ISSN 0253-2050

FAO
SOILS
BULLETIN

80

The importance of soil organic matter

Key to drought-resistant soil and sustained food production

Cover photographs:

Background: Honduras. FAO/18884/G. Bizzarri.

Inset: Honduras. FAO/18907/G. Bizzarri.

Copies of FAO publications can be requested from:

SALES AND MARKETING GROUP
Information Division
Food and Agriculture Organization of the United Nations
Viale delle Terme di Caracalla
00100 Rome, Italy

E-mail: publications-sales@fao.org
Fax: (+39) 06 57053360
Web site: http://www.fao.org

The importance of soil organic matter

Key to drought-resistant soil and sustained food and production

FAO
SOILS
BULLETIN

80

by
Alexandra Bot
FAO Consultant

and

José Benites
FAO Land and Plant Nutrition
Management Service

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2005

ISBN 92-5-105366-9

Contents

Annexes

List of boxes

List of figures

List of plates

Acknowledgements

This publication was prepared by Alexandra Bot, FAO consultant, and José Benites, technical officer, Land and Plant Nutrition Management Service (AGLL), FAO. It is based on contributions from: Gunter Englisch, Germany; Anthony Juo of Texas A&M University, the United States of America; William Payne of the International Crops Research Institute for the Semi-arid Tropics, Sahelien Centre, Niger; Maria de Fátima Ribeiro dos Santos, Ademir Calegari and Francisco Skora Neto of Paraná State Agricultural Research Station, Brazil.

The authors would like to acknowledge the valuable comments provided by: Parviz Koohafkan, chief, AGLL; Sally Bunning, land management officer, AGLL; Juan Jimenez, consultant, AGLL; Alessandro Piccolo of the University of Naples; Francis Shaxon, consultant; Martin Bwalya of the African Conservation Tillage Network; Peter Brinn, consultant; Christian Pieri, consultant; Bob Stewart of Texas A&M University; Norman Uphoff of the Cornell International Institute for Agricultural Development; Rachid Mrabet of the Institut National de la Recherche Agronomique Centre Aridoculture, Morocco; and Kurt Steiner of the German Agency for Technical Cooperation (GTZ).

Invaluable help on draft versions of this document was provided by R. Brinkman, FAO consultant; Telmo Amado of the Federal University of Santa Maria, Brazil; and Des McGarry of Queensland Government, Australia. In the production of this publication, the authors have been assisted effectively by Lynette Chalk.

Preface

Healthy soil is the foundation of the food system. It produces healthy crops that in turn nourish people. Maintaining a healthy soil demands care and effort from farmers because farming is not benign. By definition, farming disturbs the natural soil processes including that of nutrient cycling – the release and uptake of nutrients.

Plants obtain nutrients from two natural sources: organic matter and minerals. Organic matter includes any plant or animal material that returns to the soil and goes through the decomposition process. In addition to providing nutrients and habitat to organisms living in the soil, organic matter also binds soil particles into aggregates and improves the water holding capacity of soil. Most soils contain 2–10 percent organic matter. However, even in small amounts, organic matter is very important.

Soil is a living, dynamic ecosystem. Healthy soil is teeming with microscopic and larger organisms that perform many vital functions including converting dead and decaying matter as well as minerals to plant nutrients. Different soil organisms feed on different organic substrates. Their biological activity depends on the organic matter supply.

Nutrient exchanges between organic matter, water and soil are essential to soil fertility and need to be maintained for sustainable production purposes. Where the soil is exploited for crop production without restoring the organic matter and nutrient contents and maintaining a good structure, the nutrient cycles are broken, soil fertility declines and the balance in the agro-ecosystem is destroyed.

Soil organic matter – the product of on-site biological decomposition – affects the chemical and physical properties of the soil and its overall health. Its composition and breakdown rate affect: the soil structure and porosity; the water infiltration rate and moisture holding capacity of soils; the diversity and biological activity of soil organisms; and plant nutrient availability. Many common agricultural practices, especially ploughing, disc-tillage and vegetation burning, accelerate the decomposition of soil organic matter and leave the soil susceptible to wind and water erosion. However, there are alternative management practices that enhance soil health and allow sustained agricultural productivity. Conservation agriculture encompasses a range of such good practices through combining no tillage or minimum tillage with a protective crop cover and crop rotations. It maintains surface residues, roots and soil organic matter, helps control weeds, and enhances soil aggregation and intact large pores, in turn allowing water infiltration and reducing runoff and erosion. In addition to making plant nutrients available, the diverse soil organisms that thrive in such conditions contribute to pest control and other vital ecological processes. Through combining pasture and fodder species and manuring with food and fibre crop production, mixed crop–livestock systems also enhance soil organic matter and soil health. This document recognizes the central role of organic matter in improving soil productivity and outlines promising technologies for improved organic matter management for productive and sustainable crop production in the tropics.

Soil organic matter content is a function of organic matter inputs (residues and roots) and litter decomposition. It is related to moisture, temperature and aeration, physical and chemical properties of the soils as well as bioturbation (mixing by soil macrofauna), leaching by water and humus stabilization (organomineral complexes and aggregates). Land use and management practices also affect soil organic matter.

Farming systems have tended to mine the soil for nutrients and to reduce soil organic matter levels through repetitive harvesting of crops and inadequate efforts to replenish nutrients and restore soil quality. This decline continues until management practices are improved or until a fallow period allows a gradual recovery through natural ecological processes. Only carefully selected diversified cropping systems or well-managed mixed crop–livestock systems are able to maintain a balance in nutrient and organic matter supply and removal.

Farmers can take many actions to maintain, improve and rebuild their soils, especially soils that have been under cultivation for a long time. A key to soil restoration is to maximize the retention and recycling of organic matter and plant nutrients, and to minimize the losses of these soil components caused by leaching, runoff and erosion. However, rebuilding soil quality and health through appropriate farming practices may take several years, especially in dryland areas where limited moisture reduces biomass production and soil biological activity. Thus, the challenge is to identify soil management practices that promote soil organic matter formation and moisture retention and ensure productivity and profitability for farmers in the short term.

FAO recognizes that conservation agriculture can make an important contribution to the agriculture sector through its multiple environmental and economic benefits. Conservation agriculture uses holistic production management systems that promote and enhance agro-ecosystem health, including aboveground and belowground biodiversity, biological cycles, and biological activity. These systems apply specific and precise standards of production based on no- or minimum-tillage techniques and selected cover crops and crop rotations. Their aim is to achieve optimal agro-ecosystems that are socially, ecologically and economically sustainable. Through effective harnessing of agro-ecological processes, conservation agriculture provides an opportunity for reducing external input requirements and for converting low-input agricultural systems into more productive ones. A better understanding of the linkages between soil life and ecosystem function and the impact of human interventions will enable the reduction of negative impacts and the more effective capture of the benefits of soil biological activity for sustainable and productive agriculture.

List of acronyms

Al	Aluminium
C	Carbon
Ca	Calcium
CEC	Cation exchange capacity
CO_2	Carbon dioxide
Fe	Iron
H	Hydrogen
HYV	High-yielding variety
K	Potassium
Mg	Magnesium
N	Nitrogen
NaOH	Sodium hydroxide
NH_4^-	Ammonium
P	Phosphorus
S	Sulphur
SSA	Sub-Saharan Africa
THM	Trihalomethane

Chapter 1

Introduction

On the basis of organic matter content, soils are characterized as mineral or organic. Mineral soils form most of the world’s cultivated land and may contain from a trace to 30 percent organic matter. Organic soils are naturally rich in organic matter principally for climatic reasons. Although they contain more than 30 percent organic matter, it is precisely for this reason that they are not vital cropping soils.

This soils bulletin concentrates on the organic matter dynamics of cropping soils. In brief, it discusses circumstances that deplete organic matter and the negative outcomes of this. The bulletin then moves on to more proactive solutions. It reviews a “basket” of practices in order to show how they can increase organic matter content and discusses the land and cropping benefits that then accrue.

Soil organic matter is any material produced originally by living organisms (plant or animal) that is returned to the soil and goes through the decomposition process (Plate 1). At any given time, it consists of a range of materials from the intact original tissues of plants and animals to the substantially decomposed mixture of materials known as humus (Figure 1).

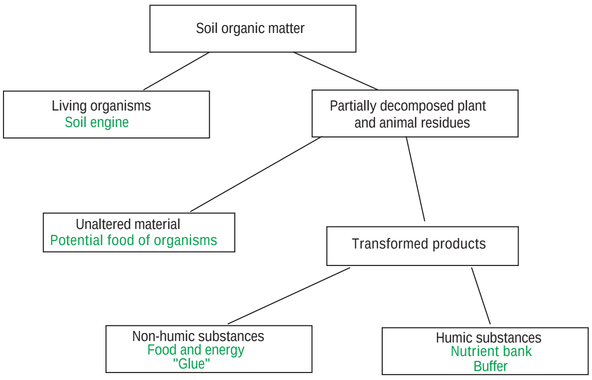
A.J. BOT

Plate 1
Crop residues added to the soil are decomposed by soil macrofauna and micro-organisms, increasing the organic matter content of the soil.

Most soil organic matter originates from plant tissue. Plant residues contain 60–90 percent moisture. The remaining dry matter consists of carbon (C), oxygen, hydrogen (H) and small amounts of sulphur (S), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg). Although present in small amounts, these nutrients are very important from the viewpoint of soil fertility management.

Soil organic matter consists of a variety of components. These include, in varying proportions and many intermediate stages, an active organic fraction including micro-organisms (10–40 percent), and resistant or stable organic matter (40–60 percent), also referred to as humus.

FIGURE 1
Components of soil organic matter and their functions



Forms and classification of soil organic matter have been described by Tate (1987) and Theng (1987). For practical purposes, organic matter may be divided into aboveground and belowground fractions. Aboveground organic matter comprises plant residues and animal residues; belowground organic matter consists of living soil fauna and microflora, partially decomposed plant and animal residues, and humic substances. The C:N ratio is also used to indicate the type of material and ease of decomposition; hard woody materials with a high C:N ratio being more resilient than soft leafy materials with a low C:N ratio.

Although soil organic matter can be partitioned conveniently into different fractions, these do not represent static end products. Instead, the amounts present reflect a dynamic equilibrium. The total amount and partitioning of organic matter in the soil is influenced by soil properties and by the quantity of annual inputs of plant and animal residues to the ecosystem. For example, in a given soil ecosystem, the rate of decomposition and accumulation of soil organic matter is determined by such soil properties as texture, pH, temperature, moisture, aeration, clay mineralogy and soil biological activities. A complication is that soil organic matter in turn influences or modifies many of these same soil properties.

Organic matter existing on the soil surface as raw plant residues helps protect the soil from the effect of rainfall, wind and sun. Removal, incorporation or burning of residues exposes the soil to negative climatic impacts, and removal or burning deprives the soil organisms of their primary energy source.

Organic matter within the soil serves several functions. From a practical agricultural standpoint, it is important for two main reasons: (i) as a "revolving nutrient fund"; and (ii) as an agent to improve soil structure, maintain tilth and minimize erosion.

As a revolving nutrient fund, organic matter serves two main functions:

- ➢ As soil organic matter is derived mainly from plant residues, it contains all of the essential plant nutrients. Therefore, accumulated organic matter is a storehouse of plant nutrients.
- ➢ The stable organic fraction (humus) adsorbs and holds nutrients in a plant-available form.

Organic matter releases nutrients in a plant-available form upon decomposition. In order to maintain this nutrient cycling system, the rate of organic matter addition from crop residues, manure and any other sources must equal the rate of decomposition, and take into account the rate of uptake by plants and losses by leaching and erosion.

Where the rate of addition is less than the rate of decomposition, soil organic matter declines. Conversely, where the rate of addition is higher than the rate of decomposition, soil organic matter increases. The term steady state describes a condition where the rate of addition is equal to the rate of decomposition.

In terms of improving soil structure, the active and some of the resistant soil organic components, together with micro-organisms (especially fungi), are involved in binding soil particles into larger aggregates. Aggregation is important for good soil structure, aeration, water infiltration and resistance to erosion and crusting.

Traditionally, soil aggregation has been linked with either total C (Matson *et al.*, 1997) or organic C levels (Dalal and Mayer, 1986a, 1986b). More recently, techniques have developed to fractionate C on the basis of lability (ease of oxidation), recognizing that these subpools of C may have greater effect on soil physical stability and be more sensitive indicators than total C values of carbon dynamics in agricultural systems (Lefroy, Blair and Strong, 1993; Blair, Lefroy and Lisle, 1995; Blair and Crocker, 2000). The labile carbon fraction has been shown to be an indicator of key soil chemical and physical properties. For example, this fraction has been shown to be the primary factor controlling aggregate breakdown in Ferrosols (non-cracking red clays), measured by the percentage of aggregates measuring less than 0.125 mm in the surface crust after simulated rain in the laboratory (Bell *et al.*, 1998, 1999).

The resistant or stable fraction of soil organic matter contributes mainly to nutrient holding capacity (cation exchange capacity [CEC]) and soil colour. This fraction of organic matter decomposes very slowly. Therefore, it has less influence on soil fertility than the active organic fraction.

Chapters 2 and 3 deal with the transformation of organic matter by soil organisms and with natural factors influencing the level of organic matter content in the soil.

Chapter 4 discusses the various management practices that affect the accumulation of organic matter in the soil. Chapter 5 examines how to create drought-resistant soil, while Chapter 6 explores various aspect of sustained food production. Chapter 7 examines the role of conservation agriculture, and Chapter 8 presents the conclusions.

Annex 1 provides background information on the different soil organisms of importance in agriculture. Annex 2 provides details of the effects of organic matter on biological, chemical and physical soil properties.

Chapter 2

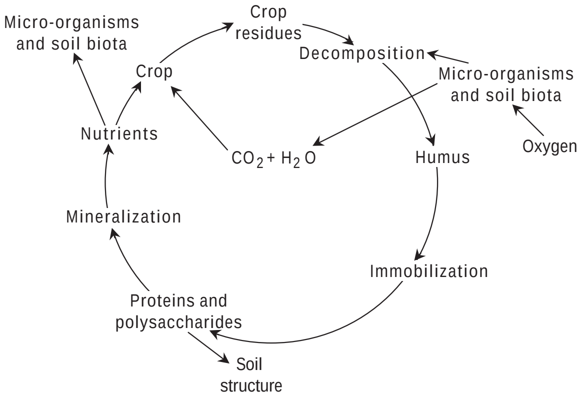
Organic matter decomposition and the soil food web

SOIL ORGANIC MATTER

When plant residues are returned to the soil, various organic compounds undergo decomposition. Decomposition is a biological process that includes the physical breakdown and biochemical transformation of complex organic molecules of dead material into simpler organic and inorganic molecules (Juma, 1998).

The continual addition of decaying plant residues to the soil surface contributes to the biological activity and the carbon cycling process in the soil. Breakdown of soil organic matter and root growth and decay also contribute to these processes. Carbon cycling is the continuous transformation of organic and inorganic carbon compounds by plants and micro- and macro-organisms between the soil, plants and the atmosphere (Figure 2).

FIGURE 2
Carbon cycle



Decomposition of organic matter is largely a biological process that occurs naturally. Its speed is determined by three major factors: soil organisms, the physical environment and the quality of the organic matter (Brussaard, 1994). In the decomposition process, different products are released: carbon dioxide (CO_2), energy, water, plant nutrients and resynthesized organic carbon compounds. Successive decomposition of dead material and modified organic matter results in the formation of a more complex organic matter called humus (Juma, 1998). This process is called humification. Humus affects soil properties. As it slowly decomposes, it colours the soil darker; increases soil aggregation and aggregate stability; increases the CEC (the ability to attract and retain nutrients); and contributes N, P and other nutrients.

Soil organisms, including micro-organisms, use soil organic matter as food. As they break down the organic matter, any excess nutrients (N, P and S) are released into the soil in forms that plants can use. This release process is called mineralization. The waste products produced by micro-organisms are also soil organic matter. This waste material is less decomposable than the original plant and animal material, but it can be used by a large number of organisms. By breaking down carbon structures and rebuilding new ones or storing the C into their own biomass, soil biota plays the most important role in nutrient cycling processes and, thus, in the ability of a soil to provide the crop with sufficient nutrients to harvest a healthy product. The organic matter content, especially the more stable humus, increases the capacity to store water and store (sequester) C from the atmosphere.

THE SOIL FOOD WEB

The soil ecosystem (Box 1) can be defined as an interdependent life-support system composed of air, water, minerals, organic matter, and macro- and micro-organisms, all of which function together and interact closely.

The organisms and their interactions enhance many soil ecosystem functions and make up the soil food web. The energy needed for all food webs is generated by primary producers: the plants, lichens, moss, photosynthetic bacteria and algae that use sunlight to transform CO_2 from the atmosphere into carbohydrates. Most other organisms depend on the primary producers for their energy and nutrients; they are called consumers.

BOX 1

Some functions of a healthy soil ecosystem

- Decompose organic matter towards humus.
- Retain N and other nutrients.
- Glue soil particles together for best structure.
- Protect roots from diseases and parasites.
- Make retained nutrients available to the plant.
- Produce hormones that help plants grow.
- Retain water.

Soil life plays a major role in many natural processes that determine nutrient and water availability for agricultural productivity. The primary activities of all living organisms are growing and reproducing. By-products from growing roots and plant residues feed soil organisms. In turn, soil organisms support plant health as they decompose organic matter, cycle nutrients, enhance soil structure and control the populations of soil organisms, both beneficial and harmful (pests and pathogens) in terms of crop productivity.

The living part of soil organic matter includes a wide variety of micro-organisms such as bacteria, viruses, fungi, protozoa and algae. It also includes plant roots, insects, earthworms, and larger animals such as moles, mice and rabbits that spend part of their life in the soil. The living portion represents about 5 percent of the total soil organic matter. Micro-organisms, earthworms and insects help break down crop residues and manures by ingesting them and mixing them with the minerals in the soil, and in the process recycling energy and plant nutrients. Sticky substances on the skin of earthworms and those produced by fungi and bacteria help bind particles together. Earthworm casts are also more strongly aggregated (bound together) than the surrounding soil as a result of the mixing of organic matter and soil mineral material, as well as the intestinal mucus of the worm. Thus, the living part of the soil is responsible for keeping air and water available, providing plant nutrients, breaking down pollutants and maintaining the soil structure.

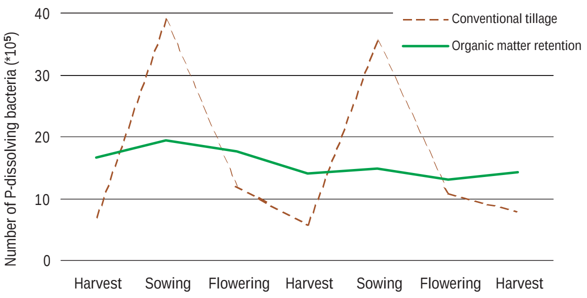
The composition of soil organisms depends on the food source (which in turn is season dependent). Therefore, the organisms are neither uniformly distributed through the soil nor uniformly present all year. However, in some cases their biogenic structures remain. Each species and group exists where it can find appropriate food supply, space, nutrients and moisture (Plate 2). Organisms occur wherever organic matter occurs (Ingham, 2000). Therefore, soil organisms are concentrated: around roots, in litter, on humus, on the surface of soil aggregates and in spaces between aggregates. For this reason, they are most prevalent in forested areas and cropping systems that leave a lot of biomass on the surface.

T. MILLER

Plate 2
Termites create their own living conditions near their preferred food sources. Inside the colony life is highly organized.

The activity of soil organisms follows seasonal as well as daily patterns. Not all organisms are active at the same time. Most are barely active or even dormant. Availability of food is an important factor that influences the level of activity of soil organisms and thus is related to land use and management (Figure 3). Practices that increase numbers and activity of soil organisms include: no tillage or minimal tillage; and the maintenance of plant and annual residues that reduce disturbance of soil organisms and their habitat and provide a food supply.

Figure 3
Fluctuations in microbial biomass at different stages of crop development in conventional agriculture compared with systems with residue retention and high organic matter input



Source: Balota, 1996

Different groups of organisms can be distinguished in the soil (Brussaard and Juma, 1995). Table 1 classifies them by size. Table 2 classifies them by function.

TABLE 1
Classification of soil organisms

Micro-organisms	Microflora	< 5 μm	Bacteria
			Fungi
	Microfauna	< 100 μm	Protozoa
			Nematodes
Macro-organisms	Meso-organisms	100 μm – 2 mm	Springtails
			Mites
	Macro-organisms	2 – 20 mm	Earthworms
			Millipedes
			Woodlice
			Snails and slugs
Plants	Algae	10 μm	
	Roots	> 10 μm	

Note: Clay particles are smaller than 2 μm.
Source: adapted from Swift, Heal and Anderson, 1979.

DECOMPOSITION PROCESS

Fresh residues consist of recently deceased micro-organisms, insects and earthworms, old plant roots, crop residues, and recently added manures.

Crop residues contain mainly complex carbon compounds originating from cell walls (cellulose, hemicellulose, etc.). Chains of carbon, with each carbon atom linked to other carbons, form the “backbone” of organic molecules. These carbon chains, with varying amounts of attached oxygen, H, N, P and S, are the basis for both simple sugars and amino acids and more complicated molecules of long carbon chains or rings. Depending on their chemical structure, decomposition is rapid (sugars, starches and proteins), slow (cellulose, fats, waxes and resins) or very slow (lignin).

During the decomposition process, micro-organisms convert the carbon structures of

TABLE 2
Essential functions performed by different members of soil organisms (biota)

Functions	Organisms involved
Maintenance of soil structure	Bioturbating invertebrates and plant roots, mycorrhizae and some other micro-organisms
Regulation of soil hydrological processes	Most bioturbating invertebrates and plant roots
Gas exchange and carbon sequestration (accumulation in soil)	Mostly micro-organisms and plant roots, some C protected in large compact biogenic invertebrate aggregates
Soil detoxification	Mostly micro-organisms
Nutrient cycling	Mostly micro-organisms and plant roots, some soil- and litter-feeding invertebrates
Decomposition of organic matter	Various saprophytic and litter-feeding invertebrates (detritivores), fungi, bacteria, actinomycetes and other micro-organisms
Suppression of pests, parasites and diseases	Plants, mycorrhizae and other fungi, nematodes, bacteria and various other micro-organisms, collembola, earthworms, various predators
Sources of food and medicines	Plant roots, various insects (crickets, beetle larvae, ants, termites), earthworms, vertebrates, micro-organisms and their by-products
Symbiotic and asymbiotic relationships with plants and their roots	Rhizobia, mycorrhizae, actinomycetes, diazotrophic bacteria and various other rhizosphere micro-organisms, ants
Plant growth control (positive and negative)	Direct effects: plant roots, rhizobia, mycorrhizae, actinomycetes, pathogens, phytoparasitic nematodes, rhizophagous insects, plant-growth promoting rhizosphere micro-organisms, biocontrol agents Indirect effects: most soil biota

fresh residues into transformed carbon products in the soil. There are many different types of organic molecules in soil. Some are simple molecules that have been synthesized directly from plants or other living organisms. These relatively simple chemicals, such as sugars, amino acids, and cellulose are readily consumed by many organisms. For this reason, they do not remain in the soil for a long time. Other chemicals such as resins and waxes also come directly from plants, but are more difficult for soil organisms to break down.

Humus is the result of successive steps in the decomposition of organic matter. Because of the complex structure of humic substances, humus cannot be used by many micro-organisms as an energy source and remains in the soil for a relatively long time.

Non-humic substances: significance and function

Non-humic organic molecules are released directly from cells of fresh residues, such as proteins, amino acids, sugars, and starches. This part of soil organic matter is the active, or easily decomposed, fraction. This active fraction is influenced strongly by weather conditions, moisture status of the soil, growth stage of the vegetation, addition of organic residues, and cultural practices, such as tillage. It is the main food supply for various organisms in the soil.

Carbohydrates occur in the soil in three main forms: free sugars in the soil solution, cellulose and hemicellulose; complex polysaccharides; and polymeric molecules of various sizes and shapes that are attached strongly to clay colloids and humic substances (Stevenson, 1994). The simple sugars, cellulose and hemicellulose, may constitute 5–25 percent of the organic matter in most soils, but are easily broken down by micro-organisms.

Polysaccharides (repeating units of sugar-type molecules connected in longer chains) promote better soil structure through their ability to bind inorganic soil particles into stable aggregates. Research indicates that the heavier polysaccharide molecules may be more important in promoting aggregate stability and water infiltration than the lighter molecules (Elliot and Lynch, 1984). Some sugars may stimulate seed germination and root elongation. Other soil properties affected by polysaccharides include CEC, anion retention and biological activity.

The soil lipids form a very diverse group of materials, of which fats, waxes and resins make up 2–6 percent of soil organic matter. The significance of lipids arises from the ability of some compounds to act as growth hormones. Others may have a depressing effect on plant growth.

Soil N occurs mainly (> 90 percent) in organic forms as amino acids, nucleic acids and amino sugars. Small amounts exist in the form of amines, vitamins, pesticides and their degradation products, etc. The rest is present as ammonium (NH_4^-) and is held by the clay minerals.

Compounds and function of humus

Humus or humified organic matter is the remaining part of organic matter that has been used and transformed by many different soil organisms. It is a relatively stable component formed by humic substances, including humic acids, fulvic acids, hymatomelanic acids and humins (Tan, 1994). It is probably the most widely distributed organic carbon-containing material in terrestrial and aquatic environments. Humus cannot be decomposed readily because of its intimate interactions with soil mineral phases and is chemically too complex to be used by most organisms. It has many functions (Box 2).

One of the most striking characteristics of humic substances is their ability to interact with metal ions, oxides, hydroxides, mineral and organic compounds, including toxic pollutants, to form water-soluble and water-insoluble complexes.

Through the formation of these complexes, humic substances can dissolve, mobilize and transport metals and organics in soils and waters, or accumulate in certain soil horizons. This influences nutrient availability, especially those nutrients present at microconcentrations only (Schnitzer, 1986). Accumulation of such complexes can contribute to a reduction of toxicity, e.g. of aluminium (Al) in acid soils (Tan and Binger, 1986), or the capture of pollutants – herbicides such as Atrazine or pesticides such as Tefluthrin – in the cavities of the humic substances (Vermeer, 1996).

Humic and fulvic substances enhance plant growth directly through physiological and nutritional effects. Some of these substances function as natural plant hormones (auxines and gibberillins) and are capable of improving seed germination, root initiation, uptake of plant nutrients and can serve as sources of N, P and S (Tan, 1994; Schnitzer, 1986). Indirectly, they may affect plant growth through modifications of physical, chemical and biological properties of the soil, for example, enhanced soil water holding capacity and CEC, and improved tilth and aeration through good soil structure (Stevenson, 1994).

BOX 2
Humic substances retain nutrients available on demand for plants

Functions of humus:
- improved fertilizer efficiency;
- longlife N – for example, urea performs 60–80 days longer;
- improved nutrient uptake, particularly of P and Ca;
- stimulation of beneficial soil life;
- provides magnified nutrition for reduced disease, insect and frost impact;
- salinity management – humates "buffer" plants from excess sodium;
- organic humates are a catalyst for increasing soil C levels.

About 35–55 percent of the non-living part of organic matter is humus. It is an important buffer, reducing fluctuations in soil acidity and nutrient availability. Compared with simple organic molecules, humic substances are very complex and large, with high molecular weights. The characteristics of the well-decomposed part of the organic matter, the humus, are very different from those of simple organic molecules. While much is known about their general chemical composition, the relative significance of the various types of humic materials to plant growth is yet to be established.

Humus consists of different humic substances:

- Fulvic acids: the fraction of humus that is soluble in water under all pH conditions. Their colour is commonly light yellow to yellow-brown.
- Humic acids: the fraction of humus that is soluble in water, except for conditions more acid than pH 2. Common colours are dark brown to black.
- Humin: the fraction of humus that is not soluble in water at any pH and that cannot be extracted with a strong base, such as sodium hydroxide (NaOH). Commonly black in colour.

The term acid is used to describe humic materials because humus behaves like weak acids.

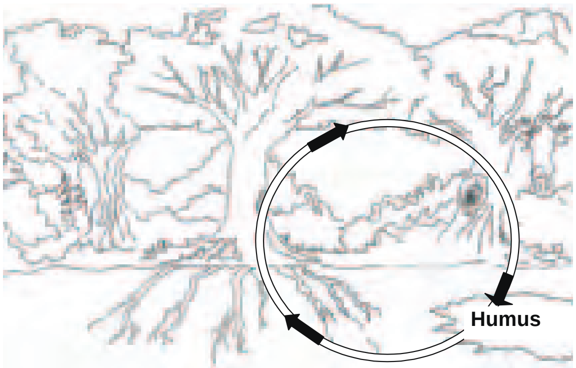
Fulvic and humic acids are complex mixtures of large molecules. Humic acids are larger than fulvic acids. Research suggests that the different substances are differentiated from each other on the basis of their water solubility.

