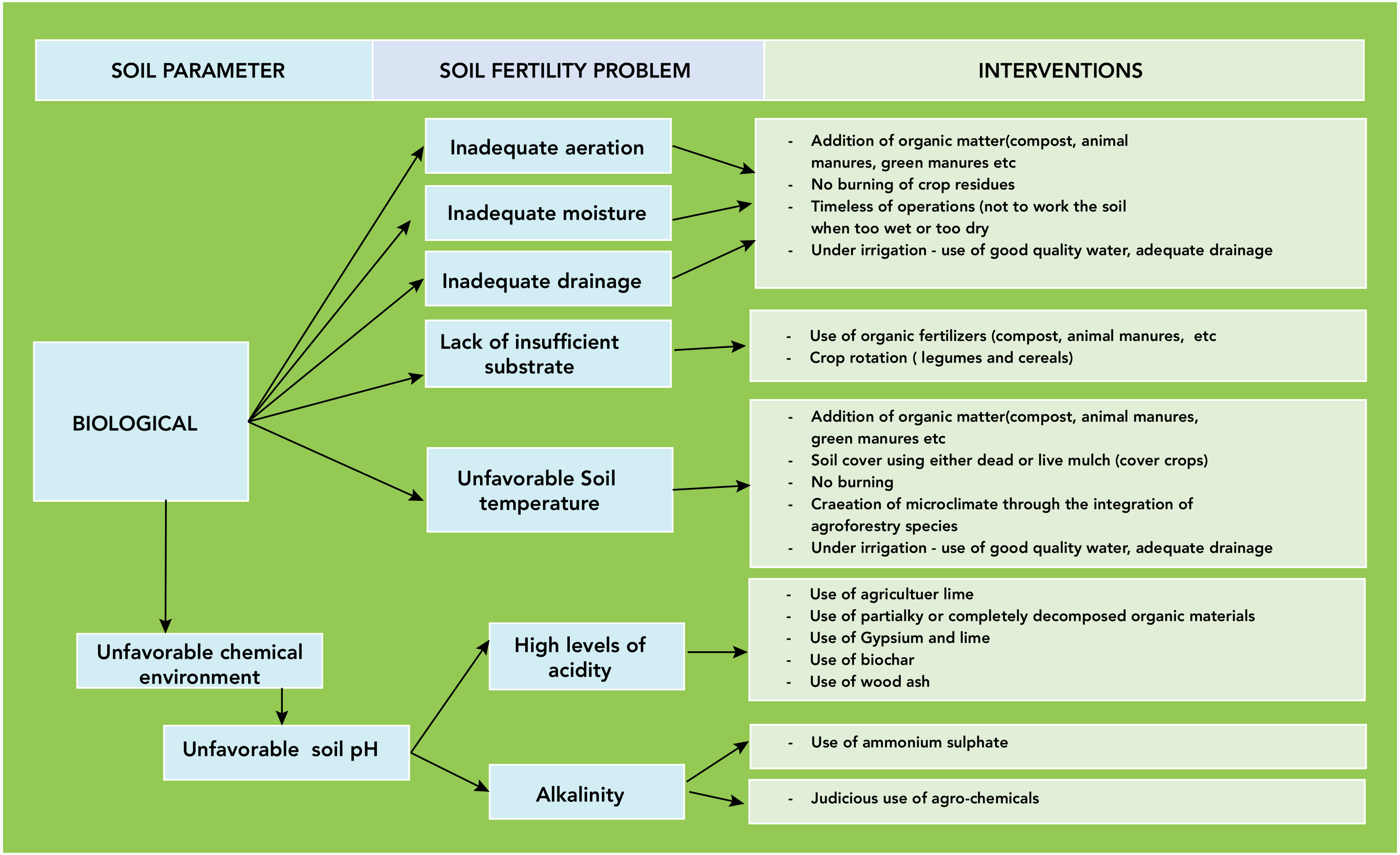


Figure 19: Summary of problems of biological soil health and related interventions

3. LOCAL ADAPTATION OF ISFM IN ZAMBIA

There are different farming systems in each of the agro-ecological regions of Zambia. The following are the five major ones:

1. Shifting cultivation;
2. Semi-permanent hoe system;
3. Semi-permanent hoe and ox-plough system;
4. Semi-commercial cultivation and;
5. Commercial systems.

Zambian agriculture has three broad categories of farmers: small-scale, medium and large-scale. Small-scale farmers are generally subsistent producers of staple foods with occasional marketable surplus. Medium-scale farmers produce maize and a few other cash crops for the market. Large-scale farmers produce various crops for the local and export markets.

In addition to the diversity of farming systems, it is also recognized that soil types vary according to agro-ecological regions, topography and parent material. Furthermore, soil fertility also varies from farm to farm, and even within the same farm.

Given the differences in the farming systems, type of farmers, as well as the soil fertility in Zambia, it is clear that general or blanket management recommendations that are usually applied across the country cannot yield desirable results. Agricultural technologies need to be targeted appropriately taking into account agro-ecological and socio-economic environments if improvement in crop yields is to be achieved.

