CHAPTER 5

Agrobiodiversity and Potential Use for Enhancing Soil Health in Tropical Soils of Africa

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ABSTRACT

Land degradation and soil fertility decline is often cited as a major constraint to crop production in sub-Saharan Africa (SSA). As mineral and organic fertilisers are often limited in quantity and quality, soil fertility research has focused on developing integrated management strategies to address soil fertility decline. Soil biotas are an essential component of soil health and constitute a major fraction of global terrestrial biodiversity. Within the context of Integrated Soil Fertility

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Management (ISFM), soil biota are responsible for the key ecosystem functions of decomposition and nutrient cycling, soil organic matter synthesis and mineralisation, soil structural modification and aggregate stabilisation, nitrogen fixation, nutrient acquisition, regulation of atmospheric composition, the production of plant growth substances and the biological control of soil-borne pests and diseases. Soil biological processes are not as well understood as are soil physical and chemical properties, creating opportunities for breakthroughs in biotic function to provide better services to agriculture. These services accrue through two basic approaches: indirectly, as a result of promoting beneficial soil biological processes and ecosystem services through land management, or directly, through the introduction of beneficial organisms to the soil. Because of their sensitivity to disturbance and their importance in redistributing and transforming organic inputs, some of the soil biota groups, such as earthworms and termites, represent an important indicator of soil quality. In this chapter we have highlighted the importance of soil biodiversity, especially its potential use for enhancing soil health in tropical soils of SSA.

1 Introduction

Lack of food is of central concern in Africa and presents a fundamental challenge for human welfare and economic growth. Increased population growth coupled with limited resources in many developing countries has contributed to increased levels of poverty, resulting in land sub-division and environmental and land degradation.[1] The net result is small farms, low production and increasing landlessness.[1,2]

Land degradation and soil infertility or nutrient depletion are therefore considered as major threats to food security and natural conservation in sub-Saharan Africa (SSA). Increasing population pressures and widespread food deficits in SSA have compelled national programmes and international donors to place a high priority on increased agricultural productivity and alleviation of poverty among the small-scale farmers. Despite this, few new technical packages capable of increasing net returns without deteriorating the environment have been developed. As such, the challenge of increasing crop yields to sustain the growing population is persistent.

2 Description of Soils in Sub-Saharan Africa

The soils pattern in the SSA countries is intricate because of large differences in altitude, topography, geology and climate. In particular, they are based on a wide range of parent materials, ranging from sedimentary, metamorphic to volcanic rocks. This has resulted in the formation of different soil profiles with varying texture (which in most cases determines the ability of the soil to hold and release moisture), depth and inherent soil fertility. Most of the tropical soils have serious constraints to crop production; among them, extended periods / seasonal moisture stress, perhaps the overriding constraint in much of African soils (about 14% of Africa is relatively free of moisture stress), salinity, sodicity, acidity, drainage, shallow rooting depth and fertility problems. For agricultural planning, it is therefore essential that the distribution, extent, limitations and potential of these different soil types be appreciated. The general occurrence, characteristics, use and management of the major soils found in Sub- Saharan Africa are summarised in Table 1.

Tables 2 and 3 show the physical and chemical characteristics of the major soil types of Kenya and for some west African countries (Liberia, Nigeria, Ghana, Togo, Burkina Faso, Benin, Niger, Mali and Gambia). The two tables show that most of the soils are dominated by Lixisols, Acrisols, Luvisols, Nitisols, Alisols and Ferralsols. In particular, the Kenyan soils represent the major soil types occurring in east and central Africa region. Table 2 shows soil physical and chemical properties for 45 fertiliser trails in the high and medium potential areas of Kenya for a wide range of major soil types found in the Kenyan highlands. The soils were selected for fertiliser recommendation for different agroecological zones in Kenya. It is noted in Table 2 that even within the same soil group, the soil properties can vary greatly. For instance, soils for Mumias and Chepkumia are both Acrisols, yet the texture, organic carbon and total nitrogen vary greatly in both sites (sandy loam texture, 5 g kg^{-1} organic carbon (OC) and 0.6 g kg^{-1} N for Mumias and clay loam texture, 28 g kg^{-1} OC and 4.5 g kg^{-1} N). Such variations in soil properties do re-emphasise the need for specific fertiliser recommendations rather than blanket recommendations as is mostly the case in Sub-Saharan Africa. Most of these tropical soils have undergone ferrugination and ferralitisation processes, an indication of soils that have undergone intense chemical weathering. As a result, these soils are of low inherent fertility. Coupled with low fertiliser inputs, on-farm nutrient balance is, in most cases, negative. For instance, nutrient balance calculations revealed that annual nutrient depletion in Kisii (Kenya) was 112, 2.5 and 70 kg ha^{-1} for N, P and potassium (K), respectively,[3] whereas in southern Mali the values were 25, 0 and 20 kg ha^{-1} for N, P and K, respectively.[4] In Kisii, removal of nutrients in the harvested product was the strongest contributor to the negative balance, followed by run-off and erosion. Work carried out in Kenya on the effect of erosion on soil fertility supports these findings.[5] Changes in soil pH (regression coefficient, $r = 0.77$), OC ($r = 0.59$) and total nitrogen (TN) ($r = 0.71$) were highly and positively correlated with soil loss, while maize grain yield was highly and negatively correlated with soil loss ($r = -0.91$). In the same study, sediment from the plots was 247% to 936% richer in P than the soil from which it originated. The data indicate that nutrient loss due to erosion is one of the major causes of soil fertility depletion of Sub-Saharan African soils. Soil degradation of arable land, through loss of soil organic matter (SOM) and soil structural stability also results from soil tillage and the removal of plant biomass. In many tropical cropping systems, little or no agricultural residues are returned to the soil as these are either burnt to clear the ground for crop planting, utilised as fuel, or grazed by livestock.[6] The loss of SOM and the associated deterioration of soil physical, chemical and biological fertility associated with continuous cropping and sub-optimal fertiliser use frequently result in a decline in biomass productivity and crop yields and present great challenges to many farmers in Sub-Saharan Africa.[7]

Of great concern are the low levels of phosphorus for the majority of SSA soils. For instance, of the 147 soil samples analysed for P in four irrigation projects in Rwanda, only 10 had adequate levels of P. The soils were predominantly orthic Ferralsols with their integrades, namely, ferralo-orthic Luvisols and Lixisols. Exchangeable acidity was on average >1.0 meq. In a study investigating the relationships between phosphorus sorption index (PSI) and selected soil chemical properties of these soils in Rwanda, it was found that the pH of these soils was variable, ranging from 5.3 to 5.6, *i.e.* moderately to strongly acidic. The PSI for the soils ranged from 25.93 to 295.52 ppm. The wide range on the differences in PSI indicates that blanket phosphate recommendations may not be a good strategy for most of the soils in the Sub-Saharan African countries as it may lead to under or over application of P.

3 Land Degradation in Cropping Systems

The recognised form of land degradation affecting the major soil types in sub-Saharan Africa are erosion, physical and chemical degradation, which includes salinisation, sodification, acidification and the depletion of plant nutrient content in the soil. Biological degradation is also a major contributor, leading to loss of soil organic matter and soil biodiversity. All these forms of degradation lead to a lowering of soil fertility and land productivity.[8] Land degradation is now recognised as being one of the major contributors to the persistent food deficit and high poverty levels in Sub-Saharan Africa. According to Gachene and Kimaru,[9] concerted and well-planned action needs to be taken to build soil fertility and minimise land degradation on small-scale farms. Some of the important action points are developing well-defined and specific activities to enhance plant nutrient levels as a long-term programme through consistent use of both organic and inorganic fertilisers. According to World Bank figures, Africa uses only 14 kg of fertiliser per hectare compared with 1150–200 kg in East Asia and Europe. Use of both organic and inorganic fertilisers have resulted in improved soil physical and chemical properties and increased crop yields for some of the highly weathered tropical soils,[10,11] giving adequate attention to the problem of soil acidity and finding better ways of promoting plant nutrient availability and uptake,[12] developing and adapting suitable rotations using legumes and green manure,[11] promoting agroforestry and farm forestry for better soil fertility, and increased land productivity to answer multiple needs at the farm level and beyond,[10] creating programmes to deal with the issues of tillage and depth of root bed to create sufficient storage

Table 1 Occurrence, characteristics, use and management of major soil types of the tropical region (Source: Palm *et al.*).[136]

Constraints	*Occurrence*	*Characteristics*	*Use and management*	*Soil types**
Soils with salinity problem.	Mainly in arid and semi-arid areas, on flat to very gently undulating topography and in poorly managed irrigation areas; surface and ground water may be the main source of soluble salts when used for irrigation; nature of the parent material can also be the source of soluble salts.	A saline soil profile has a pH below 8.5; white salt crystals are common on the sides of the soil profile or salt crust can be seen on the surface.	Can be reclaimed by leaching excessive soluble salts. Sometimes may be advisable to leave the soils under natural vegetation as it can be very expensive to reclaim them especially where availability of good quality water for irrigation is a limitation. Widely used for growing horticultural crops in small-scale irrigation schemes. However, salt accumulation in most of these schemes has led to their abandonment. This is because such soils require major land improvement and thus become extremely difficult to manage under low–input conditions which characterise African small-scale farmers.	Solonchaks (saline soils) or other soils classified as having a saline phase.