Fulvic acids are produced in the earlier stages of humus formation. The relative amounts of humic and fulvic acids in soils vary with soil type and management practices. The humus of forest soils is characterized by a high content of fulvic acids, while the humus of agricultural and grassland areas contains more humic acids.

Chapter 3

Natural factors influencing the amount of organic matter

FIGURE 4
Closed cycle



The transformation and movement of materials within soil organic matter pools is a dynamic process influenced by climate, soil type, vegetation and soil organisms. All these factors operate within a hierarchical spatial scale. Soil organisms are responsible for the decay and cycling of both macronutrients and micronutrients, and their activity affects the structure, tilth and productivity of the soil.

In natural humid and subhumid forest ecosystems without human disturbance, the living and non-living components are in dynamic equilibrium with each other (Figure 4). The litter on the soil surface beneath different canopy layers and high biomass production generally result in high biological activity in the soil and on the soil surface. Mollison and Slay (1991) distinguished the following five mechanisms:

- ➢a continuous soil cover of living plants, which together with the soil architecture facilitates the capture and infiltration of rainwater and protects the soil;
- ➢a litter layer of decomposing leaves or residues providing a continuous energy source for macro- and micro-organisms;
- ➢the roots of different plants distributed throughout the soil at different depths permit an effective uptake of nutrients and an active interaction with micro-organisms;
- ➢the major period of nutrient release by micro-organisms coincides with the major period of nutrient demand by plants;
- ➢nutrients recycled by deep-rooting plants and soil macrofauna and microfauna.

This equilibrium creates almost closed-cycle transfers of nutrients between soil and the vegetation adapted to such site conditions, resulting in almost perfect physical and hydric conditions for plant growth, i.e. a cool microclimate, increased evapotranspiration, good rooting conditions with good porosity and sufficient soil moisture. This facilitates water infiltration and prevents erosion and runoff. Thus, it results in clean water in the streams emanating from the area, a relatively smooth variation in streamflow during the year, and recharge of groundwater.

In human-managed systems, the soil biological activity is influenced by the land use system, plant types and the management practices. Chapter 4 outlines the influence of land management practices. The environmental and edaphic factors that control the activity of soil biota, and thus the balance between accumulation and decomposition of organic matter in the soil, are described below.

TEMPERATURE

Several field studies have shown that temperature is a key factor controlling the rate of decomposition of plant residues. Decomposition normally occurs more rapidly in the tropics than in temperate areas. Ladd and Amato (1985) reported that, despite differences in plant material and climate patterns, the decomposition of leguminous materials in southern Australian sites followed the same pattern as that of ryegrass for sites in Nigeria and the United Kingdom (Jenkinson and Ayanaba, 1977), although the time scales were different. Reaction rates doubled for each increase of 8–9 °C in the mean annual air temperature. The relatively faster rate of decomposition induced by the continuous warmth in the tropics implies that high equilibrium levels of organic matter are difficult to achieve in tropical agro-ecosystems. Hence, large annual rates of organic inputs are needed to maintain an adequate labile soil organic matter pool in cultivated soils. Soils in cooler climates commonly have more organic matter because of slower mineralization (decomposition) rates.

SOIL MOISTURE AND WATER SATURATION

Soil organic matter levels commonly increase as mean annual precipitation increases. Conditions of elevated levels of soil moisture result in greater biomass production, which provides more residues, and thus more potential food for soil biota.

Soil biological activity requires air and moisture. Optimal microbial activity occurs at near “field capacity”, which is equivalent to 60-percent water-filled pore space (Linn and Doran, 1984).

On the other hand, periods of water saturation lead to poor aeration. Most soil organisms need oxygen, and thus a reduction of oxygen in the soil leads to a reduction of the mineralization rate as these organisms become inactive or even die. Some of the transformation processes become anaerobic, which can lead to damage to plant roots caused by waste products or favourable conditions for disease-causing organisms. Continued production and slow decomposition can lead to very large organic matter contents in soils with long periods of water saturation (e.g. peat soils, and tea crops in India).

With the exception of the hyperhumid regions, the climates of vast areas of the humid, subhumid and semi-arid tropics are characterized by distinct wet and dry seasons. In the wet-dry tropics, large amounts of nitrate often occur in the surface soil during the first part of the rainy season (Greenland, 1958; Mueller-Harvey, Juo and Wild,1989). This accelerated nitrogen mineralization caused by a large increase in microbial activity is the result of the first few rains activating the labile soil organic matter.

Farmers who practise “slash and burn” agriculture often choose early planting in order to take advantage of this flush of inorganic N before it is lost through leaching and runoff. In these low-input systems, the amount of nitrate present in the soil during the early part of the rainy season is related closely to the organic matter content of the soil. N availability diminishes during the later part of the rainy season.

SOIL TEXTURE

Soil organic matter tends to increase as the clay content increases. This increase depends on two mechanisms. First, bonds between the surface of clay particles and organic matter retard the decomposition process. Second, soils with higher clay content increase the potential for aggregate formation. Macroaggregates physically protect organic matter molecules from further mineralization caused by microbial attack (Rice, 2002). For example, when earthworm casts and the large soil particles they contain are split by the joint action of several factors (climate, plant growth and other organisms), nutrients are released and made available to other components of soil micro-organisms.

Under similar climate conditions, the organic matter content in fine textured (clayey) soils is two to four times that of coarse textured (sandy) soils (Prasad and Power, 1997).

Kaolinite, the main clay mineral in many upland soils in the tropics, has a much smaller specific surface and nutrient exchange capacity than most other clay minerals. Therefore, kaolinitic soils contain considerably fewer clay-humus complexes. In addition, the unprotected labile humic substances are vulnerable to decomposition under appropriate soil moisture conditions. Thus, high levels of organic matter are difficult to maintain in cultivated kaolinitic soils in the wet-dry tropics, because climate and soil conditions favour rapid decomposition. In contrast, organic matter can persist as organo-oxide complexes in soils rich in iron and aluminium oxides. Such properties favour the formation of soil microaggregates, typical of many fine-textured, oxide-rich, high base-status soils in the tropics (Uehara and Gilman, 1981). These soils are known for their low bulk density, high microporosity, and high organic-matter retention under natural vegetation, but also for their high phosphate fixation capacity on the oxides when used for crop production. Current knowledge suggests that whereas organic matter contributes to the dark colour of Vertisols (Coulombe, Dixon and Wilding, 1996), it is not considered important in determining either the development, robustness or resilience of structure in these soils (McGarry, 1996). Organic matter levels tend to be low in Vertisols; even as low as 10 g/kg (Coulombe, Dixon and Wilding, 1996).

Parent material influences organic matter accumulation not only through its effect on soil texture. Soils developed from inherently rich material, such as basalt, are more fertile than soils formed from granitic material, which contains less mineral nutrients. Moreover, the former experience more organic matter accumulation because of abundant vegetative growth.

TOPOGRAPHY

Organic matter accumulation is often favoured at the bottom of hills. There are two reasons for this accumulation: conditions are wetter than at mid- or upper-slope positions, and organic matter is transported to the lowest point in the landscape through runoff and erosion. Similarly, soil organic matter levels are higher on north-facing slopes (in the Northern Hemisphere) compared with south-facing slopes (and the other way around in the Southern Hemisphere) because temperatures are lower (Quideau, 2002).

SALINITY AND ACIDITY

Salinity, toxicity and extremes in soil pH (acid or alkaline) result in poor biomass production and, thus in reduced additions of organic matter to the soil. For example, pH affects humus formation in two ways: decomposition, and biomass production. In strongly acid or highly alkaline soils, the growing conditions for micro-organisms are poor, resulting in low levels of biological oxidation of organic matter (Primavesi, 1984). Soil acidity also influences the availability of plant nutrients and thus regulates indirectly biomass production and the available food for soil biota. Fungi are less sensitive than bacteria to acid soil conditions.

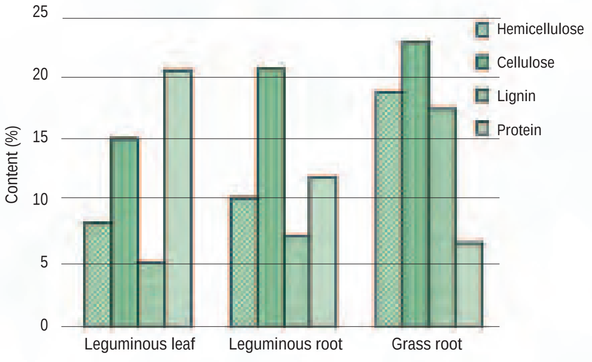
VEGETATION AND BIOMASS PRODUCTION

The rate of soil organic matter accumulation depends largely on the quantity and quality of organic matter input. Under tropical conditions, applications of readily degradable materials with low C:N ratios, such as green manure and leguminous cover crops, favour decomposition and a short-term increase in the labile nitrogen pool during the growing season. On the other hand, applications of plant materials with both large C:N ratios and lignin contents such as cereal straw and grasses (Figure 5) generally favour nutrient immobilization, organic matter accumulation and humus formation, with increased potential for improved soil structure development.

Plant constituents such as lignin and other polyphenols retard decomposition. In an experiment in southern Nigeria to compare management effects on soil organic matter accumulation, a three-year fallow with Guinea grass (*Panicum maximum*), which has a high lignin content, maintained a carbon level comparable to that under forest fallow.

FIGURE 5

Composition of leaves and roots of leguminous and grass species



Source: Primavesi, 1984

However, fallowing with leguminous species such as pigeon pea (*Cajanus cajan*) caused a significant decline in soil total C (Juo and Lal, 1977).

Palm and Sanchez (1990) reported that both the decomposition rate and the N-release patterns of three tropical legumes (*Inga edulis*, *Cajanus cajan*, and *Erythrina* spp.) were related to the amount of polyphenol compounds such as lignin in the leaf. *Erythrina* leaves had the lowest concentrations of polyphenols and the fastest decomposition rate of the three species studied.

Root turnover also constitutes an important addition of humus into the soil, and consequently it is important for carbon sequestration. In forests, most organic matter is added as superficial litter. However, in grassland ecosystems, up to two-thirds of organic matter is added through the decay of roots (Quideau, 2002).

Chapter 4

Practices that influence the amount of organic matter

HUMAN INTERVENTIONS THAT INFLUENCE SOIL ORGANIC MATTER

Various types of human activity decrease soil organic matter contents and biological activity. However, increasing the organic matter content of soils or even maintaining good levels requires a sustained effort that includes returning organic materials to soils and rotations with high-residue crops and deep- or dense-rooting crops. It is especially difficult to raise the organic matter content of soils that are well aerated, such as coarse sands, and soils in warm-hot and arid regions because the added materials decompose rapidly. Soil organic matter levels can be maintained with less organic residue in fine-textured soils in cold temperate and moist-wet regions with restricted aeration.

Practices that decrease soil organic matter

Any form of human intervention influences the activity of soil organisms (Curry and Good, 1992) and thus the equilibrium of the system. Management practices that alter the living and nutrient conditions of soil organisms, such as repetitive tillage or burning of vegetation, result in a degradation of their microenvironments. In turn, this results in a reduction of soil biota, both in biomass and diversity. Where there are no longer organisms to decompose soil organic matter and bind soil particles, the soil structure is damaged easily by rain, wind and sun. This can lead to rainwater runoff and soil erosion (Plate 3), removing the potential food for organisms, i.e. the organic matter of the topsoil. Therefore, soil biota are the most important property of the soil, and "when devoid of its biota, the uppermost layer of earth ceases to be soil" (Lal, 1991).

The factors leading to reduction in soil organic matter in an open cycle system (Figure 6) can be grouped as factors that result in:

- a decrease in biomass production;
- a decrease in organic matter supply;
- increased decomposition rates.

DECREASE IN BIOMASS PRODUCTION

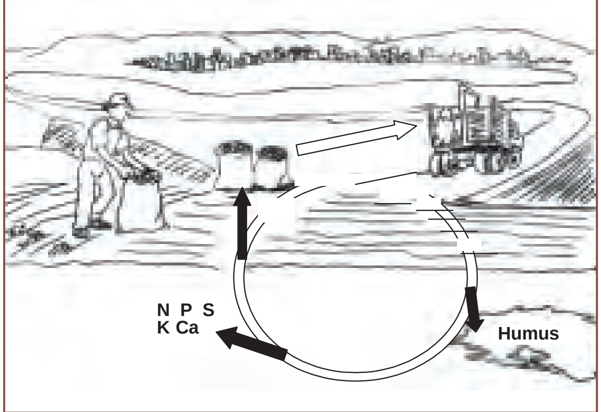
Replacement of perennial vegetation

A consequence of clearing forest for agriculture is the disappearance of the litter layer, with a consequent reduction in the


P. MUELLER

Plate 3
Severe soil erosion removes the potential energy source for soil microbes, resulting in the death of the microbial population and thus of the soil itself.

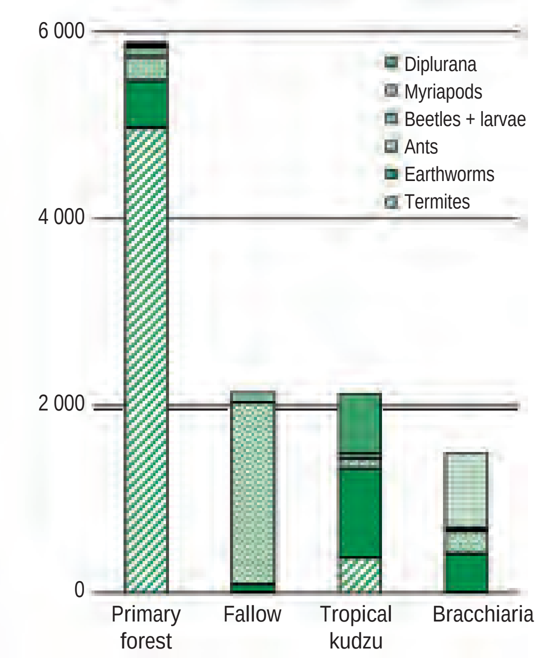
FIGURE 6
Open cycle system



numbers and variety of soil organisms. While many temperate forest species appear to adapt well to grassland (Curry and Good, 1992), the effects of deforestation in the tropics appear to be more marked (Plate 4). Studies have shown that as soil biodiversity declines, adapted species may take over from the indigenous species and the composition may change drastically.

Soil macrofaunal biomass and population density fell to 6 and 17 percent, respectively, in cultivated plots, compared with primary forest in Peruvian Amazonia (Lavelle and Pashanasi, 1989). In Suriname, the number of animals per square metre has fallen to 36 percent and the diversity of species has fallen to 28 percent compared with primary forest (Van der Werff, 1990). The indigenous species have largely disappeared, but adapted species have been available for recolonization. The composition of the macrofaunal community has changed drastically (Figure 7).

FIGURE 7
Composition of soil macrofauna under primary forest, fallow, kudzu and grass vegetation



Source: Van der Werff, 1990

A.G. BOT

Plate 4
Clearance of primary forests often leads to rapid mineralization of organic matter. This sandy soil used to sustain a tropical forest.

Replacement of mixed vegetation with monoculture of crops and pastures

The simplification of vegetation and the disappearance of the litter layer under grassland and monocrop production systems lead to a decrease in faunal diversity. Although root systems (especially of grasses) can be extensive and explore vast areas of soil, the root exudates from one single crop will attract only a few different microbial species. This in turn will affect the predator diversity. The more opportunistic pathogen species will be able to acquire space near the crop and cause harm. Continuous cultivation and grazing also leads to compaction of soil layers, which in turn affects the circulation of air. Anaerobic conditions in the soil stimulate the growth of different micro-organisms, resulting in more pathogenic organisms.

High harvest index

One of the consequences of the green revolution was the replacement of indigenous varieties of species with high-yielding varieties (HYVs). These HYVs often produce more grain and less straw, compared with locally developed varieties; the harvest index of the crop (ratio of grain to total plant mass aboveground) is increased. From a production point of view, this is a logical approach. However, this is less desirable from a conservation point of view. Reduced amounts of crop residues remain after harvest for soil cover and organic matter, or for grazing of livestock (which results in manure). Moreover, where animals graze the residues, even less remains for conservation purposes.

Use of bare fallow

Traditionally, a fallow period is used after a period of crop production to give the land some "rest" and to regenerate its original state of productivity. Usually, this is necessary in production systems that have drawn down the nutrient supply and altered the soil biota significantly, such as in slash-and-burn systems or conventional tillage systems.

Some farmers use bare fallow to regenerate their lands. However, apart from spontaneous weed growth, this means there is no energy source for the soil biota present on the land. Instead of recovering the soil food web, the soil organic matter is degraded further and the lack of cover can result in severe erosion and runoff when the rains start after the dry season.


A.J. BOT

Plate 5
The burning of residues is a common practice for clearing land, both in slash-and-burn systems and in more intensive agricultural production systems.

DECREASE IN ORGANIC MATTER SUPPLY

Burning of natural vegetation and crop residues

The burning of maize, rice and other crop residues in the field is a common practice (Plate 5). Residues are usually burned to help control insects or diseases or to make fieldwork easier in the following season. Burning destroys the litter layer and so diminishes the amount of organic matter returned to the soil. The organisms that inhabit the surface soil and litter layer are also eliminated. For future decomposition to take place, energy has to be invested first in rebuilding the microbial community before plant nutrients can be released. Similarly, fallow lands and bush are burned before cultivation. This provides a rapid supply of P to stimulate seed germination. However, the associated loss of nutrients, organic matter and soil biological activity has severe long-term consequences.

Overgrazing

There is a tendency throughout the world to overstock grazing land above its carrying capacity. Cows, draught animals and small ruminants graze on communal grazing areas and on roadsides, stream banks and other public land (Plate 6). Overgrazing destroys the most palatable and useful species in the plant mixture and reduces the density of the plant cover, thereby increasing the erosion hazard and reducing the nutritive value and the carrying capacity of the land.

Removal of crop residues

Many farmers remove residues from the field for use as animal feed and bedding or to make compost (Plate 7). Later, these residues return to contribute to soil fertility as manures or composts. However, residues are sometimes removed from the field and not returned. This removal of plant material impoverishes the soil as it is no longer possible to recycle the plant nutrients present in the residues.


R. FAIDUTTI/FAO/19452

Plate 6
Animal at pasture in the area around Asmara.

Plate 7
Removed crop residues cannot serve as food for soil organisms.

TABLE 3
Tillage induced flush of decomposition of organic matter

Type of tillage	Organic matter lost in 19 days (kg/ha)
Mouldboard plough + disc harrow (2x)	4 300
Mouldboard plough	2 230
Disc harrow	1 840
Chisel plough	1 720
Direct seeding	860

Source: Glanz, 1995

INCREASED DECOMPOSITION RATES

Tillage practices

Tillage is one of the major practices that reduces the organic matter level in the soil. Each time the soil is tilled, it is aerated. As the decomposition of organic matter and the liberation of C are aerobic processes, the oxygen stimulates or speeds up the action of soil microbes, which feed on organic matter. This means that:

- When ploughed, the residues are incorporated in the soil together with air and come into contact with many micro-organisms, which accelerates the carbon cycle. The decomposition is faster, resulting in the formation of less stable humus and an increased liberation of CO_2 to the atmosphere, and thus a reduction in organic matter.
- The residues on the soil surface slow the carbon cycle because they are exposed to fewer micro-organisms and thus wane more slowly, resulting in the production of humus (which is more stable), and liberating less CO_2 to the atmosphere.

In terms of short-term organic matter loss, the more a soil is tilled, the more the organic matter is broken down (Table 3). There are also longer-term losses, attributed to repeated, annual cultivation. Cropping systems that return little residue to the soil accelerate this decline. Many modern cropping systems combine frequent tillage with small amounts of residue, with resultant reductions in the organic matter content of many soils. Historically, manure application (from farm livestock) was common, and it was a dynamic way of maintaining organic matter levels despite repeated cultivation and low residue returns to the soil. Increased on-farm mechanization has reduced livestock numbers, so this source of organic material has been reduced considerably.

Organic matter production and conservation is affected dramatically by conventional tillage, which not only decreases soil organic matter but also increases the potential for erosion by wind and water (Plate 8). The impact occurs in many ways:

- Ploughing leaves no residues on the soil surface to lessen the impact of rain.
- Ploughing reduces the quantity of food sources for earthworms and disturbs their burrows and living space, hence populations of certain species decrease drastically. Moreover, reduction of earthworm numbers reduces their impact, through burrowing, in increasing porosity and aeration (particularly continuous macropores) and lowers their ability to bury and incorporate plant residues, which facilitates rapid decomposition of organic matter.
- Tillage by repeated hoeing or discing smoothes the surface and destroys natural soil aggregates and channels that connect the surface with the subsoil, leaving the soil susceptible to erosion. Old root channels and earthworm holes are eliminated, as are the cracks between natural aggregates. The large pores, the ones destroyed by conventional tillage practices, are necessary to conduct water into the soil during rainfall.
- The development of a plough pan or hoe pan, a layer of compacted soil resulting from smearing action at the bottom of the plough or hoe, may retard both root penetration and water infiltration.

- Ploughing or discing under dry conditions exacerbates the pulverization of the soil, causing the soil surface to crust more easily, leading to greater water runoff and erosion. This is exacerbated by reduced soil surface roughness, which leaves few depressions for temporary storage of water during intense storms.
- Increased runoff during rainstorms may also increase the possibility of drought stress later in the season, because water that runs off the field does not infiltrate into the soil to remain available to plants.

In some circumstances, imbalances of certain soil organisms can disrupt soil structure and processes, e.g. certain earthworm species in rice fields or pastures.


R. JONES/FAO/19862

Plate 8

Intensive soil tillage makes the land vulnerable to erosive processes, as the organic matter is lost through increased oxidation in the soil, the upper subsoil is compact, and the loosened topsoil can more readily wash away.

Drainage

Decomposition of organic matter occurs more slowly in poorly aerated soils, where oxygen is limiting or absent, compared with well-aerated soils. For this reason, organic matter accumulates in wet soil environments. Soil drainage is determined strongly by topography – soils in depressions at the bottom of hills tend to remain wet for extended periods of time because they receive water (and sediments) from upslope. Soils may also have a layer in the subsoil that inhibits drainage, again exacerbating waterlogging and reduction in organic matter decomposition. In a permanently waterlogged soil, one of the major structural parts of plants, lignin, does not decompose at all. The ultimate consequence of extremely wet or swampy conditions is the development of organic (peat or muck) soils, with organic matter contents of more than 30 percent. Where soils are drained artificially for agricultural or other uses, the soil organic matter decomposes rapidly.

Fertilizer and pesticide use

Initially, the use of fertilizer and pesticides enhances crop development and thus production of biomass (especially important on depleted soils). However, the use of some fertilizers, especially N fertilizers, and pesticides can boost micro-organism activity and thus decomposition of organic matter. The chemicals provide the micro-organisms with easy-to-use N components. This is especially important where the C:N ratio of the soil organic matter is high and thus decomposition is slowed by a lack of N.

PRACTICES THAT INCREASE SOIL ORGANIC MATTER

Increased concern about the environmental and economic impacts of conventional crop production has stimulated interest in alternative systems. Central to such systems is the need to promote and maintain soil biological processes and minimize fossil fuel inputs in the form of fertilizers, pesticides and mechanical cultivation. All activities aimed at the increase of organic matter in the soil (Box 3) help in creating a new equilibrium in the agro-ecosystem.

For a system of natural resource management to be balanced, and thus sustainable, it must be able to withstand sharp climatic fluctuations, and to evolve steadily in response to social changes and changes in the costs and availability of inputs of land,

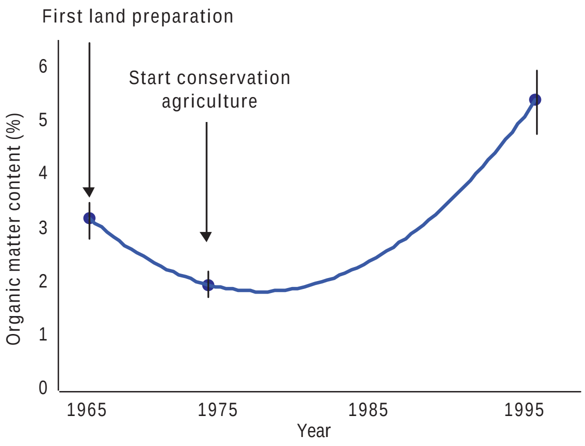
BOX 3

Ways to increase organic matter contents of soils

- compost
- cover crops/green manure crops
- crop rotation
- perennial forage crops
- zero or reduced tillage
- agroforestry

FIGURE 8

Evaluation of the organic matter content of a soil in Paraná



Source: adapted from Derpsch, 1997.

labour and knowledge. The more diverse and complex an agricultural system is, the more stable and sustainable it will be in the face of unpredictable vagaries of climate and market. Thus, annual crops, woody perennials and non-woody perennials may be combined in various ways with livestock or trees, or both, in what are now commonly called agrosilvipastoral systems.

Different approaches are required for different soil and climate conditions. However, the activities will be based on the same principle: increasing biomass production in order to build active organic matter. Active organic matter provides habitat and food for beneficial soil organisms that help build soil structure and porosity, provide nutrients to plants, and improve the water holding capacity of the soil.

Several cases have demonstrated that it is possible to restore organic matter levels in the soil (Figure 8). Activities that promote the accumulation and supply of organic matter, such as the use of cover crops and refraining from burning, and those that reduce decomposition rates, such as reduced and zero tillage, lead to an increase in the organic matter content in the soil (Sampson and Scholes, 2000).

INCREASED BIOMASS PRODUCTION

Increased water availability for plants: water harvesting and irrigation

In dry conditions, water may be provided through irrigation or water harvesting. The increased water availability enhances biomass production, soil biological activity and plant residues and roots that provide organic matter.

The concept of water harvesting includes various technologies for runoff management and utilization. It involves capture of runoff (in some cases through treating the upstream capture area), and its concentration on a runon area for use by a specific crop (annual or perennial) in order to enhance crop growth and yields, or its collection and storage for supplementary irrigation or domestic or livestock purposes. The objective of designing a water harvesting system is to obtain the best ratio of the area yielding runoff to either the area where runoff is being directed or the capacity of the storage structure (volume of water collected). In this way, the water captured for crop production during runoff periods can be stored either directly in the soil for subsequent use by plants or in small farm reservoirs or collection tanks (Plate 9). This aids stabilization of crop production by enhancing soil moisture availability or allowing irrigation during a dry period within the rainy season or by extending crop production into the dry season. Some factors to be considered regarding these runoff farming systems and reservoirs include: site selection, watershed size and condition, rainfall distribution and runoff, and water requirements of crops. Where a minimum water depth of about 1 m can be maintained in a reservoir, fish can be raised to provide additional food (FAO, 1984).

Numerous water harvesting systems have been developed over the centuries, especially in arid areas. The principle of collecting runoff for crop production is also inherent to many other soil and water conservation technologies that apply the concept of runoff and runon areas at a microwatershed level, such as negarims, trapezoidal or "eyebrow" bunds and tied ridges.

Plate 9
Hollows are dug in the ground to gather water during the rainy season.

Balanced fertilization

Where the supply of nutrients in the soil is ample, crops are more likely to grow well and produce large amounts of biomass. Fertilizers are needed in those cases where nutrients in the soil are lacking and cannot produce healthy crops (FAO, 2000) and sufficient biomass. Most soils in sub-Saharan Africa (SSA) are deficient in P. P is required not only for plant growth but also for N fixation. Unbalanced fertilization, for example mainly with N, may result in more weed competition, higher pest incidence and loss of quality of the product. Unbalanced fertilization eventually leads to unhealthy plants. Therefore, fertilizers should be applied in sufficient quantities and in balanced proportions. The efficiency of fertilizer use will be high where the organic matter content of the soil is also high. In very poor or depleted soils, crops use fertilizer applications inefficiently. When soil organic matter levels are restored, fertilizer can help maintain the revolving fund of nutrients in the soil by increasing crop yields and, consequently, the amount of residues returned to the soil.

Cover crops

Growing cover crops is one of the best practices for improving organic matter levels and, hence, soil quality. The benefits of growing cover crops include:

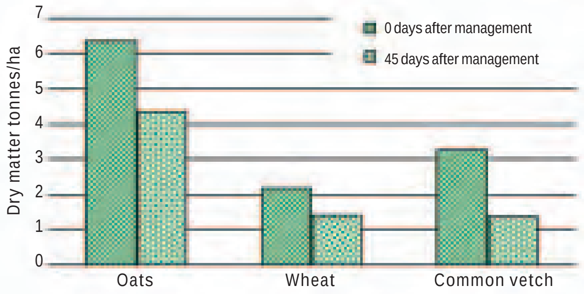
- They prevent erosion by anchoring soil and lessening the impact of raindrops.
- They add plant material to the soil for organic matter replenishment.
- Some, e.g. rye, bind excess nutrients in the soil and prevent leaching.
- Some, especially leguminous species, e.g. hairy vetch, fix N in the soil for future use.
- Most provide habitat for beneficial insects and other organisms.
- They moderate soil temperatures and, hence, protect soil organisms.

