MODULE 4:

SOILS AND THEIR MANAGEMENT FOR CLIMATE-SMART AGRICULTURE

Overview

This module looks at soil management in the context of climate change. It begins with an overview of some of the principles of soil health and the way soils interact with the atmosphere and with terrestrial and freshwater ecosystems. Sustainable soil management options are presented as "win-win-win" strategies that sequester carbon in the soil, reduce greenhouse gas (GHG) emissions and help intensify production, all while enhancing the natural resource base. The module also describes practices that contribute to climate change adaptation and mitigation, and build the resilience of agricultural ecosystems.

Key messages

- Knowing the status and condition of soils and their properties is fundamental for making decisions about sustainable soil management practices that contribute to climate-smart land use.
- Soils that have been degraded are at much greater risk from the damaging impacts of climate change. Degraded soils are vulnerable due to serious losses of soil organic matter (SOM) and soil biodiversity, greater soil compaction and increased rates of soil erosion and landslides. In addition, land degradation is itself a major cause of climate change.
- Management practices that increase soil organic carbon (SOC) content through organic matter management rather than depleting it will bring win-win-win benefits. These practices will maintain productive soils that are rich in carbon, require fewer chemical inputs and sustain vital ecosystem functions, such as the hydrological and nutrient cycles.
- The sound management of the interrelations among soils, crops and water can increase SOM, improve the soil's capacity to retain nutrients and water, and enhance soil biodiversity. Integrated management practices can create optimal physical and biological conditions for sustainable agricultural production (including food, fibre, fodder, bioenergy and tree crops, and livestock).

Contents

List of Figures

List of Tables

List of Boxes

4.1 Principles of soil health, key functions and soil: plant-water interrelations

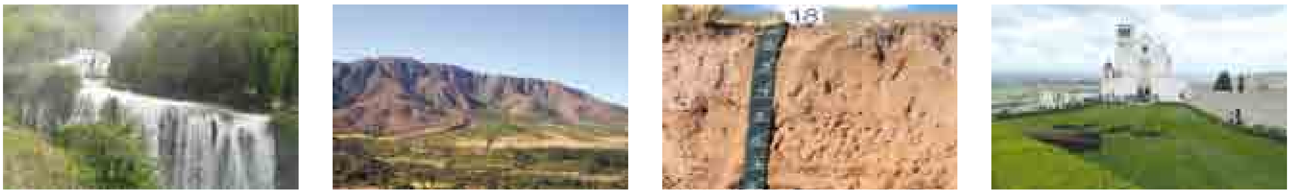
Soils are formed over long periods of time. They are made up of differing proportions of weathered rock, decayed plant and animal matter and a diversity of living plants and animals. Due to differences in local geology, topography, climate, vegetation and human management often over thousands of years, soils are highly variable, both across landscapes and in depth. The diversity and abundance of life that exists within the soil is greater than in any other ecosystem. A handful of soil can contain billions of different organisms that play a critical role in maintaining soil health and ensuring the soil carries out its functions.

Figure 4.1
Definition of soil. Soils contribute to a range of vital ecosystem services and functions[1]

Soil is the thin layer of material (organic and inorganic) on the Earth's surface. It is the foundation on which plants establish themselves and grow, and the basis for crop, forest and livestock production. Soil provides nutrients and water that are taken up through plant roots and contribute to the regulation of water and atmospheric gases.

[1] Ecosystem functions and services are the processes by which the environment produces resources critical to the good functioning of the Earth's life-support system and that contribute to human welfare.

Figure 4.2
Provision of ecosystem services and functions by soils



Life support services	Provision services	Regulating services	Cultural services
• The soil renews, retains, and delivers plant nutrients and provides physical support to plants. • It sustains biological activity, diversity and productivity. • The soil ecosystem provides habitat for the dispersion and dissemination of seeds, which ensures the continued evolution of the gene pool.	• Soil is the basis for the provision of food, fibre, fuel and medicinal products that sustain life. • It holds and releases water for plant growth and water supply.	• The soil plays a central role in buffering, filtering and moderating the hydrological cycle. • Soils regulate the carbon, oxygen and plant nutrient cycles (e.g. nitrogen, potassium, phosphorus, calcium, magnesium and sulphur) that affect plant production and the climate. • Soil biodiversity contributes to regulating soil pests and diseases. Soil micro-organisms process and break down wastes and dead organic matter (e.g. manure, remains of plants, fertilizers and pesticides) preventing them from building up to toxic levels and entering the water supply as pollutants.	• Soil provides the foundation for urban settlement and infrastructure. • Soils and their wider ecosystems provide spiritual or heritage value. • Soils are the basis for landscapes that provide recreation.

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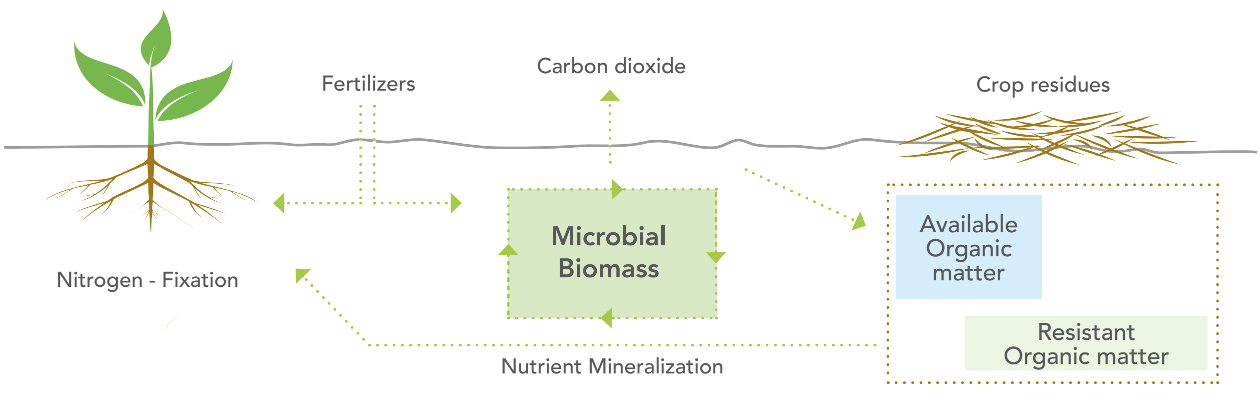
Soil health is a function of its capacity to provide the basic services for supporting plant growth and contributing to the regulation of nutrient, water, carbon and gaseous cycles. Soil health is widely linked to soil biodiversity. Soil organisms mechanically (comminution) and chemically (mineralization) break down the organic matter so they can use it as food. Excess nutrients are released into the soil and used by plants. The recalcitrant (indigestible) fraction of the organic matter is reorganized into SOM, which is less decomposable than the original plant and animal material (Figure 4.3). In turn, SOM content, especially the more stable humus, increases the soil's capacity to store water and sequester carbon from the atmosphere (Bot and Benites, 2005).

Figure 4.3
Organic matter turnover



Source: Gupta *et al.*, 1997

A soil's productivity depends on its physical, chemical and biological properties. Of particular importance are its mineral composition, organic matter content, soil life and associated biological activity. Sandy soils are the least productive as they do not have the capacity (unlike clay soils and silty soils) to retain moisture and nutrients through chemical attraction (electrical charge). However, sandy soils can be managed productively even in hot, dry climates if there is access to required water, organic materials and fertilizers to nourish plant growth.

4.2 Challenges of climate change to soils

With global warming, rainfall levels are expected to decline in many places, and/or to occur in more intense events, and evaporation and transpiration rates are projected to increase. These changes will reduce the availability of soil moisture for plant growth. The higher temperatures will also increase the rate of SOM decomposition (mineralization), especially near the soil surface, which will affect the soil's potential capacity to sequester carbon and retain water. In the scientific literature, there is common consensus that the effect of higher concentrations of carbon dioxide (CO_2) in the atmosphere and increases in temperature on photosynthesis and net primary production, and hence on carbon fixation in the biomass, will not be sufficient to counterbalance the GHG emissions due to the mineralization of SOM.

