B1 Climate-smart crop production

Overview

This module looks at the interrelations between crop production and climate change (Chapter B1-1). It presents the principles, practices and technologies for the sustainable and profitable production of annual and perennial crops to meet food, feed, energy, fibre needs and foster economic growth in a world where the global population is expanding, the climate is changing, dietary patterns are evolving and natural resources are growing scarce. These issues are presented both in terms of the projected impacts of climate change (Chapter B1-2) and crop systems (Chapter B1-3). The module also describes the off-farm elements that can enable farmers to adopt climate-smart crop production practices (Chapter B1-4).

A fundamental challenge is to address the needs of broad and diverse groups of stakeholders by identifying an appropriate set of climate-smart practices. This requires knowledge of the type and extent of expected changes in the climatic variables that affect crop production; the trade-offs and synergies between local climate and international markets; and the best adaptive management options for a given context.

This module does not provide a rigid blueprint for action. There is no standard formula that can be applied for every context. The shift towards climate-smart crop production systems will depend on a range of coping and adaptive mechanisms. These mechanisms will need to accommodate local, regional and global conditions, and may differ greatly from one farmer to another.

This module offers solutions that can be adapted to different crop systems. It addresses the subject matter from a technical perspective, but is written for the general public. In some cases, definitions for technical terms are provided.

Key messages

- The effective management of agricultural ecosystems contributes to both climate change adaptation and climate change mitigation. It is critical for the sustainable intensification of crop production.
- In rural, urban and peri-urban environments, approaches for the sustainable intensification of crop production that can support climate change adaptation and mitigation include:
    - the use of quality seeds and planting materials of well-adapted varieties;
    - the cultivation of a diverse suite of crop species and varieties in associations and/or rotations;
    - the use of integrated pest management practices;
    - the implementation of conservation agriculture and the adoption of sustainable mechanization to maintain healthy soils and manage water efficiently.
- Adaptation and adoption of climate-smart crop production practices and technologies requires knowledge of the type and extent of change in the climatic variables that affect crop production; integrated research on crop, soil and water; and the participation of farmers that needs to be promoted through system-wide activities to develop capacities.

Crop production and climate change

This chapter considers the most typical of the expected impacts of climate change on crop production, and the opportunities that exist for adapting to these changes and mitigating climate change through the sustainable intensification of crop production.

Intensifying crop production and addressing climate change must be done in an integrated and sustainable way. Although crop production and climate are deeply interconnected, the module deals with these subjects in separate chapters as a way of breaking down this complex issue and addressing it comprehensively. Chapter B1-1 discusses the interlinkages among the response actions to sustainably intensify and diversify crop productions, to adapt crop systems to the changing climate and to mitigate climate change through sustainable practices. Chapter B1-2 summarizes the impacts of climate change on crop production. Since crop production and climate change adaptation are strongly related to the specific local agro-ecological endowments and the natural resource base, readers are referred to modules B6, B7, B8 and B9 that provide a comprehensive analysis of the relationships between climate change and water, soil, genetic resources and energy. Chapter B1-3 discusses the impact of crop production on climate change.

B1-1.1 The impacts of climate change on crop production - the need for the intensification and diversification of sustainable production

The most important ecosystem service delivered by agriculture is the provision of food, feed and fibres.

The extent to which this provisioning depends on external production inputs is a fundamental issue. Agricultural ecosystems have evolved under human management. To obtain greatest possible production from the landscape, agricultural communities have developed and maintained ecosystems at their early succession state. The human selection pressure has favoured readably harvestable crops with high net production and it has penalized biomass production and accumulation on the landscape.

Since the Green Revolution, mainstreamed agriculture has mainly involved controlling crop varieties and their genetics; soil fertility through the application of chemical fertilizers; and pests with chemical pesticides. The impact of this form of agriculture on the environment has been severe. There has been a significant simplification and homogenization of the world's ecosystems. Maize, wheat, rice and barley, which were once rare plants, have become the dominant crops on earth and staples in human diets (FAOSTAT, 2014). Soil degradation is another critical concern. In agricultural ecosystems depleted of soil organic carbon, it will be increasingly difficult to produce higher yields. Each year, soil erosion destroys 10 million hectares of cropland. Forty percent of this loss is due to tillage erosion (Pimentel, 2006). In soils that have already experienced significant losses of soil organic matter, increased fertilization does not usually generate a net sink for carbon, because the production, transport and application of fertilizer releases higher amounts of carbon dioxide (Corsi *et al*., 2012).

The FAO 'Save and Grow' model of sustainable crop production intensification calls for a 'greening' of the Green Revolution to achieve the highest possible productivity by unit of input within the ecosystem's carrying capacity. This can be achieved through the use of good quality seeds and planting materials of well-adapted varieties; a diverse range of crop species and varieties grown in associations, intercrops or rotations; the control of pests through integrated pest management; and the use of conservation agriculture and sustainable mechanization to maintain healthy soils and manage water efficiently (FAO, 2011). Greater access to technological innovations and a sound understanding of agricultural ecosystems will allow farmers to work 'smarter not harder' and work in tandem with biogeochemical processes inherent in diverse and complex ecosystems. Chapter B1-2 presents agronomic management practices that reflect these principles.

The FAO model for the sustainable intensification of crop production is the cornerstone of climate-smart agriculture. It guides all climate-smart strategies aimed at overcoming the inefficiencies that are responsible for yield and productivity gaps. In each crop system, there exist many climate change adaptation and mitigation options to close yield gaps and minimize the harmful environmental impacts of crop production. Options will vary among farmers and will depend on each farmer's coping and adaptive mechanisms, and the degree to which each specific climate factor is responsible for the yield and productivity gap. The solutions identified should always be cost-effective and profitable for farmers and responsive to markets. Since most technologies have both advantages and disadvantages, trade-offs will need to be made. Ensuring that these trade-offs are properly assessed demands comprehensive capacity development for all stakeholders (see module C1). In particular, farmers must manage the foreseen business risks of changing their production practices (e.g. costs, investments and future value of the investments); consider the financial returns related to adapting to changes in local climate; evaluate the implications of local climate on local prices and markets; and anticipate the consequences climate change may have on crop prices in international markets.

For more information, consult module B8 on plant genetic resources, module B7 on sustainable soil and land management and module A3 on integrated landscape management.

B1-1.2 Climate change impact on crop production - need for adaptation to climate change

Crop production is highly sensitive to climate. It is affected by long-term trends in average rainfall and temperature, interannual climate variability, shocks during specific phenological[ii] stages, and extreme weather events (IPCC, 2012). Some crops are more tolerant than others to certain types of stresses, and at each phenological stage, different types of stresses affect each crop species in different ways (Simpson, 2017).

As climate changes, crop production strategies must change too. There will always be some uncertainty associated with modelling the complex relationships between agricultural yields and future climate scenarios. This chapter summarizes the most universally accepted effects of climate change on crop production. Chapter B8-3 addresses how climatic changes can disrupt the interactions among plants and pollinators (Kjøhl *et al*., 2011), Chapter B1-2 presents the management practices and technologies for climate change adaptation, and Chapter B1-3 presents these management practices in the context of specific crop systems.

Increased atmospheric concentration of carbon dioxide

A higher concentration of carbon dioxide in the atmosphere will have different effects on different crops.

In C$_3$ plants[iii], the photosynthesis relies on the concentration of carbon dioxide that is naturally available in the atmosphere. A higher concentration of carbon dioxide in the atmosphere will have a small fertilizing effect on these crops, if all other factors remain favorable. Adverse moisture conditions during the growing season, insufficient nitrogen availability or temperatures above the optimum range may offset this effect. However, the nutritional content of leaves, stems, roots, fruits and tubers of C$_3$plants grown at elevated carbon dioxide levels is expected to be lower particularly in protein, minerals and trace elements, such as zinc and iron (Taub *et al*., 2008; Loladze, 2014). Plants grown at higher concentrations of carbon dioxide have lower stomatal conductance[iv] and transpiration. This means that plants absorb less water and nutrients and that their biomass becomes less nutritious. One insidious aspect associated with the nutritional quality of crops is that, in addition to humans, also insect pests will have to compensate by eating more to meet their nutritional needs (Hatfield *et al.*, 2011).

C$_4$ plants[v] have the capacity to increase the carbon dioxide concentration within their leaves before the photosynthesis begins. This is why increased concentrations of carbon dioxide in the atmosphere will not provide benefits to C$_4$ plants under normal conditions. Under moisture stress conditions, however, most C$_4$ crops will lose less moisture, and their yield will be affected less (Simpson, 2017).

Temperature alterations

Temperature alterations can take many forms: changes in average temperature; changes in daytime high and nighttime low temperatures; and changes in the timing, intensity and duration of extremely hot or cold weather.

In general, crops are most sensitive to high temperatures at the reproductive stage and grain-filling/fruit maturation stage (Hatfield *et al*., 2011). However, plant responses to each type of temperature alteration is species-specific and mediated through both photosynthetic activity for biomass accumulation, which is responsible for plant growth, and the phenological and morphological changes, which occur during plant development. Each type of temperature stress has a different effect on crop duration and overall plant productivity. The effect will depend on how sensitive each species is at their stage of development when the temperature alteration occurs. Adapting to these effects will require different types of responses.

To predict the responses of species to new temperature alterations, it is necessary (although not sufficient) to know how the same species have responded in the past to similar changes. Below are some of the findings from the few phenological studies of sufficient length on annual crops.

- The increase in average temperature during the growing season typically causes plants to use more energy for respiration for their maintenance and less to support their growth. With a 1°C increase in average temperatures, yields of the major food and cash crop species can decrease by 5 to 10 percent (Lobell and Field, 2007; Hatfield *et al*., 2009).
    - The increase in average temperature during the growing season typically causes plants to use more energy for respiration for their maintenance and less to support their growth. With a 1°C increase in average temperatures, yields of the major food and cash crop species can decrease by 5 to 10 percent (Lobell and Field, 2007; Hatfield *et al*., 2009).
    - With higher average temperatures plants also complete their growing cycle more rapidly (Hatfield *et al*., 2011). With less time to reproduce, reproductive failures are more likely and this will also lower yields (Craufurd and Wheeler, 2009).
    - In general, photosynthesis in C$_3$ plants is more sensitive to higher temperatures compared with C$_4$ crops (Lipiec *et al*., 2013).

- Variations in the length of the thermal growing season[vii] will generally affect temperate perennial species (e.g. apples, cherry and grapes). Most temperate perennials require an adequate period of chilling hours[viii] during dormancy before they can resume active growth. Inadequate chilling impairs the development and/or expansion of vegetative and reproductive organs, which will affect fruiting.
- Higher temperatures can also affect the marketability of fruits and vegetables. The increased rates of respiration caused by higher temperatures lead to a greater use of sugars by the plants. As a result less sugar remains in the harvested product, and this can reduce its market value (Hatfield and Prueger, 2015). These effects become more serious as temperatures continue to rise during the grain-filling or fruit maturation stage (Simpson, 2017).
- Higher nighttime temperatures may increase respiration at night causing declines in yield (e.g. rice) and flowering or reproduction (e.g. beans).
- Most crops can tolerate higher daytime temperatures during vegetative growth, with photosynthesis reaching an optimum at between 20°C and 30°C (Wahid *et al*., 2007). During the reproductive stage, yields decline when daytime high temperatures exceed 30°C to 34°C (FAO, 2016b).
- Extremely high temperatures above 30°C can do permanent physical damage to plants and, when they exceed 37°C, can even damage seeds during storage. The type of damage depends on the temperature, its persistence, and the rapidity of its increase or plants' capacity to adjust (Wahid *et al*., 2007). It also depends on the species, the stage of plant development. As the climate changes, the frequency of periods when temperatures rise above critical thresholds for maize, rice and wheat is predicted to increase worldwide (Gourdji *et al.*, 2013).