Table 1 (*Continued*)

Constraints	*Occurrence*	*Characteristics*	*Use and management*	*Soil types**
Soils with sodicity problem (note that saline – alkaline soils affect about 24% of the continent).	Mainly in arid and semi-arid areas, on flat to very gently undulating topography, brought about by prolonged or repeated saturation with water in which sodium predominates over the other cations.	The pH ranges from 8.5 to 10.0; soils have a light, coarse-textured topsoil over a compact, heavy-textured subsoil. Easily identified as they are characterised by columnar structure in the subsoil. Sodium dominates in the exchangeable complex, with exchangeable sodium percent (ESP) of more than 15%.	Highly advised to leave the soils under natural vegetation. Gypsum and heavy application of farmyard manure (FYM) are used to reclaim these soils. Soils with high sodium content are very prone to piping and gully erosion due to the poor structure and dispersion of clay when wet.	Solonetz (soils with a high content of exchangeable sodium) or other soils classified as having a sodic phase.
Soils with acidity problem.	Commonly referred to as leached tropical soils. Mainly occur in the highlands and mountainous areas as well as in the uplands with rolling to undulating topography with high precipitation, typical in coffee, tea and pyrethrum growing areas; these soils are exposed to excessive leaching.	Mostly characterised by light brown, red or reddish brown colours. Most of the soils under this category are well drained, deep with high clay content in the subsoils (except those classified as Ferralsols). Have low pH levels, usually <5.5; problem of phosphorus fixation due to high levels of aluminium; problems with soil micronutrients, especially molybdenum (Mo) are also common.	Apparently these are some of the most productive soils of the tropics if well managed. Internal drainage, workability and water-holding capacity are good. Application of lime, inorganic and organic fertilisers is necessary in order to maximise agricultural production, application of acidifying fertilisers to be avoided, with the exception of crops that thrive well under low pH, such as tea. The soils do respond well to liming, fertiliser (especially N and P) and FYM application. Erosion may be a serious problem as they occur in steep slopes, indicating that soil conservation measures must be in place. Mostly the soils are under numerous subsistence crops, tea, coffee, pyrethrum, temperate crops and dairy farming.	Andosols (young volcanic soils), Nitisols (deep, red, well-drained tropical soils with a subsoil horizon showing shiny ped surfaces), Acrisols (strongly weathered acid soils with low base saturation), Lixisols (strongly weathered soils in which clay is washed down from the surface soil to the underlying subsoils), Alisols (strongly acid soils with subsurface accumulation of activity clays that have more than 50% Al^{3+} saturation), Luvisols (soils in which clay is washed down from the surface soil to an accumulation horizon at some depth), Ferralsols (red and yellow tropical soils with a high content of sesquioxides).

Table 1 (*Continued*)

Constraints	*Occurrence*	*Characteristics*	*Use and management*	*Soil types**
Soils with drainage problem	Occur in relatively flat areas such as alluvial plains, depressions, river valleys and valley bottomlands that are subject to waterlogging during wet seasons; they are found in both semi-arid and sub-humid regions; in particular, soils classified as Fluvisols and Gleysols are developed on a wide range of unconsolidated materials, mainly sediments.	These are generally poorly drained soils with very slow vertical drainage; the colour ranges from grey to black; workability is extremely poor; root development is hampered by oxygen deficiency during the wet periods; population of soil microbes is low due to prolonged waterlogging; other soils in this category, such as Vertisols (black cotton soils), have the capacity to expand (swell when wet) and shrink (when dry) thus affecting crop growth.	Main obstacle to the utilisation of these soils is the necessity to install a drainage system. Broad – bed and furrow systems have proved successful in the management of these soils, especially those classified as Planosols; furrows should have very slight slopes to avoid gullying; large areas under Vertisols are used for growing paddy rice, sugar cane, cotton, teff and subsistence crops while grazing is common during the dry seasons; other soils under this category, such as Gleysols occurring along the river valleys are utilised during the dry seasons for growing vegetables and horticultural crops which have a higher market value at such times. Those classified as Histosols occur mainly in wetlands and are therefore best kept under a permanent grass cover or under swamps or forest.	Planosols (vlei soils with light textured topsoil abruptly over dense subsoil), Vertisols (black cotton soils), Gleysols (soils with clear signs of excess wetness), Fluvisols (soils developed in alluvial deposits) and Histosols (peat and muck soils).

Table 1 (*Continued*)

Constraints	*Occurrence*	*Characteristics*	*Use and management*	*Soil types**
Soils with soil fertility problem.	Variable – virtually all soils in sub-Saharan Africa have fertility problem.	Low fertility and insufficient organic matter are the main soil characteristics that adversely affect crop production in the region; most of the soils are highly weathered, having undergone both ferrugination and ferralitisation processes, have low pH and high levels of aluminium toxicity which interfere with nutrient uptake; nitrogen (N) and phosphorus (P) are the most limiting nutrients and so are the low levels of organic matter; low soil fertility results from nutrient depletion – erosion, crop harvest leading to negative nutrient balance, leaching and inadequate crop fertilisation.	Used for extensive grazing and for growing a wide range of subsistence and cash crops, both annual and perennial. Requires heavy application of both organic and inorganic fertilisers including liming, depending on levels of soil pH. Appropriate agronomic practices, soil and water conservation measures are required for soil moisture conservation as well as for minimising water erosion (see Figure 1).	A wide range of soils in the region fall under this category. However, those classified as Ferralsols are naturally chemically poor as most of the primary minerals have weathered, resulting in soils having low cation exchange capacity (CEC) of <16 meq. Thus maintaining the SOM content by manuring, mulching or adequate fallow period and prevention of erosion are important management requirements.

Table 1 (*Continued*)

Constraints	*Occurrence*	*Characteristics*	*Use and management*	*Soil types**
Soils with root restriction layers (note that the term 'effective rooting depth' is used to include chemical barriers which reduce the volume of the soil for root exploitation.	Variable – found in all climatic zones in sub-Saharan Africa.	May be as a result of shallow ground water table (as is the case with soils classified as Gleysols or Histosols) or physical due to the presence of rock or other cemented materials such as plinthite and rock.	Erosion is the greatest threat to these soils. Soil moisture storage capacity may be limiting for most of the crops for soils with rooting depth limitations due to presence of rock at shallow depth. Where rooting depth is as a result of shallow ground water table, the soils can be made productive by putting in drainage measures (see above for soils with drainage problem). Thus, depending on the type of crops to be grown, such soils can be quite productive (see Figure 2).	Gleysols and Fluvisols (if having a shallow ground water table); Leptosols (*shallow soils*), Regosols (*soils in the weathered shell of the earth*), Plinthosols (*soils with plinthite*) and other soils classified as having a lithic or plinthic phase.

*Soils classified according to FAO-UNESCO Soil Classification System. (Source: Palm *et al.*).[136]

Figure 1 Intercropping (left) in an orthic Ferralsol (right). Sometimes poor agronomic practices have led to poor crop growth. Certainly the maize crop in this farm lacks nitrogen. Competition for resources such as nutrients is common under this kind of cropping systems with no fertiliser inputs. (Source: Gachene). 1

capacity for plant nutrients and water, especially for soils with a compacted sub-soil. Further issues of the required energy and the development of new or improved tillage systems and equipment need to be dealt with as crucial

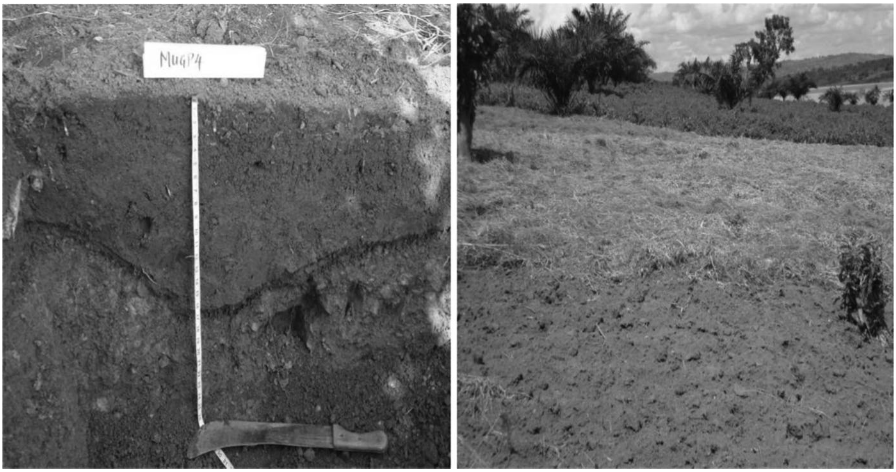

Figure 2 With proper soil and water management practices, a shallow profile like the one on the left can be made productive. This soil, when well mulched, can support a good crop of tomatoes and palm trees as shown in the right photo. The use for which the soil is been assessed is critical in land evaluation. (Source: Gachene). 2

Table 2 Physical and chemical topsoil properties at Fertiliser Use Recommendation Project trial sites in the Kenyan highlands.

Location	*Altitude (m)*	*Soil type*	*Texture class*	*Bulk density* ($g\ cm^{-3}$)	*pH* H_2O	*Org C* ($g\ kg^{-1}$)	*Total N* ($g\ kg^{-1}$)
Otambo	1790	Mollic Nitisol	C	0.89	6.4	29	3.4
Kiamokama	2020	Humic Nitisol	C	0.91	6.2	25	3.3
Kisii NARLS	1730	Mollic Nitisol	C	1.19	6.1	23	2.8
Rodi Kopany	1330	Pellic Vertisol	C	–	6.6	16	1.9
Rongo	1440	Humic Acrisol	LS	1.42	6.3	7	0.9
Oyugi Ober	1450	Chromo – luvic Phaeozem	C	1.25	6.4	18	2.1
Ukwala	1200	Orthic Acrisol	SCL	1.63	5.7	5	0.8
Siaya Obambo	1200	Chromic Luvisol	C	1.32	6.0	14	1.7
Busia Buburi	1220	Ferralo- chromic Acrisol	C	1.26	5.0	11	1.6
Kamakoiwa	1710	Rhodic Ferralsol	SC/C	1.19	5.5	13	1.6
Tongaren	1725	Ferralo- chromic Acrisol	C	1.13	6.4	14	1.0
Mumias	1270	Ferralo- chromic Acrisol	SL	1.61	5.1	5	0.6
Kakamega NARS	1520	Dystromollic Nitisol	C	1.20	5.6	24	2.3
Vihiga Malagoli	1620	Nitohumic Ferralsol	C	1.28	5.3	27	2.8
Baraton	2000	Humic Nitisol	CL	0.95	5.6	36	3.6
Chepkumia	1750	Humic Acrisol	CL	1.15	5.5	28	4.5
Sosiot	1890	Dystromollic Nitisol	C	0.89	5.6	40	5.4
Chebunyo	1840	Vertieutric Planosol	CL	1.12	6.9	43	5.4
Kitale NARS	1860	Humic Ferralsol	SC	1.42	6.2	16	2.0
Eldoret	2140	Ferraric Cambisols	C	–	5.0	13	1.1
Turbo	1850	Ferralo- chromic Acrisol	SC	1.34	5.0	15	1.1
Kapenguria	2140	Humic Cambisol	SC	0.87	7.5	32	3.1
Bugar	2320	Humic Nitisol	C	1.06	5.2	19	1.9