In cropping, grazing and forest systems, in particular, climate change and variability may affect soil health for plant growth through:

- reduced or erratic rainfall and more frequent and severe periods of drought that lower the capacity of soils to make water and nutrients available to plants;
- more intense rainfall and storms that increase the risk of soil erosion by water and wind (through rain splash, accelerated runoff, strong winds); and
- increased soil surface temperatures and greater rates of mineralization of SOM.

Some soil properties, such as soil texture[2], cannot be changed. Others can be modified and enhanced to enable land users to adapt to climate change and mitigate the effects of global warming by increasing the soil's capacity to store water, supply nutrients to plants, sequester carbon and reduce GHG emissions.

- The soil properties and functions that are most important with regard to climate change are: soil structure[3] and texture, organic matter content, nutrients, soil organisms, pH and cation exchange capacity. These properties allow soils to fulfil their productive functions, especially their capacity to retain water. Soil texture is the relative share of the different sizes of mineral particles (sand, silt and clay). It influences the soil's capacity to retain water and its ability to retain and exchange nutrients. Soil structure is the arrangement of those particles into aggregates and the soil pores between them. Soil porosity depends on both soil structure and texture and is very important for soil permeability. Unlike texture, soil structure can be modified by tillage or traffic.

  Different soil types and textures have different degrees of water permeability and provide different levels of protection or bonding for SOM (Six *et al.*, 2002). Sandy soils are highly permeable due to larger sand grains and pore spaces. Consequently, they have low water retention capacity and offer limited protection to organic matter compared to soils with a higher proportion of silts and clays, which attract and retain water and nutrients.

[2] Soil texture indicates the relative content of particles of various sizes, such as sand, silt and clay in the soil.

[3] Soil structure is defined by the way individual particles of sand, silt, and clay are assembled. When single particles assemble they are called aggregates. Aggregation of soil particles can occur in different patterns, resulting in different soil structures.

- SOM is the organic fraction of the soil that is made up of dead plant and animal materials in various stages of decomposition. It does not include fresh and undecomposed plant materials lying on the soil surface which is known as litter. SOM primarily contains organic carbon (on average 58 percent), but also macro- and micronutrients essential for plant growth and some inorganic carbon. Soil organic carbon (SOC) has an impact on the overall biological resilience of agro-ecosystems. It is also important for the soil's physical properties (e.g. aggregation, water holding capacity, water infiltration and aeration) and chemical fertility (e.g. nutrient availability). SOC also acts as a sink for atmospheric carbon. In addition, SOC enhances soil structure by binding the soil particles together as stable aggregates. Part of the biomass that is returned to the soil through processes of decay is converted into carbon compounds that stay in the soil for a long time (i.e. humus and related organo-mineral complexes). The amount of this stable fraction of SOM varies depending on the quantity and quality of the biomass and is higher in ecosystems with high biodiversity (Charman and Roper, 2000). The greater the SOM content, the greater the soil biodiversity and its activity in breaking down dead and decaying organic matter into humus and in making nutrients available for plant growth.

- Soil carbon stabilization. In most soils, young and unstable macro-aggregates are formed by biological processes (e.g. growing roots, fungal, bacterial and faunal activity have a primary role in mixing fresh organic matter with soil particles and root exudates [a complex of compounds secreted from growing roots and root hairs]). Young macro-aggregates physically protect carbon and nitrogen from mineralization by microbial enzymes, but need to be further stabilized for long-term carbon accumulation. In the carbon stabilization process, micro-aggregates are first formed within the unstable macro-aggregates. These macro-aggregates are then broken down further with the liberation of the micro-aggregates. The processes for the stabilization of aggregates mainly involve biological factors (such as ageing[4], as well as the growth of roots that exert pressure, remove water and produce exudates that have a role both as cementing agents and as substrate for further microbial activity). Some climate-dependent factors (such as wet-dry cycles) are also part of stabilization processes. As mechanical soil disturbance (i.e. ploughing) disrupts these important biological processes, it is particularly detrimental for the build up of SOM.

- Soil nutrients and organisms. While decomposing SOM, the multitude of any organisms in the soil food web release nitrogen (in the form of ammonia ions), potassium, calcium, magnesium and a range of other nutrients necessary for plant growth. Many of these plant nutrients exist in the soil in the form of positively charged ions (i.e. cations). The negative charges on the surfaces of clay particles and SOM attract cations and thus provide a nutrient reserve available to plant roots. Only a small percentage of the essential plant nutrients remains 'loose' in the soil water and directly available for plant uptake. Plants obtain many of their nutrients from soil by 'cation exchange', whereby root hairs exchange hydrogen ions with the cations adsorbed on the soil particles. Clay soils have a higher cation exchange capacity and a structurally greater potential fertility than silty and sandy soils.

- Nitrogen is a nutrient that deserves special attention as it plays a key role in plant metabolism and growth but it can also be a cause of pollution when it leaches in the form of nitrates into the water table. Also, nitrogen can be released from the agro-ecosystem in form of nitrous oxide (N_2O) – a serious GHG that affects global warming. The atmosphere contains 78 percent nitrogen by volume. But it is the lack of this element that most often limits plant growth because plants cannot use gaseous nitrogen from the atmosphere. However atmospheric nitrogen can be converted into nitrate and ammonium ions in the soil through nitrogen fixation by certain soil micro-organisms (symbiotic Rhizobia bacteria associated with the roots of legumes and non-symbiotic bacteria *Clostridium* and *Azoterbacter*, which are free-living in the soil).

[4] Ageing is the deposition of polysaccharides and other organic cementing agents by microbial activity.

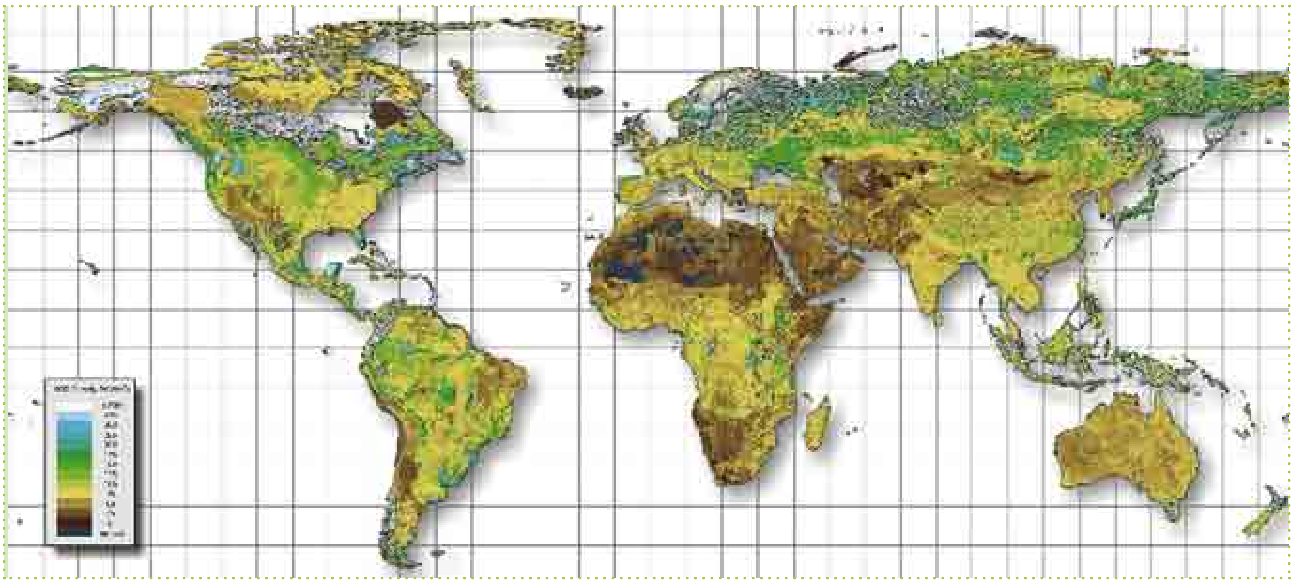
- Potassium is important in various plant physiological processes, and most crops require it in larger amounts than any other mineral element, with the exception of nitrogen. The potassium content of different soils is highly variable and depends on the parent material (the underlying bedrock or superficial deposits from which soils are formed). Unlike nitrogen and phosphorus, potassium is more dependent on the type and content of minerals than on organic matter. However, usually only less than one percent of the total potassium is present in water-soluble and exchangeable forms, and readily available for plant uptake. Potassium uptake by plants is positively related to increasing (yet not exceeding optimum levels of) soil moisture, aeration and temperature. Suggested management practices for potassium vary with the type of crop and the potassium status of soils. This status should be regularly monitored with either plant analysis or routine soil testing procedures. A positive response to potassium fertilization can be expected when soil test values are in the low range.