Changes in precipitation regimes

Changes in precipitation regimes include changes in seasonal mean, the timing and intensity of individual rainfall events, and the frequency and length of droughts. Each of these factors is critical to crop productivity. The impact of changes in precipitation will be particularly marked when they are combined with temperature alterations that affect the crop's evaporative demands. This may lead to different forms of moisture stress depending on the phenological stage the crop has reached.

The specific impacts of changes in precipitation regimes on crops vary significantly because around 80 percent of the cropped area is rainfed and produces 60 percent of world's food (Tubiello *et al*., 2007). The levels and distribution of precipitation determine whether a crop can be grown without irrigation and/or drainage, or whether investments in this area are necessary.

The general prediction is that, with climate change, areas that already receive high levels of rainfall will receive more, and those that are dry will become drier (Liu and Allan, 2013). The reduction in seasonal mean precipitation will have a greater impact on areas with degraded soils. Soils with lower levels of organic carbon retain less water at low moisture potentials. Furthermore, crops grown in nutrient-poor soils, especially those lacking potassium, recover less quickly from drought stress once water is again available (Lipiec *et al.*, 2013). To help their crops use water more efficiently, farmers must pay attention to improving and maintaining soil fertility (see module B7 on sustainable soil and land management for climate-smart agriculture, Chapter B1-2 on sustainable soil management for increased crop productivity and Box B1.3 on crop residue management for soil carbon conservation and sequestration).

As rainfall becomes more variable, farmers may no longer be able to rely on their knowledge of the seasonality of climatic variables. Shifting planting seasons and weather patterns will make it harder for farmers to plan and manage production. For example, a later start of the rainy season or an earlier end, or both, reduces the time that crops have to complete their growth cycle and, ultimately, causes yield losses (Linderholm, 2005). For photosensitive species, a change in the duration of the rainy season may cause a mismatch between their reproductive cycle, which is determined by day length, and the availability of sufficient soil moisture to produce good yields.

Another expected impact of climate change is an increased occurrence of extreme weather events. Even where mean values for precipitation are not projected to change, there are likely to be more significant extreme weather events that will reduce crop yields. Heavy rain, hail storms and flooding can physically damage crops. Extremely wet conditions in the field can delay planting or harvesting. Prolonged droughts can cause complete crop failure (Tubiello and van der Velde, 2010).

Pests

As discussed in Chapter B8-4, climate change modifies the interactions between plants and their pests in space and over time. Plants weakened by the direct effects of weather stresses are generally more vulnerable to indirect stresses. For example, plants suffering from waterlogging are less resilient to viruses, and plants affected by drought are less able to outcompete weeds for soil moisture and nutrients (Simpson, 2017). In addition, if pests shift into regions outside the distribution of their natural enemies, the effectiveness of biocontrol will decrease unless a new community of enemies will provide some level of control.

The distribution of insect pests is influenced by temperatures. With global warming, insects, whose body temperature varies with the temperature of the surrounding environment (poikilothermic[x]) are most likely to move polewards and to higher elevations (Bebber *et al*., 2013). Pest distribution will also respond to changes in cropping patterns to cope with climate change. Major insect pests of cereals, pulses, vegetables, and fruit crops, which may move to temperate regions, include cereal stem borers (*Chilo*, *Sesamia*, and *Scirpophaga* spp.), pod borers (*Helicoverpa*, *Maruca*, and *Spodoptera* spp.), aphids, and whiteflies (Sharma, 2014). The extent of crop losses will depend on geographical distribution of insect pests; the dynamics of the insect population; insect biotypes; the alterations in the diversity and abundance of arthropods; changes in herbivore-plant interactions; the activities and abundance of natural enemies; species extinctions; and the efficacy of crop protection technologies.

Weeds will also be affected by climate change. For invasive plants with tolerances for higher temperatures, which are currently restricted by low temperatures, such as *Vallisneria* spp. and those intolerant to freezing such as *Pistia stratiotes*, *Eichhornia crassipes* and *Salvinia auriculata*, increasing temperatures could trigger the northward migration (Hussner *et al*., 2010). The species with higher mobility would be favoured. Traits that promote seed dispersal over long distances are common in invasive plants (Patterson, 1995a; Rejmanek, 1996; Dukes and Mooney, 2000; Malcom *et al*., 2002), such as *Imperata cylindrica* (cogon grass), *Pueraria lobata* (Kudzu) and *Striga asiatica* (witchweed). *Pueraria lobata*, whose range is restricted by low winter temperatures of -15°C, may spread with increases in minimum temperatures (Ziska *et al*., 2010). This may also be the case for the parasitic weed *Striga*, which grows well in temperatures of 30°C to 35°C in semi-arid environments, and spreads under conditions where soil fertility is poorly managed and cereal monoculture is practiced. The specific influence of climate change on *Striga* species and recommended control management are addressed in Box B1.2.

The competition between crops and invasive weeds could also be influenced by the effects of rising temperatures on plant physiology (Ziska and Reunion, 2007). For example, higher mean annual temperatures have been shown to favour the assimilate partitioning towards root biomass in the shrub *Parthenium juliflora*. Greater root biomass of this species aids in the rapid and robust regeneration of branches after lopping for fuelwood (Kathiresan, 2006a).

Competition between C_4 weed species and C_3 crops under different climate conditions and carbon dioxide concentrations may significantly alter crop productivity (Patterson, 1993). For example, a 3°C increase in the average temperature would favour the perennial invasive C_4 weed *Rottboellia cochinchinensis* (itch grass), which would cause significant yield reductions in various important C_3 crop systems (Patterson *et al*., 1979; Lencse and Griffin, 1991; Lejeune *et al*., 1994).

B1-1.3 The impact of crop production on climate change - the need for mitigation

Soil and water management for crop production has a strong impact, both negative and positive, on the drivers of climate change.

A large number of crop production practices contribute to emissions of greenhouse gas, and in particular to carbon dioxide, methane and nitrous oxide. Soil degradation, for example, is a major driver of climate change. Changes in land cover that leave the soil less protected hasten the mineralization of soil organic carbon, a process that releases carbon dioxide, nitrous oxide and methane (Bullock *et al*., 1995). The global warming potential for methane is approximately 20 times higher than it is for carbon dioxide; for nitrous oxide, it is 310 times higher. The many factors involved in crop production make the accurate measurement of greenhouse gas emissions from agriculture sectors more difficult than it is for other economic sectors. Despite this complexity, the processes causing greenhouse gas emissions from crop production have been described qualitatively.

- Carbon dioxide emission sources include the burning of crop residues in the fields, which also releases methane and nitrous oxide; the energy used in field operations, mainly for the mechanical tilling of the soil and pumping for irrigation; the production, transport and application of crop production inputs; and the mineralization of soil organic carbon. Tillage deserves special mention, as it is the field operation that produces the maximum carbon dioxide flux and has many direct effects on the carbon dioxide exchange between the soil surface and the atmosphere. Ploughing is the farm operation that disturbs the highest volume of soil and requires the most energy and fuel. Direct seeding requires the least amount of energy. Tillage also undermines the processes (the stabilization of microaggregates within macroaggregates) and damages the organisms (mainly fungi) responsible for the formation of soil organic carbon (Grandy *et al*., 2006; Six *et al*., 1998). Tillage accelerates the mineralization of the soil by speeding up the oxidative breakdown of soil organic carbon. In upland landscapes, tillage is the major cause of severe soil erosion and losses in soil organic carbon (Lobb *et al*., 1995; Lobb and Lindstrom, 1999; Reicosky *et al*., 2005).
- Methane flux from soil to atmosphere is the net result of two bacterial processes that are strongly influenced by land use, land management and the type of soil: methane production in strictly anoxic micro-environments (methanogenesis); and methane consumption and oxidation in aerobic micro-environments by methane-oxidizing bacteria (methanotrophs). Most emissions of methane from crop production are related to methanogenic bacteria living in flooded soils under rice cultivation (see Chapter B1-3.1) and the anaerobic decomposition of animal manure (e.g. liquid or slurry) and crop residues under very wet conditions.
- Most nitrous oxide emissions are generated from manure during its storage and from humid and compacted soils (asphyctic soils) in which nitrogen is present (IPCC, 2007). Microbial transformations of nitrogen, which can be caused by the application of synthetic fertilizers, animal waste, sewage sludge and crop residues, are responsible for nitrous oxide emissions through nitrification (the biological process by which ammonia is converted to nitrites and then nitrates) and denitrification (the biological process by which nitrate is converted to nitrogen gas). Denitrification is the most important of these two processes. The main factors controlling the speed of these processes is the presence of ammonia in the case of nitrification and oxidized nitrogen forms (nitrates and nitrites) in the case of denitrification. Nitrification is enhanced in microaerophilic soil conditions[xi], and specifically at values for water-filled pore space from 20 to 80 percent. Denitrification is enhanced under anaerobic soil conditions (i.e. in soils that are permanently or seasonally saturated by water). Nitrification is also favoured at high temperatures and is inhibited when the soil's pH values are acidic.

Some crop production practices (Chapter B1-2) enhance the capacity of the soil to conserve and accumulate soil organic carbon. These practices can reduce greenhouse gas emissions at the source and, at the same time, maintain or improve yields and enable crop systems to adapt to the projected impacts of climate change. The broader social benefits include enhanced wildlife habitats and the reduction of sediments, nutrients and pathogens in the runoff from agricultural fields (Box B7.3). The goal of sequestering carbon in the soil received renewed attention at the United Nations conference on climate change held in Paris in 2015 through the '4 per thousand' initiative'. This was launched with the objective to increase the existing soil organic carbon by 0.4 percent each year globally as a compensation for the global emissions of greenhouse gases. Lal (2004) estimates that the world's cropland has the potential to store 0.4 to 1.2 gigatonnes of carbon equivalents per year (see module B7 for further details).

In addition to enhancing the sinks of greenhouse gases, a number of crop production practices can also reduce greenhouse gases while maintaining or improving yields and adapting the crop system towards the future projected climate change impacts.

- Emissions can be reduced by improving the efficiency of farm machinery in terms of its productivity, operating times and fuel usage. This can be done by using equipment that is best suited for the given farm type. The right machinery, such as two-wheel tractors, combined with agronomic innovations, such as direct seeding technology, can contribute to climate change adaptation and mitigation. Small tractors using tined equipment instead of disc ploughs, or modern direct seeding equipment are more productive than tillage-based systems. Smaller equipment may also be more accessible and affordable to smallholder producers, farmer organizations and service providers. In mechanized systems, decisions regarding the trade-offs between increased farm productivity, including energy efficiency, and affordability are especially important to the rural poor. Impoverished farmers have a particularly acute need to produce more and become more efficient but they are less likely to have access to the resources needed to make the required improvements, and to pay for them.
- Shifting production from one crop variety to another or to different locally adapted annual or perennial species may be another option for reducing emissions.
- Any changes in output, particularly changes in the primary crops grown in a given community, present technical and economic challenges with broad social implications. Decisions to implement changes of this nature must take into consideration broader strategies for rural development, and specifically the impact these changes will have on diets and employment (see module C7). Given the low labour costs in some countries and the generally low labour absorption capacity of perennial crop production, a change in the orientation toward perennial crops would need to include effective risk management activities. This would involve, for example, employment policies and programmes to increase opportunities for the rural poor, especially vulnerable groups, such as women and young people, in obtaining decent jobs (Blowfield, 1993; Devi, 2006).