Table 2 (*Continued*)

Location	*Altitude (m)*	*Soil type*	*Texture class*	*Bulk density* $(g\ cm^{-3})$	*pH* H_2O	*Org C* $(g\ kg^{-1})$	*Total N* $(g\ kg^{-1})$
Kasoiyo	1990	Dystric Nitisol	C	1.10	6.1	20	1.7
Eldama Ravine	2100	Nitochromic Luvisol	C	0.90	5.6	25	1.9
Ol Ngarua	1970	Nitoferric Luvisol	C	1.18	6.0	23	2.6
Upepo farm	2180	Chromic Luvisol	C	1.11	5.7	22	2.4
Rotian	2180	Luvic Phaeozem	CL	1.12	5.7	25	2.3
Ol Joro Orok Charagita	2780	Nitochromic Luvisol	CL	0.98	6.2	34	4.3
Ol Joro Orok ARS	2360	Andoluvic Phaeozem	C	1.14	6.3	27	3.0
Tulaga	2530	Eutric Planosol	CL	1.12	6.0	21	1.5
Njabini	2530	Andoluvic Phaeozem	CL	1.01	6.3	32	4.6
Githunguri	1930	Humic Nitisol	C	0.85	5.9	19	3.3
Kandara	1640	Humic Nitisol	C	1.08	5.3	23	1.9
Makuyu	1430	Dystric Nitisol	C	1.07	5.3	15	1.2
Muirungi	2080	Andohumic Nitisol	CL	0.85	5.7	42	4.7
Chehe	1920	Andohumic Nitisol	CL	0.71	4.9	27	3.3
Kerugoya	1480	Humic Nitisol	C	1.20	5.6	29	3.4
Kavutiri	1700	Andohumic Nitisol	C	0.77	4.7	36	3.9
Gachoka	1200	Rhodic Ferralsol	C	1.07	5.7	17	1.4
Embu ARS	1510	Humic Nitisol	C	0.99	5.8	21	2.4
Kaguru	1460	Humic Nitisol	C	0.91	5.0	11	1.6
Kilome Upepo	1680	Rhodic Ferralsol	SCL	1.13	6.9	14	1.4
Makutano	1310	Orthic Acrisol	LS	1.51	6.1	6	0.6
Weruga	1690	Chromic Acrisol	SC	1.22	5.6	14	1.7

Table 3 Some chemical characteristics of selected sites in West Africa. (Source: Sy).[81]

Site	*Soil classification*	*Organic matter (%)*	*Soil pH (H_2O)*	*CEC (cmol kg^{-1})*	*Available P (bray 1) (mg kg^{-1})*
Fendal (Liberia)	Plinthic Acrisol	1.5	5.0	1.0	6
Owem (Nigeria)	Acrisol	2.2	4.8	5.2	6
Kwadaso (Ghana)	Acrisol	1.3	4.9	3.5	2.2
Samaru (Nigeria)	Lixisol	1.0	5.8	4.3	3.5
Davie (Togo)	Nitisol	0.8	6.0	2.8	1.4
Kaboli (Togo)	Lixisol	1.1	5.9	2.4	1.2
Farakoba (Burkina Faso)	Lixisol	1.0	5.4	0.8	2.7
Agonkamey (Benin)	Alfisol	0.6	6.6	2.3	2.0
Yundum (Gambia)	Lixic Ferralsol	1.1	5.5	8.1	15.2
Saria (Burkina Faso)	Arenosol	0.6	5.3	1.8	2.5
Gaya (Niger)	Arenosol	0.7	6.3	1.7	2.3
Sadore (Niger)	Aridic Arenosol	0.3	5.0	1.0	2.8
Sotuba (Mali)	Lixisol	0.5	5.4	2.3	1.7

elements in the process. Such improved methods of tillage should lessen the problem of hardpans and plough soles. This will greatly enhance soil water uptake for plant growth,[13] developing efficient systems of irrigation that increase production without degrading the soil,[14] and adopting soil conservation measures that are simple, effective and affordable.[15] Thus, understanding the soil is the key to its improvement as there are many physical, chemical and biological properties of the various soil types that affect plant growth.

4 Soil Biology: Role of Soil Biodiversity and Functions (Ecosystem Services)

Soil biota are an essential component of soil health and constitute a major fraction of global terrestrial biodiversity.[16] Within the context of Integrated Soil Fertility Management (ISFM), soil biota are responsible for the key ecosystem functions of decomposition and nutrient cycling, soil organic matter synthesis and mineralisation, soil structural modification and aggregate stabilisation, nitrogen fixation, nutrient acquisition, regulation of atmospheric composition, the production of plant growth substances and the biological control of soil-borne pests and diseases.[17] Understanding biological processes is not as well advanced as those that are related to soil physical and chemical properties, creating opportunities for breakthroughs in biotic function to better service agriculture. These services accrue through two basic approaches; indirectly, as a result of promoting beneficial soil biological processes and ecosystem services through land management, or directly through the introduction of beneficial organisms to the soil.[18] Soil macrofauna, especially earthworms and termites, are important components of the soil ecosystem and as ecosystem engineers they influence formation and maintenance of the soil structure and regulate soil processes. Earthworms and termites have different feeding strategies which, in turn, affect their impact on soil. Because of their sensitivity to disturbance and their importance in redistributing and transforming organic inputs, earthworms and termites represent an important indicator of soil quality.

Soil invertebrates are important determinants of biological, chemical and physical characteristics. They enhance biodegradation and humification of organic residues in several ways: (1) by breaking down organic residues and increasing surface area for microbial activity; (2) by producing enzymes which break down complex bio-molecules into simple compounds to form humus; and (3) by improving the soil environment for microbial growth and soil-plant interactions.[19–21]

The diversity and abundance of the structures produced by soil ecosystem engineers *e.g.* earthworms and termites impact on the physical properties of soils, *i.e.* overall aggregation, porosity, water infiltration and retention and resistance to erosion.[22] Earthworms play an important role in the formation of soil organic matter (SOM) enriched macroaggregates,[23–26] which can physically protect occluded organic matter against microbial decay and, upon disintegration, release occluded carbon and nutrients.[23,27] Apart from promoting soil physical and chemical properties, earthworms also promote nodulation,[28] dispersal of mycorrhizal fungi,[29] and even disease suppression and dispersal.[30] Termites mediate the synthesis and breakdown of soil organic matter and influence water infiltration and availability to plants by modifying soil structure.[31–35] They influence soil physical properties through the construction of mounds, nests, galleries and surface sheeting[31,34,36] and also by transporting materials, thereby producing passages which improve drainage and aeration.[37–39] Mound-building termites form stable microaggregates that physically protect occluded organic matter against rapid decomposition and reduce soil erosion and crust formation.[40,41]

The importance of termites in the decomposition of plant matter in natural ecosystems is well documented;[42–45] it has been established that in the tropical rainforests of Nigeria termites play a significant role in both decomposition and litter removal. Mando and Brussard[42] found that termites alone could account for up to 80% of litter disappearance in one year. Termites play a significant role in soil nutrient availability and cycling through interactions with other soil organisms, *e.g.* bacteria and fungi, to most of which they provide food.[40] Soil from termite mounds is sometimes used as fertiliser in tropical cropping systems because of a high accumulation of nutrients.[46,47] Despite the potentially beneficial role of termites, termite pest problems have been identified as a major constraint to increasing yields of crops in sub-Saharan Africa.[48,49] The challenge therefore remains to better understand the interactions between agricultural management practices and soil fauna (*e.g.* termites) in order to find ways to enhance soil fertility and crop yields.

Soil microorganisms are a source of important medicine, including most of the early antibiotics such as penicillin. But despite their functional importance, the soil biota remains a "black box" to scientific understanding as well as to the common gaze due to a number of challenges which include lack of appropriate methods to study these myriad of organisms and their complex ecosystem. The role they play in determining some crucial ecological functions has resulted in a shift in the way scientists view them and there is a major attempt to amass knowledge so as to exploit them for development of sustainable utilisation and management of soil resource. It is against this background that the Global Environment Facility-United Nations Environment Programme (GEF-UNEP)-funded global project on the conservation and management of below-ground biodiversity (CSM-BGBD) was conceived.

5 Case Studies: Effect of Management and/or Land Use Intensification

5.1 Soil Carbon as Fuel for Soil Organisms

Maintenance of soil organic matter (SOM) through integrated soil fertility management is important for soil quality and agricultural productivity, and for the persistence of soil faunal diversity, abundance and biomass. In turn, soil macrofauna affect SOM dynamics through organic matter incorporation, decomposition and the formation of stable aggregates that protect organic matter against rapid decomposition.

Integrated soil fertility management (ISFM), widely advocated in sub-Saharan Africa, recognises the benefits of combining organic and inorganic fertilisers for sustainable nutrient management.[51,52,56] The beneficial effect of soil organic matter (SOM) on soil productivity through supplying plant nutrients, enhancing cation exchange capacity, improving soil aggregation and soil and water retention, is well established.[53–55] In addition, SOM supports various soil biological processes by being a substrate (source of carbon) for decomposer organisms and ecosystem engineers, such as earthworms and termites that play an important role in soil structure formation, organic matter decomposition and nutrient mineralisation.[53,54] Ayuke *et al.*[56] showed that arable cropping has significant negative effects on earthworm, but little effect on termite diversity as compared to long-term fallow. Under continuous crop production, higher earthworm and termite diversity was observed under agricultural management that had resulted in high-C *versus* low-C soils.