A range of crops can be used as vegetative cover, e.g. grains, legumes and oil crops. All have the potential to provide great benefit to the soil. However, some crops emphasize certain benefits; a useful consideration when planning a rotation scheme. It is important to start the first years with (cover) crops that cover the surface with a large amount of residues that decompose slowly (because of the high C:N ratio). Grasses and cereals are most appropriate for this stage, also because of their intensive rooting system, which improves the soil structure rapidly.

In the following years, when soil health has begun to improve, legumes can be incorporated in the rotation. Leguminous crops enrich the soil with N and their residues decompose rapidly because of their low C:N ratio. Later, when the system is stabilized, it is possible to include cover crops with an economic function, e.g. livestock fodder.

The selection of cover crops should depend on the presence of high levels of lignin and phenolic acids. These give the residues a higher resistance to decomposition and thus result in soil protection for a longer period and the production of more stable humus.

FIGURE 9
Reduction of dry matter of different cover crops



Source: Ruedell, 1995

Another determining factor in the dynamics of residue composition is the biochemical composition of the residues. Depending on species, their chemical components and the time and way of managing them, there will be differences in decomposition rates (Figure 9). The grain species (oats and wheat) show more resistance than common vetch (legume) to decomposition. The latter has a lower C:N ratio and a lower lignin content and is thus subject to a rapid decomposition.

Agricultural production systems in which residues are left on the soil surface, such as direct seeding and the use of cover crops, stimulate the development and activity of soil fauna at many levels.

The term green manure is often used to indicate the same plant species that are used as cover crops. However, green manure refers specifically to a crop in the rotation grown for incorporation of the non-decomposed vegetative matter in the soil. While this practice is used specifically to add organic matter, this is not the most effective use of organic matter (especially in hot climates) for two reasons:

- Mechanical disturbance of the soil should be avoided as much as possible.
- When biomass is incorporated in the soil all at one time, there is a short period of high microbial activity in decomposing the material. This results in the sudden release of a large quantity of nutrients that cannot be captured by the seedlings of the following crop and is thus lost from the system.

In general, the greater the production of green manure or crop biomass, the greater is the microbial, mesofauna and macrofauna population of the soil – from fungi and micro-organisms to earthworms and termites. The dynamics of surface residue decomposition depend *inter alia* on the activity of micro-organisms and also on soil mesofauna and macrofauna. The macrofauna consists mainly of earthworms, beetles, termites, ants, millipedes, spiders, snails and slugs. These organisms help integrate the residues into the soil and improve soil structure, porosity, water infiltration, and through-flow through the creation of burrows, ingestion and secretions.

The natural incorporation of cover-crop and weed residues from the soil surface to deeper layers in the soil by soil macrofauna is a slow process. The activity of micro-organisms is regulated by the activity of the macrofauna, because the latter provide them with food and air through their bioturbation activities. In this way, nutrients are released slowly and can provide the crop with nutrients over a longer period. At the same time, the soil is covered for a long time by the residues and is protected against the impact of rain and sun.

Improved vegetative stands

In many places, low plant densities limit crop yields. Wide plant spacing is often practised as “a way to return power to the soil” or “to give the soil some rest”, but in reality it is an indicator that the soil is impoverished. Plant spacing is usually determined by farmers in relation to soil fertility and available water or expected rainfall (unless standard recommendations are enforced by extension). This means that plants are often spaced widely on depleted soils in arid and semi-arid regions with a view to ensuring an adequate provision of plant nutrients and water for all plants.

However, it is important to maintain the recommended plant spacing in order to optimize biomass production and rooting density and, hence, organic matter for food, moisture retention and habitat for soil organisms. Once the crop is established, reduced

BOX 4

Planting pits

Planting pits achieve fast rehabilitation of severely degraded land, especially in a semi-arid climate where a short fallow period of natural grass growth (2–6 years after 2–3 years under crops) cannot be expected to maintain or restore the land's agricultural productivity (FAO, 1994).

An example of the rapid restoration of productivity of degraded land is an indigenous method in the Sahel region called "zaï" (FAO, 1994). During the dry season, farmers dig out pits 15 cm deep and 40 cm in diameter every 80 cm, tossing the earth downhill. The dry desert Harmattan wind blows various organic residues into the excavated pits. The organic materials are consumed quickly by termites, which excavate tunnels through the crusted surface, allowing the first rains to soak down deep, out of danger of direct evaporation.

Two weeks before the onset of the rains, farmers spread one or two handfuls of dry dung (1–2.5 tonnes/ha) in the bottom of the pits and cover it with earth to prevent the rains from eroding away the organic matter.

Millet is sown into the pits at the onset of the rainy season. As the first rains wash over the surface crust (of the degraded land), the basins capture this runoff (enough to soak a pocket of soil up to 1 m in depth). The sown seeds germinate, break up the slaked surface crust and send roots down to the deeper stores of both water and nutrients (recycled by the termites).

At harvest time, stalks are cut at a height of 1 m and left *in situ* to reduce wind-speed and trap wind-borne organic matter. In the second year, the farmer either digs new basins between the first ones and dresses them with manure, or pulls up the stubble and sows again in the old basins. Stubble clumps laid between basins are in turn used as a food source by termites.

sunlight between closer crop rows may also reduce regrowth of weeds.

Planting pits are a way of increasing biomass production and crop yields on severely degraded land in semi-arid conditions. Rainfall is concentrated near the plants, and soil faunal activity and organic matter accumulation are concentrated in the planting pits (Box 4 and Plate 10). Planting pits have been introduced successfully in Zambia as a conservation practice for smallholder farmers, who do not have fertilizers or tractor services available to them.

Agroforestry and alley cropping

Agroforestry is a collective name for land-use systems where woody perennials (trees, shrubs, palms, etc.) are integrated in the farming system (FAO, 1989). Alley cropping is an agroforestry system in which crops are grown between rows of planted woody shrubs or trees. These are pruned during the cropping season to provide green manure and to minimize shading of crops (FAO, 1993).


T.F. SHAXSON

Plate 10
Half-moons around newly planted Acacia seedlings catch and retain rainwater.

Agroforestry covers a wide range of systems (Box 5) combining food crops, forestry and pasture species in different ways (agrosilviculture, silvipasture, agrosilvipasture and multipurpose forest production). There are two different approaches to agroforestry. One uses agricultural crops or pasture as a transitional means of utilizing the land until forest plantations

BOX 5

Examples of agroforestry systems worldwide

Poro (*Erythrina poeppigiana*) has been grown extensively in coffee plantations in Costa Rica for shade, soil enrichment, live mulching and live fences.

Albizzia spp. have been used in tea plantations in many Asian countries.

In Indonesia, leucaena (*Leucaena leucocephala*) has been planted as contour hedges on hillsides for erosion control, soil improvement and green mulch. It is estimated that some 20 000 ha of undulating land have been converted to these systems.

In West Africa and Rwanda, many farmers use trees, fruit trees, bushes and grasses planted with agricultural crops on their farms.

Many coconut plantations in the Caribbean are partly planted with bananas or used as pastures. Some small farms in Jamaica plant coconuts, banana and citrus together.

(FAO, 1989)

are fully established. The other is to integrate trees and shrubs permanently into the crop or animal production system, to the benefit of both crop production and land resource protection. Thus, agroforestry encompasses many traditional land-use systems such as home gardens, shifting cultivation and bush fallow systems (FAO, 1989).

Alley cropping can be considered an improved bush fallow system. Small trees or shrubs are planted in cropland in rows, preferably along the contour (even where east–west orientation of the rows may minimize shading of crops). The optimal spacing between rows depends on: slope; soil type and its susceptibility to erosion; rainfall; crop species; and the soil and crop management system (FAO, 1995).

Besides adding organic matter to the system, perennial trees and shrubs recycle plant nutrients from deeper soil layers through their rooting system. Through litter and pruning, these can be used again by annual crops. Probably the most important contribution of perennials in a production system lies in the fact that throughout the whole year their roots excrete root exudates and decaying root cells, which in turn are used as an energy source by soil micro-organisms. The food web in the soil is maintained, even during dry seasons when no annual crops are grown. The result is that soil biota are in place to provide the crop with nutrients at the beginning of the next cropping season.

Direct seeding is the easiest and cheapest way of establishing hedgerows around fields or in the fields (alleys). However, emerging seedlings may not be able to compete with weeds without additional care. Therefore, starting plant growth in a nursery and transplanting may be necessary for some species. Other species may be established by cuttings. With good establishment, the plants will be better able to withstand both dry spells and browsing by livestock. Crucial to a successful establishment of the hedgerow is that the selected plants should be tall enough to outgrow the weeds at the time of the first crop harvest.

P. MUELLER

Plate 11
Agroforestry plot with suboptimal stand of maize because of shading by trees.

During the cropping season, hedgerow pruning is needed in order to avoid shading of the crop (Plate 11). The timing, frequency and extent of pruning depend on the species used and the season. As a general rule, the lower the hedgerows and the taller the crop, the less frequently is pruning required. Fast-growing plants such as *Leucaena leucocephala* and *Gliricidia sepium* may require pruning every six weeks during the cropping season. They are often pruned to a height of about 50 cm. Care must be exercised as too frequent pruning can result in tree dieback.

The integration of trees and woody shrubs into the cropping system offers additional uses

BOX 6
Farmers' perceptions of the Quezungual system: benefits and disadvantages

The Quezungual system has many benefits according to local farmers:
- improved soil moisture conservation, which permits a good development of the crop even during the dry spells of 2–4 weeks halfway through the rainy season (and during the dry period of El Niño in 1997);
- production of fuelwood and fruits from the trees and shrubs;
- agricultural production is greater than in traditionally managed plots;
- plots with the Quezungual system can be cultivated for longer periods than under the slash-and-burn system;
- timber trees can be cut after about 7 years and used for construction and/or sold;
- the mulch obtained through the pruning of the trees and shrubs protects the soil surface from the impact of rain showers, thus there is less soil erosion (even during the heavy rains produced by hurricane "Mitch" in 1998 there was little soil erosion);
- minimal labour is required to establish and maintain the Quezungual system;
- the soil becomes more fertile and the effect of fertilizers on production improves;
- the workability of the soil improves because the soil becomes softer, hence less labour is needed during sowing;
- the Quezungual system provides shade for farmers while they work the plot;
- harvested products, such as beans and maize, can be dried by hanging them over the tree trunks;
- cattle can feed on the residues after maize and sorghum harvests;
- mulch cover reduces the incidence of disease in the bean crop;
- the presence of trees and shrubs in the plot attracts animals and insects, e.g. birds and butterflies.

Disadvantages mentioned by the farmers are:
- in the first year, the production is the same as or slightly less than grain production obtained with the traditional system;
- in the early years of implementation, the incidence of slugs in the bean crop is greater.
- too much soil cover can impede seed germination;
- the shade of the Quezungual system can result in a higher incidence of disease during intense rainfall periods (because of greater humidity).

(FAO, 2001)

and many benefits, as mentioned by farmers using the Quezungual system in Honduras (Plate 12 and Box 6). However, farmers with short-term land tenure may not be interested in these benefits. Furthermore, the plantation of trees sometimes has an effect on the land tenure status; therefore tenants may not be allowed to establish trees on agricultural land. Agroforestry systems can also inhibit mechanization and may need increased labour inputs, especially for hedgerow pruning.

The hedgerow species have to be selected carefully in order to avoid negative impacts on crop production because of the complex relationships (competition for light, water and nutrients, allelopathy, occurrence of pest and diseases, etc.) that are inherent to agroforestry

NELSON GONZALEZ

Plate 12
Example of the "Quezungual" system, an indigenous agroforestry system.

systems. Many farmers may consider the hedgerows as not useful, especially where their positive effects are not secure or visible. Where livestock are allowed to graze freely, it can be difficult to establish hedgerows without taking special measures to protect the young plants. Fencing or control of grazing animals may require collective efforts and agreement by the local community.

The increased labour requirement, the reduced cropped area and the difficulty of mechanization may make alley cropping uneconomic unless the hedgerow species produce direct benefits such as fruits, fuelwood or poles/timber for construction purposes (in addition to the nutrient recycling and erosion control effects).


FAO

Plate 13
Afforestation of "badlands" in the Niger.

Reforestation and afforestation

Afforestation means the establishment of a forest on land that has not grown trees recently. It can serve two principal soil and water conservation purposes: protection of erosion-prone areas, and revegetation and rehabilitation of degraded land (Plate 13). Afforestation is specifically used to provide protective cover in vulnerable, steep and mountainous areas. Afforestation helps to replenish timber resources and provide fuelwood and fodder (FAO, 1979).

The establishment of a forest cover under good management is an effective means of increasing organic matter production. However, the land must have the productive capacity to support an appropriate forest type, which differs according to climate, soil, slope and the specific purpose of the forest (timber production, livestock grazing, etc.). Therefore, the choice of species and the selection of an appropriate site are of particular importance for successful afforestation.

The procurement of adequate quantities of good quality seed of the species and provenances (adapted varieties) required is a prerequisite for any afforestation effort. However, it is often difficult to find suitable and reliable sources of such seeds.

A number of species require special pre-treatment of the seed or seedling in order to achieve satisfactory germination and uniform stand. Such treatment may consist of soaking the seed in water for varying lengths of time, alternate soaking and drying, scarifying or chipping the seed coat to render it permeable to water, plunging the seed into boiling water or even boiling it for a short time. Some tree seedlings may need a mycorrhizal treatment when planted in soils that are deprived of associated mycorrhizae species as well as rhizobium species (e.g. *Casuarina* in Senegalese sandy soils). The aim is to ensure that good numbers of plants germinate and that germination after sowing is both rapid and uniform (FAO, 1974).

Afforestation can be achieved by direct sowing or replanting young plants from a nursery. The main advantage of direct sowing is the reduced cost. However, this is usually much less reliable and is only justified where:

- seed is plentiful and cheap;
- adequate germination under field conditions can be relied on;
- the seedlings send down a deep tap root rapidly and are able to withstand adverse climatic conditions in the time after germination;
- the rate of growth is sufficiently fast to make a prolonged period of tending and weeding unnecessary.

Regeneration of natural vegetation

Regeneration of natural grasslands and forest areas increases biomass production and improves the plant species diversity, resulting in more diverse soil biota and other associated beneficial organisms. Natural regeneration may be more reliable where land is not very productive. In some cases, natural regeneration of a given area may lead to the infestation of plots by weeds. Increasingly, natural vegetation is being recognized for its multipurpose benefits, for example, fuelwood, fibre, biocontrol (e.g. neem) and medicinal species, as well as restoration of soil fertility (*Acacia albida* and other leguminous species) and habitats for various beneficial species (pollinators and natural enemies) as well as wildlife.

INCREASED ORGANIC MATTER SUPPLY

Protection from fire

Burning affects organic matter recycling significantly. Fire destroys almost all organic materials on the land surface except for tree trunks and large branches. In addition, the surface soil is sterilized, loses part of its organic matter, the population of soil microfauna and macrofauna is reduced, and no ready-to-use organic matter is available for rapid restoration of the populations. However, this practice is widely used (e.g. in Africa) in order to enhance pasture regrowth for livestock (using residual P), to control pests and diseases, and even to catch small animals for food.

A specific and difficult case is the burning of sugar cane before harvesting. It has both a technical dimension (CO_2 and greenhouse gas emissions, mechanization of harvest, sugar content, etc.) and a social dimension (manual cutting, source of survival resources for poor/landless workers). The damage depends on fire intensity, which is a function of vegetation type and climate conditions and frequency. The costs and benefits of burning and the methods to minimize harmful effects need to be identified with local populations.

Crop residue management

In systems where crop residues are managed well, they:

- add soil organic matter, which improves the quality of the seedbed and increases the water infiltration and retention capacity of the soil, buffers the pH and facilitates the availability of nutrients;
- sequester (store) C in the soil;
- provide nutrients for soil biological activity and plant uptake;
- capture the rainfall on the surface and thus increase infiltration and the soil moisture content;
- provide a cover to protect the soil from being eroded;
- reduce evaporation and avoid desiccation from the soil surface.

Depending on the nature of the following crop, decisions are made as to whether the residues should be distributed evenly over the field or left intact, e.g. where climbing cover crops (e.g. mucuna) use the maize stalks as a trellis.

An even distribution of residues: (i) provides homogenous temperature and humidity conditions at sowing time; (ii) facilitates even sowing, germination and emergence; (iii) minimizes the development of pests and diseases; and (iv) reduces the emergence of weeds through allelopathic effects.

The most appropriate method for managing crop residues depends on the purpose of the crop residues and the experience and equipment available to the farmer. Where the aim is to maintain a mulch over the soil for as long as possible, the biomass is best managed using a knife roller, chain or sledge in order to break it down but not kill it (Plate 14). Where the decomposition process should commence immediately in order to release nutrients, the residues should be slashed or mown and some N applied because dry residues have a high C:N ratio. However, in order to avoid nitrate emission, urea should not be broadcast on the surface but injected where possible.

A.J. BOT

Plate 14
Crop residue management by using a knife roller.

Utilizing forage by grazing rather than by harvesting

In many places, there is competition for the use of crop residues that can be used as fodder, for roofing, artisan handicrafts, etc. Where residues are to be used for animal feed, either the animals graze the residues directly, or they are stall- or kraal-fed.

Removal of the residues from the field can lead to a considerable loss of organic matter where animal manure is not returned to the field. By controlled grazing, the animal manure is returned in the field without a high labour input.

The experience of Guaymango, El Salvador, demonstrates that it is possible to achieve successful integration of crop and livestock components without creating competition in the allocation of crop residues (Vieira and Van Wambeke, 2002). The amount of residues produced by the system is enough to serve both as soil cover and as fodder for livestock (Choto and Saín, 1993), mainly because of the use of local sorghum varieties (instead of HYVs) that have a high straw/grain ratio (Choto, Saín and Montenegro, 1995). As farmers value crop residues as soil cover, a fodder market has developed where grazing rights, number of cattle and duration of grazing are traded.

In the northern zone of the United Republic of Tanzania, farmers have found a compromise between using the residues for grazing or soil cover, albeit one that is rather labour intensive. They separate the palatable and non-palatable parts of the crop residues. They use the non-palatable parts to cover the soil and act as food for soil organisms, while they feed the palatable parts to cattle and goats that are kept close to the homestead (Plate 15).

Integrated pest management

As with balanced fertilization, proper pest and disease management results in healthy crops. Healthy crops produce optimal biomass, which is necessary for organic matter production in the soil. Diversified cropping and mixed crop–livestock systems enhance biological control of pests and diseases through species interactions. Through integrated production and pest management farmers learn how to maintain a healthy environment for their crops. They learn to examine their crops regularly in order to observe ratios of pests to natural enemies (beneficial predators) and cases of damage, and on that basis to make decisions as to whether it is necessary to use natural treatments (using local products such as neem or tobacco) or chemical treatments and the required applications.

R. JONES/FAO/19377

Plate 15
Farmer giving fodder to cattle

Applying animal manure or other carbon-rich wastes

Any application of animal manure, slurry or other carbon-rich wastes, such as coffee-berry pulp, improves the organic matter content of the soil. In some cases, it is better to allow a period of decomposition before application to the field. Any addition of carbon-rich compounds immobilizes available N in the soil temporarily, as micro-organisms need both C and N for their growth and development. Animal manure is usually rich in N, so N immobilization is minimal. Where straw makes up part of the manure, a decomposition period avoids N immobilization in the field.


I. BALDERI/FAO/18775

Plate 16
Preparation of compost made from discarded bits of fish and village waste. The compost plant is run by a cooperative of young people.

Compost

Composting is a technology for recycling organic materials in order to achieve enhanced agricultural production. Biological and chemical processes accelerate the rate of decomposition and transform organic materials into a more stable humus form for application to the soil. Composting proceeds under controlled conditions in compost heaps and pits (Müller-Sämann, 1986).

Compost heaps should have a minimum size of 1 m^3 and are suitable for more humid environments where there is potential for watering the compost. Compost pits (Plate 16) should be no deeper than 70 cm and should be underlain with rough material for good aeration of the compost. Pits are suitable for drier environments where the compost may desiccate (Müller-Sämann, 1986). Dry composting relies on covering the compost with soil and creating an anaerobic environment. However, this is a slower process than the more usual moist aerobic process. The ratio of C to N in the compost pile is important for optimizing microbial activity. Thus, a mixture of soft, green and brown, tougher material is used. Ash and phosphate rock are often added to accelerate the process.

Composting can complement certain crop rotations and agroforestry systems. It can be used efficiently in planting pits and nurseries. It is very similar in composition to soil organic matter. It breaks down slowly in the soil and is very good at improving the physical condition of the soil (whereas manure and sludge may break down fairly quickly, releasing a flush of nutrients for plant growth). In many circumstances, it takes time to rejuvenate a poor soil using these practices because the amount of organic material being added is small relative to the mineral proportion of the soil.

Successful composting depends upon the sufficient availability of organic materials, water, manure and “cheap” labour. Where these inputs are guaranteed, composting can be an important method of sustainable and productive agriculture. It has ameliorative effects on soil fertility and physical, chemical and biological soil properties. Well-made compost contains all the nutrients needed by plants. It can be used to maintain and improve soil fertility as well as to regenerate degraded soil. However, materials for compost production may be in short supply and the technology demands high labour inputs for proper compost production and application. Therefore, compost application may be restricted to certain crops and limited application areas, e.g. vegetable production in home gardens.

Mulch or permanent soil cover

One way to improve the condition of the soil is to mulch the area requiring amelioration. Mulches are materials placed on the soil surface to protect it against raindrop impact and erosion, and to enhance its fertility (FAO, 1995). Crop residue mulching is a system of maintaining a protective cover of vegetative residues such as straw, maize stalks, palm fronds and stubble on the soil surface (Plate 17).

The system is particularly valuable where a satisfactory plant cover cannot be established rapidly when erosion risk is greatest (FAO, 1993).

Mulching adds organic matter to the soil, reduces weed growth, and virtually eliminates erosion during the period when the ground is covered with mulch.

There are two principal mulching systems:

- *in situ* mulching systems – plant residues remain where they fall on the ground (Plate 17);
- cut-and-carry mulching systems – plant residues are brought from elsewhere and used as mulch (Plates 18 and 19).

Crop residue mulching has numerous positive effects on crop production. However, it may require a change in existing cropping practices. For example, farmers may conventionally burn crop residues instead of returning them to the soil. *In situ* mulching depends on the design of appropriate cropping systems and crop rotations, which have to be integrated with the farming system. The greater labour demands of cut-and-carry systems represent a major constraint. Mulch may be more relevant in home gardens or for valuable horticulture crops (Box 7) than in less intensive farming systems.


J. BENITES

Plate 17
No-till maize under black oat mulch, Santa Catarina, Brazil

Mulch affects the soil life. Holland and Coleman (1987) have demonstrated that litter placement on the soil surface (as opposed to incorporation with ploughing) increased the ratio of fungi to bacteria – the reason being that fungi have a higher carbon assimilation efficiency than bacteria. In addition, it encourages bioturbating (mixing) effects of macrofauna that pull the materials into surface layers of the soil.

DECREASED DECOMPOSITION RATES

Reduced or zero tillage

Repetitive tillage degrades the soil structure and its potential to hold moisture, reduces the amount of organic matter in the soil, breaks up aggregates, and reduces the population of soil fauna such as earthworms that contribute to nutrient cycling and soil structure.

Avoiding mechanical soil disturbance implies growing crops without mechanical seedbed preparation or soil disturbance since the harvest of the previous crop. The term zero tillage is used for this practice synonymously with terms such as no-till farming, no tillage, direct drilling, and direct seeding.

Compared with conventional tillage, reduced or zero tillage has two advantages with respect to soil organic matter. Conventional tillage stimulates the heterotrophic microbiological activity through soil aeration, resulting in increased mineralization rate. Through breakdown of soil structure, it decreases upward and downward movements of soil fauna, such as earthworms, which are largely responsible for "humus" production through the ingestion of fresh residues. Reduced or zero tillage


G. BIZARRI/FAO/18678

Plate 18
Farmer at work in a field of lettuces.

BOX 7

Mulching in the highlands of northern Thailand

Why certain crops receive mulch and others do not

Mulching provides a particular benefit to the cultivated crop. Mulching is practised for various cash crops for specific reasons. Onion and garlic are mulched mainly to control weeds (early hand weeding would be difficult without damaging the crop). The mulch is also important to keep the soil moist and cool as these crops are usually grown during the dry season under irrigation. Mulch is also applied under flowers and strawberries, mainly to protect the fragile and valuable products from becoming soiled.

FAO

Plate 19

Mulching in the highlands of Northern Thailand.

Mulching saves labour. Mulching is often seen in maize fields, before as well as after crop establishment. Maize can compete reasonably well with weeds. Therefore, some farmers plant maize without tillage in a mulch of weeds previously killed with herbicides – a system that is less labour-demanding than a tillage operation. Because maize is planted with large spacings, it generally requires less rigorous weeding. Weeding is often done by slashing, and the weed residues are left on the ground.

(Source: Van Keer *et al*., 1996)

regulates heterotrophic microbiological activity because the pore atmosphere is richer in CO_2/O_2, and facilitates the activity of the “humifiers” (Pieri *et al.*, 2002).

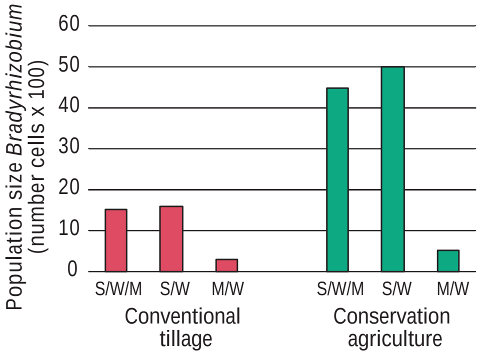
Tillage has become the most common method to control weeds. However, mulching is a more environmentally sound practice than tillage for weed control. The loose soil that results from tilling has less structure than before; the appearance is deceptive. Subsequent traffic or heavy rain soon packs this loosened soil, not only negating the expensive cultivation that produced the loose soil but also culminating in a degraded environment for water entry, seed germination and root growth. Further cultivation is then required to re-loosen the soil; more expense with the same outcome – subsequent repacking and degraded soil structure. This is a typical “downward spiral” of conventional agriculture. Moreover, tillage when the soil is too moist or too dry leads to compaction or pulverization of soil; but farmers may not have the option to wait for optimal conditions.

Severe, accelerated soil erosion and the high costs in terms of labour and energy associated with plough-based methods of seedbed preparation have led to the widespread adoption of no- or zero-tillage systems for cropping in temperate and tropical climates. In no-tillage systems, the crop is sown into a soil left undisturbed since the harvest of the previous crop. Crop residue mulch is maintained and anchored firmly to the ground. Weed control relies on mechanical slashing or cover crops (FAO, 1993). Contact herbicides are also used in some cases.

In reduced- or zero-tillage systems, soil fauna resume their bioturbating activities gradually. These loosen the soil and mix the soil components (also known as biotillage). The additional benefit of the increased soil organic matter and burrowing is the creation of a stable and porous soil structure without expensive, time-consuming and potentially degrading cultivations.

FIGURE 10

Population size of root nodule bacteria with different crop rotations



Note: S = soybean; W = wheat; M = maize.
Source: Voss and Sidirias, 1985.

In zero-tillage systems, the action of soil macrofauna gradually incorporate cover crop and weed residues from the soil surface down into the soil. The activity of micro-organisms is also regulated by the activity of the macrofauna, which provide them with food and air through their burrows. In this way, nutrients are released slowly and can provide the following crop with nutrients.

Several authors have demonstrated that some crop rotations and zero tillage favour *Bradyrhizobia* populations, nodulation and thus N fixation and yield (Voss and Sidirias, 1985, Hungria *et al.*, 1997, Ferreira *et al.*, 2000). Figure 10 indicates a 200–300-percent increase in population size of root nodule bacteria in a zero-tillage system compared with conventional tillage. The presence of soybean in the crop rotation resulted in a fivefold to tenfold increase in population size of the same bacteria compared with cropping systems without soybean.

Strictly speaking, the term zero tillage applies to methods involving no soil disturbance whatsoever, a condition that may be difficult to achieve. Broadcasting of seed is one way of applying zero tillage (Plate 20). The seed is broadcast over the previous crop residues and, where necessary, the residues are shaken to ensure that the seed falls on the soil surface.

In direct drilling, seeds such as maize, sorghum, soybean, wheat and barley are sown directly into shallow furrows cut into the previous crop residues (Plate 21). Weeds are controlled mechanically with a knife, which knocks down the plants and breaks their stems, or chemically with herbicides.

Traditional practices such as the burning of crop residues may inhibit the introduction of no-tillage systems. In many situations, a conflict exists between leaving crop residues on the surface or feeding them to livestock in the dry season when there is a shortage of fodder.

A.J. BOT

Plate 20
"Frijol tapado" or broadcast beans on the residues of maize; a common practice in Latin America.