Climate-smart crop production practices and technologies

This chapter presents management practices and technologies for climate change adaptation and mitigation. It covers practices with an explicit focus on adaptation to specific climatic stressors, and practices that simultaneously reduce production risks and lower greenhouse gas emissions. Most of these practices prevent soil damage that releases carbon and water into the atmosphere; promote soil and water conservation; and increase productivity.

Table B1.1 presents the climate-smart management practices for different crop systems that can help farmers adapt to specific climate change risks and/or mitigate these risks.

In some cases, radical changes, such as shifting to an entirely different agricultural production system, may be needed to adapt to new climate conditions. The important role policies and institutions play in supporting climate-smart strategies is dealt with in chapter B1-4.

Use of quality seeds and planting materials of well-adapted crops and varieties

An indispensable input for climate-smart crop production is quality seeds and planting materials of well-adapted varieties. It is impossible to harvest good crops with bad seeds (FAO, 2011).

National, regional and international plant breeding efforts usually involve multilocational trials and seek to develop crop varieties that are resistant to climate-related phenomena and more efficient in their use of resources to reduce their impact on the agricultural ecosystem and the wider environment. Resistance to drought, salinity and flooding are the most common climate-related traits for which crop varieties are bred. Other more location-specific factors include higher frequencies of frosts at the seedling and/or pollination stages; high temperatures at the grain-filling stage; heavy rains that compress the soil; and alternate light rains and hot temperatures that stimulate seed germination but prevent the establishment of seedlings.

The development, official release and registration of well-adapted crop varieties are the steps taken toward the ultimate goal of ensuring farmers have access to quality seeds and planting materials. However, achieving this ultimate goal also requires a reliable mechanism for delivering the seeds of the most suitable varieties to farmers. Farmers obtain seeds from formal systems and/or informal systems.

Formal seed systems are organized and underpinned by statutory requirements that ensure the seeds that farmers use pass through standardized quality assurance mechanisms. Delivering the improved varieties to farmers through formal systems is relatively straightforward. But, farmers, especially in developing countries, also obtain seeds from multiple unregulated sources. These sources can include saving seeds from their own harvests, purchasing seeds from local markets and exchanging seeds with family members and neighbours. This way of obtaining seeds constitutes the informal system or farmers' seed system. Informal systems predominate in developing countries where crop production systems are the most vulnerable to extreme weather events. For such production systems, which are typically characterized by low-input agriculture, small-scale holdings and limited market engagement, it is particularly important to support community-based seed production and distribution channels. In parts of the world where climate change is expected to have the greatest impact, most of the seeds sourced through community-based delivery systems are important food security crops. These crops include beans, peanuts, cassava, cowpeas, open pollinated maize, sweet potato and yams. Small- and medium-scale enterprises are effective means for ensuring that quality seeds of the most suitable varieties are available to small-scale farmers and are within easy reach in their communities.

Ideally, irrespective of delivery system, seeds that are meant to be sold or otherwise distributed for planting must have their quality assured. There are different options for achieving quality assurance. In the formal system, there is official control and inspection, usually by government agencies or accredited entities such as farmers' associations and seed companies, which result in certified seeds. A less demanding mechanism is the Quality Declared Seeds and Quality Declared Planting Materials systems, developed under the auspices of FAO. These options ensure that costs associated with standard certification processes do not hinder the availability of quality seeds.

Box B1.1 describes the components of a system that provides farmers with affordable quality seeds and planting materials of well-adapted crop varieties in a timely manner. Mechanisms that facilitate seed trade between countries are discussed in Chapter B1-5.

Box B1.1 Seed Systems

A seed system encompasses all the stakeholders (individuals, organizations and institutions) that are involved in the development and dissemination of crop varieties; the production, multiplication, processing, storage, distribution and marketing of seeds and related practices and processes; and the prevailing policies, regulations and laws. The following components of a seed delivery system are critical in formulating for climate-smart agriculture strategies.

Conservation of plant genetic resources for food and agriculture

Conserved and characterized plant genetic resources for food and agriculture need to be available for use as 'raw materials' for the development of varieties that are resistant to abiotic and biotic stresses. To address the challenges posed by climate change, there is the increasingly urgent need for the investment of greater resources and efforts in safeguarding the widest possible diversity of plant genetic resources for food and agriculture in their natural habitats *in situ*, on farms and in genebanks *ex situ*. The diversity of crop wild relatives, an important source of heritable traits for crop improvement, could be eroded as their natural habitats are lost due to climate change. The role of plant genetic resources in climate-smart agriculture is addressed in more detail in module B8.

Crop varietal development

Plant breeders must develop an increasingly diverse portfolio of varieties of an extensive range of crops in order to adapt production systems to climate change. Generating novel varieties will most often depend on obtaining heritable variations, especially from the non-adapted materials, including crop wild relatives, that are not usually used by breeders. This will involve institutionalizing and improving capacities for pre-breeding activities in which germplasm curators and breeders work together to identify the carriers of desirable traits, evaluate these putative parents and cross promising ones with elite lines to generate intermediate breeding materials. It may also be necessary to create novel variations that are absent in the gene pool through induced mutations and the application of biotechnological procedures, such as genetic engineering and genome editing. High-throughput genotyping and phenotyping platforms are being used more and more to make the processes for developing crop varieties, including pre-breeding, more efficient.

In farmer participatory plant breeding, farmers and plant breeders collaborate in crop varietal development. Because the perspectives of the farmers contribute to the decisions about which varieties are proposed for official release and registration, participatory plant breeding is an effective way to achieve demand-driven crop improvements for adaptation to climate change, especially in developing countries.

Seed production and delivery

An effective agricultural extension system and a responsive seed delivery system are needed to enable farmers to access quality seeds and planting materials of well-adapted crop varieties at affordable prices and in a timely manner.

- Farmers are more willing to use a new variety when they have trusted information and are confident the new variety will meet their needs. The extension system is particularly important to generate data about the performance of varieties. For instance, the FAO Farmer Field Schools approach (addressed extensively in module C2) has proven particularly effective in using demonstration plots to showcase the advantages of well-adapted crop varieties to communities of small-scale farmers.
- A responsive seed delivery system requires national policies, strategies, regulations and legal frameworks that cater to both the informal and formal seed systems and recognize their generally complementary roles.
- Climate change is expected to increase the frequency and intensity of extreme weather events, which will trigger crises that threaten the immediate food security of large populations and possibly spark famines. These events will also affect farmers' ability to obtain quality seeds and planting materials, which will jeopardize the success of subsequent cropping seasons. A seed security assessment is a way to determine the availability of seeds, their accessibility to farmers, and their quality and their compatibility with farmers' varietal preferences and production systems. It is a means for identifying the most suitable responses to the lack of seeds without hindering the development of the seed sector. Seed security assessments consider formal and informal sources of seeds and the functioning of the entire value chain to identify the main constraints farmers face in obtaining the seeds they need. The outcomes of the assessments guide the next course of action, which may be immediate interventions, such as the direct distribution of seeds to farmers, support

to seed markets, cash transfers, or longer-term developmental activities. Two useful tools for ensuring that farmers have access to quality seeds after a crisis are the *Seeds in emergencies: a technical handbook* and the *Practitioner's Guide for Seed Security Assessments*.

Source: Authors

Biodiversity management

Growing "a genetically diverse portfolio of improved crop varieties, suited to a range of agro-ecosystems and farming practices, and resilient to climate change" is a validated means for enhancing the resilience of production systems (FAO, 2011). When confronting abiotic changes (e.g. shifting rainfall and temperature patterns) and biotic disturbances (e.g. pest infestations), the level of existing biodiversity (both functional[xii] and response[xiii] diversity) can make the difference between a stressed agricultural ecosystem and a resilient one. Biodiversity management is dealt with in module B8.

All major grain crops, including maize, wheat, rice, and most other crops are often grown in monoculture systems[xiv] that require significant investments in pesticides and herbicides. In nature, one species (and especially not one crop variety) is never found alone in one field. When agricultural ecosystems are simplified, whole functional groups of species are removed, and their capacity to respond to changes and provide ecosystem services is compromised (Folke, 2006). In a cropping system, greater diversity of crops and other living organisms is an important criterion for ensuring farm resilience, economic stability and profitability. This diversity is especially important in a climate-smart approach because it contributes to pest and disease management, which has direct effect on yields and revenues and can be very costly and labour-intensive if external inputs need to be used. Enhancing on-farm biodiversity[xv] and integrating production (see module B5) also provides other environmental services, including pollination, that are essential to farmers and society as a whole. The level of biodiversity in the agricultural ecosystem influences the interactions of plant, animal, microbial species (above and below ground) at the landscape level. A landscape approach to climate-smart agriculture is addressed in module A3. At the territorial level, increasing the sustainable use of agricultural biodiversity in terms of both production and consumption in landscapes and diets offers great potential to shape rural and urban (city-region) food systems in ways that can safeguard the future food and nutrition security of expanding urban populations. Territorially-based climate-smart food systems are addressed in module B10.

The diversification of crop systems can take many forms, involving different crop species and/or varieties (intra- and/or inter-specific diversification), different spatial scales (landscape, farm, individual fields and/or crop) and different time frames.

Integrating multipurpose crop varieties, whose biomass can be used in a range of combinations for food, biofuel, feed, and/or fiber, can improve the functional and productive management on the farm and be climate-smart. Examples of multifunctional crops include living fences that can provide food and feed and serve as windbreaks. The use of perennial species as multipurpose crops is discussed in chapter B1-3.1.

In individual fields, there are several ways in which the genetic diversity of crops can be enhanced. These practices all require that the dates and rates of seeding be tested locally to ascertain the most suitable combinations of crops, crop density and sequencing matter (Chapter B1-4.1). This is needed to ensure the crops selected are appropriate for the specific conditions of each farm system and do not compete for nutrients, water and light. These options include:

- Different crop varieties of the same species can be grown in mixtures as one crop (varietal mixtures). For example, growing a mix of varieties with the same growing length that can be planted and harvested at the

same time, but that respond differently to different water regimes, is a strategy to cope with the unpredictable onset of the rainy season and increase the stability of yields.
- Different crop species can be grown:
    - simultaneously in the same surface area as mixtures or planting a second crop in the first crop (relay cropping);
    - simultaneously in different spaces (intercropping); or
    - planting a different crop after the previous crop has been harvested (crop rotations).
- Livestock and aquaculture can be integrated into crop systems. This subject is dealt with in module B5.

