Food and Agriculture Organization of the United Nations

Crops and climate change impact briefs

Climate-smart agriculture for more sustainable, resilient, and equitable food systems

Crops and climate change impact briefs

Climate-smart agriculture for more sustainable, resilient, and equitable food systems

Food and Agriculture Organization of the United Nations

Rome, 2022

Required citation:
FAO. 2022. *Crops and climate change impact briefs. Climate-smart agriculture for more sustainable, resilient, and equitable food systems.* Rome. https://doi.org/10.4060/cb8030en

ISBN 978-92-5-135510-7

Contents

3. Sustainable cowpea production

4. Sustainable maize production

5. Sustainable rice production

Acknowledgements

This publication was prepared by Heather Jacobs, who is the principle author and curator of this set of five briefs. The briefs have been published in the framework of the FAO project “International Alliance for Climate Smart Agriculture - IACSA” (GCP/GLO/534/ITA), which was funded by the Italian Ministry of Ecological Transition (MITE) and implemented by the FAO Office of Climate Change, Biodiversity and Environment (OCB) under the coordination of Federica Matteoli (FAO), Natural Resources Officer, with Tiziana Pirelli and Julian Schnetzer as Lead Technical Consultants.

We would also like to express our appreciation to our colleagues in the FAO Plant Production and Protection Division (NSP), who provided valuable expertise as co-authors of individual briefs and in particular NSP’s Climate Smart Agriculture expert, Sandra Corsi. We are grateful to Preetmoninder Lidder, Haekoo Kim, Makiko Taguchi who provided their contribution to all crop briefs. We are also thankful to Chikelu Mba, Fen Beed, Buyung Hadi, Sandra Corsi for having contributed to the rice, maize, cowpea and wheat briefs. We want to express our gratitude to Melvin Medina Navarro and Mayling Flores Rojas for having contributed to the brief on coffee, to Teodardo Calles for his contribution on cowpea brief and to Wilson Hugo who contributued to the wheat brief. Furthermore, we would like to thank Josef Kienzle and Hafiz Muminjanov for their revisions to the rice, maize and wheat briefs.

Gordon Ramsay (FAO) contributed to the editing and proofreading of the final version of this report. Graphic design and layout were by Gherardo Vittoria.

We would like to thank the external peer reviewers who contributed to the various chapters of this report as follows: Maize: B.M. Prasanna (CGIAR) and Jill Cairns (CGIAR); Wheat: Hans-Joachim Braun (CGIAR), Matthew Reynolds (CGIAR), and Tek Sapkota (CGIAR); Cowpea: BB Singh (IITA), Christian Fatokun (CGIAR), and Jeffrey Ehlers (Bill & Melinda Gates Foundation); Coffee: Peter Laderach (CGIAR) and Christian Bunn (CGIAR); Rice: Yoichiro Kato (University of Tokyo).

We are also thankful to Luigia Marro (FAO) for her help in the finalization of this document, and to Carlotta Armeni (FAO) for her administrative support.

1. Introduction to crops and climate change impact briefs

Climate-smart agriculture for more sustainable, resilient, and equitable food systems

H. Jacobs and T. Pirelli

1.1 Introduction

Climate change is one of the greatest challenges of our time. Rising temperatures, fluctuating rainfall patterns and increasingly frequent extreme weather events, all pose serious threats to food systems. The impacts of climate change are already affecting food security, and are expected to continue to threaten crop production and livelihoods, increase food prices, and negatively affect nutrition, biodiversity and labour productivity. Changing climatic conditions also increase pressures on natural ecosystems and resources such as land and water, and contribute to soil erosion, deforestation, water scarcity, pollution and overall land degradation.

The global COVID-19 pandemic has made clear the interdependence of people and the natural environment. The pandemic is a health crisis, but it has also revealed and exacerbated profound social and economic imbalances. The pandemic has underscored the importance of developing stronger and more sustainable, resilient, and equitable food systems that are better able to withstand future crises, natural disasters, and the multiple and increasingly severe impacts of climate change. Post-pandemic recovery efforts have shown that many of the usual development approaches, especially in the agriculture sector, are unsustainable. To 'build back better' innovation is needed in all sectors. Innovation is particularly urgent in the agriculture sector, where there are real opportunities to transform agri-food systems and create synergies that can speed up progress toward achieving a number of important goals, including Nationally Determined Contributions (NDCs) under the Paris Agreement and the Sustainable Development Goals (SDGs).

Governments have acknowledged the significant contribution that agriculture makes to climate change. The agriculture sector, together with forestry and land-use change, is responsible for roughly 20 percent of anthropogenic greenhouse gas (GHG) emissions (FAO, 2021; IPCC, 2019). Following the 2015 Paris Agreement and the 2030 Agenda for Sustainable Development, countries have been increasing their mitigation efforts and setting more ambitious goals for climate action. The agriculture sector is being increasingly viewed as a key sector for implementing climate change mitigation and adaptation measures that can contribute to reaching climate targets.

Agriculture, by sequestering carbon in biomass above and below the ground and in the soil, can provide a unique pathway for responding to climate change. Farmers, who are under increasing pressure to adapt their practices and engage with new technologies to maintain production levels, can play a key role in mitigating climate change by shifting to sustainable cultivation practices that reduce GHG emissions compared to business-as-usual scenarios and increase carbon sequestration in biomass and the soil.

Climate-smart agriculture (CSA), which recognizes that there are critical synergies between climate change mitigation and adaptation, and sustainable agricultural production, exemplifies the approach that is required to make the shift to more resilient agri-food systems. The successful transition to CSA and the implementation of specific CSA practices involves the establishment of an enabling environment that encompasses conducive institutional arrangements, appropriate infrastructure, processes to ensure the engagement of all stakeholders, measures to foster gender equality, and mechanism to increase the access of small-scale farmers to credit, insurance, extension and advisory services. The scaling up of CSA also requires a strong political commitment capable of underpinning the necessary level of coordination among interlinked stakeholders from diverse domains, including climate action, food security and agricultural development. Supportive policies should be implemented that can facilitate the access of small-scale farmers to critical sources of finance. All of these elements must fit together to create a solid foundation that can allow CSA to be scaled up and achieve large-scale transformations of the food system.

This series of briefing notes is intended to inform policymakers and other stakeholders about recommended practices tailored to specific crops, and support them to make a transition to more sustainable agricultural production that can deliver benefits for both climate adaptation and mitigation. Each of the five briefing note describes practices for a specific crop: coffee, cowpea, maize, rice and wheat. These notes, which outline practices that can support a transition to more sustainable and resilient crop production systems, also highlight the contributions these practices can make toward achieving the SDGs.

1.2 CSA practices as a contribution to achieve the SDGs

CSA provides multiple cross-cutting benefits and can hasten the progress being made in **the achievement of all SDGs (FAO, 2019).** The selected CSA practices presented in these briefs demonstrate the benefits that are common to most crop production systems. These practices relate to a number of key activities, particularly crop diversification; the improved efficiency in the use of nutrients and fertilizers and the minimization of nutrient losses; efficient water management; Integrated Pest Management (IPM); and conservation agriculture, which encompasses an array of practices (diversification of crop production, reduced tillage, and almost constant soil cover) that serve to increase soil carbon. The practices recommended in this series address poverty (**SDG1**), gender equality (**SDG5**), clean water and sanitation (**SDG6**), employment and economic growth (**SDG8**), sustainable consumption and production (**SDG12**), forging partnerships (**SDG17**) and the conservation of marine resources (**SDG14**). The application of these practices requires a deep knowledge of local ecosystems and their components, and strong capacities for using specific methods and technologies and fine-tuning them to the local context. Therefore, the scaling up of CSA requires the implementation of practical training that develops technical and vocational skills in rural communities (**SDG4**). IPM and improved efficiency in the use of nutrients and fertilizers can benefit human health by reducing illnesses associated with air, water and soil pollution and contamination (**SDG3**). Reducing fuel consumption by adopting conservation agriculture practices allows for energy savings and increased energy efficiency (**SDG7**). A further contribution to **SDG7** is the conversion of waste and residues to bioenergy, which can help to ensure access to affordable, reliable, sustainable and modern energy for all. For a concise overview of the contributions that the CSA practices recommended in these briefs make to specific SDGs and targets, please refer to Annex I.

- **The diversification of cropping systems** can create income opportunities to improve the livelihoods of small-scale farmers (**SDG 2.3**); support subsistence farmers in overcoming poverty (**SDG 1.1**); contribute to more sustainable and resilient food systems (**SDG 2.4**); achieve higher levels of economic productivity (**SDG 8.2**); improve carbon sequestration in agricultural ecosystems, reduce

GHG emissions, increase resource use efficiency, and prevent soil erosion and nutrient losses (**SDG 13.1**); provide multiple benefits and support the sustainable management of terrestrial ecosystems (e.g. the diversification of rice production systems, including intercropping with other cereals, annual and perennial legumes, and the integration of rice production with aquaculture) (**SDG 15.1**); and contribute to the conservation of biodiversity (**SDG 15.5**).

- **Agroforestry** is a potential method for diversifying cropping systems. Beyond the SDGs mentioned in the previous point, agroforestry can also contribute to the sustainable management of forests and curb deforestation by reducing pressure on natural forest (**SDG 15.2**). Along with mulching, agroforestry improves erosion protection and water regulation, which contributes to the sustainable management of water resources (**SDG 6**) and to efforts to reach the target of a land degradation-neutral world (**SDG 15.3**). Agroforestry also preserves or creates habitats for the conservation of biodiversity (**SDG 15.5**).
- **Introducing leguminous species** into crop rotations, intercropping them with other crops, or cultivating them as cover crops, are other potential options for diversifying cropping systems. The small nodules that develop in the roots of leguminous species fix nitrogen in the soil, and this biological process can reduce the need for external nitrogen fertilizers, improve efficiency in the use of nutrients and fertilizers, and save energy.
- **Improved efficiency in the use of nutrients and fertilizers** can have beneficial impacts on human health by reducing illnesses associated with air, water and soil pollution and contamination (**SDG 3.9**); reduce nutrient pollution in terrestrial, freshwater and marine ecosystems, and enhancing ecosystems services (**SDG 6.3, SDG 14.1, SDG 15.1**); contribute to the economy-wide target of improving global resource efficiency in consumption and production through the efficient use of nitrogen (**SDG 8.4**); and facilitate the sound management of chemicals throughout their life cycle and reduce their release into the air, water and soil, which minimizes their impact on human health and the environment (**SDG 12.4**).
- **Cowpea is a leguminous species which, when introduced into cropping systems and diets**, can improve access to nutritious food by all (**SDG 2.1**); improve yields and incomes, which contributes directly to the target of doubling agricultural productivity and incomes of small-scale food producers (**SDG 2.3**); provide nutritious fodder and support the integration of crop and livestock production, which can generate more for small-scale farmers (**SDG 2.3**) and create opportunities

for increased overall economic productivity (**SDG 8.2**); help to improve soil fertility and nutrient management and prevent erosion, which contributes to building more sustainable and resilient food systems (**SDG 2.4**); support the prevention of non-communicable diseases (**SDG 3.4**); and create opportunities for decent rural employment (**SDG 8.5**).

- **Efficient irrigation technologies and management** can contribute to sustainable management of water resources (**SDG 6**) by enhancing the efficiency of water use (**SDG 6.4**), which ultimately contributes to mitigating climate change and its impacts (**SDG 13.1**). Water-saving processing practices and treatment of wastewater can also contribute to ensuring the sustainable management of water resources (**SDG 6**); increase water use efficiency (**SDG 6.4**); improve water quality (**SDG 6.3**); contribute to sustainable consumption and production patterns, especially when accompanied by actions to promote sustainable consumer decisions and lifestyles (**SDG 12.8**); and support the sustainable management of freshwater ecosystems (**SDG 15.1**).
- **The adoption of conservation agriculture practices** can also contribute to the achievement of (**SDG 6**) and (**SDG 6.4**) by **enhancing water regulation capacities of agricultural soils.** In conservation agriculture soil disturbance is minimized through no-tillage soil management practices, and this combats land and soil degradation (**SDG15.3**). Conservation agriculture also contributes to improving access to safe drinking water (**SDG 6.1**) and enhanced water quality (**SDG 6.3**). Reduced tillage can contribute to increasing energy efficiency in the agricultural sector due to energy savings (**SDG 7.3**). Minimum and no-tillage practices are just some of the opportunities provided by the adoption of sustainable mechanization.
- **Sustainable mechanization** can contribute to the transfer, dissemination and diffusion of environmentally sound technologies to developing countries (**SDG 13**).
- **Integrated pest management (IPM)** can prevent infestations that damage crops (**SDG 2.1**) and compromise the productivity and incomes of small-scale farmers (**SDG 2.3**), which can directly and indirectly contribute to preventing famine (**SDG 2.1**). IPM also benefits human health by reducing illness caused by air, water and soil pollution and contamination (**SDG 3.9**); helps farmers to acquire new technical and vocational skills through training in farmer field schools (**SDG 4.4**); supports the sound management of chemicals throughout their life cycle and reduce their release into the air, water and soil, which minimizes impacts on human health and the environment (**SDG 12.4**); emphasizes the minimal use of harmful chemical pesticides, which reduces marine pollution from land-based activities (**SDG 14.1**); and

contributes to the sustainable management of terrestrial and inland freshwater ecosystems and their services (**SDG 15.1**).

- **Conservation agriculture, the use of improved crops and varieties, efficient water management, and IPM** contribute to mitigating climate change and its impacts (**SDG 13.1**).
- **Replacing the burning of crop residues with alternative management options** (e.g. using them for mulch, as a soil amendment, livestock fodder or bioenergy feedstock) contributes to reduced air pollution, which benefits human health (**SDG 3.9**). **Adding value to cropping systems, crop residues and by-products** can also improve efficiency in the use of nutrients and fertilizers, produce bioenergy (**SDG 7.2**), and offer a sustainable option for waste disposal and waste reduction (**SDG 12.5**).
- **Utilizing GPS-enabled precision farming** can contribute to the transfer, dissemination and diffusion of environmentally sound technologies to developing countries (**SDG 17.7**).
- **Improving seed supply and distribution** can improve equal access to seeds and create opportunities for decent rural employment (**SDG 8.5**). These objectives can be achieved through the following actions: **using landraces and crop wild relatives** in plant breeding, which also contributes to maintaining genetic diversity in cultivated plants (**SDG 2.5**); **training farmers** in seed production and engaging them in research activities, which can also support them in acquiring new technical and vocational skills (**SDG 4.4**); involving women by establishing **gender-sensitive seed systems**, which can promote women's empowerment (**SDG 5.b**); **strengthening the collaboration between formal and informal seed systems for improved seed supply**, which can also serve to promote effective public-private and civil society partnerships (**SDG 17.17**).

Climate change threatens food security and overall human well-being. During the next decade, considerable work will need to be done to achieve climate goals of the Paris Agreement. The world has entered a post-pandemic era, and has seen what can happen when countries are unprepared to heed scientific advice. It is important to learn from past experience and transform our food systems while there is still time. For those needing practical information and hands-on guidance, this series of briefs offers a good place to start.

1.3 References

IPCC. 2019. *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)].

FAO. 2019. *Climate-smart agriculture and the Sustainable Development Goals: Mapping interlinkages, synergies and trade-offs and guidelines for integrated implementation*. Rome. (also available at www.fao.org/publications/card/en/c/CA6043EN/).

FAO. 2021. FAOSTAT. In: FAO [online]. [Cited 24 July 2020]. http://faostat.fao.org

2. Sustainable coffee production

Adapting production systems to changing climatic conditions and reducing environmental impacts

H. Jacobs, M. M. Navarro, M. F. Rojas,
M. Taguchi, P. Lidder and H. Kim

2.1 Introduction

Coffee, which is one of the most widely traded agricultural commodities in the tropics, is an immensely important crop for the livelihoods of small-scale farmers. Coffee cultivation is under threat around the world due to climate change and increasingly erratic and extreme weather conditions, which are affecting productivity, quality, and price volatility. It is important for farmers to build resilience to the impacts of climate change and address the ways coffee cultivation contributes to greenhouse gas (GHG) emissions. This briefing note describes approaches for climate change adaptation and mitigation that can support a transition to more sustainable and resilient coffee production systems. It also highlights the synergies these approaches share with the Sustainable Development Goals (SDGs) in the 2030 Agenda for Sustainable Development. Strong political commitment, supportive institutions and investments are essential to give farmers access to these climate-smart approaches and enable their widespread adoption. Increased uptake of these approaches will in turn enhance yield, provide more stable incomes, ensure food security, and contribute to building resilient, sustainable and low-emission food systems.

Coffee is a perennial tropical crop that is cultivated on roughly 11 million hectares. Arabica coffee (*Coffea arabica*) is grown in cooler highland conditions, and Robusta coffee (*Coffea canephora*) is grown in warmer equatorial conditions from sea level to elevations of 2 000 m (Bertrand *et al.*, 2016). Arabica coffee originates from southern Ethiopia and Sudan, while Robusta coffee comes from Central and West Africa. Over time, coffee has spread through the tropics, and is now cultivated in 78 countries (Rising *et al.*, 2016). Only Arabica and Robusta are commercially cultivated. There are 124 wild species of coffee. Sixty percent of these wild species are under threat of extinction due to climate change, increasing pests and diseases, and deforestation (Parker, 2019). Arabica is the dominant species in Central and South America, and East Africa, and has many varieties. It is believed to produce the highest cup quality (i.e. the best tasting coffee) (WCR, 2020).