Mechanical soil disturbance also includes soil compaction through wheel impact of machinery, especially important in large-scale mechanized agriculture, e.g. plantations (sugar cane) or biannual crops (cotton). In a zero-tillage farming system, consideration must be given to reducing both the random placement of tyres/wheels in fields as well as the potential for compaction from animal hooves. Pietola, Horn and Yli-Halla (2003) reported the destructive effect of cattle trampling on the soil structure. Proffitt, Bendotti and McGarry (1995) demonstrated the almost total loss of soil porosity in the soil surface as a result of trampling by sheep. There is a belief that draught animals cause less land degradation than tractors. However, there are reports of soil compaction on smallholder farming enterprises in both Malawi (Douglas *et al.*, 1999) and Bangladesh (Brammer, 2000). The hooves of draught animals and the shearing effect of ploughs or hand hoes, which are used repeatedly at a constant depth, can cause severe compacted layers. Grazing animals should be removed from zero-till fields in moist-wet soil conditions as the compaction risk is greatest at these times.

Plate 21
Maize seedling directly drilled in residues of wheat.

S. VANEPH

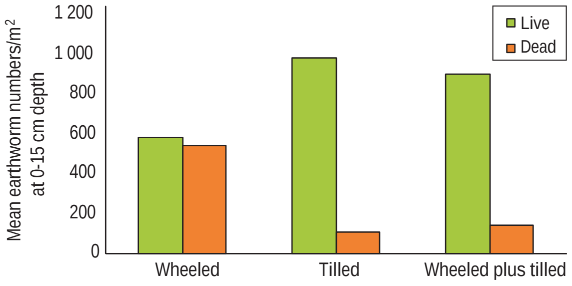
D. MCGARRY

Plate 22
A sign on a farmgate in Australia. The farmer has achieved a working combination of zero tillage and controlled traffic and is reaping the benefits of excellent water holding capacity in the soil, improved organic matter status, more guaranteed harvests, and a more predictable and rewarding farming system.

Controlled traffic, where the wheels of all in-field equipment follow permanent, defined tracks, ensures that compaction is restricted to specific known areas (Plate 22). Alternatively, flotation tyres (low ground-pressure tyres) should be fitted to all large tractors, harvesters, in-field grain bins, etc. in order to reduce their compacting potential.

Recent research has demonstrated the devastating effects of compaction from wheel impact on the occurrence and survival of eartworms (Pangnakorn *et al.*, 2003). Earthworm incidence was greater under controlled traffic than under wheeled traffic. Figure 11 shows the immediate effects of wheeling and tillage on the earthworm population. It appears that wheeling has the most detrimental effect on earthworm survival and that where wheeling is followed by tillage the survival rate is much greater. This may indicate that earthworms are able to survive an initial compaction in the field as long as it is relieved immediately. Where it is not, earthworms are inmobilized and unable to find air and nutrients.

FIGURE 11
Live and dead earthworm numbers per square metre at 0–15 cm of soil depth sampled immediately after treatment



Source: Pangnakorn *et al.*, 2003.

Chapter 5

Creating drought-resistant soil

EFFECT OF SOIL ORGANIC MATTER ON SOIL PROPERTIES

Organic matter affects both the chemical and physical properties of the soil and its overall health. Properties influenced by organic matter include: soil structure; moisture holding capacity; diversity and activity of soil organisms, both those that are beneficial and harmful to crop production; and nutrient availability. It also influences the effects of chemical amendments, fertilizers, pesticides and herbicides. This chapter focuses on those properties related to soil moisture and water quality, while Chapter 6 focuses on those related to sustainable food production.

INEFFICIENT USE OF RAINWATER

Drylands may have low crop yields not only because rainfall is irregular or insufficient, but also because significant proportions of rainfall, up to 40 percent, may disappear as runoff. This poor utilization of rainfall is partly the result of natural phenomena (relief, slope, rainfall intensity), but also of inadequate land management practices (i.e. burning of crop residues, excessive tillage, eliminating hedges, etc.) that reduce organic matter levels, destroy soil structure, eliminate beneficial soil fauna and do not favour water infiltration. However, water “lost” as runoff for one farmer is not lost for other water users downstream as it is used for recharging groundwater and river flows.

Where rainfall lands on the soil surface, a fraction infiltrates into the soil to replenish the soil water or flows through to recharge the groundwater. Another fraction may run off as overland flow and the remaining fraction evaporates back into the atmosphere directly from unprotected soil surfaces and from plant leaves.

The above-mentioned processes do not occur at the same moment, but some are instantaneous (runoff), taking place during a rainfall event, while others are continuous (evaporation and transpiration).

To minimize the impact of drought, soil needs to capture the rainwater that falls on it, store as much of that water as possible for future plant use, and allow for plant roots to penetrate and proliferate. Problems with or constraints on one or several of these conditions cause soil moisture to be one of the main limiting factors for crop growth.

The capacity of soil to retain and release water depends on a broad range of factors such as soil texture, soil depth, soil architecture (physical structure including pores), organic matter content and biological activity. However, appropriate soil management can improve this capacity.

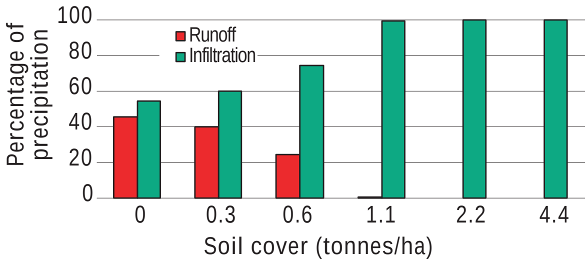
Practices that increase soil moisture content can be categorized in three groups: (i) those that increase water infiltration; (ii) those that manage soil evaporation; and (iii) those that increase soil moisture storage capacities. All three are related to soil organic matter.

In order to create a drought-resistant soil, it is necessary to understand the most important factors influencing soil moisture.

INCREASED SOIL MOISTURE

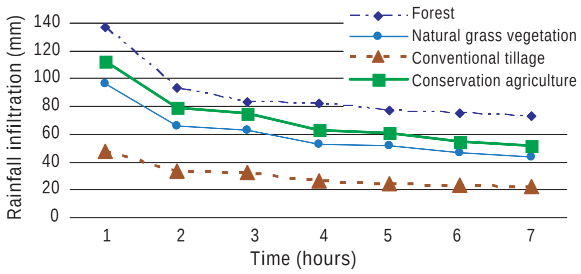
Organic matter influences the physical conditions of a soil in several ways. Plant residues that cover the soil surface protect the soil from sealing and crusting by raindrop impact, thereby enhancing rainwater infiltration and reducing runoff. Surface infiltration depends on a number of factors including aggregation and stability, pore

FIGURE 12
Effect of amount of soil cover on rainwater runoff and infiltration



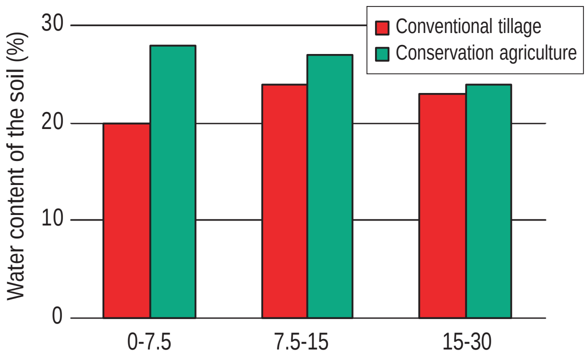
Source: Ruedell, 1994.

FIGURE 13
Water infiltration under different types of management



Source: Machado, 1976.

FIGURE 14
Quantity of water stored in the soil under conventional tillage and conservation agriculture



Source: Gassen and Gassen, 1996.

continuity and stability, the existence of cracks, and the soil surface condition. Increased organic matter contributes indirectly to soil porosity (via increased soil faunal activity). Fresh organic matter stimulates the activity of macrofauna such as earthworms, which create burrows lined with the glue-like secretion from their bodies and are intermittently filled with worm cast material.

The proportion of rainwater that infiltrates into the soil depends on the amount of soil cover provided (Figure 12). The figure shows that on bare soils (cover = 0 tonnes/ha) runoff and thus soil erosion is greater than when the soil is protected with mulch. Crop residues left on the soil surface lead to improved soil aggregation and porosity, and an increase in the number of macropores, and thus to greater infiltration rates.

Increased levels of organic matter and associated soil fauna lead to greater pore space with the immediate result that water infiltrates more readily and can be held in the soil (Roth, 1985). The improved pore space is a consequence of the bioturbating activities of earthworms and other macro-organisms and channels left in the soil by decayed plant roots.

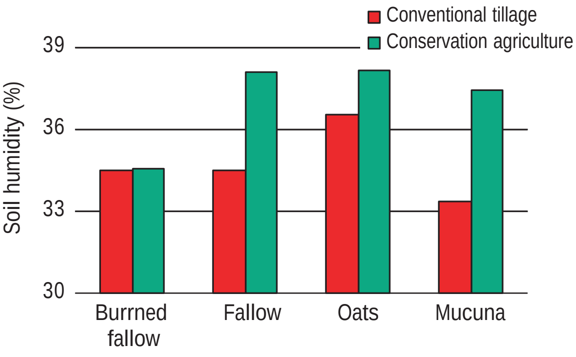
On a site in southern Brazil, rainwater infiltration increased from 20 mm/h under conventional tillage to 45 mm/h under no tillage (Calegari, Darolt and Ferro, 1998). Over a long period, improved organic matter promoted good soil structure and macroporosity. Water infiltrates easily, similar to forest soils (Figure 13).

The consequence of increased water infiltration combined with a higher organic matter content is increased soil storage of water (Figure 14). Organic matter contributes to the stability of soil aggregates and pores through the bonding or adhesion properties of organic materials, such as bacterial waste products, organic gels, fungal hyphae and worm secretions and casts. Moreover, organic matter intimately mixed with mineral soil materials has a considerable influence in increasing moisture holding capacity. Especially in the topsoil, where the organic matter content is greater, more water can be stored.

The quality of the crop residues, in particular their chemical composition, determines the effect on soil structure and aggregation. Blair *et al.* (2003) report a rapid breakdown of medic (*Medicago truncatula*) and rice (*Oryza sativa*) straw residues resulting in a rapid increase in soil aggregate stability through the release of many soil-binding components. As these compounds undergo further breakdown, they will be lost from the system resulting in a decline in soil aggregate stability over time. The slow release of soil-binding agents from flemingia (*Flemingia macrophylla*) residues resulted in a slower but more sustained increase in the stability of soil aggregates. This indicates that continual release of soil-binding compounds from plant residues is necessary for continual increases in soil aggregate stability to occur.

FIGURE 15

Effect of different soil covers on in-soil storage of water



Source: Siqueira *et al.*, 1993.

Elliot and Lynch (1984) showed that soil aggregation is caused primarily by polysaccharide production in situations where residues have a low N content. There is a strong relationship between soil carbon content and aggregate size. An increase in soil carbon content led to a 134-percent increase in aggregates of more than 2 mm and a 38-percent decrease in aggregates of less than 0.25 mm (Castro Filho, Muzilli and Podanoschi, 1998). The active fraction of soil C (Whitbread, Lefroy and Blair, 1998) is the primary factor controlling aggregate breakdown (Bell *et al.*, 1999).

In addition, although they do not live long and new ones replace them annually, the hyphae of actinomycetes and fungi play an important role in connecting soil particles (Castro Filho, Muzilli and Podanoschi, 1998). Gupta and Germida (1988) showed a reduction in soil macroaggregates correlated strongly with a decline in fungal hyphae after six years of continuous cultivation.

The in-soil storage of water depends not only on the type of land preparation but also on the type of cover or previous vegetation on the soil. Figure 15 indicates the effect of burning vegetation on the amount of water stored in the soil.

Conserving fallow vegetation as a cover on the soil surface, and thus reducing evaporation, results in 4 percent more water in the soil. This is roughly equivalent to 8 mm of additional rainfall. This amount of extra water can make the difference between wilting and survival of a crop during temporary dry periods.

A study conducted in 1999 in Guatemala, Honduras and Nicaragua to evaluate the resilience of agro-ecosystems showed that 3–15 percent more water was stored in the soil under more ecologically sound practices (Table 4).

Unger (1978) showed that high wheat-residue levels resulted in increased storage of fallow precipitation, which subsequently produced higher sorghum grain yields. High residue levels of 8–12 tonnes/ha resulted in about 80–90 mm more stored soil water at planting and about 2.0 tonnes/ha more of sorghum grain yield compared to no residue management.

The addition of organic matter to the soil usually increases the water holding capacity of the soil. This is because the addition of organic matter increases the number of micropores and macropores in the soil either by "gluing" soil particles together or by creating favourable living conditions for soil organisms. Certain types of soil organic matter can hold up to 20 times their weight in water (Reicosky, 2005). Hudson (1994)

TABLE 4

Average soil depth at which moisture starts, and difference in moisture stored

Country	Agro-ecologically sound practices cm	Conventional practices cm	Difference (%)
Honduras	9.98	10.28	2.9
Guatemala	2.44	2.99	15.0
Nicaragua	15.81	17.80	11.2

Source: World Neighbors, 2000.

TABLE 5

Economy of irrigation water through soil cover, the Brazilian Cerrados

Soil cover (%)	Water requirement (m³/ha)	Reduction in water requirement (%)	Irrigations during season (no.)	Days between irrigations (no.)
0	2 660	0	14	6
50	2 470	7	13	6
75	2 090	21	11	8
100	1 900	29	10	9

Source: Pereira, personal communication, 2001.

showed that for each 1-percent increase in soil organic matter, the available water holding capacity in the soil increased by 3.7 percent. Soil water is held by adhesive and cohesive forces within the soil and an increase in pore space will lead to an increase in water holding capacity of the soil. As a consequence, less irrigation water is needed to irrigate the same crop (Table 5).

REDUCED SOIL EROSION AND IMPROVED WATER QUALITY

The less the soil is covered with vegetation, mulches, crop residues, etc., the more the soil is exposed to the impact of raindrops. When a raindrop hits bare soil, the energy of the velocity detaches individual soil particles from soil clods. These particles can clog surface pores and form many thin, rather impermeable layers of sediment at the surface, referred to as surface crusts. They can range from a few millimetres to 1 cm or more; and they are usually made up of sandy or silty particles. These surface crusts hinder the passage of rainwater into the profile, with the consequence that runoff increases. This breaking down of soil aggregates by raindrops into smaller particles depends on the stability of the aggregates, which largely depends on the organic matter content.

Increased soil cover can result in reduced soil erosion rates close to the regeneration rate of the soil or even lower, as reported by Debarba and Amado (1997) for an oats and vetch/maize cropping system (Figure 16).

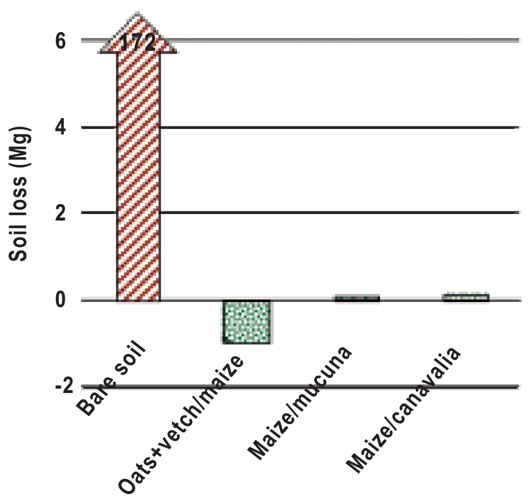
Soil erosion fills surface water reservoirs with sediment, reducing their water storage capacity. Sedimentation also reduces the buffering and filtering capacity of wetlands and the flood-control capacity of floodplains. Sediment in surface water increases wear and tear in hydroelectric installations and pumps, resulting in greater maintenance costs and more frequent replacement of turbines. Sediments can also reach the sea (Plate 23), harming fish, shellfish and coral. Eroded soil contains fertilizers, pesticides and herbicides; all sources of potentially harmful off-site impacts.

When the soil is protected with mulch, more water infiltrates into the soil rather than running off the surface. This causes streams to be fed more by subsurface flow rather than by surface runoff. The consequence is that the surface water is cleaner and resembles groundwater more closely compared with areas where erosion and runoff predominate. Greater infiltration should reduce flooding by increased water storage in soil and slow release to streams. Increased infiltration also improves groundwater recharge, thus increasing well supplies.

Bassi (2000) reported significant reductions in water turbidity and sediment concentration over a period of ten years (1988–1997) in different catchment areas in southern Brazil. The reductions varied between 50 and 80 percent depending on locally predominant soil types. These reductions were caused by increases in the incidence of planting perennial crops (banana and pasture) on hillsides, thereby decreasing erosion potential. Total sediment loss decreased by 16 percent and the cost of fertilizers declined by 21 percent; an

FIGURE 16

Soil loss due to water erosion for different maize cropping systems



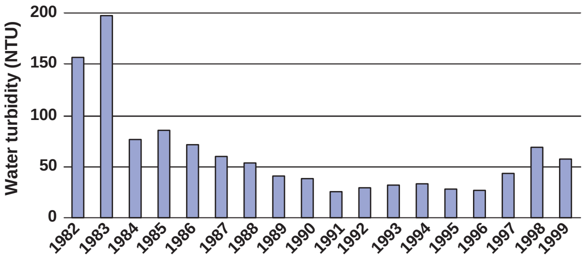
Note: Corrected with soil regeneration = 1.7 tonnes/ha/year.
Source: Debarba and Amado, 1997.

indication of the previous loss of fertilizers with the eroded soil. Guimarães, Buaski and Masquieto (2005) illustrate the same effect for one specific catchment. The catchment area of Rio do Campo, Paraná, provides 80 percent of the water supply for Campo Mourão, a city with an urban population of 357 000. In the period 1982–1999, a drastic reduction in water turbidity was measured (Figure 17).

Plate 23
Runoff and soil loss immediately after a rainstorm, Naisi catchment. Zomba Mountain, Malawi.

T.F. SHAXSON

FIGURE 17
Development of water turbidity rates in the catchment area of Rio do Campo, Paraná, 1982–1999



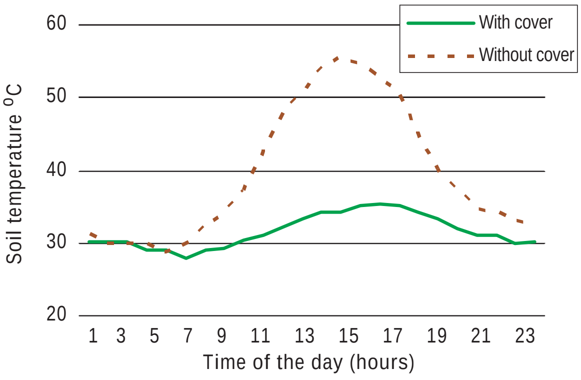
Source: Guimarães, Buaski and Masquieto, 2005.

Sediment and dissolved organic matter in surface water have to be removed from drinking-water supplies. Reduced erosion, and hence fewer soil particles in suspension, lead to lower costs for water treatment. Data from Chapecó, Brazil, indicate that the quantity of aluminium sulphate used for flocculating suspended solids fell by 46 percent in five years. Where water is chlorinated to kill disease organisms, the chlorine reacts with dissolved organic matter to form trihalomethane (THM) compounds such as chloroform. THMs are suspected of causing cancers (Fawcett, 1997). Reductions in runoff and erosion should lead to reduced formation of THMs during the chlorination process.

Erosion may also have long-lasting secondary consequences through effects on plant growth and litter input (Gregorich *et al.*, 1998). If erosion suppresses productivity, thereby limiting replenishment of organic matter, the amount of organic matter may spiral downwards in the long term.

Soil cover protects the soil against the impact of raindrops, prevents the loss of water from the soil through evaporation, and also protects the soil from the heating effect of the sun. Soil temperature influences the absorption of water and nutrients by plants, seed germination and root development, as well as soil microbial activity and crusting and hardening of the soil.

FIGURE 18
Temperature fluctuations at a soil depth of 3 cm in a cotton crop with and without a soil cover of mucuna



Source: Derpsch, 1993.

Roots absorb more water at higher soil temperatures up to a maximum of 35 °C. Higher temperatures restrict water absorption. Soil temperatures that are too high are a major constraint on crop production in many parts of the tropics. Maximum temperatures exceeding 40 °C at 5 cm depth and 50 °C at 1 cm depth are commonly observed in tilled soil during the growing season, sometimes with extremes of up to 70 °C. Such high temperatures have an adverse effect not only on seedling establishment and crop growth but also on the growth and development of the micro-organism population. The ideal rootzone temperature for germination and seedling growth ranges from

25 to 35 °C. Experiments have shown that temperatures exceeding 35 °C reduce the development of maize seedlings drastically and that temperatures exceeding 40 °C can reduce germination of soybean seed to almost nil.

Mulching with crop residues or cover crops regulates soil temperature. The soil cover reflects a large part of solar energy back into the atmosphere, and thus reduces the temperature of the soil surface. This results in a lower maximum soil temperature in mulched compared with unmulched soil (Figure 18) and in reduced fluctuations.

Chapter 6

Key factors in sustained food production

INCREASED PLANT PRODUCTIVITY

Plant productivity is linked closely to organic matter (Bauer and Black, 1994). Consequently, landscapes with variable organic matter usually show variations in productivity. Plants growing in well-aerated soils are less stressed by drought or excess water. In soils with less compaction, plant roots can penetrate and flourish more readily. High organic matter increases productivity and, in turn, high productivity increases organic matter.

INCREASED FERTILIZER EFFICIENCY

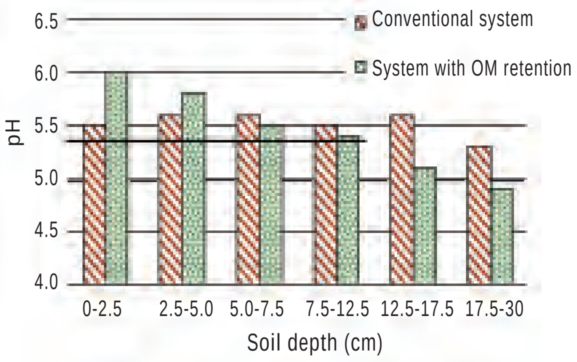
The two major soil fertility constraints of the West African savannah and in the subhumid and semi-arid regions of SSA are low inherent nutrient reserve and rapid acidification under continuous cultivation as a consequence of low buffering or cation exchange capacity (Jones and Wild, 1975). Generally, these constraints are tackled by applying chemical fertilizers and lime. However, the application of inorganic fertilizers on depleted soils often fails to provide the expected benefits. This is basically because of low organic matter and low biological activity in the soil.

The chemical and nutritional benefits of organic matter are related to the cycling of plant nutrients and the ability of the soil to supply nutrients for plant growth. Organic matter retains plant nutrients and prevents them leaching to deeper soil layers. Micro-organisms are responsible for the mineralization and immobilization of N, P and S through the decomposition of organic matter (Duxbury, Smith and Doran, 1989). Thus, they contribute to the gradual and continuous liberation of plant nutrients. Available nutrients that are not taken up by the plants are retained by soil organisms. In organic-matter depleted soils, these nutrients would be lost from the system through leaching and runoff.

Phosphate fixation and unavailability is a major soil fertility constraint in acid soils containing large amounts of free iron and aluminium oxides. In comparing the P-sorption capacity of surface and subsurface soil samples, Uehara and Gilman (1981) provided indirect evidence that soil organic matter can reduce the P-sorption capacity of such soils. This implies that for high P-fixing soils, i.e. oxide-rich soils derived from volcanic and ferro-magnesian rocks, management systems that are capable of accumulating and maintaining greater amounts of calcium-saturated soil organic matter in the surface horizon would increase P availability from both organic and fertilizer sources.

Weak acids, such as the organic acids in humus, do not relinquish their hydrogen (H) easily. H is part of the humus carboxyl (-COOH) under acidic conditions. When a soil is limed and the acidity decreases, there is a greater tendency for the H^+ to be removed from humic acids and to react with hydroxyl (OH^-) to form water. The carboxyl groups on the humus develop negative charge as the positively charged H is removed. When the pH of a soil is increased, the release of H from carboxyl groups helps to buffer the increase in pH and at the same time creates the CEC (negative charge). With an increase in organic matter, the soil recovers its natural buffer capacity; this means an increase in pH in acid soils (Figure 19).

FIGURE 19
Effect of organic matter on soil pH



Note: Original pH level was 5.3.
Source: Mielniczuk, 1996.

Table 6
Incidence of lime in the soil profile under different soil covers over the same period after surface application

Cover	Soil depth (cm)
Bare soil	0–7
Black oats	0–20
Oil radish	0–22

CEC is linked closely to the organic matter content of the soil. It increases gradually with time where organic residues are retained, first in the topsoil and later also at greater depth. Crovetto (1997) reported an increase in CEC of 136 percent (from 11 to 26 meq/100 g of soil) as a consequence of humus increase in the topsoil after 20 years of residue retention.

To overcome acidity, lime is usually incorporated in the soil. However, organic matter on the soil surface favours the transport of calcium carbonate (lime) to deeper soil layers after surface application (Table 6).

The crop residues release organic acids that cause the lime to penetrate deeper into the profile much more rapidly than when applied on bare soil. Thus, it is no longer necessary to mix lime intensively into the soil, which is appropriate for farming systems based on reduced or zero tillage.

REDUCED WATERLOGGING

Chapter 5 examined the water storage capacity of soils under improved organic management. However, in case of waterlogging, organic matter plays also an important role. The bioturbating activity of the macrofauna leaves various so-called conducting macropores in the soil, which are responsible for the drainage of water to deeper soil layers.

Chan *et al.* (2003) found a significant reduction in waterlogging after three years under no tillage compared with conventional tillage. The reduction was related to higher density of conducting macropores (140/m^2 and 5/m^2 for no tillage and conventional tillage, respectively), which was associated with higher population density of earthworms (240/m^2 and 36/m^2 for no tillage and conventional tillage, respectively). Plate 24 provide a demonstrationof this effect.

A. BOT

Plate 24
Under no-tillage conditions, the internal pore system of the soil is not distroyed through land preparation activities and able to drain rainwater from the surface to deeper layers (left). On bare soil the impact of raindrops results in sealing of the surface pores and thus poor drainage.

INCREASED YIELDS

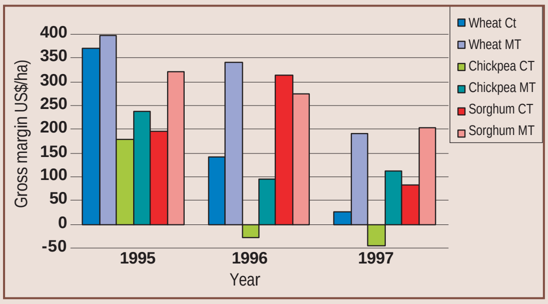
Agronomic practices that influence nutrient cycling, especially mineralization and immobilization, result in an immediate productivity gain or loss, which is reflected in the economics of the agricultural system.

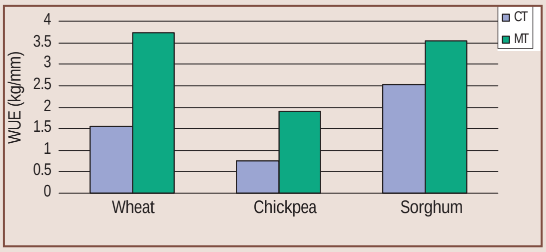
Crop yields in systems with high soil organic matter content are less variable than those in soil that are low in organic matter. This is because of the stabilizing effects of favourable conditions of soil properties and microclimate. Improvements in crop growth and vigour stem from direct and indirect effects. Direct effects stem from improvements in nutrient and water content, as described above (also Box 8). Indirect effects stem from a favourable rooting environment and possible weed suppression and a reduction in pests and diseases.

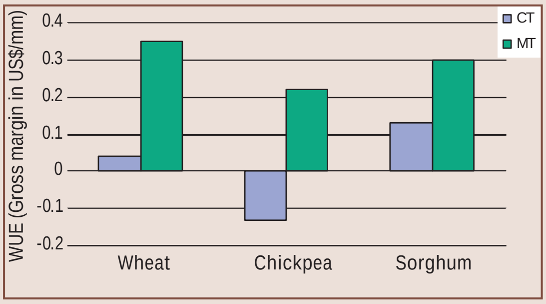
BOX 8

Does improved organic matter management pay?

There are several ways to calculate the rentability of a farm. In general, key parameters such as expenses, income, yield, cost of production and gross margin are used to analyse how well farmers have managed to reach an income. However, in areas where water is a limiting factor, it may be more useful to analyse the conversion of water into yield or even money. The following example illustrates different ways to compare outcomes of farms and their cropping systems. It is based on the cropping results of 16 farms with a cropped surface of 60 000 ha in Australia. One-third of this surface is cropped in a conventional way (CT), using intensive tillage practices, fire and several passages with herbicides for weed control. Two-thirds of the area is cropped with the aim to retain as much ground cover as possible, and thus improve the organic matter content of the soil, using specialized planters and herbicides to control weeds, also known as conservation farming (MT). An analysis of the cropping system data for three years yielded the following gross margins for three crops in rotation (wheat, chickpea and sorghum):







However, when using water-use efficiency (WUE) as means of comparing outputs across farming systems, the results are even more drastic. In this case, rather than the common method of determining WUE by breaking the season into fallow and in-crop components, a total water-use efficiency factor was used. Both grain yield and gross margin are divided by total water to obtain an insight into how well farmers managed the conversion of water into yield and money in the year 1997.