Integrated Pest Management

Climate change will affect the spread and establishment of a wide range of insect pests, diseases and weeds. This phenomenon will be in large part a consequence of changes in the distribution and health of naturally occurring host plants and crops, natural enemies, and the adaptive changes in farm management (see chapter B1-1.2). With the increasing globalization of the trade and exchange of germplasm, these changes will provide new challenges for pest management.

Integrated pest management is an ecosystem approach to crop production and protection. It is based on the careful consideration of all available pest management techniques. Integrated pest management involves the use of appropriate measures to discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified; reduce or minimize risks to human health and the environment; and disrupt as little as possible the agricultural ecosystem. The ability to make good decisions in the field is crucial for effective integrated pest management. The principles of FAO Integrated Pest Management approach include growing healthy crops; understanding ecological processes in the fields and encouraging natural pest management mechanisms that maintain ecological balances among populations of pests and their natural enemies (predators, parasitoids, antagonists); observing fields regularly; and building farmers' capacity and understanding of ecological needs so that they are empowered to take the best pest management decisions in their own fields. Chapter B1-2 on biodiversity management covers the role that diversified crop systems can play in enhancing the resilience of cropping systems and providing ecological insurance against crop failures. Chapter B1-3 on sustainable soil and land management addresses the links between soil management, integrated pest management and the impacts of climate change. In tilled soils, for example, when the soil surface remains exposed for parts of the season (e.g. between the harvest of one crop and the establishment of the next) and in specific spaces (e.g. between rows or beds until the crop has closed canopy), empty ecological niches are formed where the soil is unoccupied and moisture and nutrients are not utilized. In areas where humidity is guaranteed throughout the year, this is the ideal environment for annual weeds to proliferate. Controlling them requires energy, costly tillage, pulling, mowing and/or herbicides. In environments where the primary productivity is low, the exposed soil lead to losses in soil organic matter and biodiversity, increased compaction and greater erosion rates. Crops growing in these soils are less resilient and climate change affects them more (Chapter B1-1.2).

Integrated pest management is valid in a variety of different and evolving farming conditions. Independently of how climate change will affect agricultural ecosystems, farmers who understand integrated pest management principles will be better equipped to cope with the effects of climate change and develop sound and location-specific adaptation strategies (Allara *et al*., 2012). This is why, on farms and in farming communities, FAO integrated pest management programmes are often implemented through Farmer Field Schools, which facilitate learning by doing and experimentation of different management options by farmers (see module C2). Specific details on the control of the parasitic weed Striga is presented in Box B1.2.

As the climate changes, national regulatory, policy and institutional frameworks must be strengthened to enable the adoption of integrated pest management practices on farms and in rural communities. In particular, frameworks should support farmer training in integrated pest management; maintain the surveillance systems, including those used in community groups, that are used to detect and report changes in the behaviours of pests and natural enemies; develop appropriate quarantine procedures to prevent the entry and establishment of plant pests; and formulate appropriate management strategies to respond to potential outbreaks. Other important elements of any strategy to promote a shift to resilient crop production systems include phytosanitary frameworks and measures that can facilitate the creation of markets for sustainable products; and the transparent collaboration among policy makers, industries and farmers on the national registration processes for the most appropriate pesticides to a climate-smart approach (FAO & INRA, 2016).

Regionally and internationally, common regulations and strategic frameworks (e.g. the International Plant Protection Convention (IPPC) and the FAO International code of conduct on Pesticide Management to limit the impact of invasive species and the unregulated use of chemical pesticides. However, pest management systems would benefit from more coordinated actions to prevent crises associated with transboundary pests, major pest outbreaks and climate change. Greater coordination in this area can be achieved by building new partnerships and alliances that can connect stakeholders, including farmers, at local, national and regional levels, and enable them to address common challenges (Allara *et al*., 2012).

The enabling environment for climate-smart crop production and protection is addressed in Chapter B1-4.

Further information on integrated pest management can be found at the following web sites: FAO Plant Production and Protection Division: Integrated Pest Management; Vegetable Integrated Pest Management Asia programme; Integrated Production and Pest Management Programme in Africa.

Box B1.2 The influence of climate change on *Striga* distribution and management

The genus *Striga* is a member of the family Orobanchaceae, which includes several other parasitic plants. *Striga* species are root parasitic weeds that siphons of water and nutrients from their hosts and substantially reduce their growth. *Striga*, which is native to the grasslands of sub-Saharan Africa, includes about 40 species with several different strains and some new variants (Fischer, *et al*., 2011). The physiological requirements of *Striga* have checked its spread outside the tropics, but climate change projections suggest that some species may spread, with some even reaching temperate areas (Mohamed *et al*., 2007; Cotter *et al*., 2012).

While the majority of *Striga* species have remained in the wild grassland ecosystems in which they evolved, a few have adapted to agricultural ecosystems and have become weeds (FAO, 2003). They mostly affect cereal crops including sorghum, millets, maize and upland rice. *Striga gesnerioides* is a parasite of dicotyledons such as cow pea (*Vigna unguiculata*), which is a major source of plant protein in sub-Saharan Africa. The most economically important parasitic weeds affecting production of cereals are *Striga hermonthica*, across much of northern tropical Africa, and *Striga asiatica* in central and southern Africa and across Asia and isolated regions of Australia. These species also harm sugarcane production. On average, *Striga* species infest as much as 40 million hectares of farmland in sub-Saharan Africa, can cause yield losses of up to 100 percent (IAASTD, 2009) and an average reduction in productivity of 12 to 25 percent. In Africa, it affects the livelihoods of about 300 million people (FAO, 2003). Projections from the last comprehensive study (Sauerborn, 1991) estimate annual cereal losses to *Striga* at about 4.1 million metric tonnes at a cost of USD 12.8 billion (Ejeta, 2007).

Farmers use a variety of *Striga* control methods (organic manure, crop rotation, fallow), but the results can often be unsatisfactory. In fact, the problem continues to worsen due to the high fecundity of the parasite and mismanagement that have favoured the build-up of prohibitively large *Striga* populations (Babiker, 2007). The monoculture of cereals, in which farmers use continuous cropping and follow poor agronomic practices, such as a lack of crop rotations, are conducive for the build up of *Striga* populations. This is particularly true in agricultural ecosystems where high human population densities put strong pressures on arable land (Eplee, 1992).

The solution to *Striga* infestation resides in breaking its life cycle. Effective *Striga* management options should be built around three pillars: (i) preventing the production of new *Striga* seeds; (ii) decreasing the soil seed bank of *Striga*; and (iii) improving soil fertility.

Striga management projects that take into account those three pillars have been implemented in Benin, Burkina Faso, Mali, Niger and Senegal to compare different management methods to alleviate the problem (FAO, 2008b). Rotation with non-host crops, particularly legumes (e.g mucuna) substantially reduces *Striga* infestation and improves soil fertility.

Source: Adapted from Ejeta, G. and Buttler, L.G. 1993.

Improved water use and management

Where water is a limiting factor, improving water management can be achieved through measures that conserve soil and water; and/or with deficit irrigation that can maximize crop yields per volume of water applied; and/or more efficient irrigation technologies that can reduce unproductive evaporation losses. Water management for climate-smart agriculture is dealt with in greater detail in module B6.

Achieving greater efficiency in irrigation often involves additional energy costs (see module B9). For this reason, the expansion of irrigation needs to be accompanied by appropriate energy technologies (e.g. solar powered pumps).

Strategies for changing agricultural water management and governance must be done by integrating a water balance analysis into decision-making processes. Water balance assessments, both at field level and at the catchment level, are necessary to understand the repercussions that changes in water use for agriculture will have on the hydrological cycle. For example, in upstream areas, the introduction of rainwater harvesting techniques on a large scale may affect ground water recharge rates and return flows and cause adverse effects for downstream water users.

Sustainable soil and land management for increased crop productivity

Sustainable soil and land management are discussed in detail in module B7, and are also addressed in module A3 on integrated landscape management.

At the landscape level, reducing land-use change by carefully limiting the need to expand cropland and grazing land can reduce emissions and increase the capacity of the soil to store carbon.

At the field level, increasing productivity allows to grow more from the land already under production. This eliminates the need to open new land for agriculture and helps reduce the emissions associated with agricultural expansion. In this chapter, the focus is on agronomic management for increasing crop productivity and improving the efficiency in the use of resources as a way of addressing climate change. The most cost-effective management strategies for sustainable intensification of crop production involve achieving a balanced cycling of nutrients through the production system and protecting the soil on the field. Nutrient cycling refers to the movement and exchange of organic and inorganic matter into the production of crops and it is dealt with in Box B7.3.

Soil protection can be achieved by practicing direct seeding in combination with the sustainable management of crop residues and within a broader framework of integrated soil fertility management. Box B1.3 provides a useful reference to optimize the management of crop residues and the decisions that influence their composition (i.e. the types of crop grown in rotation) and their decomposition (i.e. the conservation on the soil surface as opposed to its incorporation into the soil).

Box B1.3 Crop residue management for soil carbon conservation and sequestration

Carbon accumulates in the soil when the nitrogen input (i.e. from nitrogen fixation, organic matter restitutions or fertilizers) is higher than the nitrogen exported with harvested produce and lost through leaching or emissions in gaseous forms (Corsi *et al.*, 2012). This box summarizes the crop management practices that regulate the composition of the residues accumulating on the soil surface, and the potential to augment soil carbon stocks.

- Effective crop rotations for carbon accumulation maintain a positive nitrogen balance. Crop residues with an average carbon-to-nitrogen ratio in range of 25 to 30 can be achieved by rotating between crops high in carbon and crops high in nitrogen. This allows the carbon to accumulate in the soil and enables the nitrogen in the decaying surface residues to be released slowly to the next crop. If the amount of nitrogen in the crop residues is too low, microorganisms use the mineral nitrogen existing in the soil (nitrogen immobilization), which reduces the amount of nitrogen available to the growing crop until (weeks) the carbon in the crop residues starts to deplete (Gál *et al.*, 2007).
- Increasing the complexity of the crop rotations and integrating legume crops supports carbon sequestration. Active roots produce exudates and, notably in the case of legumes, favorable mycorrhizal[xvi] associations. The decomposition of old rooting systems adds organic matter at greater depths. Deep rooting systems are ideal for taking carbon deep into the soil, where it is less susceptible to oxidation. In agricultural ecosystems, about 80 percent of biological nitrogen fixation is achieved through the symbiotic association between legumes and the soil bacteria *Rhizobia*. Farmers have some scope to influence these natural processes by selecting legume species that are particularly effective at fixing nitrogen; increasing the proportion of legume and grass seed in forage mixtures; inoculating the legumes with bacteria (e.g. Rhizobia); improving crop nutrition, especially nitrogen and phosphorous; managing diseases and pests; choosing the best planting time, cropping sequence and cropping intensity; and managing the defoliation frequency of forage swards.
- Keeping the soil covered with a layer of evenly distributed crop residues with an average carbon-to-nitrogen ratio in the 25-30 range after harvest produces a positive residual fertilizer effect on the subsequent crops. The removal of crop residues (e.g. burning, black fallows) leaves only the crop's root biomass to be incorporated into the soil organic matter pool, which causes the accumulation of soil organic carbon to decline. For the same reasons, grain legumes should be harvested by cutting the plants; they should not be pulled up and uprooted.
- Mixing crop residues with soil (e.g. by disking or chiselling) may cause or accelerate the immobilization of nutrients in the soil and make them unavailable for the subsequent crop during the early part of the growing season. Crop residues mechanically incorporated into the soil decompose more quickly than those left on the soil surface, and nitrogen immobilization can occur very early in the season. Incorporating crop residues rich in readily decomposable carbon, such as residues with low carbon-to-nitrogen ratio or liquid manure, generally induces a priming effect on soil organic matter and increases carbon dioxide emissions. In contrast, when crop residues are not mixed into the soil, their composition does not affect the decay of the stable soil organic matter already present in the soil (Kuzyakov *et al.*, 2000; Fontaine *et al.*, 2004; Sisti *et al.*, 2004; Fontaine, 2007).
- Using best management practices for nitrogen fertilization minimizes residual soil nitrate, which reduces nitrous oxide emissions. Best management practices for nitrogen fertilization include integrated nutrient management, and targeted applications of the precise amount of mineral

fertilizer required.
- Using controlled traffic and growing crops that produce large amounts of root biomass can keep the soil from becoming compacted and improve drainage. This can help farmers avoid anaerobic soil conditions, which can increase nitrous oxide emissions and create a generally unfavorable environment for plant growth.