Coffee plants take 3 to 4 years before they generate fruit, and do not fully mature until they are between 9 to 12 years old. Blossoming, which occurs after temperatures fall, is often induced by several periods of rainfall, and takes only three or four days. The fruits of Arabica coffee plants are ready for harvest 6 to 8 months after flowering and after 10 to 11 months for Robusta plants (Rising *et al.*, 2016).

Temperature, precipitation, direct sunlight, humidity, soils and wind all have an impact on cultivation, but the impacts will vary depending on the variety (Rising *et al.*, 2016). Arabica requires mean annual temperatures between 18 °C to 22 °C. High temperatures can speed up the berry development, which tends to lower the coffee quality. Frost and excessive cold can damage the plant.

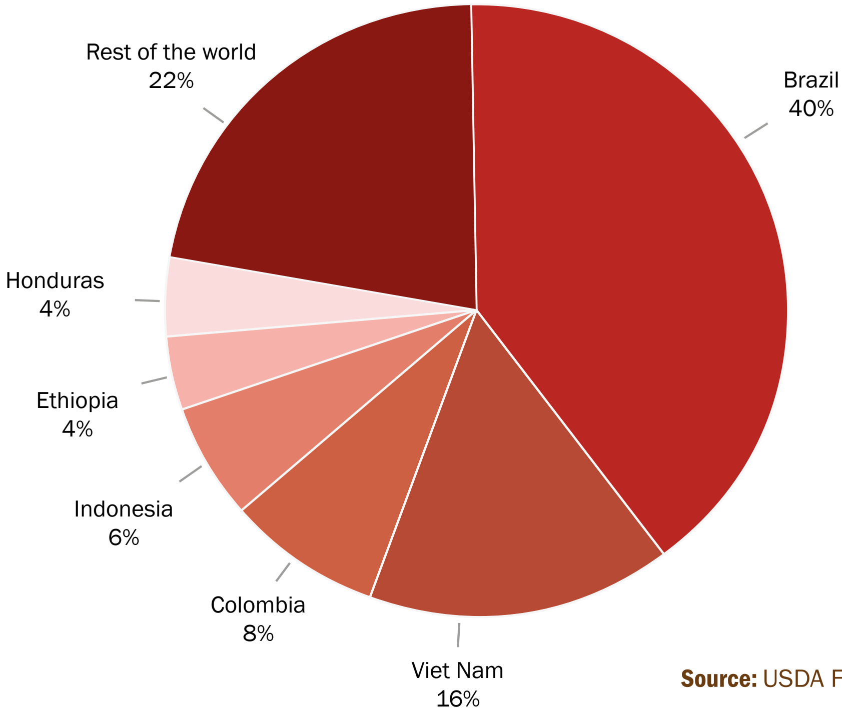
Arabica coffee production is dependent on the following series of weather events:

- a dry period of three months to provide stress for plants to stimulate flowering;
- a soaking precipitation event to initiate flowering;
- moderate temperatures;
- regular precipitation for the duration of the berry development stage; and
- a drier period leading up to harvest (Fischersworring *et al.*, 2015).

Robusta coffee can withstand higher mean annual temperature ranging from 22 °C to 30 °C. Robusta also tolerates higher humidity and more sunlight. It requires heavier precipitation, and may require increased use of irrigation as droughts become more frequent and severe as a result of climate change. Robusta is also more resistant to some pests and diseases (Rising *et al.*, 2016).

Soil for coffee cultivation should generally be well aerated and well drained. Ideal conditions can be found in fertile, volcanic soils, or deep, sandy loams. However coffee can be grown in somewhat diverse soil conditions (Pohlan and Janssens, 2010).

Figure 1: Share of coffee production by country (tonnes), 2020-2021



Source: USDA FAS, 2021

Approximately 70 percent of the world's 25 million coffee producers, are small-scale farmers (Stuart, 2014). In 2020-2021, 58 percent of global coffee production was Arabica, 42 percent Robusta. Brazil is the largest coffee producer (4.2 million tonnes), followed by Viet Nam (1.7 millon tonnes). Colombia, Indonesia, Ethiopia, and Honduras are the next highest producers. Other countries account for 22 percent of global production (USDA FAS, 2021).

This brief, which serves as a companion volume to the Climate-smart Agriculture (CSA) Sourcebook (FAO, 2017), summarizes best practices for coffee production systems under climate change scenarios. It is intended to provide a reference for policymakers, researchers and other groups and individuals working to support sustainable crop production intensification. In plain language and with case studies, the brief lays out a checklist of actionable interventions that could be adopted to enhance or sustain the productivity of coffee production systems that are at risk from climate change. The strategies for sustainable coffee production presented in this brief address the three pillars of CSA: sustainably increasing agricultural productivity and incomes; adapting and building resilience to climate change; and reducing and/or removing greenhouse gas (GHG) emissions, where possible. The strategies can be used to adapt coffee production systems to increased biotic and abiotic stress that results from changing climatic conditions, and reduce GHG emissions from these systems. This coffee-focused brief is one in a series of crop-specific briefs on CSA.

2.2 Impacts of climate change and projections for coffee

High temperatures generally decrease berry quality and increase water requirements of coffee plants. Climate change is likely to increase the threat of pests and diseases, as some of the most prevalent coffee pest and diseases are expected to become more active in higher temperatures. Climate change is predicted to increase the risk of floods and extended droughts, and modify the patterns, the timing, and the quantities of precipitation (IPCC, 2014). Given that coffee requires a consistent rainfall pattern along with distinct rainy and dry seasons, climate change has already started to affect coffee production and the impacts will continue to be felt in the future.

Adapting coffee production to climate change is crucial to avoid severe economic impacts on coffee exporting countries (**SDG Target 8.2**) and on the livelihoods of small-scale coffee producers (**SDG Target 2.3**).

Climate change has already reduced the productivity of Arabica coffee and shifted its production to higher latitudes due to increasing temperatures. (Gay *et al.*, 2006; Schroth *et al.*, 2009; Zullo *et al.*, 2011). Ovalle-Rivera *et al.* (2015) projected that by 2050 the increase in global temperature and changes in the seasonality of precipitation are expected to reduce climatic suitability for Arabica coffee at low elevations and increase the suitability of higher elevation areas.

Arabica production is predicted to be the most affected in Mexico and Central America, with impacts being particularly pronounced in El Salvador and Nicaragua (Läderach *et al.*, 2017). Because Arabica coffee is an important export for these countries, this region could suffer severe economic impacts (Ovalle-Rivera *et al.*, 2015). Severe negative impacts are also expected in Brazil, India and Indochina, with the Andes region, southern Africa and Madagascar suffering intermediate impacts (Zullo *et al.*, 2011). The regions least affected by higher temperatures include East Africa (except Uganda) and Papua New Guinea. Some coffee producing countries may be able to compensate for production losses in other countries within the same region, but production may also shift globally from regions where climate change has a significant impact on production to less affected regions (Ovalle-Rivera *et al.*, 2015). This global shift could prove catastrophic for the affected countries and the farmers.

The shift of Arabica cultivation to higher elevations may increase pressure on forests and natural resources at higher altitudes (Läderach *et al.*, 2017). Not all of the land at higher elevation areas where coffee production is projected to shift can be converted to coffee farms. There are a number of reasons for this, including soil conditions and the potential unwillingness by farmers to cultivate coffee instead of other crops (Ovalle-Rivera *et al.*, 2015).

Although Robusta coffee can endure higher temperatures than Arabica, it is unclear if it would serve as a suitable replacement on commodity markets (Bunn *et al.*, 2015). As temperatures rise, coffee will also be forced up slope to higher altitudes (Schroth *et al.*, 2009). Under a scenario of 2 °C to 2.5 °C of warming, the minimum altitude for coffee production in Central America and Kenya is predicted to increase by roughly 400 m (Dasgupta *et al.*, 2014).

A 2016 Columbia University report (Rising *et al.*, 2016) predicts that up to 20 countries could lose all naturally suitable land for coffee cultivation, with a global decrease of 56 percent for Arabica and an increase of 87 percent for Robusta. Temperatures have already risen in the coffee belt (i.e. the land area between the tropic of Cancer and the tropic of Capricorn) by 0.16∘C per decade and are expected to rise 1.7∘C to 2.5∘C by 2050, while precipitation is expected to increase by 1.7 percent. The dry periods, however, could become even drier. Excessively hot days tend to cause substantial yield losses. In Brazil, for example, days with temperatures reaching over 38∘C lead to large losses, while other countries can sustain losses at temperatures as low as 33∘C (Rising *et al.*, 2016).

By 2050, average yields in existing growing areas are expected to decrease by 20 percent with substantial variation among countries. The McKinsey Global Institute (2020) reported that in Ethiopia, the likelihood of a 25 percent or greater drop in coffee yield in any given year currently stands at about three percent, but is projected to rise to roughly 4 percent by 2030. In their analysis of potential climate change impacts on coffee production in Africa and the Americas, the Intergovernmental Panel on Climate Change (IPCC) has predicted that temperature and rainfall fluctuations could reduce the Central American coffee growing area between 38 and


©FAO / Florita Botts

89 percent by 2050, and raise the minimum altitude for coffee production from roughly 600 to 1 000 meters above sea level (Dasgupta *et al.*, 2014). IPCC scientists projected losses of coffee area in Costa Rica, El Salvador, Guatemala, Honduras, Mexico and Nicaragua. They also predicted diverse impacts within Brazil. For example, in Minas Gerais and São Paulo, the potential coffee growing area, which now stands at between 70 to 75 percent of the states' total land area, could be reduced to only 20 to 25 percent; in Paraná there could be a 10 percent decrease in land suitable for growing coffee; and in Goiás, scientists predicted that coffee production would no longer be possible anywhere. New areas were identified as being suitable for coffee cultivation, but these would not compensate for the size of the losses elsewhere (Dasgupta *et al.*, 2014; Rising *et al.*, 2016).

Not all of the effects of climate change will damage coffee production. Coffee production may benefit in areas where minimum temperatures are no longer low enough to present a risk of frost, which is a current threat to coffee farms. Regions that are further from the equator will have more areas that are suitable for coffee production. Countries with the most new areas suitable for Arabica coffee are Brazil, Mexico, and Angola (Rising *et al.*, 2016).

The El Niño/La Niña cycle, known as ENSO, is a potential threat, as it usually produces weather changes over a large portion of the tropics. These decadal events can be devastating and may become worse in the future. During the last large El Niño in 1997-98, the tropics experienced both severe droughts and floods, which coincided with crop failures across the tropics (Hsiang and Meng, 2015). However, ENSO events are often easier to predict and plan for than weather events. ENSO events can be predicted up to several months in advance, which means there is a window of opportunity to prepare them that may exist for regular weather events (Rising *et al.*, 2016).

Impacts of coffee production on climate change

In addition to being affected by climate change, coffee production also contributes to GHG emissions. In coffee production systems, the primary sources of GHG emissions are deforestation caused by the conversion of natural forests to coffee plantations and the conversion of shade-grown production systems to full-sun systems; the demand for fully-washed coffee that uses methane-emitting wet processing techniques; and fertilizer and pesticide use that contributes to GHG emissions of non-carbon dioxide GHGs (e.g. nitrous oxide). These impacts and approaches for their mitigation are discussed further in Section III.

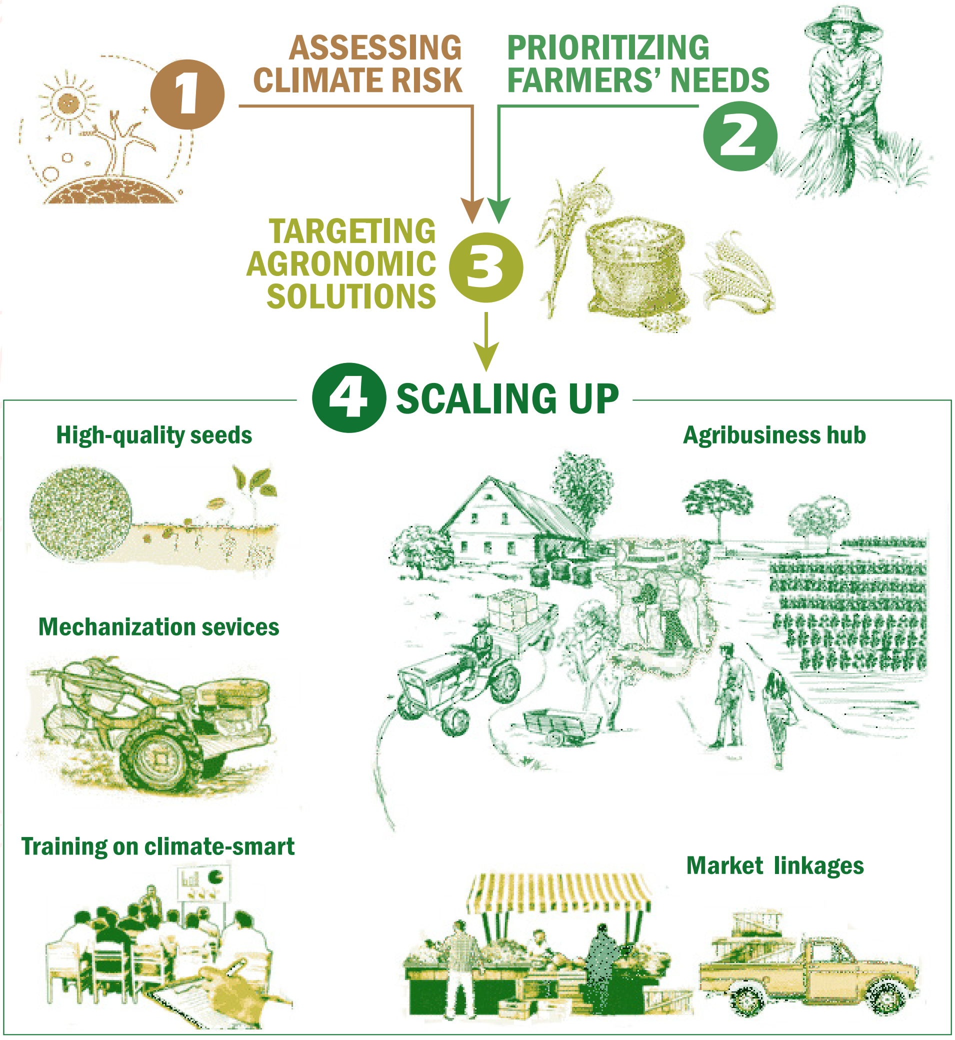
2.3 Climate change adaptation approaches

Higher temperatures, shifts in rainfall regimes, changes in the distribution patterns of coffee pests, and more frequent and more extreme weather events are examples of the challenges that farmers will face as climate changes. Coffee production systems need to become more resilient to these climate hazards, and the adaptive capacities of coffee farmers need to be strengthened. Progress in this area will contribute to achieving Sustainable Development Goal (SDG) 13 (Climate Action) particularly in reaching SDG Target 13.1. Key approaches for reaching these objectives include conservation agriculture, the use of improved crops and varieties, efficient water management, and integrated pest management. Enabling policies and legislation are instrumental to enable farmers to adopt these climate-smart practices. Extension services and institutional support are critical to improve nursery production practices. They are also needed to provide farmers greater access to seeds of improved coffee varieties and more information about these varieties, as well as to encourage the acceptance of hybrid varieties by small-scale farmers and increase the accessibility of these hybrids so that more small-scale producers can benefit from them.

FAO works with countries to reduce adverse impacts of climate change on crop productivity and the contributions crop production systems make to climate change. Based on lessons learned in the field, FAO (2019) has proposed a four-step approach to climate change adaptation and mitigation:

1) assess climate risk;
2) prioritize farmers' needs;
3) target agronomic solutions; and
4) scale up successful interventions.

Figure 2: The Save and Grow approach



Source: FAO, 2019

The FAO 'Save and Grow' approach to sustainable crop production intensification relates to step 3 in this four-step sequence. The 'Save and Grow' approach consists of a set of practices that include conservation agriculture; the use of improved crops and varieties; efficient water management; and integrated pest management (IPM). This section describes in greater detail the application of these practices in coffee-based production systems.

Being a perennial plant, coffee is perhaps more resilient to climatic shocks than annual crops. However, because coffee plants take several years to reach maturity, it is more difficult for farmers to make interannual adjustments such as changing varieties or switching crops (Läderach *et al.*, 2017; Tucker *et al.*, 2010). It is also difficult for farmers to invest in improved practices and technologies due to the time they must wait for harvest. It is a challenge for many small-scale farmers to take up CSA practices for coffee because of the uncertainty in yields, product quality and market prices under changing climatic conditions.

Box 1: Four degrees of adaptation efforts

Läderach *et al.* (2017) devised specific adaptation recommendations based on predicted shifts in elevation for Arabica coffee as temperatures increase in Nicaragua. The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) in conjunction with Feed the Future and the United States Department of Agriculture (USDA), developed policy briefs on climate-smart coffee for specific regions such as Central America and East Africa, presenting this concept as the 'four degrees of adaptation effort.'