To reiterate the benefits of ISFM as promoter of soil biodiversity, Ayuke *et al.*[57] demonstrated that long-term application of manure in combination with fertiliser result in higher earthworm taxonomic richness and biomass (see Table 4), which leads to improved soil aggregation and enhanced C and N stabilisation within this more stable soil structure.[57] It is possible that the long-

Table 4 Earthworm and termite taxonomic richness, mean count (number) and biomass (in parentheses) per monoliths (0.0625 m^{-2}) of the 0–30 cm soil layer of a Humic Nitisol under different residue, manure and mineral fertiliser management at the Kabete field trial, Kenya.

Treatment		*C-F*	*C+F*	*R-F*	*R+F*	*FYM-F*	*FYM+F*	*NF*
Organic fertilizer (OF)		None	None	Residue	Residue	Manure	Manure	na
Mineral fertilizer (MF)		?	+	?	+	?	+	na
Taxonomic group	**Functional group**[a]							
Earthworm Ocnerodrilidae								
Nematogenia lacuum	Endogeic	17 (0.3)	13 (0.2)	5 (0.1)	5 (0.1)	7 (0.1)	23 (0.5)	14 (0.2)
Gordiodrilus wemanus	Endogeic	?	?	?	?	?	?	1 (0.01)
Acanthodrilidae								
Dichogaster (Dt.) affinis	Epigeic	?	?	?	?	?	1 (0.05)	1 (0.02)
Dichogaster (Dt.) bolaui	Epigeic	?	?	?	?	?	1 (0.04)	3 (0.1)
Eudrilidae								
Polytoreutus annulatus	Epigeic	?	?	?	?	?	?	4 (0.2)
Stuhlmannia spec nov	Epigeic	?	?	?	?	?	?	1 (0.01)
Species richness (S)		1	1	1	1	1	3	6
Termites Termitidae-Macrotermitinae								
Microtermes spp.	G II (FWLG)	1 (0.1)	10 (0.01)	3 (0.0)	?	?	24 (0.1)	3 (0.0)
Odontotermes spp.	G II (FWLG)	4 (0.0)	6 (0.01)	18 (0.1)	?	9 (0.0)	25 (0.4)	60 (0.0)
Pseudacanthotermes spp.	G II (FLSD)	11 (0.0)	?	?	7 (0.0)	?	?	?
Genus richness (S)		3	2	2	1	1	2	2

C−F = control minus fertiliser, C+F = control plus fertiliser, R−F = residue minus fertiliser, R+F = residue plus fertiliser, FYM−F = farm yard manure minus fertiliser, FYM+F = farm yard manure plus fertiliser, NF = natural fallow, n.a. = not applicable (Source: Ayuke *et al.*).[56]

term application of combined farmyard manure and fertilizer (FYM +F) resulted in increased soil C concentration, providing food sources for earthworms and mulching effect on their habitat and also stimulating plant growth and litter return,[58] resulting in higher earthworm biomass.

5.2 Soil Macrofauna in Tropical Agroecosystems

In large parts of sub-Saharan Africa (SSA), pests, weeds, diseases and soil fertility decline are major biophysical causes of low *per capita* food production.[59] Degradation processes, such as loss of soil carbon and nutrient depletion in general, can occur quickly and are difficult to reverse.[60] Moreover, loss in yield cannot be corrected by the use of fertilisers in economies where cash flow is minimal. Under such circumstances, Integrated Soil Fertility Management (ISFM), *i.e.* integration of fertilisers with organic resources, has been regarded as a feasible alternative in low-input systems, compensating for the high costs of fertilisers.[52] Manipulation of the soil environment *via* tillage, application of organic residues and manipulating soil fauna are among the factors affecting SOM dynamics under cropping systems.[61,62] In low-input agricultural systems, soil fauna has been found to play a crucial role in soil organic matter dynamics, in soil physical properties improvement, and in nutrient release for crop production.[63] However, soil macrofauna composition, abundance and activity, and hence their impacts on soil processes, vary depending on residue inputs and soil management practices.[25,64,65] Climate, soil texture and management have been indicated to influence the activity of soil macrofauna (*e.g.* earthworms and termites) that produce biogenic structures.[66] It can therefore be postulated that differential land-management effects on soil fauna functional groups can translate into differential effects on the structures they produce, thus affecting soil organic matter, soil aggregation, porosity and water and nutrient availability to plants.

Figure 3 shows a hierarchical model of inter-correlated factors that determine soil biodiversity and processes. Management practices (*e.g.* crop rotation, tillage, organic resource use and application of agrochemicals such as pesticides, herbicides and inorganic fertilisers) can cause positive or negative changes in species composition, community structure and population sizes. Some of the negative effects of management practices may be long-lasting and result in a decline in the abundance and/or biomass of soil macrofauna populations, or eliminate or reduce key species, *i.e.* species that play a disproportionate role in ecosystem processes.[67,68] The use of organic inputs and crop diversification through rotation favours macrofauna diversity due to improvement in the abiotic conditions and increased substrate supply.[58,69–71] Agroforestry technologies, such as alley cropping, natural fallows (bush fallows), planted fallows and biomass transfer systems can restore activities of organisms such as earthworms, termites, ants and other microarthropods.[72–74] Ayuke *et al.*[69,72] found that organic residues from *Senna spectabilis* and *Tithonia diversifolia* increased the population of earthworms by 400% and

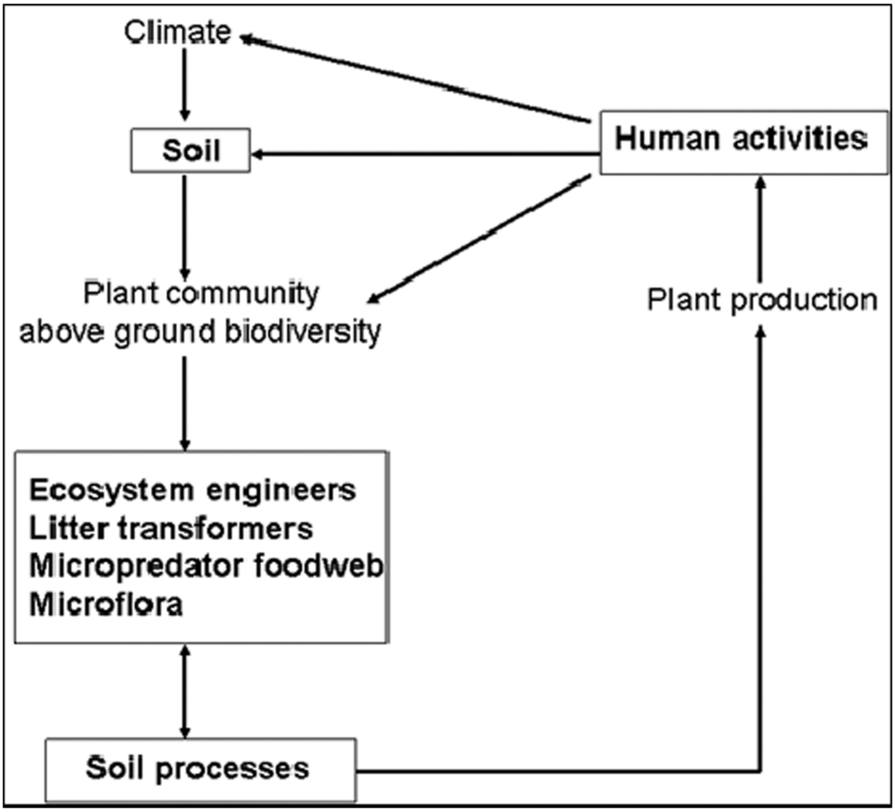

Figure 3 A hierarchical model of factors that determine soil biodiversity and soil processes.[161]

240% over a no-input control, respectively, while termites increased by 150% and 120% when the two different organic residues were added to the soil (see Table 5). Tian *et al.*[71] similarly found higher earthworm and microarthropod populations under planted fallows than under continuous cropping systems

Table 5 The abundance of soil macrofauna under different treatments in soil at Maseno, Western Kenya.

Treatment	*Earthworms*	*Termites* ----- *Number (m^{-2})* -----	*Other macrofauna*
Control	99 (9.5) c	229 (14.0) b	43 (6.3) d
Fertiliser	132 (11.0) c	348 (16.0) b	90 (9.4) c
S. spectabilis	572 (22.5) a	737 (25.4) a	391 (15.5) b
T. diversifolia	339 (18.5) b	652 (21.4) ab	309 (14.0) b
SED	(1.0)	(6.3)	(1.1)

Means followed by the same letter in a column are not significantly different at $p < 0.05$. Values in parenthesis are square root transformed. SED = Standard error of difference of means. (Source: Ayuke).[72]

and attributed this to higher litter fall, lower temperature and higher soil moisture.

5.3 Mesofauna

Mesofauna includes organisms less than 4 mm long (or 2 mm wide). They mostly live in the litter or soil cracks and pores. Examples are the microarthropods, mites, springtails, enchytraeidae, *etc.*

The structure, organisation and behaviour of individuals within soil fauna communities dynamically respond to seasonal and diurnal changes in environmental conditions. In addition, the distribution of individuals in space is heterogenous within a given habitat. Variation in environmental conditions, biotic interactions and colonisation history result in uneven distribution of soil fauna in space. As such, management practices that alter the environmental conditions are likely to have greater impact on the diversity of mesofauna groups as well.[74]

In a maize-based system of western Kenya, faunal composition and abundance within the agroecosystem were dominated by macrofauna groups (90.2%), while mesofauna groups constituted only 9.8%.[72] Maribe *et al.*[75] monitored the abundance and diversity of mesofauna groups such as mites along a gradient of land-use types in Taita Taveta, Kenya. They found that land-use types significantly influenced the abundance and diversity such that intensification lowered the diversity and abundance, resulting in a less complex mite community structure (see Table 6). Higher abundance, richness and diversity were observed in less disturbed forest ecosystems unlike the agroecosystems, which are often disturbed during cultivation.[76]

In another study, Birgit *et al.*[76] found that application of organic amendments such as cow manure encouraged proliferation of collembolan

Table 6 Mean abundance, richness and diversity of soil mites at Taita Taveta during long rains in April 2008.