Source: Authors

Conservation agriculture[xv] is an approach that combines limiting soil disturbance to a minimum, maintaining soil cover and diversifying crop production. Although developed to reduce soil erosion and restore degraded soils, conservation agriculture provides a strategic entry point for climate change adaptation. Conservation agriculture seeks to reproduce the most stable soil ecosystem attainable in each agricultural ecosystem in order to reduce producers' reliance on external inputs for plant nutrition and pest management. Keeping the soil covered reduces moisture loss, stabilizes soil temperature, reduces erosion by water and wind, restores soil carbon through the decomposition of crop residues, and provides food for beneficial soil organisms. Rotating and diversifying crops reduces crop pests and diseases and replenishes soil nutrients. Avoiding mechanical soil tillage increases the populations of earthworms, millipedes, mites and other animals living in the soil. This microfauna takes over the task of tillage and builds soil porosity and improves soils structure. Conservation agriculture incorporates organic matter from the soil surface. The excrement from soil organisms provides stable soil aggregates and the vertical channels created by worms drain excess water. The organic matter incorporated by soil microfauna into the soil improves soil structure and water storage capacity, which in turn helps plants to survive longer during periods of drought. Because untilled soil can act as carbon sink by sequestering and storing carbon, conservation agriculture has also been recognized for its ability to mitigate climate change. Not tilling the soil also reduces the number of farm operations required for crop production, which lowers fuel consumption (Lal, 2003). The potential of conservation agriculture to bring about significant energy and fuel savings is one of the reasons why it has become a more attractive option to farmers in times of high energy costs (Doets *et al*., 2000). In 2013, conservation agriculture was practiced on around 157 million hectares worldwide. For more information, visit the FAO web pages on conservation agriculture and sustainable agricultural mechanization. The short video produced by World Bank provides information on the links among soil degradation, climate change and conservation agriculture.

Minimum mechanical soil disturbance is a long-term management approach to increasing the amount of carbon stored in the soil. However, the accumulation of soil organic carbon is a reversible process, and any short-term disturbances, such as the periodic tillage of land otherwise under no-tillage, will not bring about significant increases in soil organic carbon (Jarecki and Lal, 2003; Al-Kaisi *et al*., 2008). Although the benefits and reduce risks and costs in the future gained from improving soil health and increasing soil organic carbon accrue slowly over decades, taking action can also bring immediate financial dividends, help maintain crop productivity. When soil rebuilds, it grows and stores more oil organic matter and water, thus improving ecosystem functions and services (e.g. the control of rainfall runoff and soil erosion) that are critical for climate change adaptation and mitigation.

Sustainable mechanization

The availability of appropriate machinery to carry out sustainable crop management practices increases productivity per unit of land. It also increases efficiency in the various production and processing operations and in the production, extraction and transport of agricultural inputs, including coal and oil. Specific examples of the appropriate use of farm machinery in crop production are listed.

- Using smaller tractors, making fewer passes across the field and reducing working hours, when combined

with conservation agriculture, reduce carbon dioxide emissions, minimize soil disturbance, and curtail soil erosion and degradation that are common in tillage-based crop systems.
- Tractor-operated tillage is the single most energy-consuming operation in crop production. Operating a plough is the main reason many farmers require high horse power, diesel-fueled tractors. Conservation agriculture is flexible enough to accommodate the socio-economic resources of smallholder farmers as well as large-scale farming operations. Minimum soil disturbance can be achieved through digging sticks, jab planters, or mechanized direct seeders specifically developed to drill the seed through a vegetative layer. With the introduction of conservation agriculture, the machinery park of mechanized farms changes to equipment that requires less pulling power than a plough does. This means that smaller tractors, including two-wheel tractors, can be used; less fuel is consumed; work time is reduced; and the depreciation rates of equipment is slower. All of this leads to emission reductions from the various farm operations and from machinery manufacturing (Lal, 2016).
- The timely availability of agricultural equipment, such as drills, harvesters and threshers, permits producers to plant, harvest and process crops in an efficient manner. This increases yields and reduces post-harvest losses. Case study B1.1 presents the case of smallholder conservation agriculture mechanization scheme in Zambia to increase smallholder farmers’ access to sustainable mechanization technologies for illustrative purposes.
- Precision farming equipment along with controlled release and deep placement technologies, make it possible to accurately match production inputs with plant needs. This improves efficiency in the use of inputs and reduces direct and indirect greenhouse gas emissions. In the future, larger orchards and plantations will be increasingly monitored by drones. Cameras with colour filters are able to reveal spots that require specific interventions.
- Agricultural machinery powered with renewable energy, such as wind and solar chargeable accumulators can lower producers' dependence on expensive fossil fuels. These renewable energy sources emit less greenhouse gases and reduce the need to engage in the complex logistics and construction of the heavy infrastructure required to supply fossil fuels to rural areas. However, examples of farm machinery powered by renewable energy are rare. They are often at piloting stage, but they have great potential to play a significant role in climate-smart mechanized systems.

Investments in mechanization enable farmers to expand the range of their activities and diversify their livelihoods in ways that can reduce their vulnerability to climate change. Sustainable mechanization can create opportunities to provide hired services for field operations, improve transportation and agro-processing and increase the possibilities for adding value to farm production. In a long-term approach, the initial investment in mechanization is compensated in the following years by higher returns on farming and labour; surplus production or increases in the amount of land under production; and greater efficiency in the use of resources and the associated savings.

Technologies for decision-making

Developing simple and robust scientific tools that can guide the decision-making of farmers on a seasonal and long-term basis is essential for planning strategies to address climate change.

In terms of risk management, some of the most relevant technologies relate to weather forecasting and early warning systems. The improved timing and reliability of seasonal forecasts and hydrological monitoring enables farmers to make better use of climate information, take pre-emptive actions and minimize the impact of extreme events (Faurès *et al.*, 2010; Gommes *et al.*, 2010). Risk reduction strategies and technologies are addresses extensively in module C5.

In modern commercial horticulture production systems, weather stations often monitor irrigation in accordance with the water requirements of crops. In this way, the irrigation is automatically adjusted to changes in climate.

Information and communications technologies can also support the exchange of information that is needed to respond adequately to climate change (see module C1).

Table B1.1. Climate-smart practices and technologies to increase the resilience of specific crop systems against disturbances brought about by climate change and their relation to climate change adaptation (CCA) and/or for climate change mitigation (CCM).

		CROP SYSTEMS	CLIMATE-SMART PRACTICES AND TECHNOLOGIES FOR RISK REDUCTION	CCA	CCM
CLIMATE CHANGE IMPACTS	Climatic variability	All systems	Using quality seeds and planting materials, including rootstock and scion combinations, of well-adapted varieties is good agricultural practice and is climate-smart. Choosing crop species and varieties adapted to the prevalent or expected impacts of climate change for the given region and farming system is the most economical and environmentally friendly means of safeguarding crops against abiotic and/or biotic stresses, such as climate-driven extreme weather events and upsurges in pests and diseases. Useful traits include time to ripening, early and late maturity, blooming, and resistance to pests and diseases. Newly introduced crops and/or their varieties must be relevant to farmers, and farmers must know how best to grow them. To identify horticultural cultivars and cropping practices adapted to local requirements and environmental conditions, FAO has developed and maintains the **HORTIVAR** database.		
		Systems including annual crops perennial crops	Promoting intra- and inter-specific diversity over space (e.g. intercropping, using crop variety mixtures) and/or time (e.g. crop rotations) increases the stability of crop yields. Crop associations and rotations designed for specific adaptation goals use cover crops to partially or entirely replace mineral fertilizer inputs, and/or mechanical soil tillage. In climate-smart systems, the main function of cover crops is not necessarily seed production. Cover crops need to be terminated when appropriate to achieve the agronomic goal they are designed for. When including cover crops in the crop rotation, farmers must 'adjust' the cover crops to fit into the already-existing cropping system, rather than accommodating the farming system to the cover crops. Growing a single crop, using a mixture of appropriately chosen genotypes of a given species, such as a mixture of high-yielding hybrid varieties and traditional varieties, increases the producer's resilience in the face of climate unpredictability. Growing annual crops (e.g. leguminous crops) in the rows between perennial crops requires the accurate selection of species to avoid competition for water in the most vulnerable phenological stages.	*	(*)
	Unpredictable onset of rainfall	Systems including annual crops perennial crops	The proper interpretation of reliable seasonal forecasts allows farmers to: Select crop varieties and to adapt crop calendars to new temperatures and rainfall patterns. Plan the timing of husbandry operations, such as irrigation; pruning to avoid damage from heat or moisture; fruit thinning to balance excessively high rates of fruit set and reduce competition for developing fruit in case of excessive flowering; protecting early bloom from late frosts through short-term interventions.	*	
		All systems	Implementing soil and water conservation techniques or *in situ* water conservation (e.g. soil mulching, rainwater harvesting) enhances crop productivity.	*	*
		Systems including annual crops	Sustainable agricultural mechanization allows for timely seeding and harvesting, greater efficiency in the use of production inputs and less waste of resources, which increases productivity. To ensure timely seeding, reduce greenhouse emissions and deliver gains in energy efficiency, the use of no-tillage must be supported by crop rotations that are intensive (in space) and diversified (in time).	*	*
	Thermal alterations	Systems including perennial crops	Inducing flower by spraying or by irrigation is a short-term intervention to break dormancy when natural climate phenomena for breaking dormancy are absent.	*	
		Systems including perennial crops	Shading and/or painting trunks decrease the effect of excessive sun and heat. Misting helps control both freezing temperatures and heat.	*	
	Extreme events		Measures aiming at preventing crop losses may include:	*	
		All systems	Selecting species capable of resisting specific extreme weather conditions (e.g. root and tuber crops in cyclone-prone areas) or species with short growing cycles from seed to yield.		
		Systems including perennial and horticultural crops	Protecting crops with: - mulch of different materials and colours, for controlling weeds and reducing evapotranspiration; - nets, for bird control, insect proofing, hail protection and shading; - floating mulch for protection against late frost and insects; - greenhouses of different types, sizes, and different covering materials (e.g. glass, polyethylene, ethylene vinyl acetate) Greenhouses are mainly used to grow vegetables, flowers and condiments, but simple covered structures are also used to protect fruit crops like grapes for early or late harvest (e.g. in Sicily and Puglia, Italy); peach trees (e.g. in Liguria, Italy); Mango (e.g. in Egypt); and banana (e.g. in Morocco).		
		All systems	Preparedness to quickly restore the production capacity in the disaster-affected areas requires knowledge of the appropriate adapted species and cultivars and rapid access to seeds, planting materials and other inputs on short notice.	*	