- **Incremental adaptation** is appropriate in areas where climate is most likely to remain suitable (i.e. typically medium and high elevations where coffee production can be sustained under low or high adaptation efforts) and is comprised of improved strategies, change of practices and actions farmers take to meet current objectives under different conditions, such as changing varieties and management practices, shade and irrigation. Incremental adaptation generally occurs over a short timeframe at lower altitudes.
- **Systemic adaptation** is needed where climate is most likely to remain suitable but with substantial stress and involves a comprehensive change of practices as well as a change of strategy. Examples include adding or changing irrigation systems or diversifying with productive shade trees.
- **Transformative adaptation** is necessary in areas where climate is likely to make coffee production unfeasible, necessitating a more fundamental change in objectives (Stafford et al, 2011), including perhaps a reconfiguration of livelihoods, diets and geography of farming and food systems (Kates *et al.* 2012; Rickards and Howden, 2012), and entailing actions such as replacement of Arabica coffee by Robusta coffee or by cocoa at low elevations.
- **Opportunity (or expansion)**, the fourth degree, occurs when coffee production becomes a new option for farmers in previously unsuitable regions, most likely at very high elevations where positive changes are projected.

Source: Bunn *et al.*, 2019; Smith *et al.*, 2011.

2.3.1. Agroforestry and diversification of crop production

Actions

Agroforestry practices are beneficial for coffee production in many ways, providing microclimatic, ecological, and socio-economic benefits (Vaast *et al.*, 2016). Shade trees for example provide a favorable microclimate for coffee plants. Agroforestry also supports the maintenance of species associations and enables a more sustainable use of existing natural resources. Agroforestry provides socio-economic benefits, as it allows farmers to diversify their sources of income. It also enhances the resilience of coffee cropping systems, which reduces risks posed by climate change (Martins *et al.*, 2017).

The following components of the coffee agroforestry system are important.

Diversification of coffee production systems, for example through agroforestry and intercropping, provides multiple benefits.

Diversification contributes to building more sustainable and resilient food systems (**SDG Target 2.4**), supports the sustainable management of terrestrial ecosystems (**SDG Target 15.1**), and the conservation of biodiversity (**SDG Target 15.5**).

Diversification is also a strategy to achieve higher levels of economic productivity (**SDG Target 8.2**) and creates income opportunities for small-scale farmers (**SDG Target 2.3**).

- **Diversification of crop production** should be promoted. As mentioned, some coffee production regions are predicted to become unsuitable for coffee cultivation, which makes the need for crop diversification even more imperative. Intercropping or afforestation (e. g. cultivating species such as banana, macadamia, papaya, coconut, mango, avocado, jackfruit) increase biodiversity, improve microclimatic conditions and mitigate environmental stresses in coffee plants (Vaast *et al.*, 2016). Cover crops, preferably legumes that can provide nitrogen and protect the soil, can be grown between rows of coffee trees. Inadequate crop management (i.e. allowing the growth of cover crop to become too vigorous) can lead to competition for soil moisture and nutrients between coffee and cover crops, and make the harvest of fallen berries difficult (Initiative for coffee & climate, 2021).

- **Planting of shade trees.** Growing coffee under the shade of trees is a common practice. By moderating the fluctuation of ambient air temperature and reducing the amount of heat that reaches plants during the day, shade trees provide a beneficial microclimate. At night the shade trees protect the plants from cooler nighttime temperatures. Trees also offer protection from wind and hail damage. In addition, they also add organic matter to the soil in the form of leaf litter. This leaf litter also helps to conserve soil and water, minimize erosion by moderating the intensity with which rain hits the ground, and reduce evapotranspiration from both soil and plants. Most trees also have deep root systems, which help water infiltrate into the inner soil layers and reduce runoff. Shade trees also provide a home to natural enemies of pests, which helps to ward off infestations through biological control (Alemu, 2015).

- **Planting the appropriate shade trees for coffee production.** Ideal shade trees typically have a deep root system that strengthens resilience to strong winds. They should also belong to the legume family and fix atmospheric nitrogen into the soil. They are wind-resistant and generally have a tall and spreading growth habit. Some examples that are commonly used on coffee plantations are *Acacia albida, Leucena leucocephala, Cordial africana, Grevillea robusta, Citrus sinensis, Sesbania sesban, Pterocarpus marsupium, Cedrela toona, Terminalia bellirica, Artocarpus integrifolia, Artocarpus hirsutus, Bischofia javanica, Erythrna lithosperma, Albizia sp.,* and *Ficus sp.* In many cases, faster growing tree species are preferred to provide required shade. Gandul (pigeon pea) may be planted as a quickly growing tree to provide shade in six months (Ssebunya, 2011; Parker, 2019).

- **Diversification of income sources.** Shade trees can provide benefits in the form of edible fruits, timber and firewood. Coffee growers can earn additional income through the agroforestry activities and at the same time contribute to preserving the ecosystem, and in many cases, conserving bird species (Parker, 2019). Diversification of income fits into the category of a transformative adaptive action that should be undertaken when climate change has medium to high impacts on coffee production systems.

Box 2: Recommendations for coffee agroforestry multistory systems

These systems should be established using a mixture of crops reaching a diversity of heights to form a multistory system.

Upper story (shade): Shade trees create optimum microclimates by providing protection from too much direct sunlight, increasing humidity, and contributing to the prevention of soil erosion.

Middle story: Fruit trees (e.g. bananas or citrus) can be cultivated, but with wide spacing as coffee plants also grow at this level. Leguminous trees such as Leucaena diversifolia, Calliandra calothyrsus, Sesbania sesban and Gliricidia sepium can be planted in the fields or along the boundaries.

Understory: This level consists of annual crops that are intercropped with coffee during early cultivation. Legume ground covers can be cultivated, such as jack bean (Canavalia ensiformis), Lablab (Lablab purpureus), or velvet beans (Mucuna pruriens). Other perennial non-climbing species can be grown as well, and all should be regularly pruned.

Source: Ssebunya, 2011

Agroforestry and mulching in coffee plantations enhance erosion protection and water regulation, which supports efforts to reach the target of a land degradation-neutral world (**SDG Target 15.3**) and contributes to the sustainable management of water resources (**SDG 6**).

Mulching is a common practice in East and Central Africa, and Central and South America. The mulch controls soil erosion, reduces soil temperature, retains moisture in the soil, adds organic matter, protects the soil surface from the impact of rain, and reduces weeds growth. In areas where coffee is cultivated under sunlight in dry areas, mulch is often the most important farming practice. Generally, mulching is done using Napier grass, Guinea grass, Guatemala grass, coffee pulp, coffee husks, sorghum straw, maize stover and other crop residues, which are dried before mulching. Mulching can be carried out before the rainy season begins or before it ends, depending on the quantity of rainfall and the method used (Tummakate, 1999).

***Brachiaria* grass** may deliver benefits in some systems if it is grown as a cover crop, as it can reduce soil temperatures in areas with less shade. *Brachiaria* grass has a robust root system that penetrates compacted soils, which increases water infiltration and adds soil organic matter when the roots break down. *Brachiaria* grass also prevents erosion, and its cuttings can be used to protect the soil where the coffee roots develop (Initiative for coffee & climate, 2021).

2.3.2. Improved crops and varieties

The development of improved coffee varieties is important for enhancing the resilience to a number of biotic and abiotic stressors in the face of climate change. In many cases, this can be done without sacrificing yield or quality. There are several challenges that still need to be overcome with regard to the acceptance and accessibility of new and improved varieties by small-scale farmers.

Actions

Using coffee varieties that match local conditions is an important adaptive practice. This simple recommendation highlights the importance of using appropriate varieties (e.g. drought-resistant, heat-resistant, cold-resistant, disease-resistant, nematode-resistant) for the local ecological, socio-economic and climate conditions.

Using F1 hybrids. Hybrids are offspring from the crossing of two genetically distinct parents. F1 hybrids are a group of cultivars created by crossing genetically distinct parents and combining the best traits of both parents. Desirable traits include the potential for high yields, cup quality, adaptation to environmental stresses, and disease resistance. Research has shown that hybrids are more resistant to coffee leaf rust. F1 hybrids tend to have much higher production than non-hybrids, and can also produce yields in the second year of cultivation rather than the traditional variety, which usually requires three years (Perfect Daily Grind, 2020; WCR, 2020).

The use of landraces and crop wild relatives in plant breeding contributes to maintaining genetic diversity in cultivated plants (**SDG Target 2.5**).

Grafting Arabica scion onto Robusta rootstock. Some Robusta varieties have deeper and more extensive roots than Arabica varieties. Resistance to drought may be enhanced by grafting Arabica onto Robusta rootstock. Because Robusta rootstock is also nematode-resistant, this practice is also beneficial in areas where coffee plants are vulnerable to nematodes (Initiative for coffee & climate, 2021).

Improve nursery production practices and access to improved variety coffee seeds and plants. In Ethiopia, many farmers continue to use local varieties that produce lower yields than improved varieties. Tadesse *et al.* (2020) points out that unlike other crops, no responsibility has been taken by public and/or private sectors to produce and market coffee seed, and there is no national coffee seed standard or certification scheme. According to World Coffee Research (WCR), several country studies have reported that more than half of coffee plants produced by small and informal nurseries die either before or soon after being transplanted to the field. The improved varieties never reach farmers

Box 3: BREEDCAFS

Since 2017, CIRAD (the French agricultural research and cooperation organization working for the sustainable development of tropical and Mediterranean regions) has been coordinating the BREEDCAFS (Breeding Coffee for Agroforestry Systems) Horizon 2020 Project. CIRAD began selecting F1 Arabica hybrids in the early 1990s with partners Tropical Agricultural Research and Higher Education Center (CATIE), the Regional Cooperative Program for the Technological Development and Modernization of Coffee Production (PROMECAFE) and ECOM Agroindustrial Corporation. This partnership led to the dissemination of high-performance hybrids such as Starmaya, H1-Centroamericano, H3, and Cassiopeia. Because several traditional coffee varieties are not suitable for shade cultivation, BREEDCAFS uses new breeding strategies to create coffee varieties that are well adapted to agroforestry systems and more resilient to climate change. With funding from the European Union, the BREEDCAFS project selects new hybrids for shade to maximize the adaptation of coffee production to shade conditions. F1 hybrids can produce high yields in both full sun and shaded conditions, delivering on average up to 40 percent more than conventional varieties cultivated under both sets of conditions. BREEDCAFS partners are testing hybrids in Cameroon, Costa Rica, Nicaragua and Viet Nam to determine how they cope in different weather conditions, soil types and management regimes. F1 hybrids could bolster coffee production in countries that have already begun experiencing setbacks due to environmental stresses.

There are barriers to adoption of these hybrids due to the lack of accessibility and acceptance by farmers as well as the coffee industry. Generally, technological innovation has benefitted medium and large coffee producers more than small-scale producers because of the high production and operating costs associated with reproduction techniques.

Source: BREEDCAFS, 2020; Perfect Daily Grind, 2020

because of problems in the nurseries. WCR bolsters the coffee seed sector. By developing the capacity of small nurseries to produce healthy seedlings for small-scale farmers, the Nursery Development Programme ensures that the development of the coffee seed sector does not exclude small-scale farmers (WCR, 2019).

Improve access to information about improved varieties. Farmers often lack knowledge about improved varieties and have limited access to information about them. One study in Uganda showed that despite the existence and availability of improved varieties, 30 percent of farmers had little or no information about them (Mukadasi, 2019; Tadesse *et al.*, 2020). The WCR, through its Global Coffee Monitoring Program (GCMP), is conducting farmer-led trials to generate data on the combinations of coffee varieties and climate-smart agronomic practices that provide the highest returns to farmers. The GCMP is a global study of on-farm drivers of profitability that seeks to transform coffee growing practices and contribute to the economic sustainability of coffee farming. Trial sites are located in farmers' fields and managed by the farmers themselves with support from partnering supply chain agronomists.

2.3.3. Efficient water management

Generally, coffee needs an annual rainfall of 1 500 to 3 000 mm (Mutua, 2000). Precipitation requirements vary depending on whether the varieties are grown in areas with year-round precipitation or areas with distinct rainy and dry seasons (Rising *et al.*, 2016). The optimum annual rainfall range is between 1 200 to 1 800 mm for Arabica coffee (Alègre, 1959). A similar range is required for Robusta, but it adapts better than Arabica to intensive rainfall exceeding 2 000 mm (Coste, 1992). For both species, a short dry period is needed to stimulate flowering. However, water must be available and abundant during the period of berry growth to ensure large seed yields. Excess precipitation (over 3 000 mm in a year) can damage the coffee plant, erode the soil, and promote coffee diseases (Wrigley, 1988; Abberton *et al.*, 2016). Water stagnation harms coffee plants, so well drained slopes are preferred.

Processing methods for coffee vary. The wet processing method is recognized as producing higher quality coffee and fetching higher prices on national and international markets. However, this method uses substantial amounts of water at each step in the process from de-pulping to fermentation. It also requires equipment to separate the pulp from the grain after being harvested (Perfect Daily Grind, 2017). Wet processing emits methane, causes water pollution and creates waste byproducts. Sugar from the berries may end up fermenting in the water and creating acetic acid. The water often ends up returning to local water systems and threatening these systems.

The dry method, also known as the natural/ecological process, requires little equipment, but requires intensive physical labour. The process consists of drying the whole berry after harvest without removing the skin or pulp. This process is used especially in areas with hot climates and/or water shortages. It is less suitable in areas with more rain and higher humidity.

Actions

Water management in high-density plantations using drip irrigation. Water management is critical for the growth and development of the coffee plant. Insufficient moisture in the soil during vegetative development (i.e. between germination and flowering) is the major factor influencing coffee productivity. In high density plantation systems, the application of fertilizer through drip irrigation systems (fertigation) could reduce nitrogen and potash use by 30 percent (Sobreira *et al.*, 2011). The time of flowering varies depending on the rainfall distribution, the severity of the dry

Efficient water management in coffee cropping systems, which can be achieved, for example, through water conservation practices and irrigation technologies, contributes to ensuring the sustainable management of water resources (**SDG 6**), and increasing water use efficiency in particular (**Target 6.4**).

season, and the type of soil and its depth. The benefits of irrigation need to be assessed in terms of yield and economical return (Carr, 2001). Further research is required to assist in the planning and more efficient use of irrigation systems (sprinkler, micro-jet or drip) for the production of reliable, high-quality coffee depending on the geographic area and rainfall patterns.

Shade trees for water management. With their deep rooting system, shade trees promote the deep infiltration of rainwater (Alemu, 2015). Shaded plantations protect against the effects of drought as they moderated temperatures and ensure a minimum loss of soil moisture through evaporation and transpiration. Shaded plantations have more organic matter that retains moisture for longer during dry periods (Martins *et al.*, 2017). Shade trees also help to minimize the impact of rainfall and erosion by reducing the intensity of the rain that strikes the ground.

Incorporate windbreaks and/or shelter trees. Wind stress may reduce leaf area, and hot winds can accelerate evapotranspiration, which can increase rainfall or irrigation requirements. Where strong winds are a common occurrence, windbreaks or shelter trees provide a barrier.

Crop planting density. A higher plant density provides a buffered microclimate, decreases evaporation of soil water and provides water stability (DaMatta and Rena, 2002; de Jesus Junior *et al.*, 2012). An increased number of coffee plants is recommended in areas with water deficits and pronounced precipitation fluctuations.

Mulching and a **combination of mulching and shading** are also effective water conservation techniques. Mulching (see Section II.i) helps slow the flow of runoff rainwater (Ssebunya, 2011).

Gypsum application to soil. In certain types of soils (oxisols, highly acidic soils, or soils with high levels of aluminum) the application of gypsum (calcium sulfate) or limestone (calcium oxide, calcium carbonate) increases soil pH and nutrient availability. These applications also allow the coffee roots to grow more deeply into the soil and access more moisture during the dry season and extended droughts. Gypsum, which is more soluble than lime, can penetrate deeper into soils. It also has calcium that enhances the formation of soil aggregates, which can counteract soil crusting and allow air, water and nutrients to penetrate deeper as well. However, the high calcium may interfere with the uptake of other ions. Consequently, these applications may not be beneficial over the longer term and farmers, would benefit from expert guidance in this area (Initiative for coffee & climate, 2021).

Water use for processing should be reduced. Using dry or natural/ ecological processing methods for coffee instead of the fully washed process saves water and reduces methane emissions and pollution from the discharge of wastewater. It is important to note that consumer preferences and market demand largely influence farmers' processing methods. It may not be feasible to change processing methods if consumers are not willing to buy the product. It is important to educate consumers about the issues associated with the water requirements and other impacts of washed coffee.

Water-saving processing practices for coffee berries and treatment of wastewater contribute to ensuring the sustainable management of water resources (**SDG 6**) and improving water quality in particular (**Target 6.3**). These practices also support the sustainable management of freshwater ecosystems (**SDG Target 15.1**).

These practices do not necessarily change the quality of the product, but a lack of awareness may reduce acceptance by consumers. Consequently, they need to be accompanied by actions to promote sustainable consumer decisions and lifestyles (**SDG Target 12.8**).

In some cases, water can also be purified. In 2015, Cenicafe, Colombia's National Research Center, developed an anaerobic treatment using plant-based biofilters (Sistema Modular de Tratamiento Anaerobio) for wastewater that can be applied after fermentation (Perfect Daily Grind, 2017). Cenicafe also designed a machine that removes the mucilage from coffee beans called the Becolsub (Beneficio Ecologicos Sub-productos). The machine does not use water and maintains the same quality as coffee processed by natural fermentation. Traditionally, mucilage removal is done through a fermenting process that takes 14 to 18 hours for the mucilage to become degraded so that it can be easily removed with water. The Becolsub also has a hydromechanical device that removes floating fruits and minor impurities, as well as hard objects. It uses a cylindrical screen to remove fruits with skins not separated in the pulping machine (Gmünder *et al.*, 2020).