Land use types	*Mean abundance*	*Mean richness*	*Shannon-Wiener index*
Maize-based	72.3 ±24.7d	6.5 ±1.9c	1.3 ±0.3bc
Coffee	120.5 ±25.7d	10.8 ±1.1bc	1.8 ±0.1ab
Horticulture	132.3 ±22.7d	6.0 ±1.1c	1.1 ±0.3c
Napier	147.7 ±70.1cd	8.7 ±2.3bc	1.1 ±0.3c
Natural forest	244.0 ±63.3bcd	12.3 ±0.9ab	2.1 ±0.1a
Fallow	413.8 ±79.4abc	12.0 ±2.9ab	1.1 ±0.2c
Pine forest	436.2 ±181.7a	15.8 ±1.6a	2.0 ±0.2a
Cypress forest	607.0 ±118.8a	16.8 ±1.1a	2.2 ±0.2a
F test	*F7,23=4.51; P = 0.003*	*F7,23=5.50; P <0.001*	*F7,23=5.57; P <0.001*

Means followed by the same letters within a column are not significantly different at $p < 0.05$ (Fisher test). (Source: Maribe *et al.*).[75]

population, whereas inorganic fertilisers negatively impacted on these organisms.[77]

5.4 Beneficial Microorganisms: Soil Fertility Promoters, Plant Growth Regulators and Biocontrols

Soil ecosystems are among the most complex of all terrestrial communities, and the role of the soil biota in maintaining plant health is progressively being understood. The composition of the soil biota is strongly influenced not only by the nature of the underlying organic matter and mineral components, but also by environmental variables such as temperature, pH and moisture. Natural soils have been shown to harbour large populations of microorganisms which exist in a state of dynamic equilibrium and controlled changing balances. These microorganisms primarily compete with each other for nutrition and space. A majority of the microbes are classified as fungi and bacteria which play beneficial and often vital roles in natural environments and agriculture. Numerous benefits are accrued from these microbes including (1) direct symbiotic association with roots (mycorrhizae, legume nodulating bacteria); (2) nutrient cycling which involves breakdown and release of minerals from organic matter present in the soil, resulting in increases in essential element availability to higher plants; and (3) biocontrol agents, through predation of disease-causing microorganisms and/or suppressing growth, or reproduction activity of harmful disease-causing microorganisms through other interactions such as chemical inhibition. Details of selected microbes with economic potential which have been well investigated in African soils are discussed in the sections below.

5.4.1 Legume Nodulating Rhizobia (LNB)

Biological nitrogen fixation is the ability of living organisms to convert inert dinitrogen gas in the atmosphere (N_2) into nitrogen-containing organic compounds through asymbiotic, associative or symbiotic processes. Microbially mediated nitrogen fixation accounts for 175 million tonnes per yr in terrestrial and aquatic environments.[78] This provides two thirds of the nitrogen required in the biosphere, most of which comes from the contribution of the association between modulating rhizobia bacteria with compatible host legumes.

The organisms that possess the nitrogenase enzyme have attracted considerable interest. These prokaryotes in the Eubacteria and Archaebacteria kingdoms which can fix nitrogen are metabolically diverse and the different bacterial N-fixing systems have been reviewed.[78] For almost 100 years the term *Rhizobium* was used to represent those organisms capable of forming nodules with specific homologous host legumes. Recently, phylogenetic analysis which uses 16S rRNA has become the standard for classification of bacteria. This new classification, which is dependent on the phenotypic traits, has confirmed a number of taxonomic divisions which include Azorhizobium, Bradyrhizobium, Mesorhizobium and Rhizobium.[79,80] The technique has been used in numerous studies of African soils which have revealed rhizobia diversity of the LNB in African soils . For instance, identification of the genus *Methylobacterium* in Senegal by Sy[81] and Samba *et al.* [82] reported a total of 117 strains of both slow- and fast-growing rhizobia from roots of Crotolaria species in Senegal. Similarly, Odee *et al.*[83] identified five bacteria genera, namely *Agrobacterium, Bradyrhizobium, Mezorhizibium, Rhizobium and Sinorhizobium,* for root nodules of legumes growing in diverse soils in Kenya, while Anyango *et al.*[84] found that beans grown in acid soils in Kenya were nodulated by different rhizobia species. In a recent study which assessed the abundance of LNB in soils of the Embu and Taita Districts in Kenya, Mwenda *et al.*[85] and Mwangi *et al.*[86] obtained similar rhizobia diversity to Odee *et al.*[83] and their diversities were positively influenced in cropping systems.

Legume inoculation is a process through which leguminous crops are provided with the effective bacterial strain of the genus *Rhizobium* which results in an effective symbiotic relationship that brings about fixation of atmospheric nitrogen into organic nitrogenous compounds in the plant. However, response to rhizobia inoculation is influenced by a number of factors which include soil nitrogen, rhizobia strain and populations of indigenous populations, crop and environmental conditions.[87] Despite these challenges, inoculant production has going on for several decades by both private and public institutions in Africa to harness benefits of the Legume-Rhizobium technology and about 100 000 tonnes of rhizobia inoculants are produced in Kenya, South Africa, Zambia and Zimbawe for inoculating food legumes such as soya bean, beans and also for fodder crops.[87]

5.4.2 Arbuscular Mycorrhizal Fungi (AMF)

Arbuscular mycorrhizal fungi (AMF) are common root-colonising fungi forming symbioses with most plants. The AMF are globally widespread and are associated with most plant species.[88,89] These fungi have been reported from diverse natural ecosystems including deserts, sand dunes, tropical forests, salt marshes, and in managed systems such as pastures, orchards and field crops.[90] In agricultural systems, edaphic factors, land use, cropping systems and management practices interact to influence AMF species composition and spore population. Consequently, changes in agricultural practices will inevitably lead to a change in the overall abundance of propagules of each fungus within a population.[90] Studies carried out on the distribution of AMF in legume-based systems in Nigeria showed prolific arbuscular mycorrhizal colonisation in the roots.[91] Shepherd *et al.*,[92] on the other hand, found forest and grassland soils to have narrower species distribution than most farm soils, indicating some degree of ecosystem adaption. In a survey carried out in the Mount Kenya region, across different land-use types (LUTs), a total of 16 AMF species were isolated.[93] The spore community was dominated by Acaulosporaceae and Glomaceae. Land-use type had no significant effect on

AMF spore abundance or root colonisation. Trends, however, showed soils under napier (*Pennisetum purpureum* Schumach) and tea (*Camellia sinensis* L.) had the highest AMF spore abundance while natural forest and planted forest had the least spore abundance (see Figure 4). The reverse was observed for root colonisation where the highest colonisation was in soils under natural and planted forest, except tea which maintained both high spore abundance and slightly high colonisation.

Infection of crop roots with AM fungi can improve the uptake of nutrients, particularly phosphorus, and increase crop production.[94] These endomycorrhizal fungi are obligate symbiotic fungi, the hyphae of which develop mycelia, arbuscules, and in most fungal genera vesicles in roots. Soil hyphal networks produced by these symbiotic fungi provide a greater absorptive surface area than plant root hairs. As such, mycorrhizal symbiosis assists crops in recovering scarce reserves of soil phosphorus. In addition, mycorrhizal-infected plants have been shown to have greater tolerance to toxic metals, root pathogens, drought, high temperatures, saline soils, adverse soil pH and transplant shock than non-mycorrhizal plants.[95] Mycorrhizal association has been recognised for cassava production, given that it is usually grown in infertile soils, without fertiliser application.[96] Inoculation of orange-fleshed sweet potato varieties with mycorrhizal fungi and phosphate-solubilising bacteria (PSB) in the low-phosphorus soils increased phosphorus concentration in the soil and root yield. Arbuscular mycorrhizal fungi therefore constitute one of the strategic interventions for ISFM. Two basic strategies to manage mycorrhizal fungi are available through optimising crop and

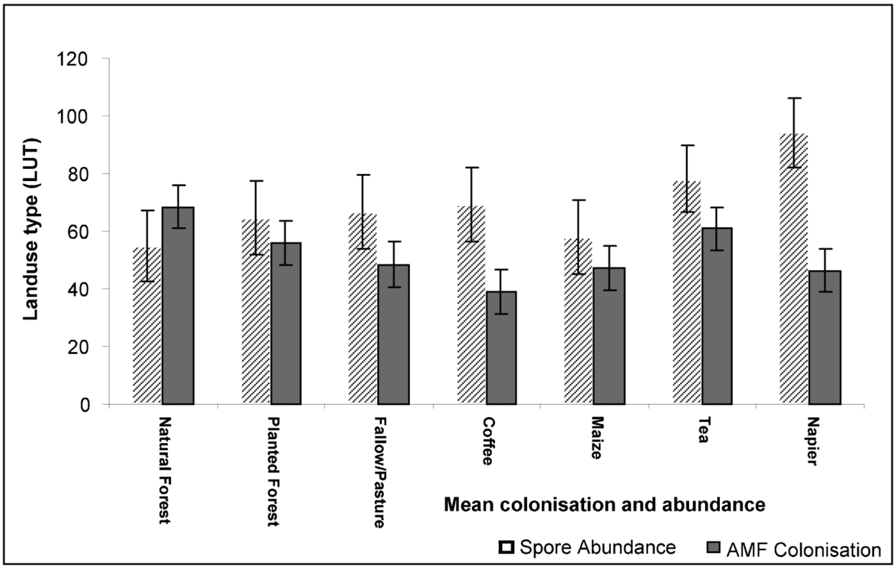

Figure 4 Impact of land use type (LUT) in order of less-to-high intensity on spore abundance and colonization. (Source: Jefwa *et al.*).[93]

management practices that affect the abundance of indigenous mycorrhizae, or through the use of mycorrhizal inoculants.[90] While it has become widely accepted that mycorrhizal symbiosis, in combination with legumes, can be harnessed to improve crop productivity, maximise root functions, and also reduce fertiliser use, there is still need to establish the distribution and functions of AMF species in different habitats and different land-use systems in order to facilitate inoculation programs. With improved methods and technologies in utilisation, approaches to studying AMF should be streamlined in order to derive maximum benefits from the association.