		CROP SYSTEMS	CLIMATE-SMART PRACTICES AND TECHNOLOGIES FOR SOIL AND WATER CONSERVATION	CCA	CCM
CLIMATE CHANGE IMPACTS	Soil degradation	All systems	Increasing efficiency in fertilizer use through site-specific nutrient management practices that optimize the use of existing soil nutrients while filling deficits with mineral fertilizers.	*	*
		All systems	Using conservation agriculture improves soil health, allows the soil to grow both at the surface and at depths, and improves water retention.	*	*
		All systems	Minimizing mechanical soil disturbance continuously over time prevents and soil compaction, slows the mineralization of soil organic carbon, increases the effectiveness of rainfall, curbs soil erosion and reduces the risks of waterlogging.	*	*
		Systems including annual crops	The year-round seeding of fields in crops/mulch, if water availability permits, protects the soil from erosion and compaction, and keeps important nutrients, especially nitrogen and phosphorus, on farmers' fields. Most nutrient losses occur during the period between seeding and the development of a dense canopy; and after harvest when there is no crop on the field. A diversified and intensive crop rotation is one that: eliminates fallow periods where possible; returns crop residues to the soil with an average carbon-to-nitrogen ratio in the 25-30 range; improves the soil and responds to specific needs related to agronomic practices (e.g. improved soil compaction) and water management either through improved drainage or reduced evaporation. - In **field crop systems**, to achieve an exponential increase in the accumulation rate of soil carbon and overcome a plateau, the crop combination or rotation should be replaced by a new, more intensive one to increase the return of fresh organic matter in time and space, as soon there is a noticeable decline in soil carbon accumulation. - In integrated crop-livestock systems, planned grazing practices can use stock effluents to distribute nutrients from areas of higher fertility to fields. Animal urine, manure and disposed beddings can be recycled and used to provide nutrients and organic matter to the soil.	*	*
		Systems including annual crops	Making the right decisions about the production and management of organic matter from crop and livestock residues contributes to soil organic carbon sequestration, improves the structure of the soil and increase soil water storage. To help producers prioritize the use of crop and livestock residues in the face of competing demands, including soil management, animal feed and bioenergy, FAO has developed three tools. The first is the **Bioenergy And Food Security Rapid Appraisal (BEFS RA)**, which can be used to define the amount of residues available at territorial level (FAO, 2015). The second tool is the residue component of **FarmDESIGN**, which assesses the implications of using residues for bioenergy on the whole farming systems (Wageningen University, 2016). The third is the residue component of the **Bioenergy And Food Security Operator Level Tool**, which uses a scorecard to help users select the best practices for their circumstances (FAO, 2016).		
		Systems/farm space management, including perennial crops	Integrating nitrogen-fixing perennial woody species (e.g. *Cajanus cajan* or pigeohttp://www-test.fao.org/?id=68045#503026n pea) and trees with annual crops increases soil fertility, produces biomass and reduces soil erosion. This practice also sequesters carbon and redistributes the carbon to deeper soil layers.		

		CROP SYSTEMS	CLIMATE-SMART PRACTICES AND TECHNOLOGIES FOR EFFICIENT WATER MANAGEMENT	CCA	CCM
CLIMATE CHANGE IMPACTS	Water stress	All systems	Crop water productivity is improved by implementing good agronomic management decisions and practices such as selecting crop varieties that are drought tolerant and/or have a higher water productivity (i.e. that deliver more yield per liter of water); adjusting cropping calendars; encouraging deeper rooting of crops; using conservation agriculture for higher water retention; and mulching.	*	
		All systems	Implementing soil and water conservation techniques (e.g. soil mulching, shading, rainwater harvesting, using fences or windbreaks to reduce evaporation) enhances crop productivity.	*	
		Systems including perennial crops	Integrating feed for livestock from annual crops with perennial feed, particularly from deep-rooting legumes, promotes soil health and provides additional quality forage during dry periods. It also improves the quality of the diet of ruminants, reducing methane emissions from enteric fermentation.	*	*
		Irrigated systems	Irrigation has become commonplace for commercial crops, such as horticulture production, because an adequate supply of water at all stages of the crop's development is the only way to produce consistent yields. In irrigated systems, increasing the efficiency of irrigation (e.g. through deficit irrigation, precise water applications, high-efficiency pumps), reducing water losses and improving water allocation and the management of water demand, optimizes yields per volume of water applied, reduces greenhouse gas emissions and brings about gains in energy efficiency, mainly in the use of fuel.	*	*
		Systems including	For increases in the quantity, frequency and intensity of rainfall, the following practices reduce or avoid damage to roots from waterlogging:	*	
		annual and perennial crops	Improving drainage.		
		perennial crops	Planting trees on berms.		

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Climate-smart crop production systems in practice

This chapter identifies four major production systems that require distinct sets of management practices. They are: annual crop systems (Chapter B1-3.1); horticultural systems, orchards and plantations (Chapter B1-3.2); integrated production systems (Chapter B1-3.3); natural and anthropogenic grasslands (Chapter B1-3.4). The management practices identified for each production system are relevant for both climate change adaptation and mitigation.

B1-3.1 Annual crop systems

Many annual crop production systems are net emitters of carbon to the atmosphere due to the accelerated mineralization of soil organic carbon and soil erosion, inefficient nitrogen management and the heavy use of fossil fuels.

Climate-smart management measures should be oriented towards increasing soil carbon stocks that improve soil and water productivity and reduce the release of greenhouse gases. Due to its specific agronomic management practices and its importance for global food security, paddy rice is addressed in a separate sub-chapter. For all other annual crop systems, the climate-smart intensification of the production can be achieved through the management practices described in Chapter B1-2 and in Box B1.3, as well as through the integration of perennial species on farms. The use of perennial species as a climate-smart agricultural practice does not require a complete conversion from annual to perennial crop production systems, and particularly not to landscapes dominated by perennial crops. It involves progressively integrating, as is locally appropriate, perennial species on farms (e.g. multifunctional edible living fences that can be used for feed or food, or windbreaks) and/or in the crop system, as appropriate). There are many possible variations in the progression towards perennial crop systems that span from relatively simple intercropping systems to fully integrated production systems, which are considered in module B5, (e.g. multistoreyed systems with shade crops growing below a productive canopy), to orchard and plantation crops, which are addressed in this module in Chapter B1-3.2.

Perennial plants[xviii] are those that complete their life cycle in more than two growing seasons. Compared to annual crops[xiv], perennial crops require less labour to maintain, and do not need to be replanted on a seasonal base. However, they usually require more up-front investments and costs, and the benefits in terms of climate change mitigation can take a considerable amount of time to materialize.

Perennial woody crops are especially important in climate-smart crop production because, in addition to food, they also provide fuel (e.g. fuelwood from coppiced nitrogen-fixing tree species), timber, materials for construction and craft making, fibers, herbicides and medicines. Introducing perennial woody food crops on the farm and/or in the crop system delivers several co-benefits for climate change adaptation and mitigation. These co-benefits, which are felt both on the farm and throughout the agricultural landscape, include the diversification of production and consequent risks; an increase in the number of harvests per season; extra sources of biomass; enhanced soil fertility; the prevention and reduction of soil erosion; the restoration of degraded land as some species are adapted to shade conditions or land ill suited for annual crops; the stabilization of slopes; and carbon sequestration. For example, crop systems in which *Cajanus cajan* (pigeon pea) is grown as a perennial crop with soybean and maize have a smothering effect on weeds and provide two harvests per season: pigeon pea and soybean; and maize and pigeon pea. Instead of growing maize alone, or maize in rotation with soybean, the pigeon pea is grown with soybean. Once these legumes are harvested, the pigeon pea is allowed to regrow; then maize is planted into the pigeon pea.

Herbaceous perennial crops have longer growing seasons and more extensive root systems than annual crops. Because of this, they are better able to compete against weeds, capture nutrients, access soil moisture and build up soil organic matter. As they do not have to be replanted each year, farmers save time, labour, money on fuel, and can also reduce their greenhouse gas emissions. Annual crop production systems offer more flexibility to shift to locally adapted crops each year. However, this potential adaptation advantage is only realized when seeding operations can be done in a timely manner.

Some perennial herbaceous crops (e.g. alfalfa) are widely used by farmers for animal feed. Efforts to develop perennial herbaceous staple crops have been made in different countries (e.g. perennial wheat in Australia and perennial rice in China). However, despite the great promise of perennial herbaceous grain staples as a strategy for addressing food security, climate change adaptation and mitigation and environmental conservation, none of these crops has received the same amount of attention by breeders as annual staples. As discussed in Chapter B1-4.1, more research is needed to develop new crop species capable of replacing annuals and scale up this technology (Batello *et al*., 2013). The cultivars available are generally not very productive, but because perennial grains regrow after seed harvest, livestock can be integrated into the system. Thanks to their deep rooting system they stabilize the soil and can be used in more marginal lands to increase the diversity on the farm. This leads to more diversified production and makes the farming system more flexible.

Rice systems

More than 90 percent of the world’s rice is produced in flooded fields. Grown in continuously flooded paddies, rice receives two to three times more water than other irrigated cereals, even though they have a similar transpiration rate. As a result, to produce 1 kg of paddy rice, often as much as 2 500 litres of water is used, which translates to a water productivity of 0.4 kg per cubic metre (Bouman *et al.*, 2007). Flooded rice fields are one of the main sources of methane emissions. Rice paddies emit methane totalling approximately 625 million tonnes of carbon dioxide equivalent annually (FAO, 2016b). In continuously submerged fields, drainage at the end of the growing season releases the methane formed by the anaerobic decomposition of the organic matter (Chapter B1-1.3). Nitrogen is also released, mainly through ammonia volatilization (Xu *et al*. 2012).

Farmers have a number of options for saving water in irrigated paddy/lowland rice production. These options include no-tillage in combination with mulching to provide soil cover; raised beds; land levelling; alternate wetting and drying irrigation; and aerobic rice (Bouman *et al*., 2007; Thakur *et al*., 2011).

The aerobic rice production system uses especially developed aerobic rice varieties that are grown in well drained, non-puddled (dryland preparation) and non-saturated soils. Because aerobic rice needs less water at the field level than conventional lowland rice, the system is targeted at relatively water-short irrigated or rainfed lowland environments. Irrigation can be applied through flash flooding, furrow irrigation (with the rice growing on raised beds) or sprinklers. Weed control is particularly important in this system, as the number of weed species is higher and their growth is faster. Soil-borne pests and diseases, such as nematodes, root aphids, and fungi are more common in aerobic rice than in flooded rice, especially in the tropics. For this reason, it is recommended to grow aerobic rice in rotation with suitable upland crops. Site-specific nutrient management can be used to determine the optimal management of fertilizers. With appropriate management, aerobic rice production systems aim for yields of at least 4 to 6 tonnes per hectare. See the International Rice Research Institute's web page on aerobic rice for more information.