2.3.4. Integrated pest management

Climate change is expected to increase outbreaks of pests and diseases or change the nature of these outbreaks. As noted earlier, climate change is also expected to shift the optimal growing conditions for coffee to higher latitudes and altitudes, and will most likely also increase the altitudinal range of pests such as the coffee borer beetle (Groenen, 2018). Higher temperatures may lead to larger outbreaks of coffee rust, which responds to changes in humidity (Rising *et al.*, 2016). The coffee berry borer and coffee white stem borer have benefited from increased temperatures in Africa (Jaramillo *et al.*, 2011; Kutywayo *et al.*, 2013). Bacterial blight and coffee leaf rust thrive in wet conditions, so the amount of rainfall under future climate change conditions will affect how these diseases spread (Groenen, 2018).

Insect pests

Coffee berry borer (Hypothenemus hampei) is considered the most serious biotic threat to global coffee production (Jaramillo *et al.*, 2013). The adult females bore holes into the coffee berry and deposit their eggs. After the eggs hatch, larvae feed on the coffee seeds inside the berry.

This pest has spread to most coffee producing regions and thrives in warmer conditions (Scott, 2015).

Other insect pests include white stem borer (*Monochamus leuconotus*), leaf miner (Leucoptera species), various species of scale insects, and mealy bugs (CABI, 2019).

Nematodes

Nematodes are parasites that are present in several coffee producing countries, particular Brazil and Viet Nam (Campos and Villain, 2005). Nematodes belonging to the Meloidogyne and Pratylenchus genera degrade the root system of the coffee plants and reduce their capacity to assimilate water and nutrients, which makes the plants more vulnerable to water stress. Higher soil temperatures resulting from climate change could shorten the life cycles of nematodes.

Weeds

Weeds can suppress seedling growth, dry out the soil, reduce yields, and help spread disease-causing organisms and insect pests. Common weeds include Cyperus spp , Ageratum, Commelina benghalensis (tropical spiderwort) Nicandra and Digitaria abbysinica (Couch grass) (Green Life Crop Protection Africa, 2021; Tadesse *et al.*, 2020).

Diseases

Coffee leaf rust, which is caused by the fungus Hemileia vastatrix, leads to the defoliation of the coffee plant and yield loss. A coffee leaf rust epidemic swept over Central America from Colombia to Mexico from 2011 to 2013, affecting more than half of the region's coffee farming land and causing production losses of over 15 percent (Scott, 2015). The epidemic was linked to higher humidity and increased temperatures (Plant Village. 2021).

Coffee berry disease, which is caused by the fungus *Colletotrichum kahawae*, affects green or immature berries of Arabica coffee. It creates lesions that spread and cover berries, and can lead to 20 to 30 percent losses in yield (Ssebunya, 2011).

Coffee wilt disease (Gibberella xylarioides) is a vascular disease also known as fusarium wilt or tracheomycosis that is devastating to Arabica, Robusta and wild coffee species. The leaves turn yellow and fold inward, before falling off entirely. It is spread through the use of contaminated tools or through soil that has been contaminated by infected plants (Ssebunya, 2011).

Actions

Integrated Pest Management (IPM) is an ecosystem approach to crop production and protection that was developed in response to the widespread overuse of pesticides. In IPM, farmers use natural methods based on field observation to manage pests. Methods include biological control (i.e. using natural enemies of pests), the use of resistant varieties, and habitat and cultural modification (i.e. the removal or introduction of certain elements from the cropping environment to reduce its suitability for pests). The rational and safe application of selective pesticides is used as a last resort (FAO, 2016). IPM capitalizes on natural pest management mechanisms that maintain a balance between pests and their natural enemies. Examples of non-chemical methods include the use of resistant varieties and the manipulation of the habitat around production fields to provide additional food and shelter for natural enemies of pests (Wyckhuys *et al.*, 2013). It is important to locate and identify pests and diseases correctly during initial stages of infestations. Farmers may need additional training on the proper sampling, scouting and monitoring of pests and diseases, which are essential actions for reducing the need for chemical pesticides.

IPM, which emphasizes the minimal use of harmful chemical pesticides, contributes to the sustainable management of terrestrial ecosystems (**SDG Target 15.1**) and reduces marine pollution from land-based activities (**SDG Target 14.1**).

The successful implementation of IPM, can prevent infestations that can severely damage coffee crops and compromise the productivity and incomes of small-scale farmers (**Target 2.3**).

IPM contributes to the sound management of chemicals throughout their life cycle and reduces their release into to air, water and soil, which minimizes their impacts on human health and the environment (**SDG Target 12.4**).

IPM can also have beneficial impacts on human health by reducing illnesses associated with air, water and soil pollution and contamination (**SDG Target 3.9**).

Shade can be a tool for pest and disease management. Shade serves as an efficient biological management tool to control pests and diseases (e.g. coffee white stem borer and leaf rust). Open areas provide ideal conditions for the spread of white stem borer to neighbouring plants, and it has been shown that cooler temperatures inhibit the movement of borer beetles. Shade trees also provide a home for a variety of predatory birds and natural enemies of white stem borer (Sánchez-Navarro *et al.*, 2020).

Natural enemies of coffee berry borers can be uses to control this pest. Natural enemies include parasitoids and predators, including birds, ants, thrips and fungi. Using a diverse set of species within the coffee plantation, as may be done with a multistory agroforestry system, provides habitat for a wide range of natural enemies. Sanitation practices that include the regular removal of infected leaves and branches, and the harvesting and collection of fallen beans, are also beneficial. In addition, it is important to limit the movement of mulch between locations. Natural sprays such as neem extracts, black jack and *tephrosia* can be used to protect nursery seedlings, or seedlings can be covered under nets (Ssebunya, 2011).

Coffee wilt disease can be controlled by limiting the movement of coffee materials both within the farm and among farms, destroying infected plants, and sterilizing field tools. Grafting onto a resistant rootstock is recommended (see Section II).

Coffee berry disease can be combatted through the use of widely available resistant varieties. Field crop hygiene that includes removing infected beans and diseased tree parts is also used to fight the disease (James *et al.*, 2019; Tadesse *et al.*, 2020).

Nematodes are spread through the planting of infected seedlings, and by soil on animals, people, machinery or water (CABI, 2021). Moving soil between fields should be avoided, as this introduces nematodes to uninfested areas. It is important to clean soil particles from tools, shoes, tires and machinery. Incorporating organic matter (e.g. manure) into the soil can stimulate microbial competition against nematodes. Creating soil surfaces or contours that are parallel to the slope so that they have a drainage pattern that minimizes erosion can also lessen the movement of nematodes. Controlling weeds between coffee plants is also beneficial (CABI, 2021). Grafting with nematode-resistant rootstock is another option.

Systemic fungicides applied to foliage are recommended to control fungal diseases (e.g. leaf rust). Contact fungicides can also be used preventatively during the first stages of disease development.

Windbreak trees can serve as a barrier to reduce the amount of fungal spores that reach the coffee fields. Heavy rains and possibly high pressure water washing can also cleanse spores from leaves and reduce the number of spores (Plant Village. 2021; Ssebunya, 2011).

Lime sulfur is an inexpensive treatment that can be used to control coffee rust. The application of a lime sulfur mix creates a physical barrier that prevents the rust spore from germinating and penetrating into the coffee leaves. This treatment has been used on other crops, but usually ends up being replaced by expensive fungicides. It is most effective when used preemptively, as it will not likely prove successful in warding off an aggressive outbreak (Initiative for coffee & climate, 2021).

Beneficial fungi (e.g. *Trichoderma*) promote growth and can help combat certain plant diseases (Initiative for coffee & climate, 2021).

Improved varieties for pest and disease resistance. Some varieties possessing genetic traits that confer pest and disease resistance have been brought over (introgressed) from another species, mainly from Robusta and sometimes *Coffea liberica*. In the 1920s on East Timor, an Arabica coffee plant and a Robusta coffee plant reproduced and created a hybrid plant that became known as the Timor Hybrid. It was an Arabica variety that possessed Robusta's coffee rust-resistant genetic material. Coffee experts started using the Timor Hybrid in experiments to create new rust-resistant varieties. They selected many different 'lines' of the Timor Hybrid and then crossed them with other high-yielding varieties. These crosses led to the creation of the two main groups of introgressed

Arabica varieties, Catimors and Sarchimors. These are not distinct varieties, but rather groups of many varieties with similar ancestry. Some introgressed varieties have been reported to yield lower quality coffee, but they have been vital for farmers facing the threat of coffee leaf rust and coffee berry disease (WCR, 2020).

Weeds can be controlled through manual weeding between the rows of coffee plants. Manual weeding is particularly important in the early stages of coffee plant's growth. **Mulching** that comprises organic matter generated from tree leaves is also helpful, as it inhibits weed growth. **Intercropping** with beans also inhibits weed growth in early stages of coffee growth (Green Life Crop Protection Africa, 2021; Tadesse *et al.*, 2020).

©FAO / Isaac Kasamani

2.4 Climate change mitigation approaches

As with other similar crops, coffee is both profoundly affected by climate change and also contributes to climate change. Transporting coffee from production locations to consumers contributes significantly to GHG emissions. The expansion of land under coffee cultivation and the shift from shade-grown coffee to full sun plantations have led to deforestation and GHG emissions. Certain coffee processing methods such as the fully washed method also generate methane emissions from the wastewater created during de-pulping and fermentation (Stuart, 2014).

2.4.1. Increasing soil carbon sequestration

Increasing soil organic matter content requires increasing carbon inputs and minimizing losses. Clearing forests for coffee cultivation causes large losses of carbon and contributes to GHG emissions. Maintaining shade trees in coffee plantations can sequester carbon dioxide, but it does not compensate for the carbon losses due to deforestation. The reduction of deforestation for the purpose of coffee cultivation and the stabilization of coffee cropping systems is a paramount priority (Thurston, Morris and Steiman, 2013; Rising *et al.*, 2016).

Actions

Reduce or eliminate deforestation. As climate change forces coffee cultivation into new areas, it is crucial to keep coffee production within the limits of current agricultural regions or ensure production is done in conjunction with reforestation programmes. Coffee plantations close to forests and wild pollinators have been shown to be more productive and produce fewer small misshapen seeds (peaberries) (Ricketts *et al.*, 2004; Rising *et al.*, 2016). A major reduction in deforestation is needed to mitigate climate change and prevent losses of biodiversity. The development of real-time deforestation monitoring and early detection warnings for both public and private stakeholders can also improve the identification of coffee-driven deforestation (Bunn *et al.*, 2019). However, additional steps must be taken to bridge the technical issues

Climate change mitigation strategies in the coffee sector, such as limiting conversion of natural forests to plantations and the promotion of agroforestry-based coffee cultivation, contribute to the sustainable management of forests and curb deforestation (**SDG Target 15.2**). They also preserve or create habitats for the conservation of biodiversity (**SDG Target 15.5**).

related to coffee production with policy aspects in order to facilitate effective action within government frameworks (Finer *et al.*, 2018). Ultimately, deforestation must be eliminated from the supply chain through zero-deforestation policies that ensure that companies operate transparently and provide mechanisms for tracing their products, do not shift production to other forested areas, and do not not contribute to the marginalization of small-scale farmers (Bunn *et al.*, 2019).

Agroforestry. As mentioned in Section II, agroforestry and shade-grown production systems have many advantages over monocultural coffee production, even though these systems are sometimes criticized for having lower productivity than monoculture systems. Agroforestry systems combine diversification of crop production with ecological benefits (see Section II). Agroforestry sequesters carbon in trees and soil. The carbon storage potential varies based on tree species, previous land use and local climate and soil conditions. The potential range for carbon sequestration from coffee agroforestry is 10 to 150 tonnes of carbon per ha (Rahn *et al.*, 2014; Vaast *et al.*, 2016).

Integrated soil fertility and nutrient management reduces land degradation and the mining of nutrients from the soil that results from unsustainable intensified agricultural production systems. The application of inorganic and organic fertilizers, which include recycled organic resources (e.g. green and farmyard manures) on the basis of crop needs can increase carbon sequestration in the soil and reduce GHG emissions. Fertilization recommendations should be adjusted in accordance with the local context, climate condition, stage of growth of the crop, and soil type. Improving soil organic carbon content enhances soil quality and reduces soil erosion and degradation, which in turn reduces carbon dioxide and nitrous oxide emissions (Kukal *et al.*, 2009). Integrated soil fertility and nutrient management for coffee is a management option that can reduce the costs of inorganic fertilizers and ensure the quantity of the compost required for efficient coffee growth is optimized to meet the local levels of irrigation water (Chemura, 2014).

Increasing soil organic carbon content helps to stabilize soils and protect them from erosion, which contributes to reaching the target of a land degradation-neutral world (**SDG Target 15.3**).

Biochar can be produced from pyrolysis (the heating of organic material in the absence of oxygen) of coffee husks and used as a soil amendment. This production can also provide an alternative to disposing of the husks as a recycled by-product. Biochar can also provide an energy source for coffee drying. The coffee husks, which make up to 14 percent of the coffee production weight, are generally spread directly on the soil with minimal nutrient effect, or burnt, which causes problems related to smoke. However, the potential coffee husk biochar businesses need to be linked with existing producers of activated carbon (Flammini *et al.*, 2020).

2.4.2. Reducing GHG emissions

Reducing carbon dioxide emissions in crop production is primarily achieved by lowering direct emissions from operations and avoiding the mineralization of the soil organic carbon. The main sources of GHG emissions in coffee production systems are: (1) the application of fertilizers and pesticides, (2) methane emissions from coffee de-pulping and fermentation, (3) direct fuel and electricity use, and (4) the release of nutrients from soils (Rising *et al.*, 2016). It has been estimated that monocultures produce 50 percent more GHG emissions than traditional and commercial coffee polycultures (van Rikxoort *et al.*, 2014).

Actions

Maintain traditional polycultures for coffee cultivation rather than shaded or unshaded monocultures. Traditional polycultures can play an important role in maintaining high carbon stocks. These systems work especially well for inhabited protected areas and where low management costs are a priority rather than high coffee yields (Cortina-Villar *et al.*, 2012; Schroth *et al.*, 2011). Carbon stocks in commercial polycultures, which are usually lower than in traditional polycultures, can still be considerable. These systems provide a way of producing coffee with a low-carbon footprint, and the diversification of farm production reduces the vulnerability of farmers to risks associated with climate and market fluctuations (Schroth and Ruf, 2014; van Rikxoort *et al.*, 2014).

Diversification of crop production as part of conservation agriculture (as mentioned in Section II) can increase carbon sequestration and nitrogen use efficiency (Corsi *et al.*, 2012). The diversification of the crop system to include legumes is important for the biological fixation of nitrogen in the soil, which reduces farmers' reliance on chemical fertilizers and lowers nitrous oxide emissions.

Appropriate use of fertilizers. There are several negative environmental impacts associated with the use of inorganic and organic fertilizers (e.g. water eutrophication, air pollution, soil acidification, and the accumulation of nitrates and heavy metals in the soil) (Mosier *et al.*, 2013). The optimal fertilization rate should be determined by taking into consideration these environmental impacts and GHG emissions, as well as yield and income. For example, inorganic fertilizers are most effective when irrigation levels are high, while organic manure performs better at lower irrigation levels (Chemura, 2014). It is also important to accurately determine the quantities of fertilizers that are required and the proper frequency for their application.

Improved efficiency in the use of nutrients and fertilizers not only lowers GHG emissions, it also reduces nutrient pollution in terrestrial, freshwater and marine ecosystems, and enhances related ecosystems services (**SDG Targets 15.1, 6.3, 14.1**).

This increased efficiency can also have beneficial impacts on human health by reducing illnesses associated with air, water and soil pollution and contamination (**SDG Target 3.9**).

Foliar fertilization can be a sustainable management option to address specific soil fertility issues (e.g. micronutrient deficiencies) and reduce pollution that is associated with the high rates of loss when fertilizers are applied to the soil. Nanotechnologies (e.g. zinc sulfate and zinc oxide nanoparticles) can also have a significant impact on coffee fruit set and quality (Rossi *et al.*, 2019).

It is recommended to use dry or natural and ecological methods to process coffee instead of wet processing methods (i.e. the fully washed method) to reduce methane emissions (see Section II). When large fermentation tanks and washing channels are used during the fully washed process, much larger volumes of water per kg of coffee are used (van Rikxoort *et al.*, 2014). This method creates methane emissions, water pollution and waste by-products. As mentioned, sugar from berries may end up fermenting in the water and becoming acetic acid, and the disposal of this water can threaten local water systems. Methane emissions are caused by the anaerobic decomposition of the mucilage and may be accompanied by additional carbon dioxide emissions if fossil fuel energy is used to dry the coffee. It is critical to build awareness among coffee consumers that traditional wet processing methods cause significant GHG emissions (van Rikxoort *et al.*, 2014).

Capturing methane from coffee processing wastewater through biogas plants and using it as cooking gas and to generate power for de-pulping machinery and pumps in wet mills are mitigation options for large-scale production operations (Rodríguez Valencia and Zambrano Franco, 2010; van Rikxoort *et al.*, 2014).

By-products (e.g. defective beans, coffee husk and wood from stumped trees) **can be used as biofertilizers (e.g. biochar), biofuel and biomass for energy** (Perfect Daily Grind, 2017).