ISFM emphasizes targeting technologies to specific situations taking into account differences in agro-ecological regions, soil types and socio-economic status of farmers. As noted by Horrigan et al. (2002), ISFM technologies are site-specific. As such, a farming system that is applicable in a high rainfall area might not be appropriate in an arid climate. For instance, in the high rainfall areas (Region III) where soils are acidic, application of lime is necessary, while this may not be necessary in areas/regions where acidity is not a problem. Similarly, water harvesting techniques are better suited to low rainfall areas (Region I).

In conclusion, the promotion of ISFM technologies should consider the suitability of these practices to local conditions taking into account the farming systems, the environmental conditions and socio-economic characteristics.

3.1 Timely planting dates as a sound agronomic ISFM Practice

Zambia's agriculture is predominantly rain fed. As earlier discussed, Zambia has three agro ecological regions classified based on rainfall and other parameters such as soil types and climate. For rain-fed crop production, the planting dates for different crops vary across the regions. In Region I, maize, sorghum and millets are the main crops grown. Because this region has the shortest growing season, early maturing varieties of maize are the most appropriate. These should be planted as soon as the rain starts, from early November up to about mid-December.

Region IIA which has a growing season of between 100-140 days and a relatively high amount of sunshine during the rainy season (average 5-6 hours per day). The recommended planting period for maize is from the first week of November to mid-December. Rain-fed maize and other crops like soya beans are commonly grown in this area. This region produces the bulk of these crops in the country. Soya beans should be planted between mid to end of December.

Region III has the longest growing season ranging from 120 to 150 days. In this region, the dominant crops are cassava, beans, millets and maize. Crop production is constrained by low soil fertility, inadequate fallow periods between successive cultivation periods, high humidity and cloud cover in the rainy season. In this region late maturing maize varieties are recommended and the planting period range is from late October to mid-December.

4. WHAT THEN IS ISFM? INTEGRATION OF ISFM PRACTICES IN FARMING SYSTEMS

Soil fertility replenishment in Zambia as in most Sub-Saharan countries in Africa is increasingly viewed as critical to the process of poverty alleviation. Pedro Sanchez, a pioneer in the field, identified soil fertility depletion as the 'fundamental biophysical root cause of declining per capita food production in Africa' and advocated for integrated problem-solving approaches.

As elaborated in the earlier chapters, soils in Zambia exhibit a variety of constraints: physical soil loss from erosion, nutrient deficiency, low organic matter, low cation exchange capacity, aluminum and iron toxicity, acidity, alkalizations, crusting, and moisture stress. Whereas some of these constraints occur naturally in tropical soils, degradation processes related to land management also come to play and worsen the problem. The result is the high yield gap between farmers' potential and actual yields. In most farmers' fields, observed yields for maize, for example, gravitate around 1 to 1.2 tons/ha, yet a potential of 8 -12 tons/ha is attained in on-station trials and by commercial farmers.

This huge yield gap between the experimental station yields, farmers' potential yields and farmers' actual yields is attributed to the low inherent fertility and low use of inputs. Fertilizer use is extremely low, averaging 8 kg/ha. Given this scenario, there is a need to improve fertilizer use to reverse the current trends of low crop yields and land degradation. While mineral fertilizers are an important source of nutrients for crop growth and development, they cannot be a standalone means for nutrient management. The most sustainable gains in crop productivity per unit nutrient are better achieved by use of mixtures of fertilizers and organic inputs.

The practices in an ISFM paradigm include the appropriate inorganic and organic resource input management and the use of improved seed. ISFM is not characterized by unique field practices but is rather a new approach to combining available technologies in a manner that improves/manages soil quality (chemical, physical and biological) while promoting its productivity. The focus of ISFM is improving Agronomic Use Efficiency (AUE) in crop production. In other words ISFM focuses on maximizing the fertilizer and organic resource use efficiency by the crop. Agronomic efficiency (AE) is defined as the extra produce generated (in kg) per unit of nutrients applied (in kg). Thus ISFM provides a better option that can overcome the challenges of bridging the yield gap as it offers farmers better returns to investment in fertilizer through its combination with indigenous agro-minerals and available organic resources.

5. REFERENCES

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6. DEFINITIONS /GLOSSARY

Agro-ecological zone: The main system of land resource assessment based on length of available growing period (LGP), which is defined as the period (in days) during the year when rain fed available soil moisture supply is greater than half potential evapotranspiration (PET). It includes the period required for evapotranspiration of up to 100 mm of available soil moisture stored in the soil profile. It excludes any time interval with daily mean temperatures less than 5° C. Used for better planning and management and monitoring of these resources.

Agro-forestry or Agroforestry: Land use management systems in which trees are managed together with crops and/or animal production systems in agricultural settings. It combines agricultural and forestry technologies to create more diverse, productive, profitable, healthy, and sustainable land-use systems.

Aquifers: An underground layer of water-bearing permeable (saturated with water) rock or unconsolidated materials (gravel, sand, or silt) from which groundwater can be brought to the surface through natural springs or by pumping from a water well.

Bicarbonates: Are salts containing hydrogen carbonate, bicarbonate (HCO_3^-) anion.