- Soil pH influences soil nutrient availability and biological activity. A soil pH level of 4 to 7 is acidic, while a soil pH level from 7 to 9 is alkaline. More fertile soils are usually between pH 6.0 and 7.0. Acidity reduces bacterial activity and consequently the decomposition of organic matter and nutrient release. Nitrogen-fixing *Rhizobia* and legumes generally do not do well in acidic soils. Also, strongly alkaline soils have suppressed biological activity and as a result fewer nutrients are available for plants. Strongly alkaline soils are also at risk of SOM decomposition, salinity, soil crusting and the accumulation of toxic levels of sodium and other minerals. Soil salinization is affected by climate change in that higher temperatures and evaporation rates increase the accumulation of salts (including sodium, phosphorus, calcium and magnesium) in the surface soil layers through capillary action. In addition, climate change may lead to higher rainfall, which will contribute to leaching out accumulated salts through increased drainage. Salinization is one of the progressive causes of soil degradation that threatens to limit plant growth and reduce yields on productive agricultural lands. High levels of soil salinity can only be tolerated if salt-tolerant (halophytic) plants are grown. Recent data show that globally about 11 percent of irrigated land is salt-affected, and about 53 percent of the global groundwater is also saline. In almost every irrigated area in the world, the groundwater is affected to some extent by salinity (Palaniappan and Gleick, 2009; FAO, 2011b). When the sodium ion predominates, soils can become sodic. This presents particular challenges because sodic soils tend to have very poor structure that limits or prevents water infiltration and drainage, and exacerbates the risk of erosion.

4.3 Soil principles for climate change adaptation and mitigation and enhancing resilience in different contexts

Sustainable crop, grazing and forest systems can sequester substantial and variable amounts of carbon from the atmosphere and store it in soils and vegetation as indicated in Figure 4.4 (see also Modules 7 on crops, 8 on livestock and 9 on forests). The carbon sequestration potential of any soil depends on many variables. When assessing carbon sequestration, rates should always refer to specific carbon pools, as each carbon category has a very different turnover rate. For instance, carbon accumulated in the first ten years is young and highly oxidizable. Soil carbon becomes more stable over time. In addition, to assess the effects of management practices on soils, it is necessary to have some reference base for similar soil types under the same climatic conditions. Undisturbed soils under natural vegetation should be used as a benchmark and used when comparing soils disturbed by human activities. In addition, data analysis should be carried out at the level of agro-ecological zones (Corsi *et al.*, 2012) to take into account the effects of climate.

Figure 4.4 Estimates of global soil organic carbon (t/ha of carbon) from amended Harmonized World Soil Database

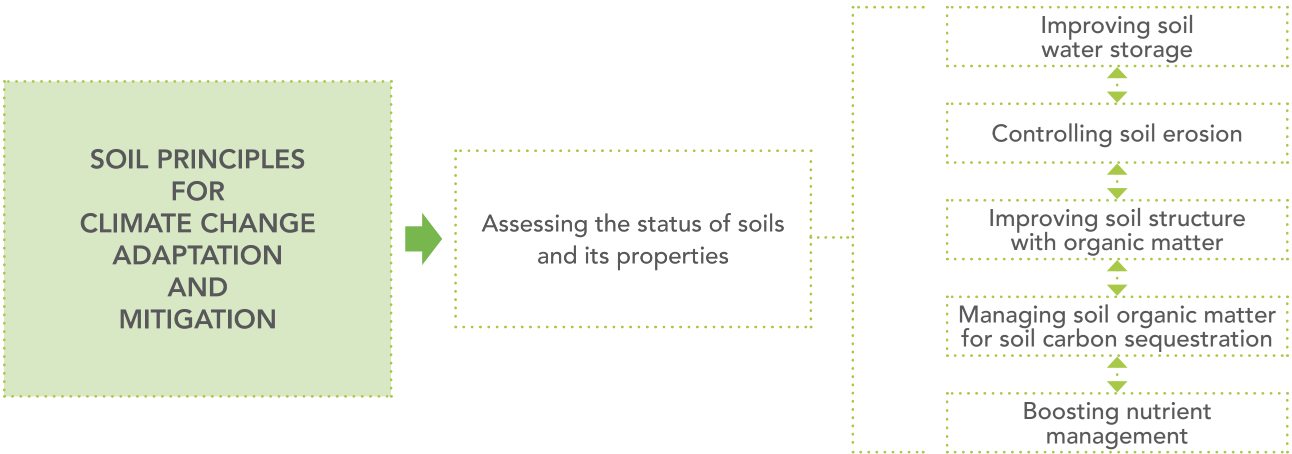


Source: Hieder and Kocky, 2011

Carbon sequestration will not only stabilize climate but will also make agricultural production more sustainable, increase the overall resilience of agro-ecosystems and maintain the ecosystem services that are supported by soils.

There are already proven soil management practices that can help farmers adapt to the likely adverse effects of increasing weather variability and climate change. These practices also often reduce GHG emissions from agriculture[5] and build resilience in farming systems (see Annex A.4.1). Widespread adoption of these practices has the potential to make major contributions to the achievement of national food security and development goals. There is a need to assess and provide incentives for the adoption of systems with the greatest production, mitigation and adaptation potential (win-win-win). The following figure (Figure 4.5) provides the basic soil principles for climate change adaptation and mitigation.

Figure 4.5
Soil principles for climate change adaptation and mitigation, and enhancing resilience



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[5] While other GHGs may be affected, most agricultural land management activities target only one of the three major gases: CO2, by sequestering carbon in the soil; N_2O, by reducing emissions; and methane (CH_4) by reducing emissions or increasing their uptake in the system (Eagle *et al.*, 2012).

Assessing the status of soils

Knowing the status and condition of soils and their properties is fundamental for making decisions about sustainable soil management practices that contribute to climate-smart land use. In this respect, it is crucial to carry out soil assessments and undertake the analysis and mapping of data and information through soil surveys, including in-situ visual soil assessments (FAO, 2008). These surveys should involve land users and be supported by technical experts. In addition, they need to be backed up by laboratory testing for specific properties. Various conventional and digital mapping tools should be used to extrapolate the findings across a range of soil and terrain units, vegetation types, and/or agro-ecological zones. Ideally, soil information will be made available as continuous maps that emphasise soil's attributes. Visual soil assessments should also involve land users and be supported by technical experts to assess physical properties (texture, structure, water holding capacity, dispersion) and chemical properties (ph, nutrients, salinity). For quantitative chemical characterizations soil test kits are available in many countries or can be ordered through the internet. For example, the United Sates Department of Agriculture has developed a soil quality test kit for nine soil parameters (USDA and NRSC, 1998). However, the kit does not include any for the labile SOC fraction – the parts of soil organic carbon with most rapid turnover through oxidation by microbial activity which releases CO_2 into the atmosphere. These labile fractions of SOC are important to study in their own right as they fuel the soil food web and greatly influence nutrient cycles and biologically-related soil properties. The use of dilute, slightly alkaline potassium permanganate and calcium chloride and a colorimeter represents a simple method of estimating changes in biologically active SOC that can be conducted in the field and may provide an early indication of soil degradation or how management practices are affecting soil quality (Weil *et al.*, 2003; FAO, 2012).