Capturing methane from coffee processing wastewater and using it as a biofuel contributes to increasing the share of renewable energy (**SDG Target 7.2**).

The recycling of by-products for nutrient management and bioenergy production also contributes to reducing waste (**SDG Target 12.5**).

2.5 Coffee environmental and sustainability certifications

Coffee certifications can demonstrate to consumers that coffee has been produced sustainably and can increase its market value, if there is sufficient demand. However, because of cost and infrastructure involved, standard third-party verification systems have excluded many small-scale farmers. Other factors also prevent small-scale farmers from obtaining certification, for example, a lack of access to technical information. An enabling environment with an increased focus on capacity development, as well as the creation of policies and incentives that raise the demand for these types of certifications, would make their attainment more viable and profitable for farmers. Alternatively, farmers may take part in participatory guarantee systems.

Coffee certification attests to the sustainable and environmentally friendly and/or organic practices of coffee producers. Certified coffee is produced under specific guidelines outlined by the certification agency and is verified by an independent third-party certification organization. Certifications can be used to increase coffee's value on the international market. However, it is mainly larger coffee producers and a smaller number of small-scale farmers who benefit from these standards, since they can be costly and labour intensive, as well as administratively difficult to obtain and to maintain. The following certification standards demand high commitment to environmental sustainability and restrict the use of chemical fertilizers; promote social and economic benefits for famers; and provide farmers with fair value for their coffee:

- Fair Trade Certified,
- Rainforest Alliance/UTZ,
- Bird-Friendly (Smithsonian Migratory Bird Center),
- USDA Organic, and

- other private and voluntary initiatives such as Starbucks Coffee and Farmer Equity (C.A.F.E.) Practices, Nespresso AAA Sustainable Quality Coffee Program, and 4C (The Common Code for the Coffee Community)

Participatory Guarantee Systems (PGS) are certification systems that have been developed to overcome the mounting criticisms of third-party certifications. Some of the drawbacks that critics have noted include the strict separation of extension services and certification; their inability to account for the diverse economic, ecological and sociocultural contexts inherent to organic farming (Fouilleux and Loconto, 2017; Källander, 2008; Meirelles, 2003), and the perceived imposition of standards from the Global North on the Global South (Home *et al.*, 2017; Schwentesius de Rindermann, 2016). PGS were developed as more locally adapted certification schemes for domestic markets. They are intended to empower small-scale farmers, facilitate farmer-to-farmer learning and enhance food security and sovereignty (Kaufmann and Vogl, 2018). Many proponents believe that PGS play a vital role in rural development and farmer empowerment since they engage farmers throughout the entire process of verification, decision making, and marketing (Buena, 2020). Despite the expansion of PGS in recent years, however, challenges have also been identified for their successful implementation. These challenges include the lack of legal recognition of PGS as organic certification schemes (Home *et al.*, 2017; Meirelles, 2003; Nelson *et al.*, 2010); the inability to obtain sustainable financing (Fonseca, 2004; Nelson *et al.*, 2010); and difficulties in securing participation of producers and consumers (Bellante, 2017; Home *et al.*, 2017; Nelson *et al.*, 2010; Schwentesius de Rindermann, 2016).

Box 4: Participatory Guarantee Systems in the Philippines.

In 2020, the Senate in the Philippines approved a bill that amended the existing national legal framework for organic agriculture and recognized PGS. With this legal recognition, organic farmers are now able to receive training and certification for their produce. In 2010, the Republic Act 10068, or the Organic Agriculture Law, was enacted, which supported the growing organic agriculture movement in the country. However, Section 17 of the law allowed only third-party certification to be labelled as 'organic', which prohibited small-scale organic farmers from obtaining certification since they often cannot afford to pay the costs. After 2010, PGS training sessions were conducted to raise awareness of the issue throughout the country. This process led to the presentation of a position paper by the International Federation of Organic Agriculture Movements (IFOAM) President to the National Organic Agriculture Board that called for action to change the law. The Department of Agriculture formed a technical working group to draft guidelines for PGS development. After the draft guidelines garnered strong support, committee hearings were held, and finally, 10 years after the enactment of the Organic Agriculture Law, the amendment was approved in June 2020.

Source: Buena, 2020

2.6 Enabling policy environment

The transition to CSA, which involves the scaling up of specific climate-smart practices, demands strong political commitment as well as coherence and coordination among the various sectors dealing with climate change, agricultural development and food security. Before designing new policies, policymakers should systematically assess the effects of current agricultural and non-agricultural agreements and policies on the objectives of CSA while considering other national development priorities. They should exploit synergies between the three objectives of climate-smart agriculture (sustainable production, adaptation, and mitigation), as well as address potential trade-offs and if possible avoid, reduce or compensate for them. Understanding the socio-economic and gender-differentiated barriers and incentive mechanisms that affect the adoption of CSA practices is critical for designing and implementing supportive policies.

In addition to supportive policies, the enabling environment also encompasses fundamental institutional arrangements; stakeholder involvement and gender considerations; infrastructure; credit and insurance; and farmers' access to weather information, extension and advisory services, and input/output markets. For example, weather index-based insurance involves payouts that are triggered by predicted weather events and do not require verification of losses, which minimizes transaction costs. A well-designed index could address the variation in coffee yields and quality that is essential for profits. However, index insurance has been met with low uptake among intended beneficiaries, particularly small-scale farmers. Targeting weather index-based insurance to groups (e.g coffee cooperatives) could increase its uptake. For coffee growers in Uganda, van Asseldonk *et al.* (2020) found high uptake among members of a producer cooperative that acted as broker for index-based drought insurance. The determining factors for adoption were information sharing through the cooperative to ensure that farmers understand how the insurance work and the flexible modalities for paying insurance premiums that were offered by the cooperative (e.g. payment through mobile phones, or delayed payment at delivery of the coffee harvest).

The laws, regulations and incentives that underpin the enabling environment establish the foundation for sustainable climate-smart agricultural development. The development of institutional capacity is essential to support farmers and extension services and reduce the risks that may discourage and prevent them from investing in proven practices and technologies to enable them to adapt to the impacts of climate change and other shocks. Institutions are a key organizing force for farmers and decision-makers and are critical for scaling up CSA practices.

2.7 Conclusion

Coffee production systems need to adapt to ensure they contribute to rural livelihoods and sustainable food systems under a changing climate. The specific adaptation and mitigation approaches will vary according to location. In the world's coffee producing regions, there is a wide variety of agro-ecological conditions, microclimates within the soil, climate risks and socio-economic contexts. It is crucial to collect data and information to determine the best course of action and adapt practices to local needs. This information allows for a continuous learning process and can feed into the improvement of future policies. Close coordination and collaboration among stakeholders at all levels are needed to build an enabling environment that gives farmers opportunities to adopt targeted measures to enhance the productivity, resilience and sustainability of coffee production in the face of climate change.

The precise challenges that will be created by climate change on coffee production systems remain uncertain. These challenges will vary from one farming communities to another, but it is certain that they will be especially daunting for countries already coping with high levels of food insecurity. However, there is a clear way forward to overcoming these challenges. Options include the adoption of context-specific good agronomic practices, such as conservation agriculture, efficient water and nutrient management and IPM. These options will complement the gains that can be made through the cultivation of improved varieties.

2.8 References

Abberton, M., Batley, J., Bentley, A., Bryant, J., Cai, H., Cockram, J., Costa de Oliveira, A., Cseke, L. J., Dempewolf, H., de Pace, C., Edwards, D., Gepts, P., Greenland, A., Hall, A. E., Henry, R., Hori, K., Howe, G. T., Hughes, S., Humphreys, M., & Yano, M. 2016. Global agricultural intensification during climate change: A role for genomics. *Plant Biotechnology Journal*, 14(4):1095-1098. https://doi.org/10.1111/pbi.12467

Alègre, C. 1959. Climats et caféiers d'Arabie. *L'Agronomie Tropicale*, 14:23–58.

Alemu, M. M. 2015. Effect of Tree Shade on Coffee Crop Production. *Journal of Sustainable Development*, 8:66. https://doi.org/10.5539/jsd.v8n9p66

Bellante, L. 2017. Building the local food movement in Chiapas, Mexico: rationales, benefits, and limitations. *Agriculture and Human Values*, 34:119-134. https://doi.org/10.1007/s10460-016-9700-9

Bertrand, B., Marraccini, P., Villain, L., Breitler, J.-C. & Etienne, H. 2016. Healthy Tropical Plants to Mitigate the Impact of Climate Change—As Exemplified in Coffee. In E. Torquebiau, ed. Climate *Change and Agriculture Worldwide*, pp. 83-95. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-7462-8_7

BREEDCAFS. 2020. BREEDCAFS [online]. [Cited 18 June 2021]. https://www.breedcafs.eu

Buena, M.R.A. 2020. How PGS Changed the Law on Organic Agriculture in the Philippines. In: *Organic Without Boundaries: Digging Deeper* [online]. [Cited 18 June 2021]. www.organicwithoutboundaries.bio/2020/06/24/how-pgs-changed-the-law-on-organic-agriculture-in-the-philippines/ Accessed 29.07.2021.

Bunn, C., Läderach, P., Ovalle-Rivera, O. & Kirschke, D. 2015. A bitter cup: climate change profile of global production of Arabica and Robusta coffee. *Climatic Change*, 129:89-101. https://doi.org/10.1007/s10584-014-1306-x

Bunn, C., Läderach, P., Quaye, A., Muilerman, S., Noponen, M. & Lundy, M. 2019. Recommendation domains to scale out climate change adaptation in cocoa production in Ghana. *Climate Services*, 16(8):100123. https://doi.org/10.1016/j.cliser.2019.100123

CABI. 2019. *Common Pests and Diseases of Coffee*. [online]. [Cited 18 June 2021]. https://www.cabi.org/ISC/FullTextPDF/2013/20137804172.pdf

CABI. 2021. Cultural Control of Root Nematodes in Coffee. In: *Plantwise Knowledge Bank: Plantwise Factsheets for Farmers* [online]. [Cited 18 June 2021]. https://www.plantwise.org/KnowledgeBank/factsheetforfarmers/20167800023

Campos, V. P. & Villain, L. 2005. Nematode parasites of coffee and cocoa. In M. Luc, R.A. Sikora, & J. Bridge, eds. *Plant Parasitic Nematodes in Subtropical and Tropical Agriculture: Second Edition*, pp. 529-580. UK. CABI Publishing. https://doi.org/10.1079/9780851997278.0529

Carr, M. K. V. 2001. The water relations and irrigation requirements of coffee. *Experimental Agriculture*, 37(1):1-36. https://doi.org/10.1017/S0014479701001090

Chemura, A. 2014. The growth response of coffee (Coffea arabica L) plants to organic manure, inorganic fertilizers and integrated soil fertility management under different irrigation water supply levels. *International Journal of Recycling of Organic Waste in Agriculture*, 3 (article 59). https://doi.org/10.1007/s40093-014-0059-x

Corsi, S., Friedrich, T., Kassam, A., Pisante, M. & de Moraes Sà, J. 2012. Soil Organic Carbon *Accumulation and Greenhouse Gas Emission Reductions from Conservation Agriculture: A review of evidence*. Integrated Crop Management, Vol. 16. Rome, FAO.

Cortina-Villar, S., Plascencia-Vargas, H., Vaca, R., Schroth, G., Zepeda, Y., Soto-Pinto, L. & Nahed-Toral, J. 2012. Resolving the conflict between ecosystem protection and land use in protected areas of the sierra madre de chiapas, Mexico. *Environmental Management*, 49:649-662. https://doi.org/10.1007/s00267-011-9799-9

Coste, R. 1992. *Coffee: the plant and the product*. London, Macmillan Press.

DaMatta, F. & Rena, A. 2002. Ecofisiologia de cafezais sombreados e a pleno Sol. In L. Zambolim, ed. *O estado da arte de tecnologias na produção de café*, pp. 93-135. Brasil. Universidade Federal Viçosa, Departamento de Fitopatologia.

Dasgupta, P., Morton, J.F., Dodman, D., Karapinar, B., Meza, F., Rivera-Ferre, M.G., Toure Sarr, A. & Vincent, K.E. 2014. Rural areas. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 613-657.

FAO. 2016. Save and grow in practice: maize, rice and wheat - A guide to sustainable cereal production. Rome. (also available at www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1263072/).

FAO. 2017. Climate-Smart Agriculture Sourcebook, second edition [online]. [Cited 18 June 2021] http://www.fao.org/climate-smart-agriculture-sourcebook/about/en/

FAO. 2019. Sustainable Food Production and Climate Change. (also available at www.fao.org/3/ca7223en/CA7223EN.pdf).

FAO. 2021. FAOSTAT. In: FAO [online]. [Cited 24 July 2020]. http://faostat.fao.org

Gay, C., Estrada, F., Conde, C., Eakin, H. & Villers, L. 2006. Potential impacts of climate change on agriculture: A case of study of coffee production in Veracruz, Mexico. *Climatic Change*, 79:259-288. https://doi.org/10.1007/s10584-006-9066-x

Finer, B. M., Novoa, S., Weisse, M. J., Petersen, R., Mascaro, J., Souto, T., Stearns, F. & Martinez, R. G. 2018. Combating deforestation: From satellite to intervention. *Science*, 360(6395):1303-1305. https://doi.org/10.1126/science.aat1203

Flammini, A., Brundin, E., Grill, R. & Zellweger, H. 2020. Supply Chain Uncertainties of Small-Scale Coffee Husk-Biochar Production for Activated Carbon in Vietnam. *Sustainability*, 12(19):8069. https://doi.org/10.3390/su12198069

Fischersworring, B., Schmidt, G., Linne, K., Pringle P. & Baker, P. 2015. *Climate Change Adaptation in Coffee Production: A step-by-step guide to supporting coffee farmers in adapting to climate change*. Initiative for coffee & climate. https://www.researchgate.net/publication/272290999_Climate_Change_Adaptation_in_Coffee_Production

Fonseca, M. F. 2004. *Alternative Certification and a Network Conformity Assessment Approach.* Bonn, International Federation of Organic Agriculture Movements (IFOAM).

Fouilleux, E. & Loconto, A. 2017. Voluntary standards, certification, and accreditation in the global organic agriculture field: a tripartite model of techno-politics. *Agriculture and Human Values*, 34:1-14. https://doi.org/10.1007/s10460-016-9686-3

Gmünder S., Toro C., Rojas Acosta J.M., Rodriguez Valencia N. 2020. *Environmental footprint of coffee in Colombia - Guidance Document.* Quantis and Cenicafé.

Green Life Crop Protection Africa. 2021. Coffee Weed Management. In: *Green Life Crop Protection Africa* [online]. [Cited 18 June 2021]. https://www.greenlife.co.ke/coffee-weed-management/

Groenen, D. 2018. The Effects of Climate Change on the Pests and Diseases of Coffee Crops in Mesoamerica. *Journal of Climatology & Weather Forecasting, 6:3*. https://doi.org/10.4172/2332-2594.1000239

Home, R., Bouagnimbeck, H., Ugas, R., Arbenz, M. & Stolze, M. 2017. Participatory guarantee systems: organic certification to empower farmers and strengthen communities. *Agroecology and Sustainable Food Systems*, 41(5):526-545. https://doi.org/10.1080/21683565.2017.1279702

Hsiang, S. M. & Meng, K. C. 2015. Tropical economics. *American Economic Review,* 105(5):257-61. https://doi.org/10.1257/aer.p20151030

Initiative for coffee & climate. 2021. *Initiative for coffee & climate toolbox*. [online]. [Cited 18 June 2021]. https://toolbox.coffeeandclimate.org

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

James, M. G., Wilson, M. T., Chripine, O. O. & John, M. I. 2019. Evaluation of coffee berry disease resistance (Colletotrichum kahawae) in F2 populations derived from Arabica coffee varieties Rume Sudan and SL 28. *Journal of Plant Breeding and Crop Science*, 11(9):225-233. https://doi.org/10.5897/jpbcs2019.0829

Jaramillo, J., Muchugu, E., Vega, F. E., Davis, A., Borgemeister, C. & Chabi-Olaye, A. 2011. Some like it hot: The influence and implications of climate change on coffee berry borer (Hypothenemus hampei) and coffee production in East Africa. *PLoS ONE,* 6(9):e24528. https://doi.org/10.1371/journal.pone.0024528

Jaramillo, J., Setamou, M., Muchugu, E., Chabi-Olaye, A., Jaramillo, A., Mukabana, J., Maina, J., Gathara, S. & Borgemeister, C. 2013. Climate Change or Urbanization? Impacts on a Traditional Coffee Production System in East Africa over the Last 80 Years. *PLoS ONE*, 8(1):e51815. https://doi.org/10.1371/journal.pone.0051815

de Jesus Junior, W.C., Martins, L.D., Rodrigues, W.N., Moraes, W.B., do Amaral, J.F.T. Tomaz, M.A. & Alves, P.R. 2012. Mudanças climáticas: potencial impacto na sustentabilidade da cafeicultura. In A. J. Tomaz, J.F.T. do Amaral, W.C. de Jesus Junior, A.F.A. da Fonseca, R.,Ferrão, G. Ferrão, L.D. Martins & W.N. Rodrigues, eds. Inovação, difusão e integração: bases para a sustentabilidade da cafeicultura (pp. 179-201). Alegre, Brazil, CAUFES.

Källander, I. 2008. *Participatory Guarantee Systems-PGS*. Stockholm, Swedish Society for Nature Conservation.