Biochar: Charcoal that is used for agricultural purposes. It is created using a pyrolysis process of biomass (heating biomass in a low oxygen environment).

Carbonate: A compound that contains the CO32- anion. Inorganic carbonates are ionic compounds that combine metal cations with the carbonate ion.

C: N ratio: Ratio of carbon to nitrogen. It is an indicator of decomposition rate.

Compost: Organic matter that has been decomposed and recycled as a fertilizer and soil amendment. Compost is a key ingredient in organic farming.

Conservation Agriculture: A concept for resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment.

Cover crop: A crop planted primarily to manage soil erosion, soil fertility, soil quality, water, weeds, pests, diseases, biodiversity and largely shaped by humans across a range of intensities to produce food, feed, or fiber.

Fertilizer (or fertiliser): Any material of natural or synthetic origin that is applied to soils or to plant tissues (usually leaves) to supply one or more plant nutrients essential to the growth of plants.

Germplasm: A collection of genetic resources for an organism. For plants, the germplasm may be stored as a seed collection (even a large seed bank) or, for trees, in a nursery.

Gross Domestic Product (GDP): One of the primary indicators used to gauge the health of a country's economy. It represents the total monetary value of all goods and services produced in a country over a specific time period.

Herbicides: Chemicals commonly called weed killers which are used to manipulate or control undesirable vegetation; Selective herbicides kill certain targets while leaving the desired crop relatively unharmed.

Land degradation: A process in which the value of the biophysical environment or land resource undergoes destruction or reduction in quality; or any change or disturbance to the land perceived to be deleterious or undesirable.

Leach: To drain away, or lose a mineral or chemical dissolved in rainwater from the soil.

Legume: A plant in the family Leguminosae. Legumes are grown agriculturally, primarily for their food grain seed, for human, livestock forage and silage, and as soil-enhancing green manure. Legumes have symbiotic nitrogen-fixing bacteria in structures called root nodules. These bacteria permit legumes to fix atmospheric nitrogen into the soil.

Manure: Manure is organic matter used as organic fertilizer in agriculture.

Micronutrients: Are elements (nutrients) needed by life (including animals and plants) in small quantities to support a range of physiological functions.

Monocropping: Is the agricultural practice of growing a single crop year after year on the same land.

Mulch: A layer of material, dead or living, applied to the surface of an area of soil. Its purpose is any or all of the following: to conserve moisture, to improve the fertility and health of the soil, to reduce weed growth or to enhance the visual appeal of the area.

Nutrient retention: Keeping or holding of nutrients in the soil profile: the act of retaining nutrients or the condition of nutrients being retained in the soil root zone.

Organic fertilizers: Fertilizers derived from animal matter or vegetable matter. (E.g. Compost manure).

Parent material: Material from which soil develops. This can come from many different sources.

Pesticides: Any substance used to kill, repel, or control certain forms of plant or animal life that are considered to be pests. Pesticides include herbicides.

Soil: Soil is the unconsolidated mineral and organic material on the immediate surface of the Earth which provides nutrients, moisture, and anchorage for land plants.

Soil acidity: A condition where a soil has a pH of less than 7.0 (neutral). Acidity is due to hydrogen (H+) ion concentrations in the soil. The higher the H+ concentration, the lower the pH.

Soil aggregates: Are groups of soil particles that bind to each other more strongly than to adjacent particles. An aggregate possesses solids and pore space. Aggregates are separated by planes of weakness and are dominated by clay particles. Aggregates are described by their shape, size and stability.

Soil alkalinity: See soil pH.

Soil compaction: The physical consolidation of the soil by an applied force that destroys structure reduces porosity, limits water and air infiltration, increases resistance to root penetration and often results in reduced yields.

Soil fertility: The quality of a soil that enables it to provide a conducive chemical, physical and biological environment necessary for the healthy growth of specified plant.

Soil hard pan: Is a general term for a dense layer of soil, usually found below the uppermost topsoil layer and can be naturally caused or man-made.

Soil pH: An indication of the alkalinity or acidity of soil. It is based on the measurement of pH, which is based in turn on the activity of hydrogen ions (H^+) in a water or salt solution. Aqueous solutions with pH values lower than 7 are considered acidic, while pH values higher than 7 are considered alkaline. Alkaline soils have a high saturation of base cations (K^+, Ca^{2+}, Mg^{2+} and Na^+).

Soil productivity: Soil productivity is an economic concept and signifies the capability of soil to produce specified plants or parts or a sequence of plants under well-defined and specified system of management, inputs and environmental conditions. It is measured in terms of outputs or harvests in relation to production factors for a specified kind of soil under a physically defined system of management.

Soil salinity: Soil containing excess salts (especially salts of sodium and magnesium).

Soil structure: The arrangement of soil aggregates into different forms.

Soil micro-organisms: Microbes that dwell in soil (collectively the soil microbial biomass), these are the agents of transformation of soil organic matter, nutrients and of most key soil processes.

Technology: A method or methodology that applies technical knowledge, tools, materials, and devices to solve practical problems.