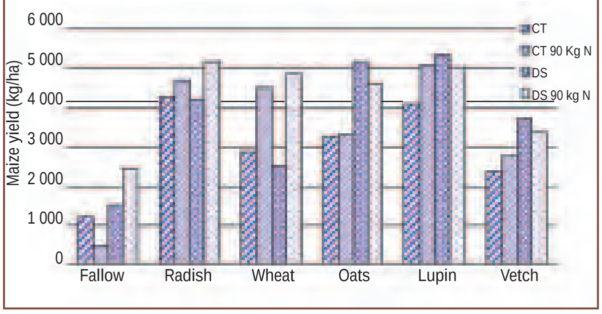
Source: Rummery and Coleman, 1999.

Immobilization of N may occur in systems with crop residue management, especially where C:N ratios of the residues are high (tough, woody materials). This can cause a decrease in maize yield. Figure 20 shows the effect of tillage and the preservation of crop residues on maize yield. The preservation of wheat and horse-radish residues on the soil surface led to immobilization of N, which was overcome through the application of N fertilizer. Based on these data, maize with oats, lupine and vetch as a winter cover crop (without fertilization) can produce a yield that is comparable with or higher than those obtained with conventional tillage and a fertilizer treatment of 90 kg/ha. In this case, the yield increase was highly correlated with the P content of the leaves and the P availability in the soil. This occurred because of the higher moisture content in the soil under the mulch layer, which led to a higher P uptake by plant roots.

Grain crops can also have residual effects on each other through the decomposition of chemical compounds in the residues.

FIGURE 20

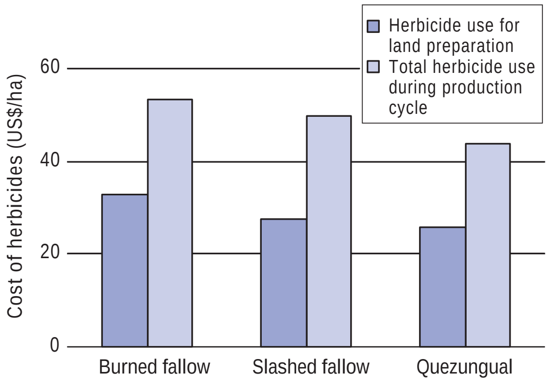
Maize yield under conventional tillage and direct sowing, with and without 90 kg of N fertilizer



Source: Calegari, 1998.

FIGURE 21

Herbicide costs in different production systems in Lempira Sur, Honduras



Source: CDR, 2000.

REDUCED HERBICIDE AND PESTICIDE USE

Some people are concerned that intensified systems with reduced or zero tillage will increase herbicide use and in turn lead to increased contamination of water by herbicides. According to Fawcett (1997), total herbicide use in the United States of America declined during the period of adoption of no-tillage systems. He concludes that herbicides are important, but that farmers using conventional tillage methods use similar amounts of herbicides to no-tillage farmers. In Honduras, a strong decline in the use of herbicides has been observed (Figure 21). Farmers who no longer burn their fields prior to preparation spend less money on herbicides. Farmers who have adopted the Quezungual system spend less on herbicides and make savings, both in terms of land preparation and total costs.

It is becoming evident that the need for herbicide use diminishes over time in well-managed no-tillage cropping systems. The principal reason is that the system reduces the existing seed bank in the soil by the synergy of two activities: reduction of the production of new seeds through avoidance of flowering and fruit setting; and reduction of seeds that are brought to the surface by tillage practices.

With direct seeding, the reservoir of seeds differs from conventional tillage because:

- the weed seeds remain on the soil surface, where they are susceptible to attacks from insects, birds and soil organisms and to atmospheric influences;
- the soil remains covered by residues, which prevents light reaching the seeds and thus reduces germination;
- weed seeds already at certain depths are not brought to the surface again, where they could germinate;
- perennial weeds are no longer redistributed by equipment.

The result is that the soil weed seed store diminishes in time and, consequently, the weed problem also diminishes, as does the need to use herbicides.

The concentration of soil organic matter in the topsoil layer plays an important role in the absorption of herbicides. When the concentration of organic matter in the topsoil decreases, contamination of the environment by herbicides is likely to increase. Enhanced levels of organic matter cause enhanced adsorption of pesticides, followed by gradual degradation. Herbicides, like other pesticides, can be used by micro-organisms as a substrate to feed on (Haney, Senseman and Hons, 2002). Herbicides are broken down in soil and water by micro-organisms into natural acids, NH_4^-, amino acids, carbohydrates, phosphate and CO_2 (Schuette, 1998). As microbes cause more rapid degradation of pesticides, enhancing microbial activity may reduce leaching of pesticides.

Many herbicides, including glyphosate and paraquat, which are the most common herbicides used in reduced-tillage systems, are bound tightly to clay and organic matter by electrostatic forces and hydrogen bonding. Once they are bound to soil organic matter, the herbicides become inactive and no longer affect plants. Moreover, they can form insoluble complexes with metals in the soils. This also contributes to their rare stability in the soil and low potential for leaching into groundwaters (Ahrens, 1994a, 1994b). Some studies have shown that there is no reason to believe that glyphosate may cause any unexpected damage to the environment (Torstenson, 1985). However, other studies illustrate negative effects on soil life or its functions.

Farming systems that increase soil organic matter content (e.g. no tillage) reduce the probability of environmental contamination by herbicides.

INCREASED BIODIVERSITY

Conventional agriculture tends to reduce aboveground and belowground diversity. Thus, it brings about significant changes in the vegetation structure, cover and landscape. The change in vegetal cover during the conversion of forest and pastures to cropping affects plants, animals and micro-organisms. Through increasing specialization of certain plant species (food and fibre crops, pasture and fodder crops, and tree crops) and livestock species, some functions may be affected severely, e.g. nutrient cycling and biological control. Some non-harvested or associated species profit from the change and become pests. However, many organisms either disappear completely or their numbers are reduced drastically, e.g. pollinators and beneficial predators, unless efforts are made to retain a suitable habitat (Box 9).

Associated species can be managed to a certain extent. Through appropriate crop rotations, crop–livestock interactions and the conservation of soil cover, a habitat can be created for a number of species that feed on pests. This will in turn attract more insects, birds and other animals. Thus, rotations and associations of crops and cover crops as well as hedgerows and field borders promote biodiversity and ecological functions. Because of the complexity and richness of soil biodiversity, the effects of crop and pasture management are less well understood. However, the effects on certain functional groups and, hence, specific soil functions are being recognized increasingly as vital for agricultural productivity and system sustainability.

BOX 9

Effect of different tillage practices on scarab beetle-grub holes and their volumes

Before the transformation of native grasslands and forests into agricultural areas, a large number of species of scarab beetles and their larvae (white grubs) inhabitated the soils in southern Brazil. With the transformation of these areas, some of these beetles disappeared, while others became so well adapted and, lacking biological control agents, became important soil-dwelling pests. However, there are other species that can be considered as facultative pests. The larvae prefer feeding on surface litter or surface deposited animal excrements, but may become pests when not enough surface litter is present for them to feed on, like the genera *Diloboderus* and *Bothynus*. The large beetles create large, permanent galleries (holes) in the soil, down to a depth of more than 1 m, in which they spend most of their lives. The holes may serve as preferential pathways for water infiltration and root growth, and the chambers become niches of increased soil fertility. Both chambers and galleries provide temporary and permanent refuge for many other soil-dwelling invertebrates and microfauna.

Research revealed that beetle grub holes were more abundant under no tillage (NT) (8.8–9.6 holes/m^2) than conventional tillage (CT) (0.7–1.3 holes/m^2). The largest and deepest holes were also found in NT (up to 33.5 mm in diameter and 117 cm deep). Consequently, the total volume of pores opened in NT (450–503 cm^3) was up to almost 10 times greater than in CT (53–107 cm^3).

Source: Brown *et al.*, 2003.

Soil has the ability to restore its life-support processes provided that the disturbance is not too drastic and that sufficient time is allowed for such recovery. Organic matter and biodiversity of soil organisms are the driving factors in this restoration. Decreases in numbers and types of soil organisms and available substrate (organic matter) lead to a decrease in resilience, which in turn can result in a downward spiral of degradation.

RESILIENCE

Resilience can be defined as the ability of a system to recover after disturbance (Elliot and Lynch, 1994). Soil resilience depends on a balance between restorative and degrading processes. Factors affecting resilience can be grouped in two categories: endogenous and exogenous. Endogenous factors are related to inherent soil properties (rooting depth, texture, structure, topography and drainage) and microclimate and mesoclimate. Exogenous factors include land use and farming system, technological innovations and input management (Lal, 1994). Hence, appropriate agricultural practices can influence these factors in order to enhance soil resilience.

Organic matter and soil organisms play important roles in conserving and improving soil properties that are related to soil resilience. In addition to creating more pores through biological activity, organic matter plays an important role in the formation and stabilization of soil aggregates through bonds between the organic matter and the mineral soil particles. Soil aggregation can take place through two binding agents:

- waste products of bacteria – polysaccharides;
- fungal and bacterial hyphae.

The preservation of aggregate stability is important in order to reduce surface sealing and increase water infiltration rates (Whitbread, Lefroy and Blair, 1998). With increased stability, surface runoff is reduced (Roth, 1985).

Chapter 7

The role of conservation agriculture in organic matter deposition and carbon sequestration

PRINCIPLES OF CONSERVATION AGRICULTURE

Conservation agriculture makes use of soil biological activity and cropping systems to reduce the excessive disturbance of the soil and to maintain the crop residues on the soil surface in order to minimize damage to the environment and provide organic matter and nutrients. It is based on four principles:

- minimal mechanical soil disturbance, mainly through direct seeding;
- permanent soil cover, organic matter supply through the preservation of crop residues and cover crops;
- crop rotation for biocontrol and efficient use of the soil profile;
- minimal soil compaction.

Although the principles are not new (except for that of minimal disturbance to the soil), it is the fact that they are applied together in conservation agriculture that generates positive outcomes. All the practices (minimal tillage, soil cover and crop rotation) are combined for synergy and added value. In the past, farmers may have tried but abandoned the use of cover crops or zero tillage because of weed problems or yield declines. There is also a need for improved weed control and rotations for biocontrol of pests and diseases and nutrient uptake. Integration of the conservation agriculture principles provides a win–win situation for both people and the environment, which has catalyzed successful expansion of the area under conservation agriculture worldwide.

Conservation agriculture aims to:

- provide and maintain optimal conditions in the rootzone (maximum possible depth for crop roots) in order to enable them to grow and function effectively and without hindrance in capturing plant nutrients and water;
- ensure that water enters the soil so that: (i) plants have sufficient water to express their potential growth; and (ii) excess water passes through soil to groundwater and streamflow, not over the surface as runoff where it can cause erosion. There is greater potential for increased cropping efficiency as more water is held in the soil profile than under conventional systems;
- increase beneficial biological activity in the soil in order to: (i) maintain and rebuild soil architecture for enhanced water entry and distribution within the soil profile; (ii) compete with potential soil pathogens; (iii) contribute to decomposition of organic materials to soil organic matter and various grades of humus; and (iv) contribute to the capture, retention and gradual release of plant nutrients;
- avoid physical or chemical damage to roots and soil organisms that would disrupt their effective functioning.

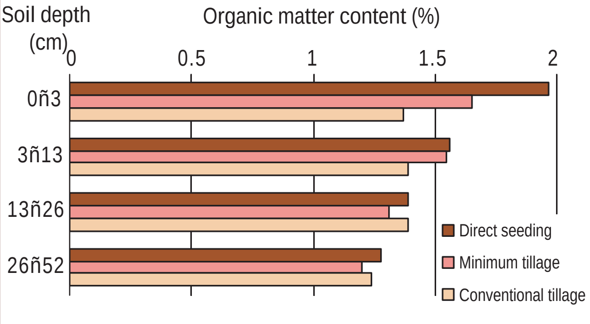
ORGANIC MATTER DEPOSITION

The reduction of soil disturbance through zero-tillage, the use of cover crops and the preservation of crop residues on the soil surface result in increased activity of the soil and in the accumulation of organic matter, mainly in the topsoil (Figure 22).

An argument often heard in the discussion on conservation agriculture is that it is only feasible in the humid and subhumid tropics and that the generation of sufficient

FIGURE 22

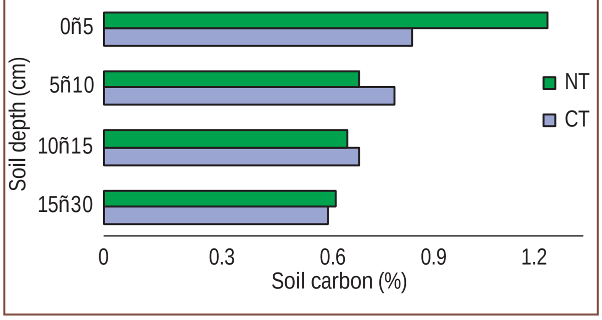
Organic matter content of a soil under different tillage management



Source: FAO, 2002.

FIGURE 23

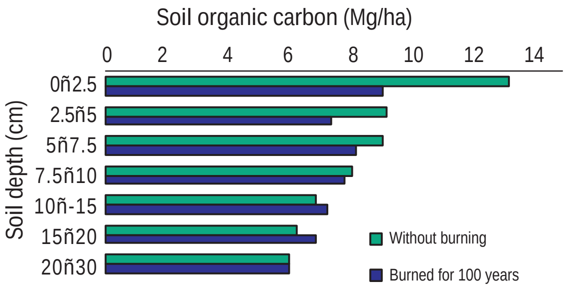
Soil carbon concentration at various soil depths affected by management system



Note:Conventional (CT) and conservation (NT) agriculture, after two complete cropping cycles (4 years).
Source: Prior *et al.*, 2003.

FIGURE 24

Effect of crop residue burning once every two years on soil carbon stock



Source: Spagnollo, 2004.

biomass in semi-arid regions is the limiting factor to start implementing conservation agriculture. However, recent research has shown that even in semi-arid areas of Morocco the application of the principles of conservation agriculture bears its fruits. Mrabet (2000) reports higher yields through better water use and improved soil quality; the latter caused by an increase in soil organic C and N and a slight pH decline in the seedzone (Bessam and Mrabet, 2003; Mrabet *et al.*, 2001a, 2001b).

INCREASED CARBON SEQUESTRATION

World soils are important reservoirs of active C and play a major role in the global carbon cycle. As such, soil can be either a source or sink for atmospheric CO_2 depending on land use and the management of soil and vegetation (Lal, 2005) (Figure 23). The conversion of native ecosystems (e.g. forests, grasslands and wetlands) to agricultural uses, and the continuous harvesting of plant materials, has led to significant losses of plant biomass and C (Davidson and Ackerman, 1993), thereby increasing the CO_2 level in the atmosphere.

In particular, the practice of burning agricultural fields before cultivation has a disastrous effect on soil organic carbon content. Figure 24 shows the reduction in soil organic carbon in agricultural fields after 100 years of burning crop residues and weeds compared with an area that was not burned or ploughed during the same period. The topsoil layer (0–5 cm) represented the greatest carbon loss (36 percent) compared with the area that was not burned. Soil N stock in the same layer was reduced by 16 percent. The carbon stock was reduced not only through burning, but because of the whole land-use management, especially a drastic reduction in diversity of species as monocropping was practised (Amado *et al.*, 2005).

Table 7 lists general practices that determine whether soil will be a sink or a source of atmospheric CO_2.

As shown in Table 7, soil can play a part in mitigating CO_2 levels (Paustian, 2002). This removal process is achieved naturally, and quite effectively, through photosynthesis. Living plants take CO_2 from the air in the presence of sunlight and water, convert it into seeds, leaves, stems and roots. Part of the CO_2 is retained or “sequestered”, or stored as C in the soil when decomposed.

In particular, systems based on high crop-residue addition and no tillage tend to accumulate more C in the soil than is lost to the atmosphere. Carbon sequestration in managed soils occurs when there is a net removal of atmospheric CO_2 because C inputs (crop residues, litter, etc.) exceed C outputs (harvested materials, soil respiration, C emissions from fuel and the manufacture of fertilizers, etc.) (Izaurralde and Cerri, 2002). Management practices that increase soil C comply with a number of principles of sustainable agriculture: reduced tillage, erosion control, diversified cropping system, balanced fertilization, etc.

TABLE 7

Land use and land management determining whether soil will be a sink or source of atmospheric CO_2

Soil as a source of CO_2	Soil as a sink of CO_2
Soil properties: coarse textured soil, excessive drainage, high susceptibility to erosion	Soil properties: clayey soil, poorly drained ecosystems, depositional sites, including footslopes
Land use: seasonal crops, simple ecosystem, shallow roots and low root–shoot ratio	Land use: perrenial crops, diverse ecosystem, deep roots and high root–shoot ratio
Soil management:: intensive tillage based on plough, negative nutrient balance, residue removal and/or burning, continuous cropping, loss of soil and water by runoff and erosion	Soil management:: no tillage, positive nutrient balance, mulch farming, cover crops in rotation cycle, soil and water conservation

Source: adapted from Lal, 2005.

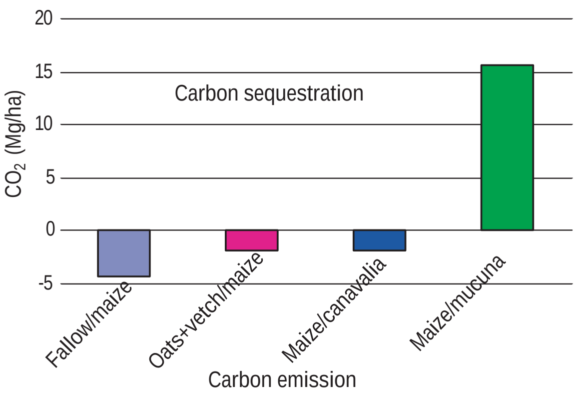
In the early years of no-tillage systems, the organic matter content of the soil is increased through the decomposition of roots and the contribution of vegetative residues on the surface. This organic material decomposes slowly, and thus the liberation of C to the atmosphere also occurs slowly. In the total balance, net fixation or sequestration of C takes place; the soil is a net sink of C.

Figure 25 illustrates the fact that some cropping systems can act as a sink for CO_2. In this example, the carbon stock in soils under natural vegetation is used as a reference (steady state: $\Delta C = 0$). In eight years, the fallow/maize system liberated 4.3 tonnes of CO_2 per hectare. The maize/mucuna system showed a positive balance of almost 20 tonnes of CO_2 per hectare compared with fallow/maize. Compared with soils under natural vegetation, this means a capture of atmospheric CO_2 of more than 15 tonnes/ha in eight years. Lovato (2001) found an increase of 2 tonnes/ha/year over 13 years in a rotation system of oats – common vetch/maiz – cowpea. These figures confirm the potential of conservation agriculture for carbon sequestration. However, the "simple" change from soil tillage to zero tillage is not enough. According to Lovato *et al.* (2004), a minimum addition of 4.2 tonnes/ha/year of carbon in vegetative residues in cropping systems and 4.5 tonnes/ha/year in mixed systems of pastures and crops (Nicoloso, Lovato and Lanzanova, 2005) is necessary for maintaining soil organic matter at stable levels. This means that below these values CO_2 emission will or can take place and, thus, that for conservation agriculture systems to become successful in promoting carbon sequestration, it is necessary to include crops and pastures in the rotation that add large quantities of biomass.

Even more C can be stored by adding leguminous cover crops to the rotation cycle. This is shown in Figure 26, based on two long-term experiments in Rio Grande do Sul, Brazil. Besides addition of C to the soil, legumes add a substantial quantity of N to the soil, which results in increased biomass production of succeeding crops.

FIGURE 25

Estimation of emission and sequestration of CO_2 (total over 8 years) under different maize production systems with cover crops under direct sowing compared with natural vegetation in southern Brazil



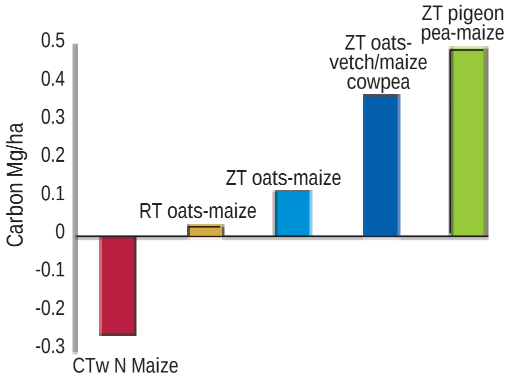
Source: Amado *et al.*, 2001.

Assuming an average carbon accumulation of 0.5 tonne/ha/year, an area like southern Brazil (Rio Grande do Sul, Santa Catarina and Paraná) under conservation agriculture would have the potential to sequester 5 million tonnes of C annually, which corresponds to 18 million tonnes of atmospheric CO_2. To compare, Brazil as emitted an estimated 84 million tonnes of CO_2 in 2000 (Carbon Dioxide Information Analysis Center, 2003).

Recent studies have shown that soil temperature is one of the main climate factors that influence CO_2 emission. High soil temperatures accelerate soil respiration and thus increase CO_2 emission (Brito *et al.*, 2005). This has implications for the landscape and land use in a certain area. On convex slopes and hilltops, emission is greater than in foothills, where temperatures are normally lower. The foregoing indicates that not only for soil and water conservation is it important to protect the soil with vegetation (reduction in soil temperature), but that it is advisable to cover the soil also with a view to reducing greenhouse gas emissions.

FIGURE 26

Potential for carbon sequestration in long-term experiment in southern Brazil



Notes: CT = conventional tillage, RT = reduced tillage, ZT = zero tillage, CTwN = conventional tillage without N fertilizer.
CT oats–maize (=0).
Source: Adapted from Amado *et al.*, 2005.

Chapter 8

Conclusions

The maintenance of soil organic matter levels and the optimization of nutrient cycling are essential to the sustained productivity of agricultural systems. Both are related closely to the bioturbating activities of macrofauna and the microbially-driven mobilization and immobilization processes, which the activities of large invertebrates also encourage. Maintaining soil organic matter content requires a balance between addition and decomposition rates. As changes in agricultural practices can engender marked changes in both the pool size and turnover rate of soil organic matter, it is important to analyse their nature and impacts.

Crop production worldwide has generally resulted in a decline in soil organic matter levels and, consequently, in a decline of soil fertility. Converting grasslands and forestlands to arable agriculture results in the loss of about 30 percent of the organic C originally present in the soil profile. On reasonably fertile soils with reliable water supply, yields in long-term arable agricultural systems have been maintained at very high levels by applying substantial amounts of fertilizer and other soil amendments. In low-input agricultural systems, yields generally decline rapidly as nutrient and soils organic matter levels decline. However, restoration is possible through the use of fallow lands, mixed crop–livestock and agroforestry systems, and crop rotations.

Traditional mould-board plough and disc-tillage cropping systems tend to cause rapid decomposition of soil organic matter, leave the soil susceptible to wind and water erosion, and create plough pans below the cultivation depth. By contrast, reduced- or zero-tillage systems leave more biological surface residues, provide environments for enhanced soil activity, and maintain more intact and interconnected large pores and more soil aggregates, which are better able to withstand raindrop impact. Water can infiltrate more readily and rapidly into the soil with reduced tillage and this helps protect the soil from erosion. In addition, organic matter decomposes less rapidly under reduced-tillage systems. No-tillage systems have proved especially useful for maintaining and increasing soil organic matter.

Crop rotation is the basis for the sustainability of direct sowing systems. A production system that includes cover crops, legumes for N fixation, crop rotation and no tillage can be adapted regionally and, therefore, contribute to the sustainability of soil management in the region. Where rainfall intensities are very high, or biomass management options are limited by a water shortage, maintenance of soil surface cover by crop canopies or crop residues during periods of high erosion risk is essential. With improved land management, at least part of the organic matter lost can be restored. The increase in soil organic matter in the absence of tillage can transform agricultural soils into carbon sinks.

The relatively low levels of active organic matter fractions in zero-tillage systems have highlighted the extreme dependence of such systems on the maintenance of high levels of surface protection by crop residues. Residue accumulation, including cover crops and crop residues, increases the levels of some soil nutrients and soil organic C. The active fraction of organic matter plays a very important role in aggregate stability and rainfall infiltration. Building up active C levels in the soil in rainfed cropping systems may have a greater impact in reducing surface crusting and improving rainfall infiltration capacity than would simply changing to zero-tillage systems. Management practices designed to maximize C inputs and to maintain a high proportion of active C should be seen as essential steps towards more sustainable cropping systems.

Cover crops, intercropping and crop rotations can also help to promote biodiversity both below the soil surface and aboveground. This diversity is important to maintaining a well-functioning and stable ecological system. Where many different types of organisms coexist, there are: fewer problems with diseases, insects and nematodes; more competition among species; and more possibility for many types of predators to thrive. In such a situation, no single pest organism is able to reach a population of sufficient size to affect crop yield seriously.

Bibliography

Ahrens, W.A. 1994a. Glyphosate. *In: Herbicide handbook*, pp. 149–152. Seventh Edition. Weed Science Society of America.

Ahrens, W.A. 1994b. Paraquat. *In: Herbicide handbook*, pp. 226–228. Seventh Edition. Weed Science Society of America.

Amado, T.J.C., Bayer, C., Eltz, F.L.F. & De Brum, A.C.R. 2001. Potencial de culturas de cobertura em acumular carbono e nitrogênio no solo no sistema plantio direto e a conseqüente melhoria da qualidade ambiental. *Rev. Bras. Ciên. Solo*, 25:189–197.

Amado, T.J.C., Lovato, T., Conceição, P.C., Spagnollo, E., Campos, B. & Costa, C. 2005. O potencial de sequestro de carbono em sistemas de produção de grãos sob plantio direito na região sul do Brasil. *In: Simpósio sobre Plantio direto e Meio ambiente; Seqüestro de carbono e qualidade da agua*, pp. 63–71. Anais. Foz do Iguaçu, 18–20 Maio 2005.

Balota, E.L. 1996. Alterações microbiológicas em solo cultivado sob plantio direto. *In* R. Trippia dos Guimarães Peixoto, D.C. Ahrens & M.J. Samaha, eds. *Plantio direto: o caminho para uma agricultura sustentável*. Palestras do I Congresso Brasieleiro de Plantio Direto para uma Agricultura Sustentável. Ponta Grossa. 275 pp.

Bassi, L. 2000. *Impactos sociais, econômicos e ambientais na microbacia hidrográfica do Lajeado São José, Chapecó, SC*. Estudio de caso. Florianópolis, Brazil, EPAGRI. 50 pp.

Bauer, A. & Black, A.L. 1994. Quantification of the effect of soil organic matter content on soil productivity. *Am. J. Soil Sci. Soc.*, 5: 185–193.

Bell, M.J., Moody, P.W., Connolly, R.D. & Bridge, B.J. 1998. The role of active fractions of soil organic matter in physical and chemical fertility of Ferrosols. *Aust. J. Soil Res.*, 36: 809–819.

Bell, M.J., Moody, P.W., Yo, S.A. & Connolly, R.D. 1999. Using active fractions of soil organic matter as indicators of the sustainability of Ferrosol farming systems. *Aust. J. Soil Res.*, 37: 279–287.

Bessam, F. & Mrabet, R. 2003. Long-term changes in particulate organic matter under no-tillage systems in a semiarid soil of Morocco. *In: Proc. 16th ISTRO Conference*, pp. 144–149. 13–18 July 2003, Brisbane, Australia.

Blair, N. & Crocker, G.J. 2000. Crop rotation effects on soil carbon and physical fertility of two Australian soils. *Aust. J. Soil Res.*, 38: 71–84.

Blair, G.J., Lefroy, R.D. & Lisle, L. 1995. Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. *Aust. J. Soil Res.*, 46: 1459–1466.

Blair, N., Faulkner, R.D., Till, A.R. & Prince, K.E. 2003. The impact of plant residues with different breakdown rates on soil carbon and soil structure. *In: Proc. 16th ISTRO Conference*, pp. 175–181. 13–18 July 2003, Brisbane, Australia.

Brammer, H. 2000. Ploughpans and tillage problems. *In: Agroecological aspects of agricultural research in Bangladesh*, pp. 151–158. Dhaka, UPL.