Kates, R. W., Travis, W. R. & Wilbanks, T. J. 2012. Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences of the United States of America*, 109(19):7156-7161. https://doi.org/10.1073/pnas.1115521109

Kaufmann, S. & Vogl, C.R. 2018. Participatory Guarantee Systems (PGS) in Mexico: a theoretic ideal or everyday practice? *Agriculture and Human Values*, 35:457-472. https://doi.org/10.1007/s10460-017-9844-2

Kukal, S. S., Rasool, R. & Benbi, D. K. 2009. Soil organic carbon sequestration in relation to organic and inorganic fertilization in rice-wheat and maize-wheat systems. *Soil and Tillage Research*, 102(1):87-92. https://doi.org/10.1016/j.still.2008.07.017

Kutywayo, D., Chemura, A., Kusena, W., Chidoko, P. & Mahoya, C. 2013. The Impact of Climate Change on the Potential Distribution of Agricultural Pests: The Case of the Coffee White Stem Borer (Monochamus leuconotus P.) in Zimbabwe. *PLoS ONE*, 8(8):e73432. https://doi.org/10.1371/journal.pone.0073432

Läderach, P., Ramirez–Villegas, J., Navarro-Racines, C., Zelaya, C., Martinez–Valle, A. & Jarvis, A. 2017. Climate change adaptation of coffee production in space and time. *Climatic Change*, 141:47-62. https://doi.org/10.1007/s10584-016-1788-9

Martins, L., Eugenio, F., Rodrigues, W., Junior, W., Tomaz, M., Ramalho, J. & Santos, A. 2017. *Climatic Vulnerability in Robusta Coffee Mitigation and Adaptation. Climatic Vulnerability in Robusta Coffee Mitigation and Adaptation*, Alegre, Brazil, CAUFES. https://doi.org/10.18677/ufes1

McKinsey Global Institute. 2020. *Climate Risk and response - Physical hazards and socioeconomic impacts.*

Meirelles, L. 2003. *La certificación de productos orgánicos. Encuentros y desencuentros*. Lapa, Brazil, Centro Ecologico Ipe.

Mosier, A., Syers, J.K. & Freney, J. R. 2013. *Agriculture and the nitrogen cycle: assessing the impacts of fertilizer use on food production and the environment*. SCOPE Report, No. 65. Washington, D.C., Island Press.

Mukadasi, B. 2019. Relational effects of land resource degradation and rural poverty levels in Busoga Region, Eastern Uganda. *International Journal of Environment, Agriculture and Biotechnology,* 4:1054-1062. https://doi.org/10.22161/ijeab.4425

Mutua, J. 2000. *Post Harvest Handling and Processing of Coffee in African Countries.* Rome, FAO. (also available at *http://www.fao.org/3/X6939E/X6939e00.htm*)

Nelson, E., Gómez Tovar, L., Schwentesius de Rindermann, R. & Gómez Cruz, M.Á. 2010. Participatory organic certification in Mexico: An alternative approach to maintaining the integrity of the organic label. *Agriculture and Human Values*, 27: 227-237.

Ovalle-Rivera, O., Läderach, P., Bunn, C., Obersteiner, M., & Schroth, G. 2015. Projected shifts in Coffea arabica suitability among major global producing regions due to climate change. *PLoS ONE*, 10(4):e0124155. https://doi.org/10.1371/journal.pone.0124155

Parker, S. 2019. *The Fight to Save Coffee from Climate Change Heats Up. In: Sustainable Food Trust: Articles* [online]. [Cited 18 June 2021]. https://sustainablefoodtrust.org/articles/the-fight-to-save-coffee-from-climate-change-heats-up/

Perfect Daily Grind. 2017. *Green Coffee: How Wet Processing Is Becoming More Eco-Friendly.* In: *Perfect Daily Grind: Farming* [online]. [Cited 18 June 2021]. https://perfectdailygrind.com/2017/08/green-coffee-how-wet-processing-is-becoming-more-eco-friendly/

Perfect Daily Grind. 2020. *Combating Climate Change's Impact With Hybrid Coffee Varieties.* In: *Perfect Daily Grind: Varieties* [online]. [Cited 18 June 2021]. https://perfectdailygrind.com/2020/07/combating-climate-changes-impact-with-hybrid-coffee-varieties/

Plant Village. 2020. Coffee. In: *Plant Village* [online]. [Cited 18 June 2021]. https://plantvillage.psu.edu/topics/coffee/infos

Pohlan, H. A. J. & Janssens, M. J. J. 2010. Growth And Production of coffee. In W.H. Verheye, ed. *Soils, Plant Growth and Crop Production*, pp. 102-134. London , Encyclopedia of Life Support Systems (ELOSS).

Rahn, E., Läderach, P., Baca, M., Cressy, C., Schroth, G., Malin, D., van Rikxoort, H. & Shriver, J. 2014. Climate change adaptation, mitigation and livelihood benefits in coffee production: where are the synergies? *Mitigation and Adaptation Strategies for Global Change*, 19:1119-1137. https://doi.org/10.1007/s11027-013-9467-x

Rickards, L. & Howden, S. M. 2012. Transformational adaptation: Agriculture and climate change. *Crop and Pasture Science*, 63(3):240-250. https://doi.org/10.1071/CP11172

Ricketts, T. H., Daily, G. C., Ehrlich, P. R. & Michener, C. D. 2004. Economic value of tropical forest to coffee production. *Proceedings of the National Academy of Sciences of the United States of America*, 101(34):12579-12582. https://doi.org/10.1073/pnas.0405147101

Rising, J., Foreman, T., Simmons, J., Brahm, M. & Sachs, J. 2016. *The impacts of climate change on coffee: trouble brewing*. The Earth Institute, Columbia University. http://eicoffee.net/application/files/report/public.pdf

Rodríguez Valencia, N. & Zambrano Franco, D. 2010. Los subproductos del café: fuente de energía renovable. *Avances Técnicos 393*, Cenicafé.

Rossi, L., Fedenia, L. N., Sharifan, H., Ma, X. & Lombardini, L. 2019. Effects of foliar application of zinc sulfate and zinc nanoparticles in coffee (Coffea arabica L.) plants. *Plant Physiology and Biochemistry*, 135:160-166. https://doi.org/10.1016/j.plaphy.2018.12.005

Sánchez-Navarro, V., Marcos-Pérez, M. & Zornoza, R. 2020. A comparison between vegetable intercropping systems and monocultures in greenhouse gas emissions under organic management. 22nd European Geosciences Union (EGU) General Assembly, held online 4-8 May, 2020.

Schroth, G., Läderach, P., Dempewolf, J., Philpott, S., Haggar, J., Eakin, H., Castillejos, T., Moreno, J. G., Pinto, L. S., Hernandez, R., Eitzinger, A. & Ramirez-Villegas, J. 2009. Towards a climate change adaptation strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mexico. *Mitigation and Adaptation Strategies for Global Change*, 14:605-625. https://doi.org/10.1007/s11027-009-9186-5

Schroth, G., da Mota, M. do S. S., Hills, T., Soto-Pinto, L., Wijayanto, I., Arief, C. W. & Zepeda, Y. 2011. *Linking Carbon, Biodiversity and Livelihoods Near Forest Margins: The Role of Agroforestry*. In B. Kumar & P. Nair, eds. *Carbon Sequestration Potential of Agroforestry Systems. Advances in Agroforestry*, vol 8, pp. 179-200. Dordrecht, Springer. https://doi.org/10.1007/978-94-007-1630-8_10

Schroth, G. & Ruf, F. 2014. Farmer strategies for tree crop diversification in the humid tropics. A review. *Agronomy for Sustainable Development*, 34:139-154. https://doi.org/10.1007/s13593-013-0175-4

Schwentesius de Rindermann, R. 2016. Participatory guarantee systems and the re-imagining of Mexico's organic sector. *Agriculture and Human Values*, 33(2):373-388. https://10.1007/s10460-015-9615-x

Scott, M. 2015. Climate & Coffee. In: *NOAA Climate.gov: News & Features*. [online]. [Cited 18 June 2021]. https://www.climate.gov/news-features/climate-and/climate-coffee

Ssebunya. B. 2011. *African Organic Agriculture Training Manual--Module 9 (Crops), Unit 13 (Coffee) A Resource Manual for Trainers*. Research Institute of Organic Agriculture (FiBL). https://www.organic-africa.net/fileadmin/organic-africa/documents/training-manual/chapter-09/Africa_Manual_M09-13.pdf

Smith, M. S., Horrocks, L., Harvey, A. & Hamilton, C. 2011. Rethinking adaptation for a 4 °C world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369:196-216. https://doi.org/10.1098/rsta.2010.0277

Sobreira, F. M., Guimaraes, R. J., Colombo, A., Scalco, M. S. & Carvalho, J. G. 2011. Nitrogen and potassium fertigation in coffee at the formation phase with high plant density. *Pesquisa Agropecuária Brasileira*, 46(1):9-16.

Stafford, M., Horrocks, L., Harvey, A. & Hamilton, C. 2011. Rethinking adaptation for a 4 °C world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369:196-216. https://doi.org/10.1098/rsta.2010.0277

Stuart, I. 2014. *Coffee & climate change, a round-up story*. In: CCAFFS: News [online]. [Cited 18 June 2021]. https://ccafs.cgiar.org/fr/blog/coffee-climate-change-round-story#.X4mJBebityx

Tadesse, T., Tesfaye, B. & Abera, G. 2020. Coffee production constraints and opportunities at major growing districts of southern Ethiopia. *Cogent Food & Agriculture*, 6(1). https://doi.org/10.1080/23311932.2020.1741982

Thurston, R., Morris, J. & Steiman, S. 2013. Coffee: A Comprehensive Guide to the Bean, the Beverage, and the Industry. Rowman & Littlefield Publishers.

Tucker, C. M., Eakin, H. & Castellanos, E. J. 2010. Perceptions of risk and adaptation: Coffee producers, market shocks, and extreme weather in Central America and Mexico. *Global Environmental Change*, 20(1):23-32. https://doi.org/10.1016/j.gloenvcha.2009.07.006

Tummakate, A. 1999. Mulching in coffee: A review. *Thai Agricultural Research Journal*, 17(1):97.

USDA FAS (United States Department of Agriculture Foreign Agricultural Service). 2021. Coffee summary and Table03A Coffee production. In: *Production Supply and Distribution (PSD) Online: PSD reports*. [online]. [Cited 29 July 2021] https://apps.fas.usda.gov/psdonline/app/index.html#/app/downloads.

Vaast, P., Harmand, J.-M., Rapidel, B., Jagoret, P. & Deheuvels, O. 2016. Coffee and Cocoa Production in Agroforestry - A Climate-Smart Agriculture Model. In E. Torquebiau, ed. *Climate Change and Agriculture Worldwide*, pp. 209-224. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-7462-8_16

van Asseldonk, M., Muwonge, D., Musuya, I. & Abuce, M. 2020. Adoption and preferences for coffee drought index-based insurance in Uganda. Studies in Agricultural Economics, 122(3):162-166.

van Rikxoort, H., Schroth, G., Läderach, P. & Rodríguez-Sánchez, B. 2014. Carbon footprints and carbon stocks reveal climate-friendly coffee production. *Agronomy for Sustainable Development*, 34:887-897. https://doi.org/10.1007/s13593-014-0223-8

WCR (World Coffee Research). 2019. *Annual Report 2019: Creating the future of coffee*.

WCR. 2020. *Arabica Coffee Variety Catalog*. [online]. [Cited 18 June 2021]. https://varieties.worldcoffeeresearch.org/varieties

Wrigley, G. 1988. Coffee. Tropical Agriculture Series. London, John Wiley and Sons, Inc

Wyckhuys, K. A. G., Lu, Y., Morales, H., Vazquez, L. L., Legaspi, J. C., Eliopoulos, P. A. & Hernandez, L. M. 2013. Current status and potential of conservation biological control for agriculture in the developing world. *Biological Control*, 65(1):152-167. https://doi.org/10.1016/j.biocontrol.2012.11.010

Zullo, J., Pinto, H. S., Assad, E. D., & de Ávila, A. M. H. 2011. Potential for growing Arabica coffee in the extreme south of Brazil in a warmer world. *Climatic Change*, 109:535-548. https://doi.org/10.1007/s10584-011-0058-0

3. Sustainable cowpea production

Adapting production systems to changing climatic conditions and reducing environmental impacts

H. Jacobs, T. Calles, S. Corsi, C. Mba,
M. Taguchi, B. Hadi, F. Beed, P. Lidder and H. Kim

©FAO / Sumy Sadurni

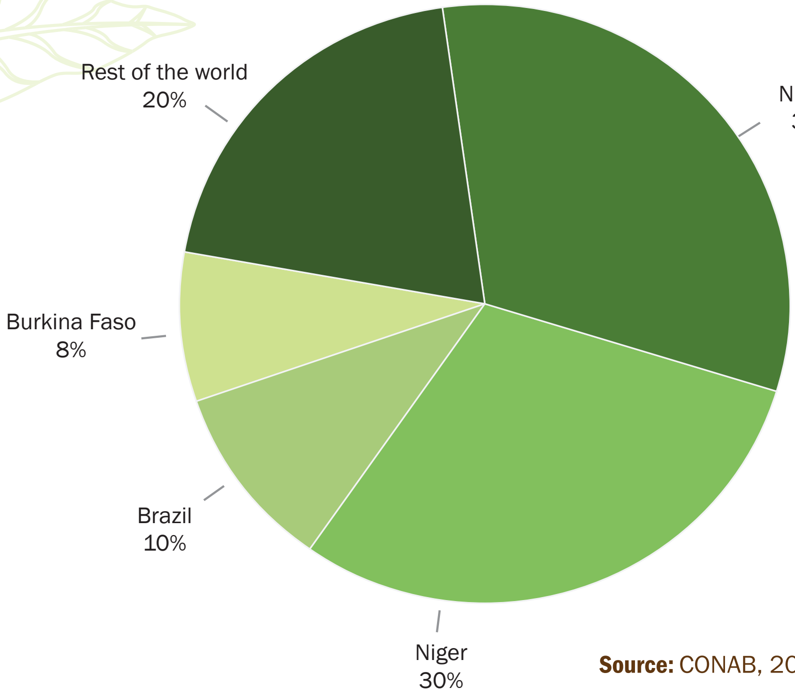
©FAO / P. Lowrey

3.1 Introduction

Cowpea is an important legume crop in tropical and subtropical regions, especially in Africa. Cowpea has nutritional properties that may be beneficial for human health. A recent increase in cowpea research has focused on improving productivity under changing climatic conditions and enhancing the ability of cowpea production to sequester carbon in the soil. Cowpea inherently possesses a level of drought resistance. Nevertheless, it is becoming essential for farmers to pursue climate change adaptation and mitigation approaches for cowpea cultivation under increasingly erratic and extreme weather conditions. This briefing note describes approaches for climate change adaptation and mitigation that can support a transition to more sustainable and resilient cowpea production systems. It also highlights the synergies these approaches share with the Sustainable Development Goals (SDGs) in the 2030 Agenda for Sustainable Development. Strong political commitment, supportive institutions and investments are essential to give farmers access to climate-smart approaches and enable their widespread adoption. Increased uptake of these approaches will in turn enhance yields, provide income stability, ensure food security, and contribute to building resilient, sustainable and low-emission food systems.

Cowpea (*Vigna unguiculata* [L.] Walp.) is a warm-season annual legume that originated in Southern Africa and is currently cultivated for food and forage throughout the semi-arid tropics (Timko and Singh, 2008). It is one of the most economically important crops in sub-Saharan Africa and a staple legume in the Sahel (Casas, 2017). Cowpea is cultivated on 14.5 million hectares, with about 84 percent of this area in Africa. African cowpea is mainly used for food, animal feed and seed (IITA, 2019). Cowpea has also shown good results when used as a green manure as it fixes nitrogen in the soil and helps control soil erosion (Ajeigbe *et al.*, 2010). Nigeria, Niger, Brazil, and Burkina Faso are the largest producers of cowpea both in terms of harvested area and grain production (CONAB, 2018; FAO,2021).

Figure 1: Share of cowpea production by country (tonnes), 2018



Source: CONAB, 2018; FAO 2021

Cowpea is commonly cultivated at elevations below 1 200 m and grows well on a wide range of soil types and pH levels. However, light soils are preferred with an optimum pH range of around 6.0 to 7.8. Cowpea is inherently tolerant to drought and heat, but it does not survive frost (Casas, 2017; IITA, 2019).

As with other legume species, cowpea can improve nitrogen cycling because of its ability to fix nitrogen in the soil. Because of this characteristic, cowpea and other legumes play a vital role in sustainable agriculture. Cowpea can figure prominently in crop rotations in arid regions and other areas where nitrogen may be low (Mousavi-Derazmahalleh *et al.*, 2019). Cowpea is often intercropped or relay cropped with sorghum, millet or maize.

Introducing cowpea into cropping systems and diets can improve access to nutritious food by all (**SDG Target 2.1**) and support the prevention of non-communicable diseases (**SDG Target 3.4**).

Cowpea is an important crop for food and nutrition. It has over 25 percent protein with a high iron and zinc content. It also contains folate, lignans, saponins, antioxidants and dietary fibre. It is low in fat content and high in essential amino acids (e.g. lysine and tryptophan), folic acid and vitamin B. Cowpea also has anti-diabetic, anti-cancer and anti-inflammatory properties, as well as properties that can prevent or counteract the accumulation of lipids in the blood, and reduce high blood pressure. Because of these properties, increased cowpea production and consumption may be able to contribute to global efforts to combat obesity and non-communicable diseases (Jayathilake *et al.*, 2018).