Preventing land conversion and protecting vulnerable lands to high SOM losses

Intensive land uses are expanding into areas where SOC stocks are less resilient. For example, semi-arid savannas and grasslands, tropical rainforests and peat lands are all being converted to arable land at an increasing rate. Temperate humid grasslands lose about 30 percent of their SOC after 60 years of cultivation (Tiessen and Stewart, 1983; Guo and Gifford, 2002). Soil carbon stocks in semi-arid environments can decrease by 30 percent in less than five years when native vegetation or pastures are converted to cropland (Zach *et al.*, 2006; Noellemeyer et al., 2008). Pastures established on cleared Amazon rainforest emit between 8 and 12 tonnes of carbon per hectare (Fearnside and Barbosa, 1998; Cerri *et al.*, 2007). Cultivation of tropical forest soils causes losses of more than 60 percent of original SOC stocks in just a few years (Brown and Lugo, 1990).

Tropical peatlands converted to cropland or plantations are a hotspot of carbon emissions (see examples of peatland management also in Module 2 on landscape approach). Draining peat soils to introduce commercial production systems in tropical environments causes ongoing losses of up to 25 tonnes of carbon per hectare per year (Jauhiainen *et al.*, 2011). In boreal peatlands, emissions from cropland are around 7 tonnes of carbon per hectare per year (Couwenberg, 2011). Although drylands[6] have lower mitigation potential per hectare than humid lands, their overall contribution could be highly significant since dry and sub-humid lands cover 47 percent of the Earth's land surface. Moreover, many dryland regions affected by land degradation and are sub-optimally managed could rapidly respond to improvements in management (Farage *et al.*, 2007).

Assessments of land resources are needed to understand trends in land conversion; the type, extent and severity of various land degradation processes; and the extent and effectiveness of existing improved or sustainable land management measures. Such assessments will identify hotspots and bright spots in terms of land degradation (soil, water and biodiversity) and climate change. Land use planning can then be used to determine suitable land uses and provide policy support or incentives to reduce land conversion and promote the adoption of sustainable practices, with particular attention given to peatlands and drylands that are more vulnerable to climate change.

[6] Drylands are areas characterized by lack of water, which constrains their two major interlinked services of primary production and nutrient cycling (FAO, 2005).

Preventing and mitigating land degradation

Soils that have been degraded are at much greater risk from the damaging impacts of climate change. Degraded soils are vulnerable due to serious losses of SOM and soil biodiversity, greater soil compaction and increased rates of soil erosion and landslides. In addition, land degradation is itself a major cause of climate change. It is estimated that overall, land use and land use changes account for around 31 percent of total human-induced GHG emissions (Scherr and Sthapit, 2009b). In the 1990s, 56 percent of the world's cropland (65 percent in Africa, 38 percent in Asia and 51 percent in Latin America and the Caribbean) and 73 percent of rangelands were estimated to be degraded (Oldeman, 1992; Dregne and Chou, 1992). About 22 percent of these lands have been degraded since the 1950s.

Various sources suggest that about 5-10 million hectares are being lost annually to severe degradation. Declining yields (or increased input requirements to compensate) can be expected over a much larger area. These losses results from: physical degradation by water and wind, crusting, sealing and waterlogging; biological degradation due to the depletion of organic matter depletion and loss of soil flora and fauna; and chemical degradation by acidification, nutrient depletion, pollution from excessive use of pesticides and fertilizers or human and industrial waste.

Unsustainable land management practices that are degrading soils include: continuous cropping with reductions in fallow and rotations, repetitive tillage and soil nutrient mining; overstocking, overgrazing and burning of rangelands; and the overexploitation or clearance of wooded and forest lands. During a time of rising demand for food, fibre, fuel, freshwater, fodder, timber and household energy, these practices are reducing the productive capacities of the world's croplands, rangelands and forests.

There is a need for greater policy support and investment in identifying and promoting appropriate production systems and management practices that simultaneously reverse or minimize degradation, conserve above- and below-ground biodiversity, sequester carbon, reduce GHG emissions and at the same time ensure sustained productivity.

Controlling soil erosion

Soil erosion is a widespread and serious degradation process. Intense rains can cause devastating soil erosion on cultivated lands on moderate to steep slopes where runoff rates are high and the ground has inadequate vegetative cover. Studies have identified tillage-induced soil erosion as the major cause of the severe soil carbon loss and soil translocation on upland landscapes (Lobb et al., 1995; Lobb and Lindstrom, 1999; Reicosky *et al.*, 2005). Even on gradual slopes, alkaline soils may suffer from dispersion or crusting that will increase soil erosion risk. Runoff and resulting soil erosion can be substantially reduced through the adoption of minimum to no-tillage techniques combined with optimizing soil cover (cover crops, residues, mulch). On steeper slopes, soil erosion can also be reduced by planting cross-slope vegetation; using soil and water conservation structures, such as terraces, earth bunds and tied ridges to optimize water capture and infiltration; and creating grassed waterways to convey excess water safely off the slopes.

Increased incidence of windstorms could also accelerate soil erosion as the blown sand may be deposited on productive land or sand dunes may encroach on these lands. Measures to reduce erosion by wind include optimizing vegetation cover with drought-resistant species, using rotational grazing to sustain rangeland vegetation quality, and planting windbreaks perpendicular to the prevailing winds.

Improving water storage

Water storage in the soil depends on many factors, including rainfall, soil depth, soil texture (clay content) and soil structure. Soil management can influence rainwater infiltration and the capacity of the soil to reduce soil water evaporation and store water in the soil. Groundcover management can have highly beneficial effects on soil surface conditions, SOM content, soil structure, porosity, aeration and bulk density. Improvements in these properties influence infiltration rates, water storage potential and water availability to plants. These improvements also increase the effectiveness of rainfall and enhance productivity. They also reduce rates of erosion, the dispersion of soil particles and the risks of waterlogging and salinity in drylands.

Within the soil matrix, stable forms of organic carbon, such as humus, can hold up to seven times their own weight in water. Table 4.1 gives an example of how changes in SOC modifies the soil's capacity to store water. An increase of 14.4 litres (almost two buckets) of extra water could be stored per square metre in the top 30 cm of soil for every 1 percent increase in the level of SOC. On one hectare that is equivalent to an additional 144 000 litres of water.

Table 4.1
Capacity of a soil with a bulk density of 1.2 g/cm^3 to store water as affected by SOC content to 30 cm soil depth.

The calculation of these figures was based on a conservative estimate that one part of SOC retains four parts of soil water.

Change in SOC content	Extra SOC	Extra water		CO_2 sequestered
[%]	[kg]	[litres/m2]	[litres/ha]	[t/ha]
1	3.6	14.4	144 000	132
2	7.2	28.8	288 000	264
3	10.8	43.2	432 000	396

Source: Jones, 2006 a and b

Sandy soils are inherently permeable and in hot, dry areas, evaporation rates are high and organic matter breaks down very quickly. For these reasons in drylands and coarse-textured soils the accumulation rate of organic matter is expected to be lower (Zingore *et al*., 2005; Chivenge *et al*., 2006). Crop management systems that reduce soil disturbance (e.g. ploughing and hoeing) and bring about a high accumulation of organic matter should be introduced. Mulching is a simple technique that buffers soil temperature and helps the soil-crop system reduce evaporation and the mineralization of organic matter. Mulching also counteracts the nutrient loss.

Precision farming is a more sophisticated management strategy based on observing and responding to intra-field variations to optimize returns on inputs while preserving natural resources. For example, precision agriculture is used to optimize the quantities of water and nutrients required by providing these inputs directly to the plant when needed through scheduled sprinkler irrigation or drip irrigation systems. Implicit in this type of management is an increased level of knowledge of crop requirements and local soil, terrain and climatic conditions (e.g. soil, slope, aspect).

Improving soil structure with organic matter

Many clay or loamy soils are compacted due to repetitive hoeing or ploughing. In mechanized systems, soil compaction is caused by the passing of heavy machinery through the fields for tillage. In grazing lands, soil is compacted by the trampling of livestock or wildlife. Compaction reduces airspaces in the soil and decreases the penetration of plant roots. Only stronger roots are able to penetrate the soil. The growth of lateral roots or fine root hairs, which are important for moisture and nutrient uptake, is restricted. Compacted soils and shallow soils are seriously affected by dry spells that limit root growth and the plant's access to moisture and nutrients. Subsoiling[7] to break up compacted layers can have a huge beneficial effect on root growth and soil productivity.