Brito, L.F., La Scala Jr, N., Merques Jr, J. & Pereira, G.T. 2005. Variabilidade temporal da emissão de CO_2 do solo e sua relação com a temperatura do solo em diferentes posições na paisgem em área cultivada com cana-de açúcar. *In: Simpósio sobre Plantio direto e Meio ambiente; Seqüestro de carbono e qualidade da agua, pp. 210–212. Anais. Foz do Iguaçu, 18–20 de Maio 2005.*

Brown, G.G., Oliveira, L.J., Norton, D., Alberton, O., Brandão Jr., O., Saridakis, G.P. & Torres, E. 2003. Quantifying scarab beetle-grub holes and their volume as affected by different tillage and crop management systems. *In: Proc. 16th ISTRO Conference*, pp. 213–218. 13–18 July 2003, Brisbane, Australia.

Brussaard, L. 1994. Interrelationships between biological activities, soil properties and soil management. *In* D.J. Greenland & I. Szabolcs, eds. *Soil resilience and sustainable land use,* pp. 309–329. Wallingford, UK, CAB International.

Brussaard, L. & Juma, N.G. 1995. Organisms and humus in soils. *In* A. Piccolo, ed. *Humic substances in terrestrial ecosystems,* pp. 329–359. Amsterdam, The Netherlands, Elsevier.

Calegari, A. 1998. *The effects of winter green manure and no-tillage on soil chemical properties and maize yield.*

Calegari, A., Darolt, M.R. & Ferro, M. 1998. Towards sustainable agriculture with a no-tillage system. *Adv. Geo. Ecol.*, 31: 1205–1209.

Carbon Dioxide Information Analysis Center. 2003. *National CO_2 emissions from fossil-fuel burning, cement manufacture, and gas flaring: 1751–2000*, by G. Marland, T.A. Boden & R.J. Andres, eds. (available at http://cdiac.esd.ornl.gov).

Castro Filho, C., Muzilli, O. & Podanoschi, A.L. 1998. Estabilidade dos agregados e sua relação com o teor de carbono orgânico num Latossolo roxo distrófico, em função de sistemas de plantio, rotações de culturas e métodos de preparo das amostras. *Rev. Bras. Ciên. Solo*, 22: 527–538.

CDR. 2000. *Servicios financieros rurales y economía campesina sostenible*. Un estudio de caso en el departamento de Lempira, Honduras. I. Informe principal. Centro de Estudios para el Desarrollo Rural, Universidad Libre de Amsterdam, The Netherlands. 80 pp.

Chan, K.Y., Heenan, D.P., Oates, A. & Munro, K. 2003. Hydraulic properties of an Alfisol with pre-existing pan under conservation tillage – effect of earthworms. *In: Proc. 16th ISTRO Conference*, pp. 300–304. 13–18 July 2003, Brisbane, Australia.

Choto, C. & Saín, G. 1993. *Análisis del mercado de rastrojo y sus implicaciones para la adopción de la labranza de conservación en El Salvador*. Síntesis de resultados experimentales del PRM 1992. Vol. 4. pp. 212–222.

Choto, C., Saín, G. & Montenegro, T. 1995. *Productividad y rentabilidad del sistema de producción maíz-sorgo bajo labranza de conservación en El Salvador.*

Coulombe, C.E., Dixon, J.B. & Wilding, L.P. 1996. Mineralogy and chemistry of Vertisols. *In* N. Ahmad & A. Mermut, eds. *Vertisols and technologies for their management,* pp. 115–200. Developments in Soil Science 24. Amsterdam, The Netherlands, Elsevier.

Crovetto, C. 1997. La cero labranza y la nutrición del suelo. *In: Agricultura sustentable de alta producción, ya!* pp. 73–78. 5° Congreso Nacional de AAPRESID, Mar del Plata, Argentina.

Curry, J.P. & Good, J.A. 1992. Soil faunal degradation and restoration. *Adv. Soil Sci.,* 17: 171–215.

Dalal, R.C. & Mayer, R.J. 1986a. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in Southern Queensland. I. Overall changes in soil properties and trends in winter cereal yields. *Aust. J. Soil Res.*, 24, 265–279.

Dalal, R.C. & Mayer, R.J. 1986b. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in Southern Queensland. II. Total organic carbon and its rate of loss from the soil profile. *Aust. J. Soil Res.*, 24, 281–292.

Davidson, E.A. & Ackerman, I.L. 1993. Changes in soil carbon inventories following cultivation of previously untilled soil. *Biogeochemistry,* 20: 161–193.

Debarba, L. & Amado, T.J.C. 1997. Desenvolvimento de sistemas de produção de milho no sul do brasil com características de sustentabilidade. *Rev. Bras. Ciên. Solo,* 21: 473–480.

Derpsch, R. 1993. Sistema de Plantio Direto em Residuos de Adubos Verdes em Pequenas Propriedades no Paraguai - Desenvolvimento e Difusão. *In: I Encontro Latino Americano sobre Plantio Direto na Pequena Propriedade*, pp. 375–386. Ponta Grossa. Anais.

Derpsch, R. 1997. Importancia de la siembra directa para obtener la sustentabilidad de la producción agricola. *In: Agricultura sustentable de alta producción, ya!* pp. 153–176. 5° Congreso Nacional de AAPRESID, Mar del Plata, Argentina.

Douglas, M.G., Mughogho, S.K., Saka, A.R., Shaxson, T.F. & Evers, G. 1999. *Report on an investigation into the presence of a cultivation hoe pan under smallholder farming conditions in Malawi.* Investment Centre Division FAO/World Bank Cooperative Programme. Washington, DC, World Bank.

Duxbury, J.M., Smith, M.S. & Doran, J.W. 1989. Soil organic matter as a source and sink of plant nutrients. *In* D.C. Coleman, J.M. Oades & G. Uehara, eds. *Dynamics of soil organic matter in tropical ecosystem,* pp. 33–67. USA, University of Hawaii Press.

Elliot, L.F. & Lynch, J.M. 1984. The effect of available carbon and nitrogen in straw on soil and ash aggregation and acetic acid production. *Plant Soil,* 78: 335–343.

Elliot, L.F. & Lynch, J.M. 1994. Biodiversity and soil resilience. *In* J. Greenland & I. Szabolcs, eds. *Soil resilience and sustainable land use,* pp. 353–364. Wallingford, UK, CAB International.

FAO. 1974. *Tree planting practices in African savannahs*. FAO Forestry Development Paper No. 19. Rome.

FAO. 1979. *Watershed development with special reference to soil and water conservation*. FAO Soils Bulletin No. 44. Rome.

FAO. 1984. *Tillage systems for soil and water conservation*. FAO Soils Bulletin No. 54. Rome.

FAO. 1989. *Soil conservation for small farmers in the humid tropics*. FAO Soils Bulletin No. 60. Rome.

FAO. 1993. *Soil tillage in Africa: needs and challenges*. FAO Soils Bulletin No. 69. Rome.

FAO. 1994. *Land husbandry. Components and strategy*. FAO Soils Bulletin No. 70. Rome.

FAO. 1995. *Tillage systems in the tropics. Management options and sustainability implications*. FAO Soils Bulletin No. 71. Rome.

FAO. 2000. *Fertilizers and their use. A pocket guide for extension officers*. Fourth edition. FAO/IFA. 70 pp.

FAO. 2001. *Conservation agriculture. Case studies in Latin America and Africa*. FAO Soils Bulletin No. 78. Rome. 69 pp.

FAO. 2002. Farm management and economics. *In: Training modules on Conservation Agriculture*. FAO Land and Water Digital Media Series, Volume 22. Rome.

Fawcett, R.S. 1997. Influences of the no-till system on drinkability of water; consequences on water treatment and availability of water. *In*: *II seminário internacional do sistema plantio direto,* pp. 3–10. Passo Fundo. Anais.

Ferreira, M.C., Andrade, D.S., Chueire, L.M.O., Takemura, M. & Hungria, M. 2000. Tillage method and crop rotation effects on the population sizes and diversity of bradyrhizobia nodulating soybean. *Soil Biol. Biochem.,* 32: 627–637.

Gassen, D.N. & Gassen, F.R. 1996. *Plantio direto. O caminho do futuro*. Aldeia Sul, Passo Fundo. 207 pp.

Glanz, J. 1995. *Saving our soil: solutions for sustaining earth's vital resource*. Boulder, USA, Johnson Printing.

Greenland, D.J. 1958. Nitrate fluctuations in tropical soils. *J. Agric. Sci*., 50: 82–92.

Gregorich, E.G., Greer, K.J., Anderson, D.W. & Liang, D.C. 1998. Carbon distribution and losses: erosion and deposition effects. *Soil Till. Res*., 47: 291–302.

Guimarães, R.C., Buaski, E. & Masquieto, V.L.I. 2005. Bacia do Rio do Campo, Campo Mourão - PR. *In: Simpósio sobre Plantio direto e Meio ambiente; Seqüestro de carbono e qualidade da agua*, pp. 110–115. Anais. Foz do Iguaçu, 18–20 de Maio 2005.

Gupta, V.V.S.R. & Germida, J.J. 1988. Distribution of microbial biomass and its activity in different soil aggregate size classes as affected by cultivation. *Soil Biol. Biochem.,* 20: 777–786.

Haney, R.L., Senseman, S.A. & Hons, F.M. 2002. Effect of roundup ultra on microbial activity and biomass from selected soils. *J. Env. Qual*. Madison.

Holland, E.A. & Coleman, D.C. 1987. Litter placement effects on microbial and organic matter dynamics in an agro-ecosystem. *Ecology*, 68: 425–433.

Hudson, B.D. 1994. Soil organic matter and available water capacity. *J. Soil Wat. Con.*, 49(2): 189–194.

Hungria, M., Andrade, D.S., Balota E.L. & Collozzi-Filho, A. 1997. Importância do sistema de semeadura directa na populaçâo microbiana do solo. Comunicado Técnico 56. Londrina, Brazil, EMBRAPA-CNPSo. 9 pp.

Ingham, E.R. 2000. The soil food web. *In: Soil biology primer*. Rev. edition. Ankeny, USA, Soil and Water Conservation Society.

Izaurralde, R.C. & Cerri, C.C. 2002. Organic matter management. *In: Encyclopedia of soil science,* pp. 910–916. New York, USA, Marcel Dekker Inc.

Jenkinson, D.S. & Ayanaba, A. 1977. Decomposition of C-14 labelled plant material under tropical conditions. *Soil Sci. Soc. Am. J.*, 41: 912–915.

Jones, M.J., & Wild, A. 1975. *Soils of the West African savannah*. Technical Communication No. 55. Commonwealth Bureau of Soils. Farnham, UK, Commonwealth Agricultural Bureaux.

Juma, N.G. 1998. *The pedosphere and its dynamics: a systems approach to soil science*. Volume 1. Edmonton, Canada, Quality Color Press Inc. 315 pp.

Juo, A.S.R. & Lal, R. 1977. The effect of fallow and continuous cultivation on physical and chemical properties of an Alfisol in western Nigeria. *Plant & Soil,* 47: 507–584.

Ladd, J.N. & Amato, M. 1985. Nitrogen cycling in legume cereal rotations. *In* B.T. Kang & J. Van der Heide, eds. *Nitrogen management in farming systems in humid and sub-humid tropics,* pp. 105–127. Haren, The Netherlands, Institute for Soil Fertility (IB), and Ibadan, Nigeria, International Institute for Tropical Agriculture.

Lal, R. 1991. Soil conservation and biodiversity. *In* D.L. Hawksworth, ed. *The biodiversity of microorganisms and invertebrates: its role in sustainable agriculture,* pp. 89–103. Wallingford, UK, CAB International.

Lal, R. 1994. Sustainable land use systems and soil resilience. *In* J. Greenland & I. Szabolcs, eds. *Soil resilience and sustainable land use,* pp. 41–67. Wallingford, UK, CAB International.

Lal, R. 2005. No-till farming and environment quality. *In: Simpósio sobre Plantio direto e Meio ambiente; Seqüestro de carbono e qualidade da agua*, pp. 29–37. Anais. Foz do Iguaçu, 18–20 de Maio 2005.

Lavelle, P. & Pashanasi, B. 1989. Soil macrofauna and land management in Peruvian Amazonia (Yurimaguas, Loreto). *Pedobiologia,* 33: 283–291.

Lavelle, P. & Spain, A. 2001. *Soil ecology*. Dordrecht, The Netherlands, Kluwer Academic Publishers.

Lefroy, R.D.B., Blair, G.J. & Strong, W.M. 1993. Changes in soil organic matter with cropping as measured by organic matter fractions and 13 C natural isotope abundance. *Plant Soil,* 155/156: 399–402.

Linn, D.M. & Doran, J.W. 1984. Effect of water-filled pore space carbon dioxide and nitrous oxide production in tilled and nontilled soils. *Soil Sci. Soc. Am. J.,* 48: 1267–1272.

Lovato, T. 2001. Dinâmica do carbono e nitrogênio do solo afetada por preparos do solo, sistemas de culturas e adubo nitrogenado. Porto Alegre UFRGS. 133 pp. (PhD thesis)

Lovato, T., Mielnickzuk, J., Bayer, C. & Vezzani, F. 2004. Adição de C e N e sua relação com os estoques no solo e com o rendimento do milho em sistemas de manejo. *Rev. Bras. Ci. Sol.*, 28: 175–187.

Machado, J.A. 1976. Efeito dos sistemas de cultivo reduzido e convencional na alteração de algumas propriedades fisicas e químicas do solo. Santa Maria. UFSM. (Tese de Doutorado)

Matson, P.A., Parton, W.J., Power, A.G. & Swift, M.J. 1997. Agricultural intensification and ecosystem properties. *Science,* 277: 504–509.

McGarry, D. 1996. The structure and grain size distribution of Vertisols. *In* N. Ahmad & A. Mermut, eds. *Vertisols and technologies for their management,* pp 231–259. Developments in Soil Science 24. Amsterdam, The Netherlands, Elsevier.

Mielniczuk, J. 1996. A sustentabilidade agrícola e o plantio direto. *In* R. Trippia dos Guimarães Peixoto. D.C. Ahrens and M.J. Samaha, eds. *Plantio direto: o caminho para uma agricultura sustentável*. Palestras do I Congresso Brasieleiro de Plantio Direto para uma Agricultura Sustentável. Ponta Grossa 1996. 275 pp.

Mollison, B. & Slay, R.M. 1991. *Introduction of permaculture*. Harare, The Tutorial Press. 198 pp.

Mrabet, R. 2000. Long-term no tillage influence on soil quality and wheat production in semiarid Morocco. Paper presented at the 15th ISTRO Conference, USA, 2–7 July 2000.

Mrabet, R., Ibno-Namr, K., Bessam, F. & Saber, N. 2001a. Soil chemical quality and implications for fertilizer management after 11 years of no-tillage wheat production systems in semiarid Morocco. *Land Deg. Dev.*, 12: 505–517.

Mrabet, R., Saber, N., El Brahli, A., Lahlou, S., & Bessam, F. 2001b. Total, particulate organic matter and structural stability of a Calcixeroll soil under different wheat rotation and tillage systems in semiarid areas of Morocco. *Soil Till. Res.*, 57: 225–235.

Mueller-Harvey, I., Juo, A.S.R. & Wild, A. 1989. Mineralization of nutrients after forest clearance and their uptake during cropping. *In* J. Proctor, ed. *Mineral nutrients in tropical forest and savannah ecosystems,* pp. 315–324. Spec. Publ. No. 9. The British Ecological Society. UK, Blackwell Scientific Publications.

Müller-Sämann, K. 1986. *Bodenfruchtbarkeit und standortgerechte Landwirtschaft. Eine Studie über Massnahmen und Methoden im Tropischen Pflanzenbau*. Schriftenreihe der GTZ No. 195. Eschborn, Germany.

Nicoloso, R.S., Lovato, T. & Lanzanova, M.E. 2005. Potencial de seqüestro ou emissão de carbono em áreas de integração lavoura-pecuária no sistema plantio direito. *In: Simpósio sobre Plantio direto e Meio ambiente; Seqüestro de carbono e qualidade da agua*, pp. 219–222. Anais. Foz do Iguaçu, 18–20 de Maio 2005.

Palm, C.A. & Sanchez, P.A. 1990. Decomposition and nutrient release patterns of the leaves of three tropical legumes. *Biotropica,* 22: 330–338.

Pangnakorn, U., George, D.L., Tullberg, J.N. & Gupta, M.L. 2003. Effect of tillage and traffic on earthworm populations in a Vertisol in South-East Queensland. *In: Proc. 16th ISTRO Conference*, pp. 881–885. 13–18 July 2003, Brisbane, Australia.

Paustian, K. 2002. Organic matter and global cycle. *In: Encyclopedia of soil science,* pp. 895–898. New York, USA, Marcel Dekker Inc.

Pieri, C., Evers, G., Landers, J., O'Connel, P. & Terry, E. 2002. *No till farming for sustainable rural development*. Agriculture and Rural Development Working Paper. Washington, DC, World Bank. 65 pp.

Pietola, L., Horn, R. & Yli-Halla, M. 2003. Effects of cattle trampling on soil hydraulic and mechanical properties. *In: Proc. 16th ISTRO Conference*, pp. 923–928. 13–18 July 2003, Brisbane, Australia.

Prasad, R. & Power, J.F. 1997. *Soil fertility management for sustainable agriculture*. New York, USA, Lewis Publishers. 356 pp.

Primavesi, A. 1984. *Manejo ecológico del suelo. La agricultura en regiones tropicales*. 5ta Edición. El Ateneo. Rio de Janeiro, Brazil. 499 pp.

Prior, S.A., Runion, G.B., Torbert, H.A., Rogers, H.H. &Reeves, D.W. 2003. Effects of elevated atmospheric CO_2 on biomass production and carbon sequestration: conventional and conservation cropping systems. *In: Proc. 16th ISTRO Conference*, pp. 943–948. 13–18 July 2003, Brisbane, Australia.

Proffitt, A.P.B., Bendotti, S. & McGarry, D. 1995. A comparison between continuous and controlled grazing on a red duplex soil. I. Effects on soil physical characteristics. *Soil Till. Res.*, 35:199–210.

Quideau, S.A. 2002. Organic matter accumulation. *In: Encyclopedia of soil science,* pp. 891–894. New York, USA, Marcel Dekker Inc.

Reicosky, D.C. 2005. Alternatives to mitigate the greenhouse effect: emission control by carbon sequestration. *In: Simpósio sobre Plantio direto e Meio ambiente; Seqüestro de carbono e qualidade da agua*, pp. 20-28.. Anais. Foz do Iguaçu, 18–20 de Maio 2005.

Rice, C.W. 2002. Organic matter and nutrient dynamics. *In: Encyclopedia of soil science,* pp. 925–928. New York, USA, Marcel Dekker Inc.

Roth, C.H. 1985. Infiltrabilität von Latosolo-Roxo-Böden in Nordparaná, Brasilien, in Feldversuchen zur Erosionskontrolle mit verschiedenen Bodenbearbeitungs-systemen und Rotationen. *Gött. Bod. Ber.*, 83: 1–104.

Ruedell, J. 1994. Pesquisa em plantio direto na palha e sua importância. *In: IV Encontro nacional de plantio direto na palha,* pp. 90–105. Cruz Alta.

Ruedell, J. 1995. *Plantio direto na região de Cruz Alta*. FUNDACEP. 134 pp.

Rummery, G. & Coleman, B. 1999. Does conservation farming pay? *Cons. Farm. News*., April 1999 (available at http://www.cfi.org.au).

Sampson, R.N. & Scholes, R.J. 2000. Additional human-induced activities. *In* R.T. Watson, I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo & D.J. Dokken, eds. *Land use, land use change and forestry. A special report of the IPCC*, pp. 180–281. UK, Cambridge University Press.

Schnitzer, M. 1986. The synthesis, chemical structure, reactions and functions of humic substances. *In* R.G. Burns, G. dell'Agnola, S. Miele, S. Nardi, G. Savoini, M. Schnitzer, P. Sequi, D. Vaughan & S.A. Visser, eds. *Humic substances: effect on soil and plants*. Congress on Humic Substances. March 1986, Milan, Italy.

Schuette, J. 1998. *Environmental fate of glyphosate*. Environmental monitoring and pest management. Sacramento, USA, Department of Pesticide Regulation. (available at http://www.cdpr.ca.gov/docs/empm/pubs/fatememo/glyphos.pdf)

Siqueira, R., Yamaoka, R.S., Casão jr., R., Batista de Medeiros, G., Hamakawa, P.J. & De Souza Ladeira, A. 1993. Sistemas de preparo e coberturas vegetais em um solo de baixa aptidão agricola. *In: I Encontro Latino Americano de Plantio Direto na Pequena Propriedade,* pp. 221–237. Ponta Grossa, Anais.

Spagnollo, E. 2004. *Dinâmica da matérica orgânica em agroecosistemas submetidos a queima e manejo dos resíduos culturais*. UFSM, Santa Maria, RS, Brazil. 112 pp. (PhD thesis)

Stevenson, F.J. 1994. *Humus chemistry. genesis, composition, reactions*. 2nd edition. New York, USA, Wiley Interscience. 512 pp.

Swift, M.J., Heal, O.W. & Anderson, J.M. 1979. *Decomposition in terrestrial ecosystems*. Oxford, UK, Blackwell Scientific Publications.

Swift, M.J., Vandermeer, J., Ramakrishnan, P.S., Anderson, J.M., Ong, C.K. & Hawkins B.A. 1996. Biodiversity and agroecosystem function. *In* H.A. Mooney, J.H. Cushman, E. Medina, O.E. Sala & E.-D. Schulze, eds. *Functional roles of biodiversity: a global perspective*, pp. 261–298. New York, USA, John Wiley and Sons.

Tan, K.H. 1994. *Environmental soil science*. New York, USA, Marcel Dekker Inc. 304 pp.

Tan, K.H. & Binger, A. 1986. Effect of humic acid on aluminium toxicity in corn plants. *Soil Sci.,* 14: 20–25.

Tate, R.L. 1987. *Soil organic matter: biological and ecological effects*. New York, USA, John Wiley & Sons. 291 pp.

Theng, B.K.G. 1987. Clay-humic interactions and soil aggregate stability. *In* P. Rengasamy, ed. *Soil structure and aggregate stability,* pp. 32–73. Proc. Institute of Irrigation and Salinity Research. Tatura, Australia.

Torstenson, L. 1985. Behaviour of glyphosate in soil and its degradation. *In* E. Grossboard & D. Atkinson, eds. *The herbicide glyphosate*, pp. 137–149. Butterworth & Co. Ltd.

Uehara, G. & Gilman, G. 1981. *The mineralogy, chemistry and physics of tropical soils with variable charge clays*. Boulder, USA, Westview Press. 170 pp.

Unger, P.W. 1978. Straw-mulch rate effect on soil water storage and sorghum yield. *Soil Sci. Soc. Am. J.*, 42: 486–491.

Van der Werff, P.A. 1990. Soil and litter fauna. *In* B.H. Janssen & J.F. Wienk, eds. *Mechanized annual cropping on low fertility acid soils in the humid tropics. A case study of the Zanderij soil in Suriname*. Wageningen Agricultural University Papers 90–5.

Van Keer, K., Comtois, J.D., Ongprasert, S. & Turkelboom, F., eds. 1996. *Options for soil- and farmer-friendly agriculture in the highlands of northern Thailand*. Soil Fertility Conservation Project. Mae Jo University, Thailand, and Catholic University of Leuven, Belgium.

Vermeer, A.W.P. 1996. *Interactions between humic acid and hematite and their effects on metal ion speciation*. Wageningen University, The Netherlands. (PhD thesis)

Vieira, M. & Van Wambeke, J. 2002. Conservation agriculture and rural development. Experiences in El Salvador. *LEISA Mag.,* 18 (3): 11–12.

Voss, M & Sidirias, N. 1985. Nodulaçâo da soja em plantio direto em comparaçâo com plantio convencional. *Pesq. Agropec. Bras.,* 20: 775–782.

Whitbread, A.M., Lefroy, R.D.B. & Blair, G.J. 1998. A survey of the impact of cropping on soil physical and chemical properties in north-western New South Wales. *Aust. J. Soil Res.,* 36: 669–681.

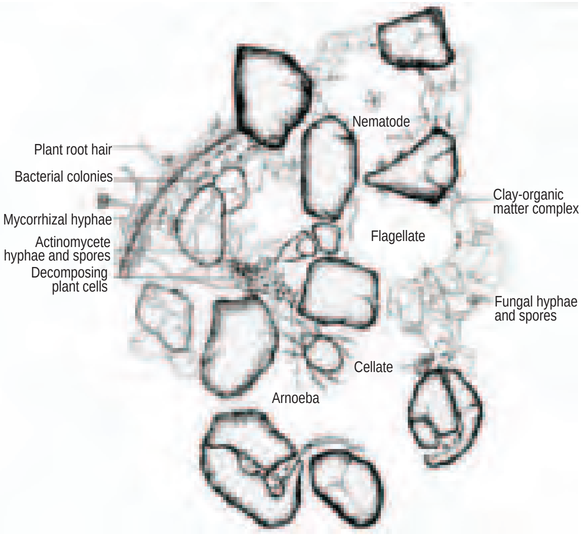
World Neighbors. 2000. *Lessons from the field. Reasons for resiliency: toward a sustainable recovery after hurricane Mitch*. Honduras. 32 pp.

Annex 1

Soil organisms

Soil organisms are responsible, to a varying degree depending on the system, for performing vital functions in the soil. Soil organisms make up the diversity of life in the soil (Figure A1.1). This soil biodiversity is an important but poorly understood component of terrestrial ecosystems. Soil biodiversity is comprised of the organisms that spend all or a portion of their life cycles within the soil or on its immediate surface (including surface litter and decaying logs) (Table A1.1)

FIGURE A1.1
The soil environment



Source: S. Rose and E.T. Elliott

Soil organisms represent a large fraction of global terrestrial biodiversity. They carry out a range of processes important for soil health and fertility in soils of both natural ecosystems and agricultural systems. This annex provides brief descriptions of organisms that are commonly found in the soil and their main biological and ecological attributes.

The community of organisms living all or part of their lives in the soil constitute the soil food web. The activities of soil organisms interact in a complex food web with some subsisting on living plants and animals (herbivores and predators), others on dead plant debris (detritivores), on fungi or on bacteria, and others living off but not consuming their hosts (parasites). Plants, mosses and some algae are autotrophs, they play the role of primary producers by using solar energy, water and carbon (C) from atmospheric carbon dioxide (CO_2) to make organic compounds and living tissues. Other autotrophs obtain energy from the breakdown of soil minerals, through the oxidation of nitrogen (N), sulphur (S), iron (Fe) and C from carbonate minerals. Soil fauna and most fungi, bacteria and actinomycetes are heterotrophs, they rely on organic materials either directly (primary consumers) or through intermediaries (secondary or tertiary consumers) for C and energy needs.

A food-web diagram shows a series of conversions (represented by arrows) of energy and nutrients as one organism eats another. The “structure” of a food web is the composition and relative numbers of organisms in each group within the soil. The living component of soil, the food web, is complex and has different compositions in different ecosystems. In a healthy soil, there are a large number of bacteria and bacterial-feeding organisms. Where the soil has received heavy treatments of pesticides, chemical fertilizers, soil fungicides or fumigants that kill these organisms, the beneficial soil organisms may die (impeding the performance of their activities), or the balance between the

TABLE A1.1
Categories and characteristics of soil organisms

Category	Characteristics	Organisms
Permanent	Whole life cycle in the soil	Mites, collembola, earthworms
Temporal	Part of life cycle in the soil	Insect larvae
Periodical	Frequently enter into the soil	Some insect larvae
Transitory	An inactive phase in the soil (e.g. eggs, pupae, hibernation) but the active period not in the soil	Some insects
Accidental	Organisms fall down or they are drawn along	Insect larvae

pathogens and beneficial organisms may be upset, allowing those called opportunists (disease-causing organisms) to become problems.

The easiest and most widely used system for classifying soil organisms is by using body size and dividing them into three main groups: macrobiota, mesobiota and microbiota (Wallwork, 1970; Swift, Heal and Anderson, 1979). The ranges that determine each size group are not exact for all members of each group.

MICRO-ORGANISMS

These are the smallest organisms (< 0.1 mm in diameter) and are extremely abundant and diverse. They include algae, bacteria, cyanobacteria, fungi, yeasts, myxomycetes and actinomycetes that are able to decompose almost any existing natural material. Micro-organisms transform organic matter into plant nutrients that are assimilated by plants. Two main groups are normally found in agricultural soils: bacteria and mycorrhizal fungi.

Bacteria

Bacteria are very small, one-celled organisms that can only be seen with a powerful light (1 000×) or electron microscope. They constitute the highest biomass of soil organisms. They are adjacent and more abundant near roots, one of their food resources. There are many types of bacteria but the focus here is on those that are important for agriculture, e.g. Rhizobium and actinomycetes.

Bacteria are important in agricultural soils because they contribute to the carbon cycle by fixation (photosynthesis) and decomposition. Some bacteria are important decomposers and others such as actinomycetes are particularly effective at breaking down tough substances such as cellulose (which makes up the cell walls of plants) and chitin (which makes up the cell walls of fungi). Land management has an influence on the structure of bacterial communities as it affects nutrient levels and hence can shift the dominance of decomposers from bacterial to fungal.