Non-continuous water regimes, like alternate wetting and drying, reduce water demand and allow water to be allocated for other uses. This is particularly beneficial in major irrigated rice areas where the water supply is forecast to be insufficient to meet demand. This technique also reduces fuel for pumping water, which reduces farmers’ expenses. Intermittent water applications also temporarily remove the anaerobic conditions. This results in a significant reduction (above 16 percent) of overall methane emissions during the growing season compared with continuous flooding. It should be noted however that nitrous oxide emissions may increase. The recurring shift between aerobic and anaerobic conditions enhances nitrification, and if the nitrates are not taken up by the plants, nitrogen may be released into the atmosphere through denitrification (the biological reduction of nitrates to nitrogen gas by bacteria (Chapter B1-1.3). In alternate the alternate wetting and drying technique, irrigation water is applied when the rice plant becomes established. The fields are kept flooded and the soils are saturated for two weeks to discourage the growth of weeds. The flooding is then interrupted, and the fields are allowed to dry out until the water level falls to 15 cm below the soil surface. During flowering, a layer of water 3 to 5 cm deep is maintained. During grain filling, the alternate flooding and drying scheme is repeated until two to three weeks before harvest. Alternate wetting and drying can be applied with different rice production methods. It can be used instead of continuous flooding as well as under System of Rice Intensification (Box B1.4)

Box B1.4 System of Rice Intensification

The System of Rice Intensification uses alternate wetting and drying in combination with land levelling. In this system, rice seedlings are transplanted at shallower depths with a wider spacing (25 x 25 cm) between plants than in flooded systems. This allows for tillers to emerge and develop easily and quickly and to develop healthy, large and deep root systems that are better able to resist drought, waterlogging and rainfall variability, all of which are potential impacts of climate change.

This system improves yields higher than those obtained in flooded systems. The rice also matures earlier, and the land becomes available sooner for the timely planting of the next crop or for the intensification of the crop rotation. Some examples are available from the FAO Save and Grow Farming Systems Fact Sheet. However, the System of Rice Intensification is more labour-intensive than flooded systems. Its success depends on the farming system’s specific characteristics and whether the increased labour required has a positive or negative effect on the local economy. The economic effects will be determined by whether the increased demand for labor generates employment for otherwise idle family labour during the dry season, or whether it translates into production costs that are too high to be sustained. Labour requirements could be lowered with technical innovations, such as seedling trays that simplify seedling preparation and transplanting, or replacing transplanting altogether with direct seeding (FAO, 2016a).

Strengthening farmers' decision-making skills through activities in which they can learn from experience and providing platforms for collaboration between farmers and researchers can help ensure that crop management practices are adapted to farmers' needs. A study carried out in the Senegal River Valley assessed the agronomic and socio-economic viability of various management practices, including the System of Rice Intensification, the farmers' current practices, and adapted practices. The adapted farmer practices, which were a combination of improved practices designed by farmers and researchers to better respond to local conditions and needs, obtained the largest yield, reduced the labour needed for weeding, lowered the need to apply herbicides, and minimized the risk of production losses in the field (Krupnik *et al*,. 2012).

The training modules available on Youtube on the System of Rice Intensification in Burundi developed by IFAD and Cornell University provide a useful knowledge-sharing tool: Seed germination and nursery preparation; Field preparation and transplanting; Weeding and water management.

Source: Authors

B1-3.2 Horticultural systems, orchards and plantations

Horticulture production systems involve the growing of fruits, vegetables, root and tuber crops, condiments and mushrooms.

Orchards and plantations are agricultural systems that are productive for many years and can provide multiple harvests.

Horticulture species are particularly rich in diversity. They offer a vast range of cultivars that can naturally perform well in many locations and accommodate changing climate variables. Along with the proper irrigation and drainage management, the initial selection of a site that best meets the crops agro-ecological requirements is of utmost importance in all climate-smart horticultural systems (Table B1.1).

The FAO HORTIVAR database provides a useful reference for field performances of all crop species and varieties under the prevailing climatic conditions in a given location during the crop cycle. The information on cultivars, their preferred planting and harvesting times and location is georeferenced, and can be linked to specific climatic parameters. This information can be extrapolated for use in areas where climate change is expected to create similar climatic conditions.

Protected cultivation

Protected cultivation, which embraces a broad range of practices, 'protect' the plants against external factors. These practices are meant to ensure consistent productivity under various and variable, sometimes unpredictable, climate variables. Protected cultivation can involve very simple practices, such as the use of soil mulch or floating mulch, as well as highly sophisticated vertical farming systems (Table B1.1). These technologies require different levels of investment and costs and cannot be equally applied to all crops. The level of technology will largely depend on the commercial value of the crop and the target market.

The major greenhouse gas emitted from greenhouse production is carbon dioxide, which is released by the burning of coal, natural gas and oil for heating and by the generation of electricity for cooling and artificial lighting. Indirect sources of greenhouse gases include the production of the greenhouse materials, such as disposable polyethylene.

Greenhouse gas emissions can be reduced by increasing productivity per unit of water, fertilizer and energy. In horticultural systems for vegetable crops, conservation agriculture, in combination with drip irrigation, has the potential to increase yields, reduce water evaporation from the soil and decrease labour. Energy savings can be achieved by ensuring greenhouse production is carried out on sites that have been selected based on careful assessments, and adopting the suitable greenhouse design and covering material. Fortunately, a major proportion of greenhouses have passive climate control systems based on ventilation and shading, and do not have heating or cooling systems, which are major sources of energy consumption and greenhouse gas emissions. Energy use can be monitored by the following values and ratios: kg per square metre of floor area (crop productivity); millijoules per square metre of floor area; millijoules per kg of product; carbon dioxide emissions per kg of product; and water (in quantity and value) used for irrigation per kg of product.

Urban and peri-urban horticulture

The objective of urban and peri-urban horticulture is to improve the availability of fresh horticulture produce in cities and increase the access of urban populations to this nutritious food, while also creating jobs and improving livelihoods. As 'proximity' food production systems with short supply chain, urban and peri-urban horticulture can save energy and reduce greenhouse gas emissions by cutting down on transport, packaging and conservation. Urban and peri-urban horticulture has emerged as a preferred activity for small-scale producers, who can grow different horticulture specialty crops within and around cities. Crops are grown either in peri-urban greenbelts, plots within the cities, home gardens or microgardens.

Microgardens are container-based small-scale production units that can be used to cultivate a wide range of vegetables, roots, tubers and condiments in small spaces, such as patios, balconies and rooftops. They are adapted to densely populated urban environments, where space is limited and water scarce. Microgardens are a good example of producing more with less, delivering higher yields and greater diversity than larger-scale production per unit of surface area, water used and labour expended. Not only do they require less space, water and labour, they also use less pesticides and mineral fertilizers and need less transport and packaging to reach consumers. They are also less affected by soil-borne diseases and produce less food waste.

Urban horticulture is gaining in popularity. It has been acknowledged as a development opportunity by the Milan Urban Food Policy Pact signed by the mayors from around the world in 2015. In 2014, the microgarden technology has been awarded the Dubai prize by UN-Habitat as the 'Best Practice' in the urban environment. The city of Barcelona has also nominated the technology as an environmentally friendly technology.

Orchards and plantations

The productivity of orchards and plantations is strongly determined by the species and cultivars that are grown. These can be identified by their 'set points', which correspond to values of the climate factors required for optimal growing, flowering and fruit development. These set points should be considered as the guiding values for site selection. Adaptation to local conditions can be enhanced by using grafting technology, whereby the rootstock can bring specific resistance to biotic and abiotic factors. The climate-smart management of orchards and plantations involves the efficient use of water and energy for husbandry operations, and the transportation and storage of produce. Climate-smart orchard and plantation crops, once established, require no-tillage and minimal fossil fuel inputs. On average, they can sequester more carbon in their biomass and in the soil than annual crop production systems. The amount sequestered depends on the climate, the species grown and their management.

As well as producing nutritious food and sequestering carbon, orchards and plantations stabilize slopes and help build soils. There are many trees and palms worldwide that produce crops that are rich in carbohydrates (in starchy fruits, seeds, nuts, pods, tubers), provide fats (in fruits, seeds, nuts), and some proteins (in nuts, beans and leaves). Research is needed to fully exploit their potential in climate-smart agricultural development.

B1-3.3 Integrated production systems

Integrated production systems are dealt with in module B5.

B1-3.4 Natural and anthropogenic grasslands

Rangelands and grazing areas, used by pastoralist, cover 38 percent of the total agricultural land. Most of those areas are arid, semiarid lands or cold mountains areas where no crops can be grown sustainably.

The world’s soils are considered to store the largest terrestrial pool of organic carbon (Amundson, 2001). Carbon stocks in the soil can be altered when changes are made in the way land is used. Changes in land use and management are considered particularly important components of any comprehensive strategy to reduce the concentration of greenhouse gases in the atmosphere (Thomson *et al.*, 2010; Deng *et al.*, 2013). The root systems of grasslands can sequester carbon and redistribute it to deeper soil layers (Nepstad *et al.*, 1991). The carbon stored in a deeper soil profile is likely to be less susceptible to decomposition (Batjes and Sombroek, 1997).

There have been several scientific research studies to assess the role of management practices on soil carbon balance in various grassland ecosystems. However, grasslands ecosystems are very complex in both plant composition and soil types. Grasslands should be considered with a holistic approach looking to the complete ecosystem preserved by pastoral use of land. Those, together with wild species and livestock breeds, contribute to soil fertility and biodiversity. There is not a one-size-fits-all approach for grassland management. However, the role of grasslands in sequestering organic carbon can be improved by ensuring that grazing is kept to sustainable levels. Controlled grazing promotes growth of herbaceous species and reduces grassland degradation. As well as increasing soil carbon sequestration, improvement in the nutrient status of grassland soils can improve forage yield and quality. The introduction of deep-rooted grasses and legumes can also play an important role in improving soil carbon sequestration (Fisher *et al*., 1994; Batjes and Sombroek, 1997; Schuman *et al*., 2002; Schuch *et al*., 2013).

Creating an enabling environment and removing barriers for the adoption of climate-smart crop production

Initiatives designed to achieve sustainable growth in productivity, deliver long-term benefits in terms of improving the adaptation responses to climate change, and reduce and/or remove greenhouse gas emissions, must be planned and address the potential constraints producers face in adopting climate-smart crop production practices and technologies. Autonomous adaptation actions[xx] that are not designed for future climate conditions and not informed by past experience, carry the risk of evolving into maladaptation. For example, pressure to bring marginal land into production to compensate for declining yields may increase land degradation and endanger the biodiversity of both wild and domestic species, which may jeopardize future efforts to respond to climate risk. Without consistent policy signals, autonomous efforts by farmers may have limited success, as the impacts of climate change gradually become more drastic. Since agriculture is a core private enterprise activity, the costs of the harmful impacts of climate change will be borne directly by farmers.

Policy responses to mainstream climate change into all agriculture sectors are dealt with in module C3. The relationship between the policy environment required to support climate-smart agricultural development and a system-wide approach for capacity enhancement is addressed in module C1. This chapter deals with specific considerations for policy makers and development practitioners on whether, how and in which crop production priorities to invest for climate change adaptation and/or mitigation purposes (Chapter B1-4.1).