It is also a nutritious fodder crop for livestock. After harvesting and threshing the seeds, the remaining stems and stalks (haulms) contain over 17 percent protein and can serve as an alternative source of protein and energy for animals during the winter and dry seasons (Singh *et al.*, 2011; Singh *et al.*, 2003). Cowpea can adapt to marginal soils and drought-prone areas (Singh and Tarawali, 1997). For this reason, cowpea could be more extensively planted for forage and fodder crop in the future, and in certain areas could serve as a substitute for crops that are less viable due to the impacts of climate change. Despite being an important nutritious food security crop with significant economic and social importance in sub-Saharan Africa, cowpea has received somewhat limited research and development attention (Fatokun *et al.*, 2020).

This brief, which serves as a companion volume to the Climate-smart Agriculture (CSA) Sourcebook (FAO, 2017), summarizes best practices for cowpea production systems under climate change scenarios. It is intended to provide a reference for policymakers, researchers and other groups and individuals working to support sustainable crop production intensification. In plain language and with case studies, the brief lays out a checklist of actionable interventions that could be adopted to enhance or sustain the productivity of cowpea production systems that are at risk from climate change. The strategies for sustainable cowpea production presented in this brief address the three pillars of CSA: sustainably increasing agricultural productivity and incomes; adapting and building resilience to climate change; and reducing and/or removing greenhouse gas (GHG) emissions, where possible. These strategies can be used to adapt cowpea production systems to increased biotic and abiotic stresses that result from climate change and to reduce GHG emissions from these systems. This cowpea-focused brief is one in a series of crop-specific briefs on CSA.

3.2 Impacts of climate change and projections for cowpea

Cowpea adapts well to high temperatures and is more tolerant to drought stress than other legumes (Hall *et al.*, 2002; Hall, 2004). However, cowpea may suffer considerable damage from frequent droughts. Farmers often choose to plant sorghum, maize or millet in the cooler regions of Africa; maize-beans, maize-groundnut, and maize in moderately warm regions; and cowpea, cowpea-sorghum, and millet-groundnut in hot regions (Kurukulasuriya and Mendelsohn, 2006). Cowpea has historically been cultivated as a reliable crop in warm areas.

However, abiotic stressors (e.g. drought, floods, salt stress and extreme temperatures) are predicted to become worse with climate change and affect cowpea production. Fluctuations in precipitation patterns and rising temperatures may usher in increasingly poor growing conditions, modify growing seasons and reduce crop productivity (Ajetomobi and Abiodun, 2010). One of the biggest challenges faced by cowpea farmers is the effect of extremely high temperatures during the late reproductive development stage of the crop, which causes pollen sterility and drastically reduces the number of pods set per plant (Lucas *et al.*, 2013). Climate change is also expected to increase occurrences of pests and diseases and wilting, reduce seed formation, slow plant growth, and cause late maturation (Semenov and Halford, 2009). Climate change is predicted to have two impacts on insect pests: shifts in the geographic distribution of pests; and higher rates of metabolism in the tropics, which will lead to higher rates of reproduction and feeding. Increased temperatures could also accelerate pest cycles, causing pests to become more difficult to control. It is important to note that, even though no scientific evidence has been published, these potential impacts on cowpea pests and diseases have been observed.

Impacts of cowpea production on climate change. In addition to being affected by climate change, cowpea production also contributes to GHG emissions. In cowpea production systems, the primary sources of GHG emissions are associated with conventional crop production practices. These practices include conventional tillage, which leads to a loss of soil organic carbon; the use of fertilizers and pesticides, which contribute to GHG emissions of non-carbon dioxide GHGs (e.g. nitrous oxide) and emissions from agricultural operations. However, as further discussed in

Section III, cowpeas and other legumes have the ability to fix atmospheric nitrogen in the soil and can help minimize the use of chemical nitrogen fertilizers. Additionally, their use as cover crops increases soil carbon sequestration.

3.3 Climate change adaptation approaches

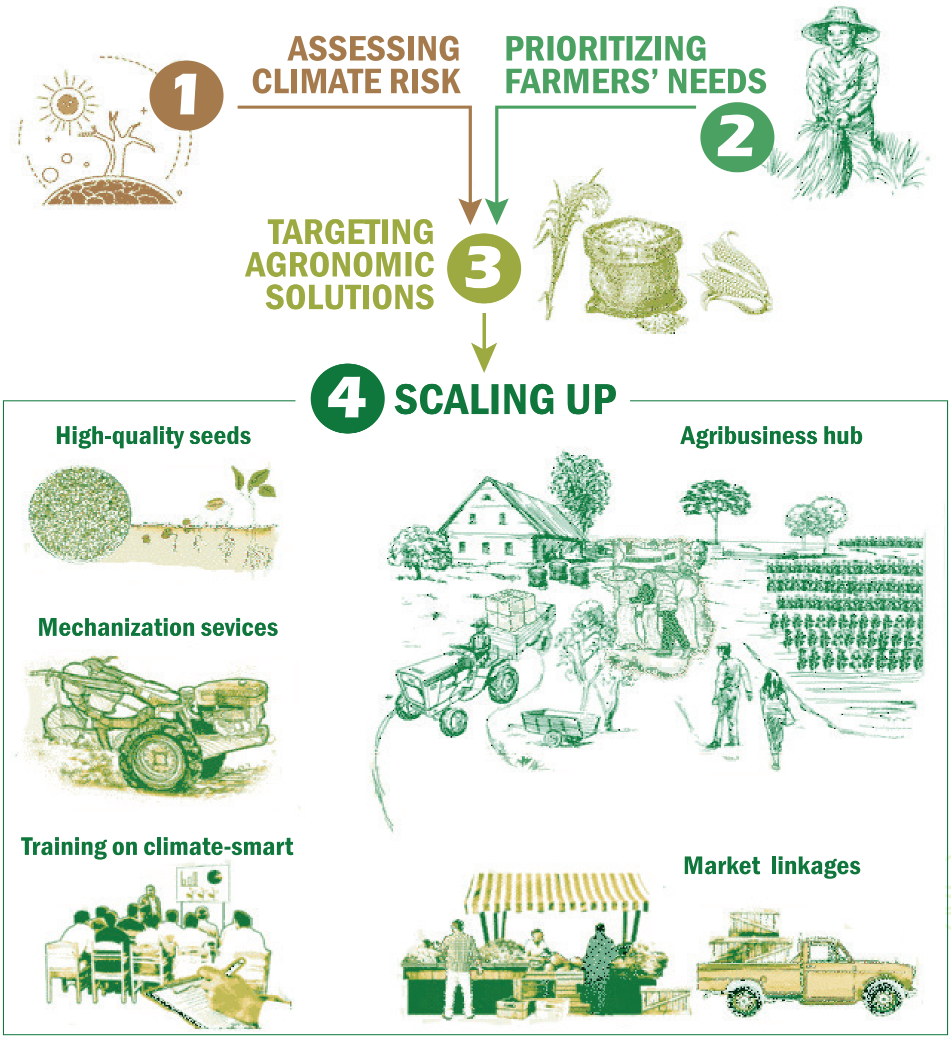
Higher temperatures, shifts in rainfall regimes, changes in the distribution patterns of cowpea pests and more frequent and more extreme weather events (e.g. heat waves and cyclones), are examples of the challenges that cowpea farmers will face as climate changes. Cowpea production systems need to become more resilient to these climate hazards and the adaptive capacities of farmers need to be strengthened. Progress in this area will contribute to achieving **Sustainable Development Goal (SDG) 13** (Climate Action), particularly in reaching **SDG Target 13.1**. Key approaches for reaching these objectives include conservation agriculture, the use of improved crops and varieties, efficient water management, and integrated pest management. Enabling policies and legislation are instrumental to enable farmers to adopt these climate-smart practices. Extension services and institutional support are critical to improve government seed programmes and seed distribution in formal and informal seed sectors, and foster improved farmer-to-farmer seed diffusion for cowpea. Involving farmers in research, promoting resistant varieties, improving training and education in legume cultivation, and increasing opportunities for women are also integral to successful adaptation approaches.

FAO works with countries to reduce the adverse impacts of climate change on crop productivity and the contributions that crop production systems make to climate change.

Based on lessons learned in the field, FAO has proposed the four-step approach (FAO, 2019) to climate change adaptation and mitigation:

1) assess climate risk;
2) prioritize farmers' needs;
3) target agronomic solutions; and
4) scale up successful interventions.

Figure 2: The Save and Grow approach



Source: FAO, 2019

The FAO 'Save and Grow' approach to sustainable crop production intensification relates to step 3 in this four-step sequence. The 'Save and Grow' approach consists of a set of practices that include conservation agriculture; the use of improved crops and varieties; efficient water management; and integrated pest management (IPM). This section describes in greater detail the application of these practices in cowpea-based production systems.

3.3.1. Conservation agriculture

Conservation agriculture is a sustainable agronomic management system that combines zero- or reduced-tillage, the maintenance of soil surface cover with mulch or cover crops, and the diversification of crop production (Cairns *et al.*, 2013; FAO, 2016, 2017).

Actions

Diversification of crop production should be promoted in part to avoid cereal monocultures and continuous cropping. Cowpea is shade tolerant and can be intercropped with other crops. Staple cereal crops (e.g. maize) require abundant nitrogen, which can be partly supplied by including legumes in the crop rotation. Growing different crops in succession reduces and prevents soil erosion caused by floods and drought; controls weeds, pests and diseases; and decreases the need for fertilizers and herbicides. Cowpea and other legumes cultivated in crop rotations can enrich the soil with nitrogen and help subsequent crops achieve higher yields. Many legume systems can be implemented using three general methods:

- **intercropping**, which involves planting legumes and cereals simultaneously in the same or alternating rows; and **modified strip-intercropping**, which involves alternating two rows of cereals with four rows of cowpea (Singh and Ajeigbe, 2007);
- **relay cropping**, which involves planting legumes and cereals on different dates but cultivating them together for a part of their life cycle; and
- **rotation**, which involves planting a cereal crop (e.g. maize or wheat) after the cowpea or other legume crop has been harvested.

The diversification of cereal cropping systems with cowpea delivers multiple benefits for sustainable development.

It helps to improve soil fertility and nutrient management and prevent erosion, which contributes to building more sustainable and resilient food systems (**SDG Target 2.4**) and improving the sustainable management of terrestrial ecosystems (**SDG Target 15.1**).

Cowpea provides nutritious fodder and can support crop-livestock integration, which create opportunities for increased economic productivity (**SDG Target 8.2**), income generation for small-scale farmers (**SDG Target 2.3**), and decent rural employment (**SDG Target 8.5**).

Minimizing nutrient losses from the use of fertilizers contributes to the reduction of marine pollution from land-based activities (**SDG Target 14.1**).

Compared to cereal crops, most traditional legume crops have low yields and take between 100 to 150 days to mature. One option to increase cowpea production is the development and use of short duration and high-yielding varieties that can be cultivated in cereal crop system rotations. This option delivers several benefits. Legumes such as cowpea improve soil fertility and contribute to the sustainability of the agricultural production system. They are also higher in protein, vitamins and minerals, offering a nutritious counterpart and complement to high-carbohydrate cereals (Singh, 2014). In the 1980s, the focus of cowpea research at the International Institute of Tropical Agriculture (IITA) shifted to developing short duration (60 to 70 days) extra-early cowpea varieties that grew in an erect to semi-erect manner. This work at IITA was led by B.B. Singh, the principal cowpea breeder at IITA from 1979 to 2006. Singh enabled the release of over 35 new varieties in 40 countries and increased global cowpea production from less than one million tonnes in 1974 to over 7 million tonnes in 2013. These varieties are now commonly grown in wheat–cowpea–rice, rice–cowpea–rice, maize–double cowpea, sorghum–millet–cowpea, and soybean–cowpea systems in many countries, and have increased global cowpea production by about 70 percent over the last decade (Singh, 2014; 2016). These 60-70 day cowpea varieties were grown in the modified strip cropping systems with maize, sorghum and millet by large number of farmers in Niger and Nigeria with excellent productivity (Singh and Ajeigbe, 2007; Singh, 2014).

Maize-legume systems are common throughout the developing world and can include beans, pigeon peas, cowpeas, groundnuts and soybean, which are grown mainly for food. Intercropping has been shown to increase total system productivity due to the combined yields of cowpea and maize, and the high market prices that cowpea can fetch, which can be 1.5 to 2.0 times that of maize (Pradhan *et al.*, 2018). It has also been shown that the effect of the maize canopy in providing shading is beneficial for enhancing the leaf water potential of cowpea (Filho, 2000).

Crop-livestock integration enables farmers to diversify their production. It provides farmers with opportunities to earn more profit from grains, seed, fodder, meat and milk. Dual-purpose cowpea varieties that produce grain and fodder have the potential to contribute to successful integrated crop-livestock production systems. Cowpea provides farmers with more flexibility in the face of climate change because it is often the first crop to be harvested before the cereal crops are ready, and farmers can decide whether to apply additional inputs and pick more beans or fewer beans. Picking fewer beans allows for the production of additional foliage, which can be used as fodder for livestock (Gomez, 2004). Crop-livestock integration also creates additional employment opportunities in rural areas (Ajeigbe *et al.*, 2010).

Zero-tillage and direct seeding involves the precise placement of seeds by drilling without the mechanical preparation of the seedbed. This enhances soil organic matter content (Sapkota *et al.*, 2017), which improves water infiltration and retention, improves water use productivity, and reduces erosion (Sapkota *et al.*, 2015). Studies have shown that zero-tillage practices can provide substantial energy savings (FAO, 2013). It has also been shown that higher carbon and nitrogen concentration levels are possible in zero-tillage soils, especially in the topmost (0 to 5 cm) soil horizon (Guzzetti *et al.*, 2020). However, it should be noted that the effects of zero-tillage on soil organic carbon and nitrogen content vary depending on soil properties, machinery, and other site-specific factors.

Enhancing the water regulation capacities of agricultural soils increases water use efficiency (**Target 6.4**), enhances water quality (**Target 6.3**) and improves access to safe drinking water (**Target 6.1**), ultimately contributing to ensuring the availability and sustainable management of water resources (**SDG 6**).

Energy savings from reduced tillage contribute to increasing energy efficiency in the agricultural sector (**SDG Target 7.3**)

3.3.2. Improved crops and varieties

Cowpea is consumed as dry grains, which have more resistance to terminal drought than either fresh peas or immature pods (Hall, 2012). However, there is a growing need for new varieties that are more resilient to the impacts of climate change. Cowpea shows considerable variation in morphological traits and yield. Among all legumes, it has the greatest diversity of plant type, growth habit, time to maturity and seed type (Singh, 2016; Sivasankar, ed., 2018).

Several varieties have been used for forage and as monocrops or intercrops with cereals. However, more genetic studies are needed on forage traits (Kulkarni *et al.*, 2018).

The use of landraces and crop wild relatives in plant breeding contributes to maintaining the genetic diversity in cultivated plants (**SDG Target 2.5**).

Recently, considerable progress has been made using genomic tools to identify trait loci and genes and alleles that can support the development of improved plant varieties through assisted breeding (Kulkarni *et al.*, 2018). Large-scale genomic resources for alfalfa, soybean and cowpea have helped to identify a number of molecular markers useful in the development of improved varieties. These advancements offer opportunities to enhance adaptation to drought and salinity (Abberton *et al.*, 2016; Batley and Edwards, 2016; Dhankher and Foyer, 2018; Kole *et al.*, 2015).

Varietal intercrops. In areas such as the Sahel, precipitation can be highly variable, and droughts are becoming more severe. Consequently, farmers have been recommended to grow at least two varieties of cowpea each year (Hall, 2004). If a mid-season drought occurs, the growth of the extra-

Box 1: IITA varieties, gene banks and farmer field schools

IITA scientists have developed early and medium maturing high-yielding varieties with resistance to major diseases, pests, nematodes, and parasitic weeds. These varieties have been released to 68 countries all over the world. In 2019, following 20 years of research and field trials, the Nigerian Biosafety Management Agency (NBMA) approved the commercial release of genetically modified cowpea to farmers in Nigeria. The NBMA approval allowed the Institute for Agricultural Research to commercially release pod borer-resistant cowpea (PBR Cowpea) AAT709A, genetically improved to resist the pod borer (*Maruca vitrata*).

The IITA gene bank holds the world's largest and most diverse collection of cowpeas, with 15 122 germplasm samples from 88 countries and nearly half of the global diversity. In addition, IITA's farmer field school (FFS) projects have trained farmers in improved pest management practices for cowpea.

early erect variety may be slow, but the medium-cycle spreading variety can grow into the space and produce large yields as the intercrop. When late-season drought occurs, the early erect variety produces plentiful grain, while the medium-cycle spreading variety produces ample hay but little grain (Hall, 2004).

Actions

Use crop varieties that match local conditions. This is an important adaptive practice. In response to a series of droughts in the Sahel that resulted in very short growing seasons, the University of California-Riverside and the Institut Sénégalais de Recherches Agricoles (ISRA) bred extra-early cowpea varieties with very short growth cycles by combining drought resistance with an erect growth habit and early synchronous flowering. These varieties do not grow extensively during the vegetative stage (i.e. the stage between germination and flowering) and it is recommended that they are planted with tight spacing (50 cm between rows and 25 cm between seeds) to improve the synchrony of pod production and early harvest (Hall, 2012). Short duration *striga*-resistant varieties were developed by IITA in collaboration with Burkina Faso, Mali, Niger and Nigeria, where they are now becoming popular.