Box 4.1
Carbon and SOM

The top metre of the world's soils holds some 2 200 gigatonnes of carbon, two-thirds of which is in the form of SOM (Batjes, 1996). This is more than three times the amount of carbon held in the atmosphere.

[7] Subsoiling, or ripping, is soil preparation treatment done with tined implements to break up hardpans without turning the soil upside down (see FAO, 2012c for more details).

Prevention measures should be adopted to avoid soil compaction. An example is controlled traffic systems that minimize traffic and keep compaction in wheel tracks out of the crop area. Another example is minimum-tillage in combination with a plant or litter cover. This provides organic matter that enhances the activity of soil fauna (e.g. earthworms and termites). The burrowing of these soil organisms breaks up compacted layers and incorporates SOM from the surface into the soil. Also, specific cover crops with strong roots such as radish or pigeon peas can be used to penetrate and break up compacted soils layers. In time, practices such as conservation agriculture (that combine minimized soil disturbance with increased soil cover and crop diversification) will allow SOM to build up and increase the soil's resilience to climate change. Such practices build up a cover of protective vegetation or litter that foster the biological-tillage activity of macro-fauna (such as earthworms) that burrow and make channels for air and water. These practices also incorporate and break down organic matter in the soil.

Managing soil organic matter for soil carbon sequestration

Soil carbon stocks and the mitigation potential they provide depend on the agroclimatic zone, the land use type and the intensity of use. The rate of SOM decomposition and turnover depends primarily on the combined effects of the soil biota, temperature, moisture and its chemical and physical composition. It is also affected by the previous land use and natural resource management practices (particularly the mechanical disturbance of the soil).

Tillage-based agricultural practices over the last 50 to 100 years, which are associated soil degradation, have caused SOC levels in many regions to decline by one to three percent. As shown in Table 4.1, a three percent loss in SOC not only represents a significant loss of water storage (432 000 litres per hectare) but also represents nearly 400 tonnes of extra CO_2 per hectare emitted into the atmosphere. Loss of SOC and water holding capacity is associated with practices such as the elimination of perennial groundcover, repetitive cultivation or continuous grazing, bare fallows, removal of crop residues and grassland burning.

The monoculture of cash crops and the high use of external inputs have been an approach farmers have adopted to achieve the highest possible yields with minimal labour. However, fossil fuel prices have increased, and the production of energy-intensive mineral fertilizers and pesticides is a major source of GHG emissions. Moreover, when incorrectly applied, these inputs leach into water resources and the resulting water contamination has serious deleterious effects on ecosystems and human health. Diversified crop rotations and improved techniques for the management of fertilizer, seeds and pesticides can make the application of inputs more efficient. This reduces the wastage of external inputs and thereby reduces the amount of inputs needed. Greater efficiency in this area can also potentially lower GHG emissions. By improving soil structure and increasing soil biodiversity, no-till cultivation and the control of soil compaction will also reduce GHG emissions, which result mainly from anaerobic soil conditions.

Boosting nutrient management

With agricultural intensification, organic fertilizers (manure, compost and plant residues) are increasingly supplemented by inorganic or synthetic fertilizers, which provide required crop nutrients, including:

- Macronutrients (e.g. nitrogen, phosphorus, potassium, calcium, magnesium and sulphur); and
- micronutrients (e.g. boron, chlorine, copper, iron, manganese, molybdenum, zinc and nickel).

Mechanized systems emit considerable GHG emissions as does the manufacturing and processing of synthetic nitrogen fertilizers. In 2007, the global emission of GHGs from the production and application of nitrogen fertilizers amounted to 750 to 1 080 million tonnes of CO_2 equivalent, or about one to two percent of total global GHG emissions (Niggli *et al.*, 2009). The fertilizer industry recognizes that it contributes directly and indirectly to emissions of GHGs, particularly CO_2 and N_2O, through the production, distribution and use of fertilizers. The industry is encouraging clean technologies and greater efficiencies in the manufacture and application of fertilizers (IFA, 2009).

Nitrogenous fertilizers are the most widely used fertilizers and deliver huge benefits in terms of productivity, especially in nutrient-depleted soils. However, these fertilizers also have a high potential for environmental damage in terms of GHG emissions and nitrate pollution:

- Through the activity of soil micro-organisms, organically-bound nitrogen in soil is mineralized as ammonia (NH_3) and ammonium ions (NH_4-) and then transformed (nitrified) into nitrates (Jiang and Bakken, 1999). Nitrate ions are not attracted to clay and SOM particles (both of which are negatively charged) so they move freely with the soil water and can be leached from the soil through drainage.
- In addition, in oxygen-limited soils, denitrifying organisms will reduce nitrate to nitrous oxide, a GHG with about 300 times the warming effect of CO_2.
- Finally, cultivation (ploughing and hoeing) disturbs the soil and the formation of new aggregates, which encourages microbial activity and the rapid mineralization of SOM.

Between 79 and 98 percent of the nitrogen loss from agricultural soils is largely determined by the nitrate content of the soil just before the rainy season starts (i.e. resulting from the mineralization of organic nitrogen in the post-harvest season when temperatures are high, not from unused fertilizer applied earlier in the year). It is estimated that fertilized soils release more than 2 billion tonnes (in terms of CO_2 equivalents) of GHGs every year (Scherr and Sthapit, 2009b).

These GHG emissions can be reduced by achieving greater efficiencies in fuel use for mechanical field operations and irrigation; making changes in the rates, timing and type of nitrogen fertilizer applications; using slow release fertilizers that control the formation of nitrates; and adding nitrification inhibitors containing ammonium to fertilizer. These practices will help synchronize the demand and supply of nitrogen.

Agronomic management can also control the biological processes that cause nitrate leaching and produce GHG emissions. Cropping patterns should provide enough structural carbohydrates (e.g. lignin) along with nitrogen to allow the nitrogen produced from decaying surface residues to be released slowly and contribute to the growth of the following crop while minimizing losses (Huggins *et al.*, 1998; Gregorich *et al.*, 2001; Gál *et al.*, 2007).

There is common consensus that zero tillage and conservation agriculture systems will considerably reduce nitrate leaching (Macdonald *et al.*, 1989). This is because, unlike mechanical tilling practices, zero tillage and conservation agriculture leave the soil undisturbed, which decreases mineralization and the subsequent production of nitrates. Cover crops take up the nitrogen and reduce its loss from the soil. At the same time, unused mineralized nitrogen remains distributed within smaller pores and is not washed out of the soil (Bergström, 1995; Davies *et al.*, 1996; Gors *et al.*, 1993). However, where no-till is used without cover crops and with herbicides to manage weeds, the effects on nitrogen uptake and reduced leaching, as well as on yields, may be less evident.

Box 4.2
Inorganic fertilizers

Current use of inorganic fertilizers is estimated at 102 million tonnes worldwide. Its use is concentrated in industrial countries and some irrigated areas of developing countries.

The positive effects of the above principles will be optimized and losses minimized by integrating soil-crop-water management practices, identifying the spatial variability within the given land area and fields, and using precision-farming techniques to apply fertilizer and water in ways that are highly efficient and site-specific. Below, Boxes 4.3 and 4.4 illustrate those principles.

4.4 Successful examples of soil management practices for climate-smart agriculture with a focus on resilience

Integrated soil-crop-water management

The sound management of soil-crop-water interrelations can increase SOM levels, improve the soil's nutrient retention capacity and enhance soil biota. This integrated management can provide optimum physical and biological conditions for crop production (food, fibre, fodder and trees).