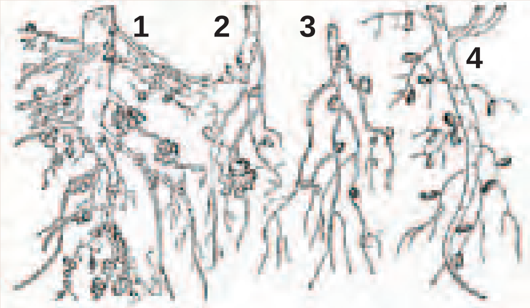
One group of bacteria is particularly important in nitrogen cycling. Free-living bacteria fix atmospheric N, adding it to the soil nitrogen pool; this is called biological nitrogen fixation and it is a natural process highly beneficial in agriculture. Other N-fixing bacteria form associations (in the form of nodules) with the roots of leguminous plants (Box A1.1).

The nodule is the place where the atmospheric N is fixed by bacteria and converted into ammonium that can be readily assimilated by the plant. The process is rather complicated but, in general, the bacteria multiply near the root and then adhere to it. Next, small hairs on the root surface curl around the bacteria and they enter the root. Alternatively, the bacteria may enter directly through points on the root surface. Once inside the root, the bacteria multiply within thin threads. Signals stimulate cell multiplication of both the plant cells and the bacteria. This repeated division results in a mass of root cells containing many bacterial cells. Some of these bacteria then change into

BOX A1.1

Rhizobium and the nodulation process

The nodulation process is a series of events in which rhizobia interact with the roots of legume plants to form a specialized structure called a root nodule.



Different types of nodules on leguminous roots: (1) soybean; (2) alfalfa; (3) pea; and (4) white clover (Soltner, 1978).

Source: FAO (2000)

a form that is able to convert gaseous N into ammonium nitrogen (they can "fix" N). These bacteria are then called bacteroids and present different properties from those of free cells. Most plants need very specific kinds of rhizobia to form nodules. A specific Rhizobium species will form a nodule on a specific plant root, and not on others. The shapes that the nodules form are controlled by the plant and nodules can vary considerably in size and shape.

Actinomycetes are a broad group of bacteria that form thread-like filaments in the soil. The distinctive scent of freshly exposed, moist soil is attributed to these organisms, especially to the nutrients they release as a result of their metabolic processes. Actinomycetes form associations with some non-leguminous plants and fix N, which is then available to both the host and other plants in the near vicinity.

Bacteria produce (exude) a sticky substance in the form of polysaccharides (a type of sugar) that helps bind soil particles into small aggregates, conferring structural stability to soils. Thus, bacteria are important as they help improve soil aggregate stability, water infiltration, and water holding capacity. However, in general their effect is less marked than that originated by large invertebrates such as earthworms.

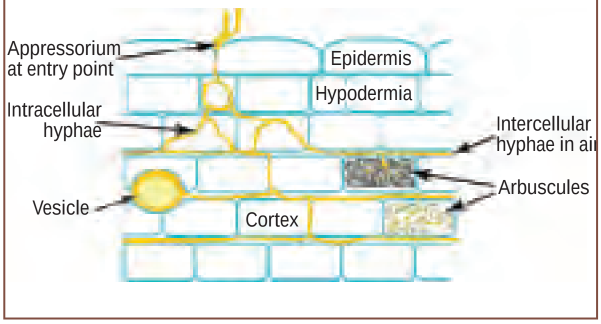
Fungi

These organisms are responsible for the important process of decomposition in terrestrial ecosystems as they degrade and assimilate cellulose, the component of plant cell walls. Fungi are constituted by microscopic cells that usually grow as long threads or strands called hyphae of only a few micrometres in diameter but with the ability to span a length from a few cells to many metres. Soil fungi can be grouped into three general functional groups based on how they source their energy:

- Decomposers – saprophytic fungi – convert dead organic material into fungal biomass, CO_2, and small molecules, such as organic acids. These fungi generally use complex substrates, such as the cellulose and lignin, in wood. They are essential for decomposing the carbon ring structures in some pollutants. Like bacteria, fungi are important for immobilizing or retaining nutrients in the soil.
- Mutualists – mycorrhizal fungi – colonize plant roots through a symbiotic relationship. The definition of symbiosis is a close, prolonged association between two or more different organisms of different species that may benefit each member. Mycorrhizae increase the surface area associated with the plant root, which allows the plant to reach nutrients and water that otherwise might not be available. Mycorrhizae essentially extend plant reach to water and nutrients, allowing plants to utilize more of the resources available in the soil. Mycorrhizae source their carbohydrates (energy) from the plant root they are living in/on and they usually help the plants by transferring phosphorus (P) from the soil into the root. Two major groups are identified: (i) ectomycorrhizae, that grow on the surface layers of the roots and are commonly associated with trees; and (ii) endomycorrhizae, such as arbuscular mycorrhizal fungi and vesicular mycorrhizal fungi, that grow within the root cells and are commonly associated with grasses, row crops, vegetables and shrubs. Arbuscular mycorrhizal fungi can also benefit the physical characteristics of the soil because their hyphae form a mesh to help stabilize soil aggregates. Vesicular-arbuscular mycorrhizae are the most widespread mycorrhizal fungi. Mycorrhizae are particularly important for phosphate uptake because P does not move towards plant roots easily. These organisms do not harm the plant, and in return, the plant provides energy to the fungus in the form of sugars. The fungus is actually a network of filaments that grows in and around the plant root cells, forming a mass that extends considerably beyond the root system of the plant (Figure A1.2).
- Pathogens or parasites cause reduced production or death when they colonize roots and other organisms. Root-pathogenic fungi, such as *Verticillium*, *Pythium*

FIGURE A1.2

Mycorrhizal roots and the associated networks of hyphae are a major component of most soils



Source: drawing by M. Brundrett, CSIRO.

and *Rhizoctonia*, cause major economic losses in agriculture each year. Many fungi help control diseases, e.g. nematode-trapping fungi that parasitize disease-causing nematodes, and fungi that feed on insects may be useful as biocontrol agents.

MICROFAUNA

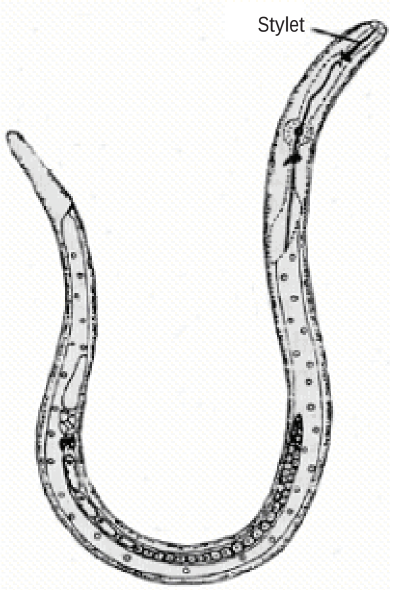
The microfauna (< 0.1 mm in diameter) includes *inter alia* small collembola and mites, nematodes and protozoa that generally live in the soil water films and feed on microflora, plant roots, other microfauna and sometimes larger organisms (e.g. entomopathogenic nematodes feed on insects and other larger invertebrates). They are important to release nutrients immobilized by soil micro-organisms.

Nematodes

Nematodes are tiny filiform roundworms that are common in soils everywhere. They may be free-living in soil water films; beneficial for agriculture or phytoparasitic (Figure A1.3), and live at the surface or within the living roots (parasites). Free-living nematodes graze on bacteria and fungi, thus they control the populations of harmful micro-organisms. These nematodes are 0.15–5 mm long and 2–100 µm wide; an exception are Mermithidae nematodes, which may be 20 cm long and are very common in tropical soils, being parasites of some arthropods such as locusts. Nematodes can only move through the soil where a film of moisture surrounds the soil particles. They live in the water (they are hydrobionts) that fills spaces between soil particles and covers roots. In hot and dry conditions, they enter into a dormant stage, and as soon as water becomes available, they spring back to activity.

FIGURE A1.3

Drawing of a plant-parasitic nematode showing the stylet used to penetrate plant roots



Nematodes are recognized as a major consumer group in soils, generally grouped into four to five trophic categories based on the nature of their food, the structure of the stoma (mouth) and oesophagus, and the method of feeding (Yeates and Coleman, 1982): bacterial feeders, fungal feeders, predatory feeders, omnivores, and plant feeders. The bacterial feeders prey on bacteria (bacterivores) and may ingest up to 5 000 cells/minute, or 6.5 times their own weight daily. This helps disperse both the organic matter and the decomposers in the soil. Bacterial- and fungal-feeding nematodes release a large percent of N when feeding on their prey groups and are thus responsible for much of the plant available N in the majority of soils (Ingham *et al.*, 1985). The annual overall consumption may be as much as 800 kg of bacteria per hectare and the amount of N turned over in the range of 20–130 kg (Coleman *et al.*, 1984).

Phytophages or plant-feeding nematodes damage plant roots, with important economic consequences for farmers. They possess stylets with a wide diversity of size and structure, and they are the most extensively studied group of soil nematodes because of their ability to cause plant disease and reduce crop yield.

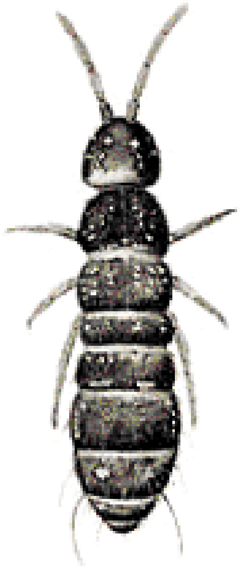
MESOFAUNA

Mesofauna (0.1–2 mm in diameter) includes mainly microarthropods, such as pseudoscorpions, springtails, mites, and the worm-like enchytraeids. Mesofauna have limited burrowing ability and generally live within soil pores, feeding on organic materials, microflora, microfauna and other invertebrates.

Collembola

Collembola or "springtails" are microarthropods that live in the litter or in the pore space of the upper 10–15 cm of soil. They are saprophagous and feed mainly on fungi, bacteria and algae growing on decomposing plant litter (Ponge, 1991). They are important as epigeic decomposers. Unlike most insects, they have no wings at any stage. They measure a few millimetres in length (Figure A1.4) and elongate with a characteristic salutatory organ, a forked "tail" which enables them to spring when in danger. Springtails are probably the most abundant group of insects on Earth.

FIGURE A1.4
A drawing of a "springtail"



Source: J.W. Folsom.

Pseudoscorpions

Pseudoscorpions are tiny arachnids rarely longer than 8 mm. They live in litter, decaying vegetation, and the soil. Pseudoscorpions superficially resemble true scorpions, bearing relatively large chelae on the pedipalps, but they do not have a telson or stinger. Pseudoscorpions feed on very small arthropods such as springtails and mites.

MACROFAUNA

Members of species classed as macrofauna are visible to the naked eye (generally > 2 mm in diameter). Macrofauna includes vertebrates (snakes, lizards, mice, rabbits, moles, etc.) that primarily dig within the soil for food or shelter, and invertebrates (snails, earthworms and soil arthropods such as ants, termites, millipedes, centipedes, caterpillars, beetle larvae and adults, fly and wasp larvae, spiders, scorpions, crickets and cockroaches) that live in and feed in or upon the soil, the surface litter and their components. In both natural and agricultural systems, soil macrofauna are important regulators of decomposition, nutrient cycling, soil organic matter dynamics, and pathways of water movement as a consequence of their feeding and burrowing activities. Here the focus is on soil invertebrates.

Earthworms

The effects of earthworms in the soil differ according to the ecological category of the species (Bouché, 1977; Lavelle, 1981) involved:

- Epigeic: they live in the litter layers, a very changing environment, subject to drought, high temperatures and predator presence. These earthworms are generally small and pigmented (green or reddish) with rapid movements.
- Endogeic: these are unpigmented (with no colour) worms that live and feed in the soil. This group is further divided into three subgroups: oligohumic, mesohumic and polyhumic, depending on the organic matter content of the soil ingested.
- Anecic: these earthworms feed on the surface litter that they generally mix with soil, but they spend most of their time in the soil. They are large, with dark anterodorsal pigmentation, and they dig subvertical burrows.

As a result of this wide range of adaptations, earthworms have diverse functions in the soil. Epigeic worms can be used as compost makers with no impact on soil structure. Anecics and endogeics do have an impact on soil structure owing to their mixing and burrowing activities, and on soil organic matter.

Earthworms generally exert beneficial effects on plant growth. However, negative effects may be induced under particular situations. The effect on grain yields is also proportional to the earthworm biomass; significant effects start to appear at biomass values > 30 g fresh weight (Brown *et al.*, 1999), although very high biomasses of single species of earthworms, (e.g. *Pontoscolex corethrurus*) may inhibit production under particular situations. Many mechanisms are involved in the growth stimulation. These vary from large-scale effects on soil structure and nutrient availability, to the enhancement of mycorrhizal infection or control of plant-parasitic nematodes. Once the earthworms are established, a dynamic cropping system – involving crop rotations with long cycle crops or perennials with good organic matter additions – contributes to securing long-lasting benefits from earthworm activities.

Termites

Termites are important members of soil macrofauna in various regions of the world. They are social insects, living in organized colonies with a number of castes (different individuals) with a set of morphological and physiological specializations. The main castes are: queen (the termite that founds the colony), worker and soldier.

Neither individual termites nor colonies normally travel long distances as they are constrained to live within their territorial border or within their food materials. A number of species feed on living plants and some may become serious pests in agricultural systems where dead residues are scarce (Wood, 1996). Most species feed on dead-plant materials above and below the soil surface. Their food sources include plant-decaying materials, dead foliage, woody materials, roots, seeds and the faeces of higher animals (Lavelle and Spain, 2001). There are also soil–wood feeders and soil feeders, which means that they ingest a high proportion of mineral material. Their nutrition derives mainly from well-decayed wood and partly humified soil organic matter. Another group of termites grow fungi in their nests (fungus-growing termites).

Termites may be classified by their feeding habits:

- grass harvesters,
- surface litter feeders,
- wood feeders,
- soil–wood feeders,
- soil feeders (humivores).

The nests formed by termites may occur in different locations, e.g. within the wood of living or dead trees, in subterranean locations, in other nests formed by other termite species, and by forming epigeal nests (above the soil surface) and arboreal nests.

Ants

Ants build a large variety of structures in the soil. However, because of their feeding habits, they are of less importance in regulating processes in the soil than termites or earthworms.

Beetles

Beetles (Coleoptera) are diverse taxonomically and differ widely in size and in the ecological role they perform in soil and litter. They are either saprophagous, phytophagous or predators. Two groups are of particular relevance in agricultural soils: larvae from the family Scarabeidae (dung-beetles), crucial to burying cow-dung in natural savannahs and grasslands used for cattle grazing (e.g. in Africa); and Melolonthinae beetles, whose larvae may be abundant in grasslands and affect crop production by feeding on living roots (Villalobos and Lavelle, 1990).

Dung beetles dig subvertical galleries 10–15 mm wide down to a depth of 50–70 cm with a variable number of chambers, which are further filled with large pellets of dung. The adult beetle lays one egg in each chamber and then the larva feeds on the pellet to complete the cycle (Lavelle and Spain, 2001). They generally give rise to small mounds a few centimetres high on the soil surface (Hurpin, 1962).


P. LAVELLE

Plate A1.1
Granular casts on the soil surface of an African soil.

Biogenic structures

Biogenic structures are those structures created biologically by a living organism. Three main groups of biogenic structures are commonly found in agricultural systems: earthworm casts and burrows, termite mounds and ant heaps. The biogenic structures can be deposited in the soil surface and in the soil, and generally they have different physical and chemical properties from the surrounding soil. The colour, size, shape and general aspect of the structures produced by large soil organisms can be described for each species that produces it. The form of the biogenic structure can be likened to simple geometric forms in order to facilitate evaluation of the volume of soil moved through each type of structure on the soil surface.

Earthworm casts

Earthworm casts vary in size depending on the size of the earthworm that produces them. They range from a few millimetres to several centimetres in diameter, weighing from only a few grams to more than 400 g.

Granular casts (Plate A1.1) are very small and formed by isolated faecal pellets (Lee, 1985). These casts can be found on the soil surface or within the soil, and are generally produced by epigeic earthworms.

Globular casts are larger and formed by large aggregates (Lee, 1985). These are normally produced by endogeic and anecic earthworms. The casts produced by anecic earthworms comprise an accumulation of somewhat isolated round or oval-shaped pellets (one to several millimetres in diameter) which may coalesce into "paste-like slurries" that form large structures. Hence, casts are large in size, tower-like, and made of superposed layers of different ages, the older (i.e. dry and hard) located at the base and the younger (i.e. fresh and soft) on the top (Plate A1.2). Casts produced by anecic earthworms have a higher proportion of organic matter, especially large particles of plant material, and a larger proportion of small mineral components than in the surrounding soil.


P. LAVELLE

Plate A1.2
Globular casts deposited by an African earthworm.

Earthworm burrows

Earthworms construct burrows or galleries (Plate A1.3) through their movement in the soil matrix. The type and size of the galleries depends on the ecological category of earthworm that is producing it.

Anecic earthworms create semi-permanent subvertical galleries, while endogeic worms dig rather horizontal burrows. These galleries may be filled with casts, which can be split into smaller aggregates by other smaller earthworms or soil organisms. Galleries are cylindrical and their wall area coated with cutaneous mucus each time the worm passes through.

Soil micro-organisms (bacteria) are markedly concentrated at the surface of the gallery walls and within the adjacent 2 mm of the surrounding soil. This microenvironment comprises less that 3 percent of the total soil volume but contains 5–25 percent of the whole soil microflora and is where some functional groups of bacteria predominate (Lavelle and Spain, 2001).

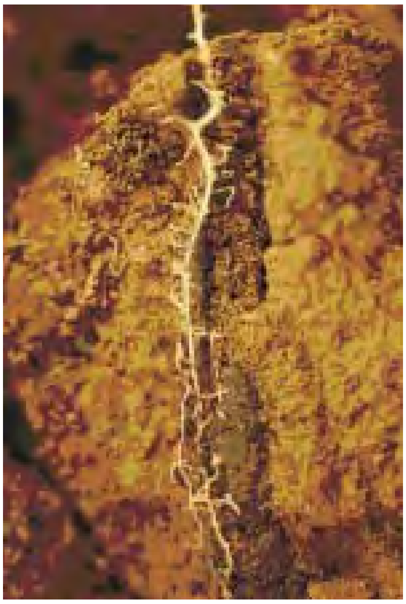

P. LAVELLE

Plate A1.3
An earthworm gallery (Martiodrilus sp.) in the Colombian savannah filled with casts and a root following the pathway opened by the earthworm. Root hairs are attached to the cast where higher availability of nutrients (C, N and P) exists compared with the surrounding soil.

Termite mounds

Termite mounds are among the most conspicuous structures in savannah landscapes. Termite mounds are of diverse types and are the epigeal part of a termite nest that originates from subterranean beginnings. In Africa, termites build up half of the biomass of the plains.

Termites process high quantities of material in their building activities, thus influencing the soil properties as compared with surrounding soils (Lee and Wood, 1971). Soil texture and structure are modified strongly in termite mounds. In general, the soil of the termite mounds exhibits a higher proportion of fine particles (clay), which termites transport from the deeper to upper soil horizons.

Ant heaps

The tropical American genera *Acromyrmex* and *Atta* leaf-cutting ants (Plate A1.4) make subterranean nests and their leaf harvesting may lead to enormous incorporations of organic matter and, hence, nutrients into the soil.

ROOTS

Although not generally considered soil organisms, roots grow mostly within the soil and have wide-ranging, long-lasting effects on both plant and animal populations aboveground and belowground, and thus they are included among soil biota.

Rhizosphere

The rhizosphere is the region of soil immediately adjacent to and affected by plant roots. It is a very dynamic environment where plants, soil, micro-organisms, nutrients and water meet and interact. The rhizosphere differs from the bulk soil because of the activities of plant roots and their effect on soil organisms.

The root exudates can be used to increase the availability of nutrients and they provide a food source for micro-organisms. This causes the number of micro-organisms to be greater in the rhizosphere than in the bulk soil. Their presence attracts larger soil organisms that feed on micro-organisms and the concentration of organisms in the rhizosphere can be up to 500 times higher than in the bulk soil.

An important feature of the rhizosphere is the uptake of water and nutrients by plants. Plants take up water and nutrients into their roots. This draws water from the surrounding soil towards the roots and rhizosphere.

The soil organisms near the rhizosphere influence plant roots because:

- They alter the movement of C compounds from roots to shoots (translocation).
- Earthworm galleries (burrows) provide an easy pathway for roots to take as they grow through the soil (Plate A1.3).

- Micorrhizal associations can increase nutrient uptake by plants.
- Some of them are pathogenic and can attack plant roots.

BENEFICIAL VS. HARMFUL ORGANISMS IN AGRICULTURAL SOILS

Plate A1.4
Deposits of soil by a fungus-growing ant in the Colombian Llanos.

Agricultural practices can have either positive or negative impacts on soil organisms. Land management and agricultural practices alter the composition of soil biota communities at all levels, with important consequences in terms of soil fertility and plant productivity. There are examples of both positive and negative effects of some groups of soil organisms, particularly micro-organisms, phytoparasites/pathogens or rhyzophages, plant roots, and macrofauna on plant production.

The different agricultural practices used by farmers also exert an important influence on soil biota, their activities and diversity. Clearing forested or grassland for cultivation has a drastic effect on the soil environment and, hence, on the numbers and kinds of soil organisms. In general, such activity reduces the quantity and quality of plant residues and the number of plant species considerably. Thus, the range of habitats and foods for soil organisms is reduced significantly. Through changing the physical and chemical environment, agricultural practices alter the ratio of different organisms and their interactions significantly, for example, through adding lime, fertilizers and manures, or through tillage practices and pesticide use.

The beneficial effects of soil organisms on agricultural productivity that may be affected include:

- organic matter decomposition and soil aggregation;
- breakdown of toxic compounds, both metabolic by-products of organisms and agrochemicals;
- inorganic transformations that make available nitrates, sulphates and phosphates as well as essential elements such as Fe and Mn;
- N fixation into forms usable by higher plants.

However, other soil organisms are detrimental or harmful to plant production. For example ants, aphids and phytophagous nematodes can be serious pests, and some micro-organisms, bacteria and actinomycetes cause also plant diseases. However, most damage is caused by fungi, which account for most soil-borne crop diseases.

Humans generally begin their influence on soil biodiversity with naturally-present communities at a particular site (resulting essentially from ecological and evolutionary forces). However, they also have the ability to introduce new organisms and, through imposition of different management practices, put selective pressures on the naturally present or introduced soil biota. This provides the opportunity to manage soil organisms and their activities in order to enhance soil fertility and crop growth. Although probably enough is known in theory to manage these communities, considerable basic and applied research is required in order to achieve appropriate levels of biological husbandry and optimal management of these biological resources.

REFERENCES

Bouché, M.B. 1977. Stratégies lombriciennes. *Ecol. Bull.*, 25: 122–132.

Brown, G.G., Pashanasi, B., Gilot-Villenave, C., Patrón, J.C., Senapati, B.K., Giri, S., Barois, I., Lavelle, P., Blanchart. E., Blakemore, R.J., Spain, A.V. & Boyer, J. 1999. Effects of earthworms on plant production. *In* P. Lavelle, L. Brussaard & P.F. Hendrix, eds. *Earthworm management in tropical agroecosystems,* pp. 87–147. Wallingford, UK, CAB International.

Coleman, D.C., Ingham, R.E., McClellan, J.F. & Trofymow, J.A. 1984. Soil nutrient transformations in the rhizosphere via animal-microbial interactions. *In* J.M. Anderson, A.D.M. Rayner & D.W.H. Walton, eds. *Invertebrates-microbial interactions,* pp. 35–58. Cambridge, UK, Cambridge University Press

FAO. 2000. *Guidelines and reference material on integrated soil and nutrient management and conservation for farmer field schools*. 164 pp.

Hurpin, B. 1962. Super-Famille des Scarabeoidea. *In* A.S. Balachowsky, ed. *Entomologie appliquée à l'Agriculture. Tome I. Coléoptères,* pp. 24–204. Paris, Masson.

Ingham, R.E., Trofymov, J.A., Ingham, E.R. & Coleman, D.C. 1985. Interactions of bacteria, fungi and their nematode grazers: effects on nutrient cycling and plant growth. *Ecol. Mono.,* 55: 119–140.

Lavelle, P. 1981. Strategies de reproduction chez les vers de terre. *Acta Oecol.*, 2: 117–133.

Lavelle, P. & Spain, A. 2001. *Soil ecology*. Dordrecht, Netherlands, Kluwer Academic Publishers.

Lee, K.E. 1985. *Earthworms: their ecology and relationships with soils and land use*. New York, USA, Academic Press. 411 pp.

Lee, K.E. & Wood, T.G. 1971. *Termites and soils*. London, Academic Press.

Ponge, J.F. 1991. Food resources and diets of soil animals in a small area of Scots Pine litter. *Geoderma*, 49: 33–62.

Soltner, D. 1978. *Phytotechnie Générale. Les bases de la production vegetale*. Tome 1, Le Sol. 7éme édition. Collection sciences et techniques agricoles. Angers.

Swift, M.J., Heal, O.W. & Anderson, J.M. 1979. *Decomposition in terrestrial ecosystems*. Oxford, UK, Blackwell Scientific Publications.

Villalobos, F.J. & Lavelle, P. 1990. The soil coleoptera community of a ropical grassland from Laguna Verde, Veracruz (Mexico). *Rev. Ecol. Biol. Sol.*, 27(1): 73–93.

Wallwork, J.A. 1970. *Ecology of soil animals*. London, UK, McGraw Hill.

Wood, T.G. 1996. The agricultural importance of termites in the tropics. *Agr. Zool. Rev.*, 7: 117–155.

Yeates, W.G. & Coleman, D.C. 1982. Role of nematodes in decomposition. *In* D.W. Freckman, ed. *Nematodes in soil ecosystems,* pp. 55–80. Austin, USA, University of Texas Press.

Annex 2

Effects of organic matter on soil properties

Organic matter affects both the chemical and physical properties of the soil and its overall health. Properties influenced by organic matter include: soil structure; moisture holding capacity; diversity and activity of soil organisms, both those that are beneficial and harmful to crop production; and nutrient availability. It also influences the effects of chemical amendments, fertilizers, pesticides and herbicides.

Soil organic matter consists of a continuum of components ranging from labile compounds that mineralize rapidly during the first stage of decomposition to more recalcitrant residues (difficult to degrade) that accumulate as they are deposited during advanced stages of decomposition as microbial by-products (Duxbury, Smith and Doran, 1989).

Freshly added or partially decomposed plant residues and their non-humic decomposition products constitute the labile organic matter pool. The more stable humic substances tend to be more resistant to further decomposition. The labile soil organic matter pool regulates the nutrient supplying power of the soil, particularly of nitrogen (N), whereas both the labile and stable pools affect soil physical properties, such as aggregate formation and structural stability. When crops are harvested or residues burned, organic matter is removed from the system. However, the loss can be minimized by retaining plant roots in the soil and leaving crop residues on the surface. Organic matter can also be restored to the soil through growing green manures, cuttings from agroforestry species and the addition of manures and compost. Soil organic matter is the key to soil life and the diverse functions provided by the range of soil organisms.

BIOLOGICAL PROPERTIES

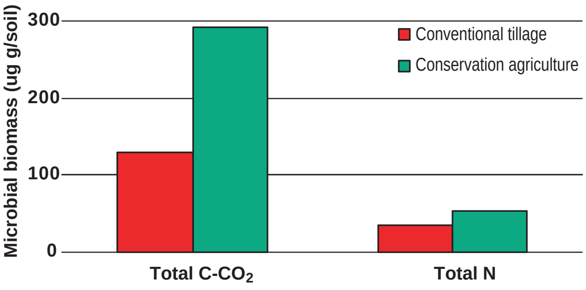
Soil micro-organisms are of great importance for plant nutrition as they interact directly in the biogeochemical cycles of the nutrients.

Increased production of green manure or crop biomass aboveground and belowground increases the food source for the microbial population in the soil. Agricultural production systems in which residues are left on the soil surface and roots left in the soil, e.g. through direct seeding and the use of cover crops, therefore stimulate the development and activity of soil micro-organisms. In one 19-year experiment in Brazil, such practices resulted in a 129-percent increase in microbial carbon biomass and a 48-percent increase in microbial N biomass (Figure A2.1

The roots of most plants are infected with mycorrhizae, fungi that form a network of mycelia or threads on the roots and extend the surface area of the roots.