The transition towards climate-smart crop production is easier to achieve when it is market-driven and fully integrated into markets. Food markets often function poorly or very locally. Adaptation and mitigation actions also need to develop local, regional, national and international markets for crops that play functional roles in crop rotation. Success in this area will depend on innovations in market institutions, improvements in the physical infrastructure (e.g. roads, irrigation schemes, facilities for bulking, processing and storage, and information and communication systems) needed to facilitate access to markets, and investments in rural areas.

In addition to infrastructure, seed laws, policies and registration processes related to the release, multiplication, distribution, quality control and sale of seeds are important for climate-smart crop production. These policies and regulations, which govern national and, increasingly, regional crop varietal development, establish the vitally important enabling environment that can ensure farmers have timely access to reasonably priced quality seeds and planting materials of the most suitable crop varieties. The harmonization of seed regulatory frameworks at the subregional and regional levels is particularly important for coping with local seed shortages. Harmonization eases administrative bottlenecks in cross-border seed trade and facilitates seed exchange among countries. At the same time, the establishment of procedures for the release of regional varieties and crop variety catalogues increases the options available to farmers (Chapter B1-3).

For climate-smart crop production practices and technologies whose adoption is determined by investments, decision-makers working on potential policies and incentives must pay careful attention to the overall economic, social and environmental context. Emphasis should be, for example, on providing financial incentives to enhance farmers' capacities or increase their access to soft loans to support initial investments in sustainable practices and technologies. One way to achieve this is to develop financial strategies that can enable farmers, especially smallholders with limited purchasing power, and streamline them into existing institutions. This can help farmers to take advantage of measures that are socially and environmentally beneficial but have high upfront costs. At the same time, incentives that support unsustainable production systems and exacerbate climate change need to be removed. A major disincentive for farmers to invest in the climate-smart management of productive resources is uncertainty regarding their rights to land and natural resources. It is particularly difficult for smallholder farmers without formal land title deeds to obtain credit for activities that can diversify their income. They remain trapped in a vicious circle of 'lows': poverty, low education levels, limited technical knowledge, limited access to production inputs, low productivity and quality levels, limited market integration and low value addition. To be effective, tenure rights need to recognized and granted legitimacy. This requires well functioning institutions for administering land tenure. These institutions are dealt with in more detail in module C1.

Many climate-smart crop production practices generate co-benefits that require time to manifest themselves. Because of this, effective risk management strategies need to include social protection mechanisms for the rural poor, especially for vulnerable groups, such as women and youth. Social protection and decent rural employment are addressed in module C7.

Prioritizing investments is not always easy because different crops and crop production systems have their advantages and disadvantages, and the trade-offs that need to be made may be hard to quantify economically and environmentally. For example, dietary changes are extremely important for climate-smart food system, as some foods have higher embodied greenhouse gas emissions or require considerably more resources per calorie or nutrient value to produce than others. Making food systems more carbon-friendly and greener is a priority, especially at the local level (Hilmi, 2016a, 2016b). In a global food system, in which there is a growing dependency on international trade, food production and consumption are often spatially disconnected. This makes it difficult to estimate the proportion of greenhouse gas emissions related to crop production; assess the environmental, social, economic and health benefits of local food compared to non-local food; and guide the evolution of food systems. Making decisions in this area requires giving weight to community relationships and producers’ economic benefit as well as to the potential environmental and health benefits. Even if a representative accounting of all variables was possible, the current understanding of the composition of a healthy diet still remains a controversial area of science. Any advice or guideline on consumption patterns would be only based on partial information (Weber *et al*., 2008; Fader *et al*., 2013). Policies and incentives for climate-smart crop production practices related to nutrient management also require a sound understanding of potential trade-offs. For example, subsidies for fertilizer inputs may encourage farmers to improve nutrient-deficient soils and decrease yield gaps. However, they may also discourage the use of recycled materials (e.g. composted residues and organic wastes) due to their associated labour costs. Such subsidies may also suppress innovations in nutrient cycling methods or technologies that make use of agricultural by-products (e.g. animal excreta and crop residues) and human waste (e.g. wastewater, sewage materials and food waste).

Trade-offs may also need to be made regarding mitigation objectives and how to reach them. For example, one mitigation option countries could pursue is to encourage farmers to phase out the spreading of manure onto the land in favour of treatment or direct incorporation into the soil. This would reduce emissions of ammonia, which is considered a secondary greenhouse gas due to its potential contribution to nitrous oxide production when it is deposited on soils and reenters the soil nitrogen cycle. Ammonia is also a source of atmospheric pollution. However, while such changes would reduce ammonia emissions, it could also generate methane emissions from the anaerobic digestion of manure, or nitrous oxide emissions from the denitrification of nitrogen incorporated into the soil (Olivier *et al*., 2002).

Recognizing the complexity inherent in developing climate-smart agricultural strategies, this chapter has identified the major necessary components for the establishment of sustainable and climate-smart crop production systems. A comprehensive account of the elements for the implementation of a climate-smart agriculture strategy at the country-level is provided in module C10.

B1-4.1 Integrated research priorities

Coping with future challenges related to climate requires more investment in research, specifically action research. It is essential to build the evidence base for climate-smart interventions and technologies; tailor the strategies that have proven to be effective to increase their applicability in specific locations; and accelerate the development and adoption of new promising technologies and practices.

Most research and modelling work on crops is directed to cereals, particularly maize, wheat and rice, and legumes, such as groundnut and soybean. However, maintaining the health of agricultural ecosystems under different climatic circumstances will require diversifying crop production and including lesser-known annual and perennial crops into crop rotations. Expanding the scope of crop research to include alternative edible species would increase the adaptation options available for farmers (Glover *et al*., 2010). Developing new varieties of edible plant species and commercially sustainable perennial grain crops that are resistant to drought, flooding, salinity, pests and diseases will involve the preservation of multiple varieties, land races, rare breeds and closely related wild relatives of domesticated species to maintain a genetic bank for use in the selection of novel traits.

Other research priorities in climate-smart crop production include the investigation of methods for adapting farming practices and technologies to site-specific conditions and needs. The adoption of climate-smart technologies is not determined simply though straightforward assessments of the fitness and resilience of a single crop to the specific context. The suitability of any intervention requires integrated scientific investigations to appraise the constraints that make it difficult for farmers to adopt climate-smart crop production system. It is necessary to devise, test and validate climate-smart cropping systems (e.g. planting and termination dates, seed rate, crops sequencing), and farmers must be involved in the identification of obstacles to adoption and the formulation of strategies to overcome them. However, in many countries, research institutions for crops, soil and water are hosted in separate entities and have different priorities. This fragmentation of research efforts is a major constraint for the efficient and integrated management of crops, soil, water and nutrients, and ultimately hinders the transition to climate-smart agriculture. Promoting and supporting integrated research produces important public goods.

The communication of research outputs must be made more 'policy friendly'. Researchers need to provide clear 'take home message' for policy makers and development practitioners and give them the instruments they require to prioritize potential policies and strategies. To foster the uptake of research by producers and ensure that research priorities are shaped by experiences on the ground, an agricultural innovation systems approach is recommended and is described in Chapter B1-4.2).

B1-4.2 Capacity development for climate-smart crop production

Developing and applying locally specific and effective climate change adaptation and mitigation strategies for crop production requires the strengthening of scientific and technical capacities at many levels, including the individual and organizational levels, in ways that create an enabling environment for change. Capacity development must be multidisciplinary and include all groups that have a stake in making crop production climate-smart. Key stakeholders include national researchers, policy makers, extension agents, farmers and the private sector, particularly small-and-medium size enterprises. It is not only people new to farming and agriculture-related businesses that need support in obtaining skills and knowledge. The capacities of policy makers, extension agents, agricultural entrepreneurs and farmers need to be enhanced and updated on a consistent basis. This demands strengthening organizational and institutional capacities, such as coordination mechanisms. A system-wide capacity development approach (discussed in module C1) is recommended because climate-smart crop production is knowledge-intensive and both highly location-specific and deeply intertwined with global dynamics.

For farmers in particular, gaining and sharing knowledge about changing climatic conditions and the sustained viability of adapted crop production practices are important when formulating strategies to cope with the limiting factors affecting their crop system; better allocate the resources they have at their disposal and those they can mobilize; and make reasoned investments in climate change adaptation and/or mitigation. Understanding the processes farmers go through when making decisions about adopting new practices and technologies is very important. This is only possible at the local level and requires a solid knowledge of how farmers manage change. In this respect, pluralistic and demand-driven extension services play a pivotal role in facilitating practical changes in climate-smart crop production. These services provide access to and the sharing of good practices and technologies, and enhance farmers' capacities to implement them. They also help to reduce the perceived, and sometimes real, risks of failure that a shift to a new system and new ways of doing business carries. For example, Farmer Field School programmes, which provide local platforms for collaboration among farmers, extension agents and researchers, can serve to develop locally adapted strategies for climate change adaptation. These programmes often combine capacity development at the local level with actions linked to the broader policy framework and governance. In many countries, public extension services have deteriorated. They have been replaced in part by messages directly sent from various entities (e.g. research institutions, government ministries, farmers organization) by cell phone, the internet, radio and television. The role of private input suppliers and service providers (e.g. throughout-grower schemes) has also increased. As a result, many farmers, particular women farmers, do not have access to any form of extension services. Module C2 addresses extension services in detail. The needs of women farmers must not be neglected in view of their significant role as food producers in many countries. This subject is addressed in module C6.

Increasing local capacities to select and evaluate crop varieties is critical for ensuring that locally appropriate varieties are available to farmers. This requires the creation of platforms (see module C1 on Multi-Stakeholder Platforms) for community-level, participatory variety breeding and evaluation. FAO has developed a multimodule toolkit for supporting capacity building along the entire seed value chain, including production, processing and quality assurance, and marketing by small- and medium-scale enterprises.

The development of capacities of the private sector in manufacturing, providing services and the marketing of agricultural machinery can also support the adoption of climate-smart crop production practices. In most developing countries, the lack of availability of locally manufactured agricultural machinery and spare parts, and the absence of local repair and maintenance services are important obstacles to sustainable mechanization[xxi] and contribute to inefficiencies in crop production.

Conclusions

Climate-smart crop production and food systems can only be successful if they increase the synergies and reduce trade-offs among the different stakeholders and their different objectives regarding sustainable food production, ecosystem conservation and livelihoods.

An integrated assessment of resource use efficiency, ecological services and economic feasibility needs to guide the choices concerning the most appropriate crops and production practices for each specific context and purpose. This must be done not only to safeguard food security, but to help reduce the concentration of greenhouse gas in the atmosphere, improve the cycling of nutrients in the soil, maintain an adequate supply of clean water and preserve the protective functions that healthy and self-maintaining agricultural ecosystems provide. All of this will be crucial for coping with the increasing changes and variability of climate.

This type of crop production requires that all stakeholders, including farmers, development cooperation professionals and policy makers, strengthen their ability to make decisions on matters that have typically been outside their area of expertise. A system-wide capacity development approach is recommended for bringing about a gradual transition towards climate-smart crop production.

The purpose of this module was to support this process by clarifying the needs and opportunities to help reach climate-smart objectives in crop production.

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