Although ectomycorrhizae have not been given much attention in agroecosystems, they are equally crucial in afforestation programmes.[97] Through hyphae, nutrients and water can be absorbed by trees. Ectomycorrhizae are mostly found in woody plants, ranging from shrubs to forest, and many belong to the families: Pinaceae, Fagaceae, Butulaceae, Casuarinaceae and Myrtaceae. Most of the above host plants are specific, such that if mycorrhizae are absent growth is highly reduced.[97] Over 4000 species of Basidiomycotina and a few Ascomycotina form ectomycorrhizae. Many of these fungi produce mushrooms and puffballs on forest floor.

5.4.3 Plant Growth Promoting Rhizobacteria (PGPR)

Beneficial free-living soil bacteria are referred to as plant growth promoting rhizobacteria or PGPR and they stimulate plant growth either directly or indirectly through secretion of phytohormones that enhance plant growth or uptake of solubilised iron from the soil.[98] Solubilisation of nutrients such as phosphorous through production of organic acids releases insoluble phosphorus into more soluble forms.[99,100] Paterno[101] concluded from his study that *Azotobacter vinelandii* and *Bacillus cereus* produced high amounts of indole acetic acid (IAA). Karawal[102] reported that the 30 isolates of *Pseudomonas fluorescens* he tested were indole-positive, indicating production of IAA. However, the *Pseudomonas fluorescens* showed higher IAA production when tryptophan concentrations were increased. Gachie (unpublished,University of Nairobi, 2012), in her screening experiment of rhizobacteria (40 isolates of *Bacillus* spp, 36 isolates of *Azotobacter* spp and 53 isolates of *Pseudomonas* spp), all from soils collected from potato-producing districts in Kenya, identified rhizobacteria isolates with plant growth promoting, phosphorus solubilisation potential, while other isolates controlled the *Ralstonia solanacearum* potato pathogen which is widespread in Kenyan soils and is a major constraint to growth of the potato industry.

5.4.4 Trichoderma

Trichoderma species are cosmopolitan fungi found in decaying wood and vegetable matter. Their dominance in soil may be attributed to their diverse metabolic capability and aggressive competitive nature.[103] They colonise roots, attack, parasitise and gain nutrition from other fungi, thus enhancing root growth. They have developed rhizosphere competence through numerous mechanisms for attacking other fungi and for enhancing plant and root growth. These properties include mycoparasitism, antibiosis, competition for nutrients or space, tolerance to stress through enhanced root and plant development, solubilisation and sequestration of organic nutrients, induced resistance, and inactivation of enzymes.[104–106] A study conducted in two benchmark sites of Embu and Taita in Kenya yielded a total of 299 and 309 *Trichoderma* isolates, respectively,[107] and the most frequently isolated and abundant species from both sites was *T. harzianum.*

Trichoderma fungus has a high potential for the biological control of fungal root pathogens that can improve plant growth in infested soils.[105] Plants not infected with root pathogens often demonstrate a positive growth response after being treated with *Trichoderma* as well, suggesting production of a growth stimulant. A study by Okoth *et al.*[108] showed that *Trichoderma* inoculation significantly increased the rate of maize seed germination, further corroborating its potential as a growth stimulant. Recently, this fungus was commercialised as a soil inoculant and seed treatment of agricultural crops, with numerous commercial products being registered around the world.[105] *Trichoderma* species have been investigated for over 70 years.[104] They have been used as biological control agents (BCAs) and their isolates recently have become commercially available.[105] This development is largely the result of a change in public attitude towards the use of chemical pesticides and fungicides such as methyl bromide.[109,110] In this respect *Trichoderma* species have been studied as BCAs against soil-borne plant pathogenic fungi.[111,112] Replacement or reduction of chemical application can be achieved through use of biologically based fungicides, a concept included in the broad definition of biological control proposed by Cook and Baker.[113] Species in the genus *Trichoderma* are important as a commercial source of several enzymes and as biofungicides/growth promoters. The most common biological control agents of the genus are strains of *T. harzianum*, *T. viride* and *T. virens.* In a study in which sixteen selected isolates of *T. harzianum* from different land use types in Embu, Kenya, were tested for antagonism against five soil-borne phytopathogenic fungi (*Rhizoctonia solani*, *Pythium sp, Fusarium graminearum, F. oxysporum f. sp phaseoli* and *F. oxysporum f. sp lycopersici*) results showed that all *T. harzianum* isolates had considerable antagonistic effect on mycelial growth of the pathogens in dual cultures compared to the controls.[114] Since all *T. harzianum* isolates evaluated were effective in controlling colony growth of the soil borne pathogens, both in dual cultures and in culture filtrates, they offer good prospect as broad spectrum biological control agents in the greenhouse and under field conditions.

5.4.5 *Bacillus subtilis*

Several strategies, including chemical nematicides, organic soil amendments, crop rotation, cover crops, resistant cultivars and biological control, have been developed for the management of plant parasitic nematodes.[115] Evidence has been provided that integrating biological control, using microbial antagonists with other possible methods, is amongst the most pragmatic strategies for managing nematodes. Biological control agents that have been assessed include egg-parasitic fungi, nematode-trapping fungi, bacteria and polyphagous predatory nematodes. Plant-growth-promoting rhizobacteria, especially the genera *Pseudomonas* and *Bacillus*, have demonstrated potential for disease suppression without negative effects on the user, consumer, or the environment. Some strains of *Bacillus subtilis* have exhibited potential as biocontrol agents in the management of root-knot nematodes.[116] In a study conducted at Kakamega County, Western Kenya, it was observed that *Bacillus subtilis* strains K158, 194 and 263 reduced the population of *Meloidogyne sp* in the following order: K158 >K263 >K194 (see Figure 5). Dual inoculants (*B. subtilis* & *Rhizobium*, *Leguminosarium biovar phaseoli*) also reduced the population of *Meloidogyne sp.*, with the Rhizobium acting as a plant-growth regulator.

Wepukhulu *et al.*[117] found that application of *Bacillus* alone as well as with manure effectively suppressed the population of *Meloidogyne* spp. by 64% and 60%, respectively.

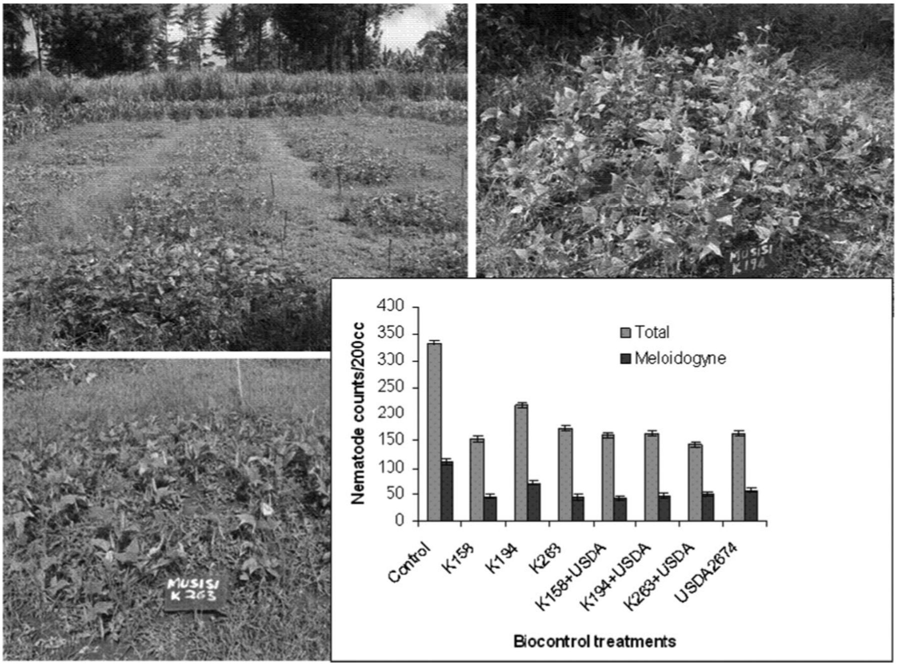

Figure 5 Biocontrol and effect on nematode infection on beans (*Phaseolus vulgaris var.*). (Source: Ayuke, unpublished).

5.4.6 Nematode-destroying Fungi

Nematode-destroying fungi are a group of microfungi that are natural enemies of plant parasitic nematodes.[76,118] They comprise fungi which parasitise nematode eggs and other life stages.[123] Although taxonomically diverse, this group of microorganisms is capable of destroying, by predation or parasitism, microscopic animals such as nematodes, rotifers and protozoans. Collectively, they have the unique ability to capture and infect nematodes in the soil and appear to be widespread in distribution.[76] The actual mechanisms by which the fungi are attracted to the nematodes have not been fully understood. However, it is generally accepted that the nematode cuticle is penetrated then the nematode is immobilised through infection bulbs, and finally digested by the trophic hyphae produced by the fungus.[120] In some cases, nematode-destroying fungi produce toxins that immobilise or kill nematodes.[121] The group also includes endoparasitic species in such genera as *Harposporium* (see Figure 6), *Nematoctonus*, *Meria* among others, which spend their entire vegetative lives within infected nematodes.[122]

Nematode-destroying fungi have drawn much attention due to their potential as biological control agents of parasitic nematodes of plants and animals.[123,124] Unfortunately, there exist multi-dimensional drawbacks to the realisation of the full potential of the nematode-destroying fungi in the management of parasitic nematodes, especially the phytoparasitic. Lack of reliable methods to visualise the fungi and demonstrate their activity in their natural habitats is a major impediment. Above all, the gaps in knowledge of the ecological factors that influence the occurrence and abundance of nematode-destroying fungi are largely unclear. Due to these factors, this group of fungi has escaped the attention of many scientists, especially in Africa.