In cropping systems, good management practices would include:

- Direct seeding (no-tillage); improved protective soil cover through cover crops, crop residues or mulch; and crop diversification through rotations (e.g. incorporating deep rooting plants and perennials pasture leys for integrated crop-livestock systems).
  Burning of crop residues should be avoided by all means.
- Integrated soil fertility management (inorganic and organic) to alleviate the problem of low nutrient retention capacity, which is more pronounced in tropical and subtropical soils where there is a quick turnover of SOM and organic compounds. Agronomic systems should be adopted that increase the protection of carbon and nitrogen from rapid mineralization. Integrated soil fertility management is a strategy used worldwide in intensified cropping systems to combine inputs of organic matter (mulch, compost, crop residues, green manure) with fertilizers to address or prevent macro- and micro-nutrient deficiencies.
- Precise management of nitrogen. The recycling of nitrogen on the farm by using manure and nitrogen fixing plants is the predominant technique used in organic and low external input agriculture to enhance soil quality and provide nutrients. When using this technique, proper timing and management are essential. Nutrients need to be delivered to the plant in times of peak demand. Organic and green manures, as well as nitrogen from legumes, can be managed very precisely through crop rotations that include cover and catch crops (for more details see Thorup-Kristensen *et al.*, 2003).
- Herbicides and other weed management options.
- Physical conservation structures (such as bunds, drainage).
- Irrigation, partial irrigation where needed or possible (see Module 3 on water management).
- Robust sources of information and extension that are tailored to local conditions.

In grazing systems, SOM can be increased through controlled grazing, which reduces vegetation degradation and restores grassland diversity. Reducing burning to the absolute minimum also increases SOM. However, in common property lands, burning is often a preferred strategy for enhancing phosphorus and encouraging young growth for grazing animals (also see Module 8 on livestock). Pasture cropping, a practice where an annual crop is grown out-of-phase with perennial pasture, builds soil at higher rates than perennial pastures alone. This is due to the year-round transfer of soluble carbon to the root-zone and the maintenance of the humification process in the non-growth period of the perennial (Cluff and Seis, 1997).

Box 4.3
Honduras: Quesungual Slash and Mulch Agroforestry System

Slash and burn is a traditional form of agriculture practiced by small-scale farmers on around 20 percent of the tropical land area. Despite the short-term benefits obtained from its use (e.g. firewood, nutrients for crop development and reduced incidence of pests and diseases), it is recognized as an environmentally unfriendly practice that does not guarantee food security and exacerbates natural resource degradation and climate change.

In southwest Honduras, in the early 1990s, experts from FAO identified native farming practices and worked together with farmers to develop a suitable production system to replace the slash-and-burn system. The 'Quesungual Slash and Mulch Agroforestry System' (QSMAS) is a smallholder production system that uses a set of technologies for the sustainable management of vegetation, soil, water and nutrients in drought-prone areas of the sub-humid tropics. QSMAS can be considered a model system that applies conservation agriculture principles to achieve sustainable food security and ensure the delivery of other ecosystem services in drought-prone hillsides that must deal with the impacts of land degradation and climate change.

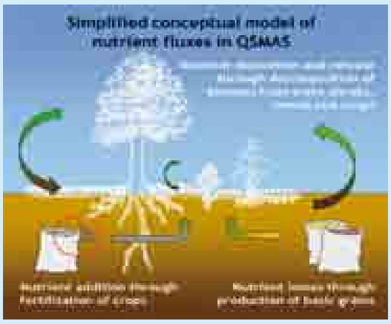
The basic Principles behind QSMAS success:

1 No Slash & burn
Management (partial, selective and progressive slash-and-prune) of natural vegetation.

2 Permanent soil cover
Continual deposition of biomass from trees, shrubs and weeds, and throgh crop residues.

3 Minimal disturbance of soil
No tillage, direct seedling and reduced soil disturbance during agronomic practices.

4 Efficient use of fertilizer
Appropriate application (timing, type, amount and location) of fertilizers.



Source: R. Vargas based on Castro *et al.*, 2008 and 2009

Water use efficiency and irrigation

As the climate changes, more attention should be placed on using water efficiently, reducing evaporation and enhancing infiltration and moisture retention in the soil profile through SOM management combined with the use of more drought-resilient species (see Module 3 on climate-smart water management).

Waterlogging from soil compaction, the over-application of irrigation water, inadequate drainage or soil puddling in paddy rice systems produces CH_4 emissions. Avoiding these emissions is particularly important as CH_4 is a much more powerful GHG than CO_2. After 20 years, CH_4 has a global warming potential 72 times higher than CO_2.

Irrigation increases crop and grassland productivity, particularly in drylands. The decomposition of roots and unharvested above-ground plant materials increases SOC, which delivers multiple benefits. The specific context will determine the most appropriate rainfed or irrigated system, as there are trade-offs that may need to be made. For example in irrigated systems, a trade-off may need to be made between reducing fossil fuel use and GHG emissions by using a gravity-fed irrigation and optimizing the efficiency of water use by using sprinkler or drip irrigation that emit more GHGs because they require fossil fuels for pumping water and transport. Addressing soil and water salinity in agricultural landscapes involves reducing salinity and using salt-affected soils and saline water through innovative soil and water management technologies and practices (Sakadevan and Nguyen, 2010). Integrated soil and water management practices for adapting to existing soil and water salinity and mitigating the potential development of salinity include: accurate irrigation scheduling (Howell, 2003); permanent raised bed (Akbar *et al.*, 2007); and soil conservation and management practices, such as reduced tillage, the incorporation of crop residues, gypsum and manure application, crop rotation and cover crops to increase soil organic matter, soil water holding capacity and infiltration.

Box 4.4
The traditional Minga system for drought management

Twenty-eight years ago, farmers from the Chiquitania region of Santa Cruz, Bolivia established a community adaption plan for climate change. As part of the plan, they have developed a practice for harvesting rainwater to cope with the greater fluctuations in rainfall, as well as the increased concentration and high variability of rains. Using a diversified production system, they grow maize, cassava, peanuts and organic coffee.

The practice consists in digging a row close to the plants, filling it with manure and then covering it with mulch or vegetation residues. According to the farmers, this technique has increased their yields and kept production stable even during droughts. The manure improves the soil structure, thereby increasing water storage. It also increases the soil's nutrient content. Currently, this technique is being spread by the Instituto Nacional de Innovación Agropecuaria y Forestal and FAO to other communities to help them cope with water scarcity resulting from climate change.


Community training


Preparing the manure


Digging the row


Filling the row with manure


Manure-filled row


Covering the surface with residues

Source: R. Vargas based on FAO-ICDS Bolivia, Photos Willy Barba

Restoring degraded soils for climate change resilience

The world's soils are estimated to have a high potential for carbon sequestration because SOC content can be effectively conserved and also readily restored or increased through appropriate land uses and agricultural management practices which can potentially be applied at landscape level (Corsi *et al.*, 2012). The widespread restoration of degraded soils is vital for carbon sequestration and can be achieved by increasing SOM content in the soil and reducing erosion and polluting factors. The highest potential for carbon sequestration is in degraded soils. However, initiating the process is slower on these soils because the soil microbial population that drives the SOC and nutrient cycles requires specific nutrient ratios that take time to achieve (Stevenson, 1986). Soil erosion by water (rainfall and runoff) or wind can be reduced by a range of soil and water conservation measures, including: maximizing vegetative cover, enhancing soil surface rugosity (clods, tied ridges); contour farming (bunds; diversion ditches); and reducing the degree and length of slopes (progressive and bench terracing). Tree planting can have win-win-win benefits in most systems (apart from light-sensitive crops). Planting trees introduces organic matter at a greater depth in the soil and can reduce wind erosion (see also Module 8 on forests). Soil carbon can be enriched by minimizing tillage, using cover crops or mulch, growing and incorporating green manures or applying biochar (see Box 4.5 below).

Green manures boost SOM and labile carbon, but they also disturb soil structure and do not maintain a protective litter, residue or plant cover.

More research is needed on the potential effects of biochar for reducing soil fertility in the longer term, binding and reducing the efficacy of some agricultural chemicals, and inhibiting microbial processes due to production of ethylene. In many contexts, because of the prohibitive cost of biochar, it is not an economically viable option.

Box 4.5
Biochar

Biochar is a stable, carbon-rich form of charcoal that can be applied to agricultural land as an element of agronomic or environmental management. It can be produced by pyrolysis, where biomass is heated with little or no oxygen (Sparkes and Stoutjesdijk, 2011). Possible biomass sources for biochar include: milling residues (e.g. rice husks, sugar cane bagasse); crop and logging residues; biofuel crops; municipal wastes; and animal manure. The suitability of the biomass for biochar production depends on its lignin content (Eagle *et al.*, 2012).