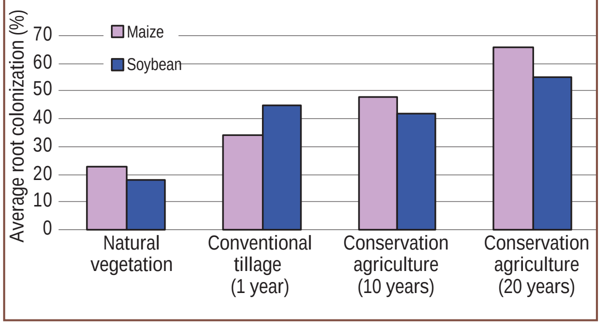
In undisturbed soil ecosystems, e.g. in conservation agriculture, colonization with mycorrhizal fungi increases strongly with time compared with colonization under natural vegetation (Figure A2.2). Fine

FIGURE A2.1
Microbial biomass (C and N) under conventional tillage and conservation agriculture



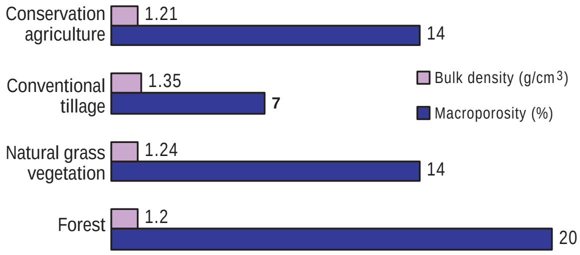
Source: Balota, Andrade and Colozzi Filho, 1996.

FIGURE A2.2
Infestation of crop roots with *Mycorrhizal* fungi



Source: Venzke Filho *et al.*, 1999.

FIGURE A2.3
Relationship between bulk density and macroporosity of a soil under different types of management



Source: Gassen and Gassen, 1996.

roots are the primary sites of mycorrhizal development as they are the most active site for nutrient uptake. This partly explains the increase in mycorrhizal colonization under undisturbed situations as rooting conditions are far better than under conventional tillage. Other factors that might stimulate mycorrhizal development are the increase in organic carbon (C) and the rotation of crops with cover crop/green manure species.

Another consequence of increased organic matter content is an increase in the earthworm population. Earthworms rarely come to the soil surface because of their characteristics: photophobia, lack of pigmentation and tolerance to periods of submergence and anaerobic conditions during rainfall. Soil moisture is one of the most important factors that determine the presence of earthworms in the soil. Through cover crops and crop residues, evaporation is reduced and organic matter in the soil is increased, which in turn can hold more water.

Residues on the soil surface induce earthworms to come to the surface in order to incorporate the residues in the soil. The burrowing activity of earthworms creates channels for air and water; this has an important effect on oxygen diffusion in the rootzone, and the drainage of water from it. Furthermore, nutrients and amendments can be distributed easily and the root system can develop, especially in acid subsoil in the existing casts. The shallow-dwelling earthworms create numerous channels throughout the topsoil, which increases overall porosity, and thus bulk density (Figures A2.3). The large vertical channels created by deep-burrowing earthworms increase water infiltration under very intense rainfall conditions.

CHEMICAL PROPERTIES

Many important chemical properties of soil organic matter result from the weak acid nature of humus. The ability of organic matter to retain cations for plant use while protecting them from leaching, i.e. the cation exchange capacity (CEC) of the organic matter, is due to the negative charges created as hydrogen (H) is removed from weak acids during neutralization. Many acid-forming reactions occur continually in soils. Some of these acids are produced as a result of organic matter decomposition by micro-organisms, secretion by roots, or oxidation of inorganic substances. Commonly used N fertilizers through microbial conversion of NH_4^+ to NO_3^-. In particular, ammonium fertilizers, such as urea, and ammonium phosphates, such as monoammonium and diammonium phosphate, are converted rapidly into nitrate through a nitrification process, releasing acids in the process and thus increasing the acidity of the topsoil (Figure A2.4).

When acids or bases are added to the soil, organic matter reduces or buffers the change in pH. This is why it takes tonnes of limestone to increase the pH of a soil significantly compared with what would be needed to simply neutralize the free H present in the soil solution. All of the free hydrogen ions in the water in a very strongly acid soil (pH 4) could be neutralized with less than 6 kg of limestone per hectare. However, from 5 to more than 24 tonnes of limestone per hectare would be needed to neutralize enough acidity in that soil to enable acid-sensitive crops to grow. Almost all of the acid that must be neutralized to increase soil pH is in organic acids, or associated with aluminium (Al) where the pH is very low.

However, with large values of soil organic matter, the pH will decrease less rapidly and the field will have to be limed less frequently. A lime application of 1–2 tonnes/ha every 2–3 years might be sufficient to regulate the acidity.

Organic matter may provide nearly all of the CEC and pH buffering in soils low in clay or containing clays with low CEC. In comparing conventional and conservation tillage in Brazil, the highest values of soil CEC and exchangeable calcium (Ca) and magnesium (Mg) were found in legume-based rotation systems with the highest organic matter content (Figure A2.5). In particular, systems with pigeon peas and lablab resulted in a 70-percent increase in CEC compared with a fallow/maize system.

Organic matter releases many plant nutrients as it is broken down in the soil, including N, phosphorus (P) and sulphur (S). Leguminous species are very important as part of a cereal crop rotation in view of their capacity to fix N from the atmosphere through symbiotic associations with root-dwelling bacteria. Again in Brazil, five years after starting an intensive system in which oats and clover were rotated with maize and cowpea, there was 490 kg/ha more total soil N in the 0–17.5-cm soil layer than under the traditional oats/maize system with conventional tillage. After nine years, no tillage in combination with the intensive cropping system had resulted in a 24-percent increase in soil N compared with conventional tillage. Although N uptake by plants was less in no-tillage systems, probably because of N immobilization and organic matter building, the maize yields under the different tillage systems did not differ. As the no-tillage system was more efficient in storing soil N from legume cover crops in the topsoil, in the long term this system can increase soil N available for maize production (Amado, Fernandez and Mielniczuk, 1998).

Calegari and Alexander (1998) noted that the P content (both inorganic P and total P) of the surface layer (0–5 cm) was higher in the plots with cover crops after nine years. Cover crops were shown to have an important P-recycling capacity, especially when the residues were left on the surface. This was especially clear in the fallow plots, where the conventional tillage plots had a P content 25 percent lower than the no-tillage plots. Depending on the cover crop, the increase was between 2 and almost 30 percent. Even more important is the effect of land preparation on the increase of P availability in the soil (Figure A2.6).

FIGURE A2.4
Nitrification process and acid formation in the topsoil

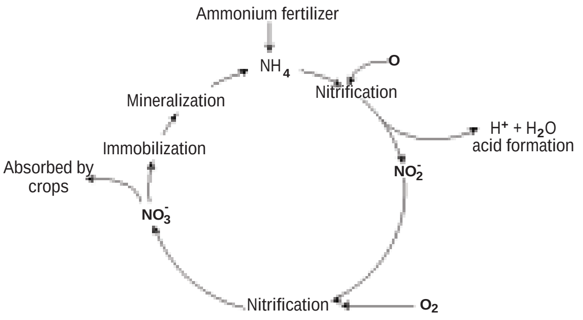
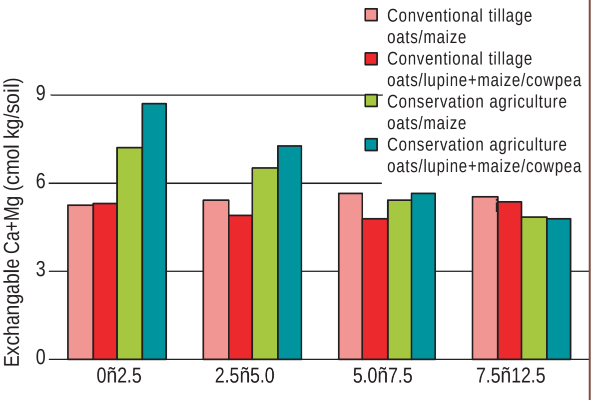


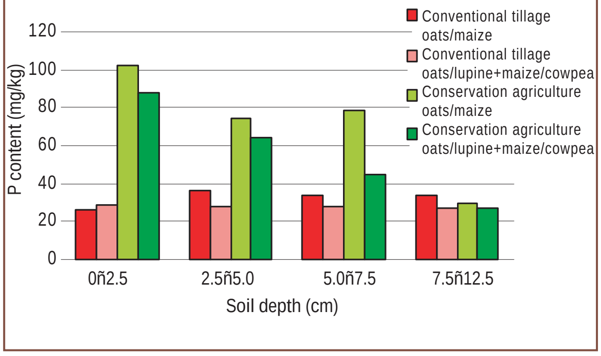
FIGURE A2.5
Exchangeable calcium and magnesium levels after 9 years of conservation agriculture, compared with conventional tillage systems



Source: Mielniczuk, 1996.

FIGURE A2.6

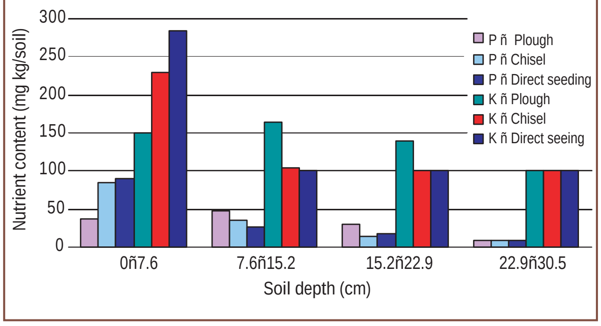
Phosphorus content of soil after 9 years of conservation agriculture, compared with conventional tillage



Note: P content of the soil (0-10 cm) was 9 mg/kg in 1985.
Source: Mielniczuk, 1996.

FIGURE A2.7

Phosphorus (blue) and potassium (orange) content of the soil at different soil depths and different types of land preparations



Source: Cruz, 1982.

Three to five years after initiating an intensified production system, both P and potassium (K) can be accumulated in the topsoil. Figure A2.7 shows that ploughing leads to an even distribution of the nutrients in the soil profile, at least in the upper 20–30 cm (ploughing depth). On the other hand, where direct seeding is practised and the crop residues are left on the surface, 50–75 percent of the nutrients were concentrated in the top layer of the soil.

PHYSICAL PROPERTIES

Organic matter influences the physical conditions of a soil in several ways. Plant residues that cover the soil surface protect the soil from sealing and crusting by raindrop impact, thereby enhancing rainwater infiltration and reducing runoff. Increased organic matter also contributes indirectly to soil porosity (via increased soil faunal activity). Fresh organic matter stimulates the activity of macrofauna such as earthworms, which create burrows lined with the glue-like secretion from their bodies and intermittently filled with worm cast material. Surface infiltration depends on a number of factors including aggregation and stability, pore continuity and stability, the existence of cracks, and the soil surface condition.

Organic matter also contributes to the stability of soil aggregates and pores through the bonding or adhesion properties of organic materials, such as bacterial waste products, organic gels, fungal hyphae and worm secretions and casts. Moreover, organic matter intimately mixed with mineral soil materials has a considerable influence in increasing moisture holding capacity.

The quality of the crop residues, in particular its chemical composition, determines the effect on soil structure and aggregation.

BENEFITS OF SOIL ORGANIC MATTER

As noted above, the benefits of a soil that is rich in organic matter and hence rich in living organisms are many. Direct organic matter amendments include:

- compost;
- animal manure;
- use of vermicompost;
- use of waste sludge.

Crop management practices that contribute to organic matter include:

- improved cropping systems and rotations;
- plant cover crops;
- maximizing crop residues and their management;
- improved rooting systems.

The effects of the management practices depend largely on the agroclimatic situation as temperature and moisture influence speed of decomposition and general cycling of organic matter and nutrients.

Benefits of soil organic matter for farmers include:

- Reduced input costs: reduced fertilizer needs owing to improved nutrient cycling and reduced leaching from the rootzone; reduced pesticide needs owing to pest–predator interactions among organisms and natural biocontrol; reduced tillage costs owing to reliance on biotillage by macrofauna under conservation agriculture approaches.
- Improved yield and crop quality: soil organic matter and soil biodiversity contribute to improved soil structure, root growth and mycorrhizal development, access to water and nutrients and hence improved root and tuber development and aboveground plant production. Improved soil and crop health reduce impacts of disease-causing organisms (pathogens and viruses and harmful bacteria).
- Pollution prevention: soil organic matter enhances biological activity of soil organisms that detoxify and absorb excess nutrients that would otherwise become pollutants to groundwater and surface water supplies. Soil organic matter is an important means of C sequestration, and organic matter management practices contribute to C storage (up to 0.5 tonnes/ha/year) and reduced greenhouse gas emissions.

SOIL ORGANIC MATTER AND DECOMPOSITION

Soil organic matter consists of living parts of plants (principally roots), dead forms of organic material (principally dead plant parts), and soil organisms (micro-organisms and soil animals) in various stages of decomposition. It has great impact upon the chemical, physical and biological properties of the soil. Organic matter in the soil gives the soil good structure, and enables the soil to absorb water and retain nutrients. It also facilitates the growth and life of the soil biota by providing energy from carbon compounds, N for protein formation, and other nutrients. Some of the nutrients in the soil are held in the organic matter, comprising almost all the N, a large amount of P and some S. When organic matter decomposes, the nutrients are released into the soil for plant use. Therefore, the amount and type of organic matter in the soil determines the quantity and availability of these nutrients in the soil. It also affects the colour of the soil.

Dead matter constitutes about 85 percent of all organic matter in soils. Living roots make up about another 10 percent, and microbes and soil animals make up the remainder.

Organic matter that has fully undergone decomposition is called humus. The origins of the materials after formation of humus cannot be recognized. Humus is dark in colour and very rich in plant nutrients. It is usually found in the top layers of a soil profile. The dark colour of humus absorbs heat from the sun, thereby improving soil temperature for plant growth and microbial activity under cooler climatic conditions.

Some of the most important functions of organic matter in the soil are:

- It increases soil fertility as it retains cations and conserves nutrients in organic forms and slowly releases required nutrients for plant uptake and growth.
- It binds soil particles together; the cementing and aggregation functions improving soil structure and aeration.
- It acts as a sponge in the soil, retaining soil moisture. Soils with high organic matter content can hold more water than those low in organic matter.
- It provides food for micro-organisms living in the soil.

Decomposition is the general process whereby dead organic materials are transformed into simpler states with the concurrent release of energy and their contained biological nutrient and other elements in inorganic forms. Such forms are directly assimilable by micro-organisms and plants, and the remaining soil organic matter may be stabilized through physical and chemical processes or further decomposed (Lavelle and Spain, 2001). These transformations of dead organic materials into assimilable forms involve the simultaneous and complementary processes of mineralization and humification:

- ➢ Mineralization is the process through which the elements contained in organic form within biological tissues are converted to inorganic forms such as nitrate, phosphate and sulphate ions.
- ➢ Humification is an anabolic process where organic molecules are condensed into degradation-resistant organic polymers, which may persist almost unaltered for decades or even centuries.

Decomposition is essentially a biological process. Nutrients taken up by plants are derived largely from the decomposition process. Micro-organisms are by far the major contributors to soil respiration and are responsible for 80–95 percent of the total carbon dioxide (CO_2) respired and, consequentl,y of the organic C respired (Satchell, 1971; Lamotte, 1989). Therefore, decomposition is a process determined by the interactions of three factors: organisms, environmental conditions (climate and minerals present in the soil); and the quality of the decomposing resources (Swift, Heal and Anderson, 1979; Anderson and Flanagan, 1989). These factors operate at different spatial and temporal scales (Lavelle *et al.*, 1993).

Living organisms are made up of thousands of different compounds. Thus, when organisms die, there are thousands of compounds in the soil to be decomposed. As these compounds are decomposed, the organic matter in soil is gradually transformed until it is no longer recognizable as part of the original plant. The stages in this process are:

1. Breakdown of compounds that are easy to decompose, e.g. sugars, starches and proteins.
2. Breakdown of compounds that take several years to decompose, e.g. cellulose (an insoluble carbohydrate found in plants) and lignin (a very complicated structure that is part of wood).
3. Breakdown of compounds that can take up to ten years to decompose, e.g. some waxes and the phenols. This stage also includes compounds that have formed stable combinations and are located deep inside soil aggregates and are therefore not accessible to soil organisms.
4. Breakdown of compounds that take tens, hundreds or thousands of years to decompose. These include humus-like substances that are the result of integration of compounds from breakdown products of plants and those generated by micro-organisms.

The easily decomposable sugars, starches and proteins are quick and easy for fungi and bacteria to decompose, hence the C and energy they provide is readily available. Most of the microbes living in the soil can secrete the enzymes needed to break up these simple chemical compounds. The larger mites and small soil animals often help in this first stage of degradation by breaking up the organic matter into smaller pieces, thereby exposing more of the material to colonization by bacteria and fungi.

Some of the energy or nutrients released by the breakdown of molecules by enzymes can be used by the bacteria and fungi for their own growth. For example, when an enzyme stimulates the breakdown of a protein, a microbe may be able to use the C, N and S for its own physiological processes and cell structure. If there are nutrients that the microbes do not use, they will be available for other soil organisms or plants to take up and use. When microbes die, their cells are degraded and the nutrients contained within them become available to plants and other soil organisms.

The second stage of decomposition involves the breakdown of more complicated compounds by many fungal and bacteria species. These compounds take longer to decompose because they are larger and are made up of more complicated units. Specific enzymes, not commonly produced by most micro-organisms, are required to break down these compounds.

Decomposition only takes place where conditions are suitable. Abiotic conditions have a considerable effect on the rate of breakdown. There must be some moisture available, soil temperatures must be suitable (usually between 10 and 35 °C) and the soil must not be too acidic or alkaline. Decomposition also occurs at higher temperatures, as in composts, or under waterlogged conditions through anaerobic processes. Thus, the types of organisms involved in breaking down the organic matter also depend on the conditions.

The type of organic matter, the way it is applied or incorporated into soil and the way it is decomposed influence the physical, chemical and biological balances in the soil and determine the various impacts. It can change:

- the amount of N available to plants;
- the amount of other nutrients available;
- how the soil binds together (soil aggregation);
- the number and type of organisms present in the soil.

Micro-organisms can access N in the soil more easily than plants. This means that where there is not enough N for all the soil organisms, the plants will probably be N deficient. When soils are low in organic matter content, application of organic matter will increase the amount of N (and other nutrients) available to plants through enhanced microbial activity. The number of microbes in the soil will also multiply, as they can use the organic matter as a source of energy. Where the number of fungi and bacteria associated with the breakdown of organic matter increases, there may be some improvements to the soil structure. Adding organic matter can also increase the activity of earthworms, which in turn can also improve soil aggregation.

REFERENCES

Amado, T.J.C., Fernandez, S.B. & Mielniczuk, J. 1998. Nitrogen availability as affected by ten years of cover crop and tillage systems in southern Brazil. *J. Soil Wat. Con.*, 53(3): 268–271.

Anderson, J.M. & Flanagan, P. 1989. Biological processes regulating organic matter dynamics in tropical soils. *In* D.C. Coleman, J.M. Oades & G. Uheara, eds. *Dynamics of soil organic matter in tropical ecosystems*, pp. 97–125. Niftal Project. University of Hawaii, USA.

Balota, E.L., Andrade, D.S. & Colozzi Filho, A. 1996. Avaliações microbiológicas em sistemas de preparo do solo e sucessão de culturas. *In: I Congresso Brasileiro de Plantio Direto para uma Agricultura Sustentável,* pp. 9–11. Resumos expandidos. Ponta Grossa.

Calegari, A. & Alexander, I. 1998. The effects of tillage and cover crops on some chemical properties of an oxisol and summer crop yields in south-western Paraná, Brazil. *Adv. Geo. Ecol.,* 31: 1239–1246.

Cruz, J.C. 1982. *Efecto de la rotación de cultivos y de los sistemas de laboreo sobre algunas propriedades del suelo; distribución radicular y rendimiento.* Cited by Monsanto, 2001. Universidad Purdue. (Tesis doctoral)

Duxbury, J.M., Smith, M.S. & Doran, J.W. 1989. Soil organic matter as a source and sink of plant nutrients. *In* D.C. Coleman, J.M. Oades & G. Uehara, eds. *Dynamics of soil organic matter in tropical ecosystem,* pp. 33–67. USA, University of Hawaii Press.

Gassen, D.N. & Gassen, F.R. 1996. *Plantio direto. O caminho do futuro.* Aldeia Sul, Passo Fundo. 207 pp.

Lamotte, M. 1989. Place des animaux détritivores et des microorganismes décomposeurs dans les flux d'énergie des savanes africaines. *Pedobiologia*, 33: 17–35.

Lavelle, P. & Spain, A. 2001. *Soil ecology.* Dordrecht, The Netherlands, Kluwer Academic Publishers.

Lavelle, P., Blanchart, E., Martin, A., Martin, S., Spain, A.V., Toutain, F., Barois, I. & Schaefer, R. 1993. A hierarchical model for decomposition in terrestrial ecosystems: application to soils of the humid tropics. *Biotropica*, 25(2): 130–150.

Mielniczuk, J. 1996. A sustentabilidade agrícola e o plantio direto. *In* R. Trippia dos Guimarães Peixoto, D.C. Ahrens & M.J. Samaha, eds. *Plantio direto: o caminho para uma agricultura sustentável*. Palestras do I Congresso Brasieleiro de Plantio Direto para uma Agricultura Sustentável. Ponta Grossa 1996. 275 pp.

Pauletti, V. 1999. A importância da palha e da atividade biológica na fertilidade do solo. *In: Fertilidade do Solo em Plantio Direto,* pp. 56–66. Resumos de Palestras do III Curso sobre aspectosbásicos de fertilidade e microbiologia do solo em plantio direto. Passo Fundo.

Satchell, J.E. 1971. Feasibility study of an energy budget for Meathop Wood. *In* P. Duvigneaud, ed. *Productivité des Ecosystèmes Forestiers*, pp. 619–630. Paris, UNESCO.

Swift, M.J., Heal, O.W. & Anderson, J.M. 1979. *Decomposition in terrestrial ecosystems*. Oxford, UK, Blackwell Scientific Publications.

Venzke Filho, S.P., Feigl, B.J., Sá, J.C.M. & Cerri, C.C. 1999. Colonização por fungos micorrízicos arbusculares em milho e soja em uma cronoseqüência de sistema plantio direto. *Rev. Plan. Dir.,* 54: 34.

FAO TECHNICAL PAPERS

FAO SOILS BULLETINS

1 Soils of the arid zones of Chile, 1965 (E*)
2 A survey of soils laboratories in sixty-four FAO member countries, 1965 (E*)
3 Guide on general and specialized equipment for soils laboratories, 1966 (E*)
4 Guide to sixty soil and water conservation practices, 1966 (E*)
5 Selection of soil for cocoa, 1966 (E* F* S*)
6 Aerial photo interpretation in soil survey, 1967 (C* E* F* S*)
7 A practical manual of soil microbiology laboratory methods, 1967 (E*)
8 Soil survey interpretation and its use, 1967 (E*)
9 The preparation of soil survey reports, 1970 (E* F* S*)
10 Physical and chemical methods of soil and water analysis, 1970 (E F S)
11 Soil fertility investigations on farmers’ fields, 1970 (E F S*)
12 The response of wheat to fertilizers, 1971 (E)
13 Land degradation, 1971 (C* E*)
14 Improving soil fertility in Africa, 1971 (E* F*)
15 Legislative principles of soil conservation, 1971 (E*)
16 Effects of intensive fertilizer use on the human environment, 1972 (E)
17 Trace elements in soils and agriculture, 1972 (E F S*)
18 Guide to the calibration of soil tests for fertilizer recommendations, 1973 (E S*)
19 Soil survey interpretation for engineering purposes, 1973 (E F* S*)
20 Fertilizer legislation, 1973 (E* S)
21 Calcareous soils, 1973 (E* F*)
22 Approaches to land classification, 1974 (E*)
23 Management properties of ferralsols, 1974 (E)
24 Shifting cultivation and soil conservation in Africa, 1974 (E* F S)
25 Sandy soils, 1975 (E*)
26 Planning and organization of fertilizer development in Africa, 1975 (E*)
27 Organic materials as fertilizers, 1975 (E* F* S*)
28 S.I. Units and nomenclature in soil science, 1975 (E)
29 Land evaluation in Europe, 1975 (E*)
30 Soil conservation for developing countries, 1976 (Ar C* E* F* S*)
31 Prognosis of salinity and alkalinity, 1976 (E)
32 A framework for land evaluation, 1976 (C* E* F* S*)
33 Soil conservation and management in developing countries, 1977 (E F)
34 Assessing soil degradation, 1977 (E*)
35 Organic materials and soil productivity, 1977 (C* E)
36 Organic recycling in Asia, 1978 (C* E*)
37 Improved use of plant nutrients, 1978 (C* E)
38/1 Soil and plant testing and analysis, 1980 (E)
38/2 Soil and plant testing as a basis of fertilizer recommendations, 1980 (E* S*)
39 Salt-affected soils and their management, 1988 (Ar E)
40 China: recycling of organic wastes in agriculture, 1977 (E F* S)
41 China: azolla propagation and small-scale biogas technology, 1978 (E* F S)
42 Soil survey investigations for irrigation, 1979 (C* E F)
43 Organic recycling in Africa, 1980 (E)
44 Watershed development with special reference to soil and water conservation, 1979 (C* E F S*)
45 Organic materials and soil productivity in the Near East, 1982 (E with Arabic summary)
46 Blue-green algae for rice production + a manual for its promotion, 1981 (E)
47 Le recyclage des résidus agricoles organiques en Afrique, 1982 (F)
48 Micronutrients and the nutrient status of soils: a global study, 1982 (E)
49 Application of nitrogen-fixing systems in soil management, 1982 (C* E F S*)
50 Keeping the land alive: soil erosion + its causes and cures, 1983 (E F S)
51 El reciclaje de materias orgánicas en la agricultura de América Latina, 1983 (S*)
52 Guidelines: land evaluation for rainfed agriculture, 1983 (C** E F S)
53 Improved production systems as an alternative to shifting cultivation, 1984 (E F S)
54 Tillage systems for soil and water conservation, 1984 (C E F S*)
55 Guidelines: land evaluation for irrigated agriculture, 1985 (C E F S)
56 Soil management: compost production and use in tropical and subtropical environments, 1987 (E F S)
57 Soil and water conservation in semi-arid areas, 1987 (C E F)
58 Guidelines: land evaluation for extensive grazing, 1991 (E)
59 Nature and management of tropical peat soils, 1988 (E)
60 Soil conservation for small farmers in the humid tropics, 1989 (E S)
61 Radioactive fallout in soils, crops and food, 1989 (E F S)
62 Management of gypsiferous soils, 1990 (Ar** E)
63 Micronutrient assessment at the country level: an international study, 1990 (E)
64 A study of the reasons for success or failure of soil conservation projects, 1991 (E F S)
65 Status of cadmium, lead, cobalt and selenium in soils and plants of thirty countries, 1992 (E)
66 Manual de sistemas de labranza para América Latina, 1992 (S)
67 Agro-ecological assessments for national planning: the example of Kenya, 1993 (E)

68 Field measurement of soil erosion and runoff, 1993 (E F S)
69 Soil tillage in Africa: needs and challenges, 1993 (E)
70 Land husbandry: components and strategy, 1996 (E F)
71 Tillage systems in the tropics: management options and sustainability implications, 1995 (E)
72 Sustainable dryland cropping in relation to soil productivity, 1995 (E)
73 Agro-ecological zoning - guidelines, 1996 (E)
74 Guidelines for quality management in soil and plant laboratories, 1998 (E)
75 New concepts and approaches to land management in the tropics with emphasis on steeplands, 1999 (E S)
76 Land and crop management in the hilly terrains of Central America: lessons learned and farmer-to-farmer transfer of technologies, 1999 (E S)
77 Soil management and conservation for small farms: strategies and methods of introduction, technologies and equipment, 2000 (E S)
78 Conservation agriculture – case studies in Latin America and Africa, 2001 (E S)
79 Optimizing soil moisture for plant production – the significance of soil porosity, 2003 (E, S)
80 The importance of soil organic matter – key to drought-resistant soil and sustained food production, 2005 (E)

Availability: October 2005

Ar	+	Arabic	Multil –	Multilingual
C	+	Chinese	*	Out of print
E	+	English	**	In preparation
F	+	French		
P	+	Portuguese		
S	+	Spanish		

The FAO Technical Papers are available through the authorized FAO Sales Agents or directly from Sales and Marketing Group, FAO, Viale delle Terme di Caracalla, 00100 Rome, Italy.

The importance of soil organic matter

Key to drought-resistant soil and sustained food production

Soil organic matter – the product of on-site biological decomposition – affects the chemical and physical properties of the soil and its overall health. Its composition and breakdown rate affect: the soil structure and porosity; the water infiltration rate and moisture holding capacity of soils; the diversity and biological activity of soil organisms; and plant nutrient availability. This *Soils Bulletin* concentrates on the organic matter dynamics of cropping soils and discusses the circumstances that deplete organic matter and their negative outcomes. It then moves on to more proactive solutions. It reviews a "basket" of practices in order to show how they can increase organic matter content and discusses the land and cropping benefits that then accrue.

ISBN 92-5-105366-9 ISSN 0253-2050
9 789251 053669
TC/M/A0100E/1/10.05/1400