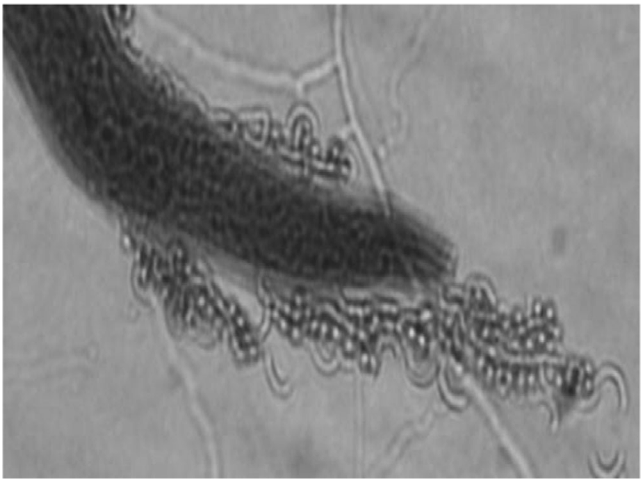

Figure 6 An example of endo-parasitic nematode-destroying fungi; *Harposporium anguillulae* with the conidiophores and conidia appearing outside the dead nematode. (Source: Wachira).

3

A study on the effect of land use and organic amendments on the occurrence and diversity of nematode-destroying fungi was conducted in Kenya.[153] From the study, it was evident that all the sampled land uses differed in terms of occurrence of nematode-destroying fungi, consistent with previous reports indicating that nematode-destroying fungi were present in all habitats but at different densities and diversities (see Table 7).

Arthrobotrys oligospora was the most abundant species of nematode-destroying fungi in the study area, and this was attributed to the application of inorganic and organic inputs by farmers. Jaffee[119] showed that organic amendments enhanced the build-up of resident nematode-trapping fungi in the soil. Higher soil organic matter content protects plants against nematodes by increasing soil water-holding capacity and enhancing the activity of naturally occurring biological organisms that compete with nematodes in the soil.[126] Apart from the presence of organic matter, the fungi also obtain their carbon and energy from two sources: from organic matter (saprophyte) and from trapping nematodes (parasite), making them adaptable to a wide range of habitats. It is possible that members of the genus were the best adapted to the biotic and abiotic conditions prevailing in the study area. This fungus should be recommended for further study with the aim of developing it as a biological control agent. Such a study should be geared towards growth parameters of the fungus, since biological, chemical and physical factors of the soil are known to inhibit fungal growth by fungistatic compounds and is made even more complicated by crop rotations. The ability of this fungus as a biological control agent could be improved through genetic engineering and then packaged for biological control purposes. Apart from introduction of particular species from the genus, agricultural practices that stimulate build-up of the fungi could be identified and recommended for adoption by farmers. The study also revealed that increased land-use intensity resulted in increased occurrence and diversity of nematode-destroying fungi. This, however, was contrary to the expectation that beneficial microorganisms decrease with increased intensity of land use.[125] A number of explanations were used to account for the higher frequency of occurrence of nematode-destroying fungi

Table 7 Effect of land use on frequency of isolation, richness and diversity of nematode-destroying fungi in Taita Taveta district, Kenya. (Source: Wachira *et al.*).[153]

Land use	*Frequency of isolation %*	*Mean evenness*	*Mean richness*	*Mean Shannon*
Forest	5.8	0.375	0.625	0.17
Maize/bean	27.9	1.000	3.000	1.07
Napier	20.9	1.000	2.250	0.76
Shrub	11.6	0.625	1.250	0.36
Vegetables	33.7	1.000	3.625	1.26
P-value	3.81×10^{-07}	7.139×10^{-05}	3.81×10^{-07}	1.062×10^{-06}

in the habitats that are subject to regular disturbance compared to the stable ecosystems like shrub land and indigenous forest. It was also possible that fungal tissues were fragmented and scattered in the course of farm operations, thus increasing their frequency of detection. As such, agricultural practices can exert positive or negative impacts on other microorganisms in the soil.[127] According to Wang *et al.*,[128] some agricultural inputs stimulate build-up of nematode-trapping fungi, hence the observed diversity, evenness and richness with increased land-use intensity compared to land uses such as forest or shrub land which are materially unchanged by human activity. Intensive cultivation is characterised by increased movement of soil, which may result in increased spread of the microorganisms in the field. Soil disturbance, coupled with frequent changes in crop cover, subjects the soil biota to stress, making it difficult for a particular species to establish itself in the soil to out-compete the others. In contrast, soils under forest and shrub are less disturbed, meaning that certain species of nematode-destroying fungi are able to establish and suppress other species that are poorly suited to compete effectively.

5.5 Farming Systems and Soil-borne Pests and Diseases

In conventional agriculture, addition of lime, inorganic fertilisers and pesticides can change the physical and chemical nature of the soil environment, thereby altering the number of organisms and the ratio of different groups of organisms, resulting in adverse effects characterised in part by an increase in soil-borne pests and diseases. Soil-borne pathogens (such as plant parasitic nematodes, fungi, bacteria, phytoplasma, protozoa and viruses) are among the most underestimated of the factors which affect plant productivity in tropical regions. The reasons for the greater severity of soil-borne diseases and pests in the tropics are the generally favourable climatic conditions, the greater pathogenicity of pest species and the more severe disease complexes.[129] In addition, cropping systems in tropical regions are generally more diverse and less reliant on chemical inputs compared to those in temperate regions. There is also a greater diversity of nematodes and other pests in tropical regions.[67] Table 8 lists some of the most common soil-borne pathogens in the tropics and the crops and trees that may be affected in different systems.

In general, plants infected by soil-borne pathogens suffer from root rot, collar rot, root blackening, wilting, stunting or seedling damping-off diseases. To some extent, losses associated with soil-borne pathogens may be reduced by a 4–5 year crop rotation programme, but this is not feasible due to economic reasons. One way in which the soil-borne pathogens can be indirectly suppressed is through the incorporation of organic amendment matter to mineral soils. In addition to improving tilth, aeration and drainage of soils where organic matter is incorporated, additional benefits occur such as proliferation of populations of beneficial soil microorganisms. This was demonstrated by Langat *et al.*[130] where amending soils with organic substrates including baggase, molasses, tea and flower composts contributed to a change

Table 8 Common soil-borne pathogens on major field crops in the tropics.

Pest/Pathogen	*Diseases*	*Common host crops*	*Reference*
Fungi			
Fusarium spp.	Wilt, crow rot, blackleg	Vegetables, banana, bean, coffee, cotton, melon, potato, tomato, cowpea, *Crotalaria* spp., *Sesbania* spp.	6, 154
Phytophthora spp.	Root rots, blights	Vegetables, soybean, cowpea, cocoa, citrus, tobacco	155
Pythium spp.	Damping off diseases	Vegetables, soybean, cowpea, common bean, chick pea	156
Rhizoctonia spp	Root rots, blights	Vegetables, soybean, cowpea, common bean, chick pea	156, 157
Sclerotium spp.	Collar rot, southern blight	Solanaceous crops, root and tuber crops, legumes, rice, *Mucuna* spp., Sesbania spp.	156, 158
Macrophomina phaseolina	Black root rot	Soybean	157
Bacteria			
Ralstonia solanacearum	Bacterial wilt	Tomato, pepper, eggplant, groundnut,	
Xanthomonas campestris	Black rot	Kale, cabbage, broccoli,	159
Agrobacterium tumefaciens	Crown gall	Roses, grape vines, stone fruit trees	
Nematodes			
Meloidogyne spp. (root-knot nematodes)	Root knot disease	Vegetables, legumes, tubers, coffee, *Sesbania* spp., *Tephrosia* spp.	160
Pratylenchus spp. (lesion nematodes)	Root lesion disease	Cereal crops, root and tuber crops, banana, coffee, tea, *Arachis* spp., forage grasses *Crotalaria* spp., *Senna* spp.	160
Radopholus similis (burrowing nematodes)		Banana, citrus, pepper and palms	160

in the nematode community structure by significantly increasing the abundance of beneficial nematodes in the soil. An important consideration is that all soils have an inherent natural level of disease-suppressive activity. In most soils, long-term management, or lack thereof, can either reduce or increase this level of suppression. A number of land-management factors such as intensification in cropping, amending soils with organic matter, weed management, and stubble retention have been shown to increase soil suppressiveness to cereal root disease. The concept of a 'suppressive soil' was first described by Menzies[131] to explain the phenomenon of soils that suppressed Streptomyces potato scab. To date, natural suppressive soils have been described containing a number of soil-borne pathogens such as *Gaeumannomyces graminis* var. tritici (take-all disease of wheat), *Fusarium oxysporum* (wilt diseases of tomato, radish, banana and others), *Phytophthora cinnamon* (root rot of eucalyptus), *Pythium* spp. and *Rhizoctonia solani* (damping-off of seedlings of several crops, including sugar beet and radish), *Thielaviopsis basicola* (black root rot of tobacco, bean, cherry trees and others), Streptomyces scabies (bacterial potato scab; that is, lesions on potato tubers), *Ralstonia solanacearum* (bacterial wilt of tomato, tobacco and others), and *Meloidogyne incognita* (root swelling and root-knot galls caused by this nematode on several crops, mostly in tropical and subtropical countries).