Biochar, because of its porous nature, high surface area and its ability to absorb soluble organic matter and inorganic nutrients is thought to have benefits for sustainable agricultural productivity. It increases biological activity and improves nutrient use efficiency, hence reducing NO_2 emissions and carbon sequestration. The use of biochar is new and more research is needed on the potential benefits and risks of its use in agricultural soils. There is a high variability in properties and its cost effectiveness depends on the biomass source and distance to the pyrolysis plant. Also, not all soils or crops show the same improvements when biochar is applied, and there may be risks associated with increased alkalinity.

Adaptive management capacity

Climate change impacts are complex and will affect natural resources and ecosystems in different ways in different places. It is important that communities understand the implications of these potential impacts in their own areas and are able to adapt. There is a need to build on farmers' knowledge and innovations and develop local capacity of land users to manage their soil systems so that they can build resilience and continue to innovate and adapt to a warming climate and changes in production systems. This requires building on practical farming skills, observation, personal experience, knowledge sharing and developing local capacity for adapting complex agro-ecosystems to change. Examples include breeding locally adapted seeds and livestock, producing organic fertilizers on farms (compost, manure, green manure), managing soil moisture and rainwater harvesting.

4.5 Conclusions

A healthy soil is fundamental for sustained agricultural productivity and the maintenance of vital ecosystem processes. To cope with climate change, the different types of production systems (crop, livestock and forest) and the specific practices used to manage them need to be adapted to take into account the diversity and current status of soils (e.g. sand, loam and clay soils, peat soils, sodic soils, shallow soils, nutrient depleted soils) and terrain (e.g. steep and flat lands, wetlands) and climatic conditions (e.g. short rainy seasons, erratic rains, high temperatures, storms).

Diversified production systems and land uses will conserve the diversity of plant and animal species and varieties in the agro-ecosystem; provide diverse habitats for beneficial predators and pollinators; and reduce farmers' risk and vulnerability if one or more crops fail or if other farming enterprises collapse. Management practices that do not deplete SOC content, but rather increase it from year to year through organic matter management, will bring win-win-win benefits. They will create productive soils that are rich in carbon, require fewer chemical inputs and maintain vital ecosystem functions, such as the hydrological and nutrient cycles. There is a need to shift away from specialized high-input systems towards the design and adoption of more integrated production systems (crop-livestock, agroforestry, agropastoral) that will reduce inorganic fertilizer use and the resulting GHG emissions. Integrated production systems also diversify farm outputs, sustain yields and reduce vulnerability to climate change and other shocks.

Notes

This module was written by Sally Bunning (FAO), Sandra Corsi (FAO) and Ronald Vargas (FAO).

Acronyms

C	carbon
CEH	Centre for Ecology and Hydrology
CH_4	methane
CO_2	carbon dioxide
GHG	greenhouse gas
IFA	International Fertilizer Industry Association
INIAF	National Institute of Agricultural and Forestry Innovation
IPCC	Intergovernmental Panel on Climate Change
ISFM	integrated soil fertility management
N	nitrogen
NH_3	ammonia
NH_4-	ammonium ions
N_20	nitrous oxide
NRSC	Natural Resources Conservation Service
SCCC	Soil Conservation Council of Canada
SOC	soil organic carbon
SOM	soil organic matter
SRI	Systems of Rice Intensification
USDA	United States Department of Agriculture

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Annex

A.4.1
Soil management for sustained crop productivity and climate change adaptation and mitigation

Conventional practices	Practices to enhance Productivity and Adaptation	Practices to enhance mitigation
Soil tillage for annual crops: Hoeing or ploughing improves the seedbed and uproots weeds. However, it disturbs microbes, destroys soil drainage created by soil fauna (e.g. earthworms), speeds decomposition of organic matter and releases CO_2. It may develop a compacted layer or hardpan which impedes plant root growth and rainwater percolation.	Conservation agriculture systems are practiced on around 125 million hectares of land worldwide. It involves three principles: • Minimizing soil disturbance (no-tillage) through digging sticks or jab planter to plant seeds or mechanized direct drill systems (mechanized systems have been developed to drill the seed through a vegetative layer and may use herbicides to manage weeds). • Keeping the soil covered with a protective layer of mulch or crop residues which reduces weed growth, reduces moisture loss, keeps the soil cooler, reduces erosion by water and wind and restores soil carbon (C) through decomposition. • Rotating and diversifying crops to reduce crop pests and diseases and use leguminous species to replenish soil nutrients. In Paraná, Brazil, no-till plots are reported to yield a third more wheat and soybean than conventionally ploughed plots and reduce erosion by up to 90% (Altieri et al., 2011).	The sequestration potential after adoption of improved management practices follows a sigmoid curve: it attains a maximum level of sequestration rates in 5 - 20 years (Cole et al., 1993; Nyborg et al., 1995; Solberg et al., 1997; Campbell, 1998; Dormaar and Carefoot, 1998; Duiker and Lal, 2000; Six et al., 2002; Lal, 2004) and continues at decreasing rates until SOC stocks reach a new equilibrium in 20 - 30 years (IPCC, 2007). Emissions reductions are smaller but a perpetual benefit is achieved. Conservation agriculture practices reduce fossil fuel emissions from tractor use, although there may be slight negative GHG impacts from application of additional chemical herbicides for weed control instead of weed control by tillage.

Conventional practices	Practices to enhance Productivity and Adaptation	Practices to enhance mitigation
Fertilizer use: A shortage of any one of the nutrients required for plant growth can limit crop yields. Increased productivity is needed to meet current and future food demand. However, fertilizer use efficiency tends to decrease with increasing applications as a great part of the nutrients are not taken up by the crop but released into water bodies and emitted into the atmosphere. Fertilizer manufacture releases GHG into the atmosphere.	Integrated soil fertility management (ISFM) aims to make available required soil nutrients by balancing different on-farm soil organic sources (amendments) with nutrients from mineral fertilizers (to address deficiencies) and reducing nutrient losses through soil and water conservation. It aims to: • Maximize the use of organic matter that provides nutrients, sequesters C and enhances water storage (e.g. compost, animal manures or green manures). • Enhance nutrient efficiency through crop rotations or intercropping with nitrogen-fixing crops and judicious/ precision use of inorganic fertilizer to reduce losses. • Minimize GHGs emissions (reduced traffic and tillage and efficient use of organic and inorganic fertilizers). • The timely provision of micronutrients in "fortified" fertilizers is a potential source of enhanced crop nutrition where deficiencies occur (FAO, 2011a). • Leguminous species can fix nitrogen (N) through symbiotic Rhizobium, however, they have a lower C/N ratio than cereals and grasses and breakdown fast, providing little cover to protect soils from erosion.	Nitrous oxide emissions are significantly related to use of organic and inorganic N fertilizer and legume-derived N. Nitrate leaching from overuse of mineral fertilizers also increases the potential for off-site nitrous oxide emissions. Options to reduce N losses and emissions include: • change the N fertilizer source from ammonium-based to urea, or switching to slow-release fertilizers; • placement of fertilizer N near the zone of active root uptake; • synchronise timing of N fertilizer application with plant N demand to reduce N losses; • improve manure application rates, applying solid rather than liquid manure, and to dry rather than wet areas when air temperatures are low; • use nitrification inhibitors.