6 Mitigation of Soil Degradation through Integrated Soil Fertility Management (ISFM) Approaches: Sustainable Soil-management Practices/Systems

Crop yields in large parts of sub-Saharan Africa are low due to declining soil fertility associated with continuous cropping and sub-optimal fertiliser use. With the liberalisation of trade and introduction of structural adjustment programmes, fertiliser costs have increased and most small-scale farmers can no longer afford them, while the challenge of increasing and maintaining crop yields to sustain the growing population in most countries south of the Sahara has remained. Animal manure, as an alternative for maintaining soil fertility and crop productivity, is available in inadequate amounts and is of low quality due to poor handling and poor quality livestock feeds.[132,133] Technologies such as improved fallow systems[49] and use of organic inputs[134,135] have been demonstrated to increase crop yields, but often organic resources used alone provide insufficient nutrients to build up longer-term soil fertility and sustain crop yields.[136] Integrated Soil Fertility Management (ISFM), *i.e.* combined use of organic and inorganic fertilisers, has been recommended for increasing nutrient use efficiency (NUE) among farmers in SSA.[52,136] One of the major challenges in such low-input systems is to develop ways of managing organic matter to optimise the maintenance of SOM, improve soil structure and enhance water- and nutrient-use efficiencies. One aspect of ISFM that is often ignored is that it offers perspective for the manipulation of community composition and activities of soil biota through the judicious management of organic inputs. Especially the stimulation of earthworm and termite activity may contribute to decomposition and humification of organic residues, maintenance of soil structure and aggregate stability, and overall restoration of degraded soils.[66] In a wider sense, the elucidation of biodiversity of soil organisms has high priority in global biodiversity research, as it appears to be key to understanding their role in soil ecosystem processes and services.[137,138]

7 Biodiversity of Tropical Soils: Socioeconomic, Institutional and Policy Issues

Conservation of natural resources, including tropical soil biodiversity, has remained one of the most challenging problems, partly due to declining fertility of tropical soils; hence the reduced capacity of such soils to produce adequate food to meet household food requirements.[139] The ensuing pursuit for household food security has, on the other hand, tended to encourage adoption of practices that degrade soils. Generally, soil degradation gradually diminishes the capacity of individual farmers and communities to raise sufficient incomes from farming activities which, in turn, results in the inability to undertake critical investments needed to conserve the soil and preserve biodiversity. It also diminishes opportunities for such households to satisfy their nutritional needs. At the same time, the households become vulnerable to external shocks and often disinvest in critical productive assets to cope with such shocks.[140] Thus, degradation of natural resources including land (and soil biodiversity) has the effect of entrenching nutritional and asset poverty, which in turn reinforce natural resource degradation, thus creating a vicious circle. This nexus between worsening poverty and degradation of natural resources raises fundamental questions of the best strategies for managing soil biodiversity in the tropics. These challenges are highest in many developing regions, representing the intersection of hot-spots of widespread poverty and fragile ecosystems (*e.g.* arid and semi-arid areas, highland regions).[139,141]

Governments, donors and development partners in many developing countries have devoted substantial resources to developing and promoting a diverse mix of sustainable soil conservation practices. The technologies promoted in this mix have included indigenous and introduced structural technologies and agronomic practices, usually aimed at enhancing soil productivity. Some of the structural methods include soil and stone bunding and terracing, while the agronomic practices include minimum tillage, organic and inorganic fertilisers, pesticides, grass strips, and agro-forestry techniques. In addition, a number of agro-forestry technologies, in particular alley cropping, have been promoted mainly because of their ability enhance soil organic matter and, in cases involving leguminous plants, replenish soil nitrogen through nitrogen fixation.[142]

Despite the increasing efforts made and the growing policy interest, there has been limited focus on the promotion of soil biodiversity, especially below-ground biodiversity, in the tropics. Instead, farm households have increased the use of soil fertility management and agronomic practices that are usually promoted to enhance agricultural productivity but tend to hurt the below-ground micro- and macro-organisms. This section first reviews the soil conservation approaches pursued in the past followed by a discussion of socioeconomic (*e.g.* incentives and capacity) and institutional (including market access and policy) and information-related factors that condition the adoption of sustainable soil conservation practices likely to affect the biodiversity of tropical soils.

7.1 Approaches to Soil Conservation: A Historical Perspective

In order to stimulate widespread adoption and adaptation of soil conservation practices in tropical agriculture, especially in marginal and vulnerable environments, three major approaches have been used,[143] namely, top-down interventions, populist or farmer-first, and neo-liberal approaches. The early soil conservation approaches used the top-down approach to promoting the use of conservation practices. The practices promoted mainly involved structural methods used to prevent soil erosion. The approach earned its name from the lack of farmer participation in technology design and the use of command-and-control type policies used in implementation of the externally developed structural measures. The policies pursued under this approach included forced adoption of soil erosion control and planting of trees on hillsides, both of which have the potential to improve soil biodiversity by either retaining or replenishing the soil organic matter. However, the policies were largely driven by fear of future consequences of inaction. Nonetheless, this approach to soil conservation continued in several tropical areas (especially in Africa) until the mid 1980s.[144,145] The majority, however, failed to realise expected gains due to lack of incentive and initiative by households, resulting in the abandonment of the technologies as soon as the authorities were not involved.

The experiences gained from the failure of top-down policies were used to formulate a new approach referred to as the "populist" approach. This approach made the farmer central to program design and implementation of soil conservation activities. It had its foundations in the book *Farmer First.*[146] The approach stressed a small-scale and bottom-up participatory approach to soil conservation using homegrown technologies[147] and rejected wholesale technology transfer. However, it faced difficulties because of its failure to address the economic, institutional and policy environments in which farmers operate.[143,148] Consequently, development agencies developed the third approach, namely the neo-liberal approach, which advocated the need to understand the structure of incentives that impede the use of soil conservation technologies. The neo-liberal approach recognised the essential role of farmer innovation but emphasised the critical role of markets, policies and institutions in stimulating and inducing farmer innovation, adoption and adaptation of suitable soil conservation options.[139] It especially focused on making soil conservation attractive and economically rewarding to farmers. The approach spearheaded the adoption of productive technologies and improved access to markets, which usually spur farmer investments in sustainable soil conservation options due to increased agricultural revenues.

The approach used in promoting soil conservation in agriculture has further changed in the last few years, moving instead towards the concept of sustainable land management (SLM) both at the farm and landscape level.[148] While there is no single all-encompassing definition of SLM, it has been suggested[149] that SLM implies a system of technologies that aims to integrate ecological, socio-economic and political principles in the management of land for agricultural and other purposes to achieve intra- and inter-generational equity. This broadening of the concept of soil conservation shows the complexity of the challenges it entails. The following section examines these challenges in the context of incentives and capacity variables, the institutional and the information-related factors that condition adoption.

7.2 Drivers of Farmers' Use of Sustainable Soil Conservation Practices

Farmers adopt new practices that enhance soil biodiversity only when the switch from the old to new methods offers additional gains either in terms of higher net returns, lower risks, or both. Thus farmers are likely to adopt soil biodiversity-enhancing practices only when the additional benefits from such investments outweigh the added costs.[150] Investment in such soil conservation practices is often just one of the many investment options available to farmers. They can therefore defer undertaking such conservation investments until the gains from such investments are perceived to be at least equal to the next-best investment opportunities available to them.[151] That is, farmers will implicitly compare the expected costs and benefits and then invest in options that offer highest net returns in terms of income or reduced risk. This implies that, in cases where private costs of investment in soil biodiversity outweigh the benefits, voluntary adoption will be greatly hampered and may only occur if the society is willing to internalise some of the costs by offering subsidies to farmers. This is indeed the reason why some development experts promote the payment for environmental services.[151]

The literature identifies a number of factors that condition the adoption of soil conservation practices in agriculture. These factors relate to incentives the farmers have and the capacity of such farmers to adopt better practices. Farmers can be constrained to adopt otherwise profitable (or economically attractive) interventions due to asset poverty (*i.e.* low endowment with needed capital items), imperfect information, poorly functioning markets, bad policies, and institutional factors. Thus the factors that condition the adoption of soil biodiversity can be broadly categorised into incentive factors, capacity factors, institutional (*e.g.* markets and policy) factors and information-related factors.

8 Synthesis

In summary, the recognised form of land degradation affecting the major soil types in sub-Saharan Africa are erosion, physical and chemical degradation, which includes salinisation, sodification, acidification and the depletion of plant nutrient content in the soil. Biological degradation is also a major contributor leading to loss of soil organic matter and soil biodiversity. All these forms of degradation lead to a lowering of soil fertility and land productivity. Land degradation problems are now recognised as being one of the major contributors to the persistent food deficit and high poverty levels in the sub-Saharan Africa. The main causes of low land productivity in smallholder farmers include very low use of organic and inorganic fertilisers; poor tillage practices, especially for hard setting soils such as Luvisols, Lixisols and Acrisols; excessive soil erosion by water and wind, affecting almost all the major soil types; lack of attention to soil acidity for soils with acidity problem; poor conservation and management of rain water for enhanced soil moisture conservation on soils occurring in rolling to undulating topography; and poor land-use planning. Concerted and well-planned action therefore needs to be taken to build soil fertility and minimise land degradation on small-scale farms. Some of the important action points are:

- Developing well-defined and specific activities to enhance plant nutrient levels as a long–term programme through consistent use of both organic and inorganic fertilisers. According to World Bank figures, Africa uses only 14 kg of fertiliser per hectare compared with 1150–2000 kg in East Asia and Europe. Use of both organic and inorganic fertilisers have resulted in improved soil physical and chemical properties and increased crop yields for some highly weathered tropical soils.
- Giving adequate attention to the problem of soil acidity and finding better ways of promoting plant nutrient availability and uptake.
- Developing and adapting suitable rotations using legumes and green manure.
- Promoting agroforestry and farm forestry for better soil fertility and increased land productivity to answer multiple needs at the farm level and beyond.
- Creating programmes to deal with the issues of tillage and depth of root bed to create sufficient storage capacity for plant nutrients and water, especially for soils with a compacted sub-soil. Further issues of the energy required and the development of new or improved tillage systems and equipment need to be dealt with as crucial elements in the process. Such improved methods of tillage should lessen the problem of hardpans and plough soles. This will greatly enhance soil water uptake for plant growth.
- Developing efficient systems of irrigation that increase production without degrading the soil.
- Adopting soil conservation measures that are simple, effective and affordable.
- Within the context of Integrated Soil Fertility Management (ISFM), soil biota are responsible for the key ecosystem functions of decomposition and nutrient cycling, soil organic matter synthesis and mineralisation, soil structural modification and aggregate stabilisation, nitrogen fixation, nutrient acquisition, regulation of atmospheric composition, the production of plant growth substances and the biological control of soil-borne pests and diseases Understanding biological processes is not as well advanced as those that are related to soil physical and chemical properties, creating opportunities for breakthroughs in biotic function to better service agriculture.

To summarize, understanding the soil is the key to its improvement, as there are many physical, chemical and biological properties of the various soil types that affect plant growth.

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