Conventional practices	Practices to enhance Productivity and Adaptation	Practices to enhance mitigation
Crop specialization and annual harvesting: Many crop production systems progressively decrease SOC as most plant growth is above ground and is removed at harvest. In intensive systems mono-cropping of cereals use high levels of fertilizers and pesticides to replace restorative fallows and rotations with perennial leys or legumes. Often crop residues are removed for fodder, fuel or industrial applications or are burned for pest control (e.g. cotton). The global potential of N availability through recycling and N fixation is far greater than the current, affected by the highly energy-intensive production of synthetic N.	**Organic agriculture systems** do not use inorganic fertilizers or pesticides but use crop rotations and mixed farm strategies, with mulch / composts / animal manures /green manures to replenish soil C, improve nutrient cycling and use by plants and suppress weeds. The enhanced biodiversity reduces pest outbreaks and severity of plant and animal diseases. **Increasing the use of perennial crops and maintenance of shrubs and trees** in the farm landscape improves soil resilience and provides diverse products (food, fuel, fibre, timber, etc.) while supporting ecosystem services. **Agroforestry systems** that integrate compatible leguminous shrubs and trees with crops restore SOM and N through the leaf litter, help fix N through symbiotic Rhizobium, they enhance diversity, build healthier soils, enhance crop and fodder production. Some species provide fruits, timber and fuelwood or bioenergy. They can also reduce erosion and provide water quality and habitat benefits through shade and deep rooting, hence enhancing resilience to climate change.	Decisions to irrigate should factor in the consideration of the cost and GHG implications of mechanized systems. Perennial crops and trees can sequester substantial amounts of C and can store C for longer periods than annuals in the biomass of roots as well as in stems and branches. The frequency of tillage is reduced, protecting SOC and other soil functions. Other soil management options in cropping systems include **breeding deep rooted crops and managing fallow periods** to increase soil C stocks. The C sequestration potential of agroforestry varies widely, depending on the specific practice, individual site characteristics and the time frame.

Conventional practices	Practices to enhance Productivity and Adaptation	Practices to enhance mitigation
Soil crusting and degradation in drylands: This is a severe problem in the Sahel due to wind erosion and loss of SOM due to high temperatures and burning. When rain falls it can no longer infiltrate the soil and the region becomes increasingly barren and arid.	**Zaï Planting pits and Stone Bunds** in Burkina Faso, Niger and Zambia were used to rehabilitate bare, crusted degraded lands. The bunds capture rainfall and reduce runoff and manure in pits prior to planting, providing nutrients and retaining water. Despite the high labour costs (40-60 days/ hectare in Burkina) of establishment and the high recurrent costs for maintenance, production and transport of manure or compost, these practices were spontaneously adopted to expand cultivated area and reduce pressure on already-cultivated sandy soils (Reij and Smalling, 2007).	

Conventional practices	Practices to enhance Productivity and Adaptation	Practices to enhance mitigation
Soil puddling in rice paddy systems: Creates anaerobic conditions and increases emissions of GHGs. Flooded rice fields globally represent one of the main sources of methane.	Systems of Rice Intensification (SRI), which are further elaborated in the column on the right, bring benefits also in terms of productivity and adaptation, e.g. by improving the growth and performance of rice crops and subsequently increasing yields.	New technologies to reduce the use of water and GHG emissions in rice cultivation are now available: • One is SRI, an approach that requires compliance with the following: i) moist (but well drained and aerated) soil conditions; ii) transplanting rice seedlings at a very young age; iii) wider spacing of plants; iv) use of organic matter (i.e. compost made from any available biomass and manure if available) and chemical inputs; and v) frequent weeding. • Another approach is interrupting the flooding: conventional irrigated rice systems with high yielding modern rice cultivars in soils with alternate wetting or drying and with high external inputs can achieve medium to high yields (Stoop et al., 2002; Bouman et al., 2005; Yang et al., 2005). However, only timely flooded rice or rainfed lowland rice in flooded fields with periods of non-submergence can help to save water and reduce CH_4 emissions, but they seem to have the potential to increase the release of N_2O. Given that irrigated aerobic rice and SRI do not require anaerobic conditions, it would appear that both practices can combine well with climate adaptation (Friedrich and Kassam, 2009).

Conventional practices	Practices to enhance Productivity and Adaptation	Practices to enhance mitigation
Grazing systems: Many extensive grazing systems are suffering from overgrazing and serious reductions in the biodiversity of the aboveground vegetation, due to the effects of declining availability of land and overstocking due to inadequate livestock management. This is resulting in a decline in the rangeland soil quality, with depletion of biomass, erosion of topsoil by water and wind, loss of SOC and reduction of ecosystem services. This results in losses of soil structure and resilience e.g. through loss of deep rooting species that can cycle nutrients and water from deep in the soil profile. Excessive trampling of livestock, in particular around watering points, further damages the soil structure and functioning.	• **Improved grazing management on pastures or rangelands** may involve reducing stocking rates, avoiding grazing during drought periods, and improving the duration and timing of grazing and its frequency. This increases the soil surface protection by living and decomposing vegetation, increases SOC status and supports wider soil ecosystem services. Applying fertilizer or other inputs can also increase annual net primary productivity. • **Altering plant species' composition** is usually beneficial for pasture soils, as a selective increase in biodiversity can increase the quality (and usually the quantity) of SOC, consequently the range of rooting depths, thus promoting improved nutrient and water cycling. Introducing leguminous species is particularly beneficial to fix atmospheric N and improve soil fertility. • **Rotational grazing** through regularly moving livestock between paddocks intensifies grazing pressure for a relatively short period of time (e.g. 1 - 3 days for ultra-high stocking density or 3 - 14 days for typical rotational grazing), leaving a rest period for re-growth in between rotations. • **Assisted natural regeneration**, leaving land ungrazed for a period of up to several years to allow tree seeds already in the soil seed bank to become established brings multiple benefits to rangeland soils; improving nutrient cycling as nutrients are drawn from deep in the soil, increasing soil organic carbon (SOC) to the soil surface as leaves drop and decompose / become incorporated into the soil. Trees also offer some protection to soils (as well as to people and livestock) from periods of intense heat, which are likely to become more frequent due to climate change. • **Fire management**. Periodic burns can promote the overall health and growth of rangelands; for example, in tall grass prairie, increased plant productivity after it's burnt more than compensates for the loss of plant carbon by ignition. Use of trees also increases production and adaptation.	Compared with more highly productive pasture, rangelands have low C sequestration rates on a per unit basis, but because of their vast area, they could capture 2 - 4 % of annual anthropogenic GHG emissions on a global basis (i.e. 20% of the CO_2 released annually from global deforestation and land-use change) (Derner and Schuman, 2007; Follett and Reed, 2010). The majority of this C capture (greater than 90 percent) is in the form of SOC. Fire management in rangelands is generally accepted to have a minimal to detrimental effect on GHG mitigation. Most studies found that SOC stays about the same or even decreases following repeated burns (Rice and Owensby, 2001). However, other negative co-effects (methane, smoke, aerosols) are also linked to climate change, making burning even less attractive as a GHG mitigation option. Through soil C and above-ground C storage, silvopasture (trees planted on grazing land) may have GHG mitigation potential on up to 70 million hectares of grazing land (Nair and Nair, 2003). However, with few field research data, the estimated soil C sequestration rates of 0.5-3.6 tonnes of CO_2 per hectare per year are largely based on expert opinions. Compared with conservation activities on harvested croplands, the above activities on pasture yield higher soil C sequestration rates. The difference is due to pastures' greater allocation of plant biomass C to below-ground soil C and the extended growing season, reduced soil disturbance and better utilization of soil water. The range in sequestration rates depends on characteristics such as soil composition, topography, climate and existing grass species. The net fluxes of GHGs are also affected by nitrous oxide, or methane cycles (Conant et al., 2005).

Conventional practices	Practices to enhance Productivity and Adaptation	Practices to enhance mitigation
Livestock wastes: While conventional stockless arable farms become dependent on the input of synthetic N fertilizers, manure and slurry from livestock farms become an environmental problem. In these livestock operations, nutrients are available in excess and over-fertilization may occur and leaching is likely to lead to water pollution and high emissions of CO_2, nitrous oxide and CH_4.	The concept of either mixed farms or close cooperation between crop and livestock operations—a common practice of most forms of sustainable farming, especially organic ones— can considerably contribute to mitigation and adaptation. In addition, different forms of compost, especially composted manure, are particularly useful in stimulating soil microbial processes and in building up stable forms of SOM (Fließbach and Mäder, 2000). On-farm use of farmyard manure (a practice increasingly abandoned in conventional production) needs to be reconsidered in the light of climate change.	