Improve distribution of seeds through formal and informal seed sectors and government seed programmes. Farmers in developing countries often acquire seeds from unregulated and informal sources, which can include purchasing them from local markets and exchanging seeds with family members and neighbours. Cowpea is a self-pollinating crop and farmers often hold onto seeds from harvests for later plantings (Kulkarni *et al.*, 2018). For this reason, community-based seed production and distribution channels are important and should be supported. This is especially important in areas that are both vulnerable to the impacts of climate change and produce crucial food security crops (e.g. cowpeas, beans, peanuts, sweet potato, yams, and cassava). Small and medium-scale enterprises can help ensure that quality seeds of improved varieties are available and easily accessible to farmers (FAO, 2017). Through the FAO project, Crop and Mechanization Systems Scaling-up, farmers are able to access seeds of adapted cowpea varieties, as well as other legumes, through local Save and Grow agri-business hubs that have been established in selected cooperatives. IITA has pointed out that a combination of strong formal and informal seed sectors supports more rapid diffusion of improved varieties because every farmer who purchases these seeds becomes a potential source of seeds to many other farmers (Ajeigbe *et al.*, 2010).

IITA has also made the following recommendations (Ajeigbe *et al.*, 2010) for improved farmer-to-farmer seed diffusion for cowpea:

- The cultivation of new and improved varieties should follow the recommended package of practices for maximum production and good quality seeds.
- Extension staff should oversee the seed production plots and provide guidance to farmers. This may include establishing demonstration plots to allow the observance of management techniques for new varieties and guidance on the quality of seeds.
- Periodically, fresh foundation seeds should be provided by research institutes or seed companies to seed growers who are the key sources of seeds within a community.

Awareness raising should be conducted about the benefits of new varieties and local seed availability through all available communication channels, including radio and television, cultural and religious groups, and market and trade associations.


©FAO / P. Lowrey

Box 2: Protecting agriculture from COVID-19 in Nigeria through government expansion of seed support

The Economic Community of West African States (ECOWAS) has estimated that the COVID-19 pandemic will increase food insecurity and threaten the nutrition of 50 million people through the disruption of food production systems and potential food crises. The pandemic will also exacerbate the impacts of climate change, drought, and fall armyworm and locust infestations in West Africa.

Seed assistance programmes are experiencing rising demand, and many African farmers were already struggling to acquire quality seed before the pandemic. Farmers often may not be sure of seed quality. There have been estimates that 95 percent of legume and dryland cereal seeds in Africa are of unknown quality. This can profoundly affect food security and produce disappointing yields, and COVID-19 is likely to worsen this problem. Governments and relief organizations will continue to be challenged by the urgent need to provide access to high-quality seeds for the most nutritious crops.

In Nigeria, as a part of an initiative to lessen the pandemic's impact on food systems, 13 states are slated to receive improved seeds of sorghum, pearl millet, cowpea and rice for 10 000 smallholders. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has been leading a group of agricultural research institutes in collaboration with the Nigerian government to launch the recent seed support initiative (ICRISAT, 2020). The Minister of Agriculture and Rural Development emphasized the need to provide this support to production systems to mitigate the impacts of the pandemic, and stated that the most suitable crops to tackle threats to food and nutrition security during the pandemic are nutrient-dense cereals and legumes including sorghum, finger millet and pearl millet, and legumes such as groundnut, chickpea, cowpea, common bean and pigeon pea. The Nigerian government has also started planning ahead in conjunction with research institutions to produce breeder and foundation seeds for high-yielding seed production for 2020-2021. Nigeria has already implemented early response strategies at national and state levels to enable the free movement of food and agriculture inputs exempted from the lockdown. Regional and public-private cooperation could build the cooperative seed system needed during the post-COVID recovery to promote nutritious diets, ensure a more resilient supply chain, establish links with markets, anticipate spikes in demand, and contribute to achieving the SDGs.

Source: Paul, 2020

Strengthening the collaboration between formal and informal seed systems and between researchers and farmers for improved seed supply contributes to the promotion of effective public-private and civil society partnerships (**SDG Target 17.17**).

Training farmers in seed production and engaging them in research activities supports them in acquiring new technical and vocational skills (**SDG Target 4.4**).

Gender-sensitive seed systems for cowpea improve equal access to seeds and promote the empowerment of women (**SDG Target 5.B**).

Involve farmers in research, improving seed training and education, and increase opportunities for women. Legume cultivation has been hindered by low yields and returns for years. According to ICRISAT, legume productivity can be improved by engaging farmers at strategic points in legume research. An example is the international legume project, Tropical Legumes, which was operational from 2007-2019 in three phases. It was funded by the Bill and Melinda Gates Foundation and implemented by three CGIAR centres (ICRISAT, IITA and the International Center for Tropical Agriculture (CIAT)) jointly with 15 national agricultural research institutes in sub-Saharan Africa and South Asia. The initiative provided guidance on growing seeds, carrying out disease diagnosis, and storing grain, and worked on developing improved high-yield varieties. Involving farmers in the research ensured that new varieties responded to farmer preferences and needs. This work has continued under the Accelerated Varietal Improvement and Seed Systems for Africa (AVISA)[1] project. In collaboration with the CGIAR Research Program on Grain Legumes and Dryland Cereals (GLDC), AVISA is working to develop high-yielding cowpea varieties with resistance to pests and diseases and increase production. The programme has identified some extra-early to early maturing varieties of cowpea that can be grown during cropping seasons that have been shortened by fluctuating rainfall patterns (CGIAR, 2019).[2]

Unequal access to improved seeds for women is an issue in several African countries. The Tropical Legumes project collected considerable data on gender dynamics in legume seed systems, which has helped to inform the development of seed systems that are suitable for both women and men. Gender-sensitive seed systems enable women to benefit from new employment opportunities created by the cultivation of cowpeas and other legume, and play a role in areas where women have been typically underrepresented, such as seed production, research and seed businesses (Paul, 2020).

3.3.3. Efficient water management

Being a short-duration and drought-tolerant crop, cowpea needs 300 to 500 mm of well distributed rainfall during the growth cycle (Casas, 2017). However, it can tolerate lower rainfall conditions better than any other major crop. It can withstand dry periods of up to seven days during

1 For more information, go to the AVISA project website: www.avisaproject.org
2 A summary of ten years of cowpea research is available at the Tropical Legumes Hub website: https://tropicallegumeshub.com/.

emergence and 10 to 15 days during the grain filling stage, but it is sensitive to dry periods of 3 to 5 days during flowering (ARCC, 2014). Cowpea's deep root system helps stabilize the soil, while the ground cover prevents moisture loss and erosion (ARCC, 2014). However, cowpea does not tolerate excess moisture, and standing water in the field for even a few hours can negatively affect crop growth.

Efficient water management in cowpea cropping systems contributes to ensuring the sustainable management of water resources (**SDG 6**), and increasing water use efficiency in particular (**Target 6.4**).

Actions

Avoid waterlogged soils. Cowpea can be planted in soils that vary from sand to clay, but it does not perform well in waterlogged soils because they inhibit nitrogen fixation (Ajetomobi and Abiodun, 2010).

Conservation agriculture practices (see Section I) can be used to enhance soil water holding capacity and reduce evaporation losses. Cowpea can be cultivated in harsh and arid conditions. However, it is still important to incorporate conservation agriculture practices (e.g. zero-tillage) to enhance the water content of the soil, as it has been shown that zero-tillage practices mitigate soil water losses compared with conventional tillage practices (Guzzetti *et al.*, 2020). Cowpea has even shown increased tolerance to water deficient conditions under zero-tillage practices, and increased yields under non-irrigated conditions (Ahamefule and Peter, 2014; Moroke *et al.*, 2011; Plaza-Bonilla *et al.*, 2017). Maintaining sufficient levels of soil organic matter also helps bolster water productivity (FAO, 2016).

Shift planting dates. The selection of the planting date is important in maximizing cowpea yield (Sivasankar, ed., 2018). However, the effects of climate change are making the prediction of planting dates more difficult. Increased climate variability in the beginning and/or end of the growing season requires shifting planting dates. Planting dates can be chosen to ensure that the critical growth stage is timed to match the availability of adequate moisture (Sivasankar, ed., 2018). Another option is cultivating varieties to cope with changes in the length of the growing season or avoid situations where the levels of moisture and temperature are not an appropriate match for the stage the crop has reached in its development (FAO, 2017).

Increase water use efficiency. This enhances adaptation to drought (Hall, 2012) and can be accomplished by **breeding cowpeas with deeper rooting** for a target production zone where they can be grown under conditions of decreased rainfall with substantial water available deeper in the soil (Hall, 2012). Several new cowpea varieties developed by IITA have deep and dense root systems and perform well in West Africa.

When soil moisture is suboptimal, the application of **potassium fertilizer** can promote root growth of cowpea and mitigate water stress in tropical cropping systems (Sangakkar *et al.*, 2001).

3.3.4. Integrated pest management

Cowpea farmers in sub-Saharan Africa have often experienced yield losses because the crop is vulnerable to an array of pests and diseases at all stages of growth.

Insect pests

Damage inflicted by pest species has been a major threat to cowpea production and post-harvest storage (Agunbiade *et al.*, 2018), and can significantly reduce yields. Cowpea productivity in sub-Saharan Africa can be poor, perhaps even less than 500 kg per ha, mainly because of insect pests (CGIAR, 2019). The legume pod borer (maruca pod borer), the larvae of a moth species (*Maruca vitrata*) that attacks flowers and pods, is the most common and damaging cowpea pest. Other major cowpea pests include the cowpea aphid (*Aphis craccivora*), which sucks the sap from leaves and stems in the seedling stage and also spreads the cowpea mosaic virus; flower thrips (*Megalurothrips sjostedti)* that feed on the growing buds and cause flowers to drop; and a number of pod sucking insects, such as the brown pod-sucking bug (*Clavigralla tomentosicollis*) and the giant coreid bug (*Anoplocnemis curvipes*) (Dumet *et al.*, 2008).

The main insect pests in storage in West Africa are the cowpea weevil (*Callosobruchus maculatus*) and the bruchid beetle (*Bruchidus atrolineatus*). Cowpea is also susceptible to nematodes, which prevent roots from absorbing nutrients and water from soil (Gomez, 2004; Agunbiade *et al.*, 2018).

Weeds

Common weeds that affect cowpea are the parasitic flowering weeds *Striga gesnerioides* and *Alectra vogelli*, which impede plant growth at all stages. Cowpea varieties with genes that confer resistence to *Striga* and *Alectra* have now been identified and improved varieties are being developed (CGIAR, 2019).

Diseases

Important diseases of cowpea include fusarium wilt, bacterial canker, southern stem blight, Cercospora leaf spot, rust and powdery mildew. Bacterial blight (*Xanthomonas vignicola*) causes severe damage to cowpea. The most frequent virus disease is Aphid-borne mosaic virus (Gaikwad and Thottappilly, 1988). Other important diseases are Yellow blister disease (*Synchytrium dolichi*) and seed-borne viruses, such as cowpea mosaic virus (*Sphaceloma spp*) (Gomez, 2004).

Actions

Integrated Pest Management (IPM) is an ecosystem approach to crop production and protection that was developed in response to the widespread overuse of pesticides. In IPM, farmers use natural methods based on field observation to manage pests. Methods include biological control (i.e. using natural enemies of pests); the use of resistant varieties; and habitat and cultural modification (i.e. the removal or introduction of certain elements from the cropping environment to reduce its suitability for pests), and biopesticides. The rational and safe application of selective pesticides is used as a last resort (FAO, 2016). IPM capitalizes on natural pest management mechanisms that maintain a balance between pests and their natural enemies. Examples of non-chemical methods include the use of resistant varieties (Cairns *et al.*, 2012) and the manipulation of the habitat around the fields to provide additional food and shelter for the natural enemies of pests (Wyckhuys *et al.*, 2013).

The control of cowpea pests remains difficult despite decades of capacity building targeted at IPM. The principles of IPM have been inadequately followed across sub-Saharan Africa. Farmers still rely heavily on chemical insecticides, which creates challenges from them due to their costs and the increasing pesticide resistance of cowpea pest and diseases (Agunbiade *et al.*, 2018).

IPM, which emphasizes the minimal use of harmful chemical pesticides, contributes to the sustainable management of terrestrial ecosystems (**SDG Target 15.1**) and reduces marine pollution from land-based activities (**SDG Target 14.1**).

The successful implementation of IPM, which can prevent infestations that can severely damage crops and cause famine, contributes to **SDG Target 2.1.**

IPM contributes to the sound management of chemicals throughout their life cycle and reduces their release into the air, water and soil, which minimizes impacts on human health and the environment (**SDG Target 12.4**).

IPM can also benefit human health by reducing illnesses caused by air, water and soil pollution and contamination (**SDG Target 3.9**).

Use of resistant varieties. Varieties resistant to insect pests have been developed following the evaluation of hundreds of germplasm accessions from the IITA gene bank. Several varieties with resistance to the main cowpea diseases and pests have been developed and released in many countries (see Table 1). Examples include IT98K-205-8 and IT97K-499-35, which have the combined resistance to major diseases, aphids, bruchid beetles, and the weeds *Striga gesnerioides* and *Alectra vogelli*. Several studies have assessed mechanisms of varietal resistance to *Maruca vitrata*. However, the level of resistance to the maruca pod borer has remained low because genes conferring resistance for this insect was not available in cultivated cowpea germplasm, but only in wild cowpea varieties such as the Vigna vexillata lines, TVNu 72 and TVNu 73 (Jackai, 1982; 1990; Oghiakhe *et al.*, 1995). However, the Vigna vexillata lines cannot be used in practical applications. The lowest incidence of *Maruca vitrata* was noted in extra-early maturing IT93K-452-1 and early-maturing IT86D-719 varieties (Adati *et al.*, 2007). Despite these research findings, high levels of resistance have yet to be found for nearly all cowpea pests except for cowpea aphid.

Table 1: Cowpea varieties with resistance to the main cowpea diseases and pests

Varieties	Characteristic	Resistance to
IT98K-205-8 and IT97K-499-35	Cultivated varieties	Aphid, bruchid beetle, *Striga*, *Alectra*
SAMPEA 20 PBR (Bt-version of IT97K-499-35)	Genetically modified variety	Maruca pod borer (reduced pod damage)
IT93K-452-1	Extra-early maturing variety	*Maruca vitrata* (low incidence)
IT86D-719	Early maturing variety	*Maruca vitrata* (48% pod damage)
TVNu 72 and TVNU 73	Wild cowpea	Maruca pod borer *Maruca vitrata* (high levels of resistance)

To overcome the low level of resistance of cowpea to *Maruca vitrata*, a multipartner initiative supported by USAID, IITA, Nigeria and African Agricultural Technology Foundation (AATF) was launched in 2001 to transfer genes from *Bacillus thuringiensis* (Bt), a bacterium that is a commonly biological pesticide, to cowpea. This initiative has succeeded in producing a Bt-version of the cowpea variety IT97K-499-35 that is resistant to pod borers. Named as SAMPEA 20 PBR, the Bt-version was released in 2019 in Nigeria. Similar Bt-cowpea varieties are to be released in Burkina Faso and Ghana. A series of studies showed that Bt cowpea expressing a high dose of Cry1Ab protein is effective in reducing pod damage due to *Maruca vitrata* and increasing overall yield (Addae *et al.*, 2020). A risk assessment exercise concluded that the deployment of Bt cowpea is likely to have negligible impacts on beneficial insects, spiders and other arthropods in cowpea ecosystems in West Africa (Ba *et al.*, 2018). The released Bt cowpea does not confer resistance against sap sucking insects, so a combination of other pest management tactics is needed (e.g. use of botanical insecticides). The breakdown of resistance remains a potential challenge for *Bt* cowpea. An insect resistance management strategy, such as a combination of non-*Bt* cowpea and the provision of natural refuges near the fields where Bt cowpea is grown, is crucial (Addae *et al.*, 2020).

Planting resistant, early maturing and extra-early maturing varieties may help avoid periods of infestation by thrips, maruca pod borers, and pod sucking bugs (Ajeigbe *et al.*, 2010).

Planting date management can serve as an important component of IPM for cowpea (Kamara *et al.*, 2018). Farmers in the dry savannahs often adjust cowpea planting dates to avoid insect pest infestations. Earlier planting dates can be advantageous since there is usually an accumulation of pests as the season progresses, causing damage to late-planted cowpea. Studies have found that early planting with only few targeted insecticide applications is an effective combination (Javaid *et al.*, 2005). Karungi *et al.* (2000) found that early planting decreased infestation levels of aphids, thrips and pod-feeding bugs, but increased maruca pod borer infestations.

Intercropping is also advantageous. It has been shown that intercropping cotton with cowpea in India increased the levels of predatory ladybugs and the incidences of parasitism by beneficial wasps of bollworms (Bowman *et al.*, 1998). Intercropping cowpea with sorghum, millet, or cassava can reduce thrips populations.

There are however, some intercropping arrangements that make cowpea more vulnerable to infestation by certain pests (Adati *et al.*, 2007). Andow (1991) analysed 209 comparative studies on pests under monocultures and mixed crop conditions and found that, compared with monocultures, insect pest populations in intercrops were lower (149 species) in 52 percent of the studies and higher (44 species) in 15 percent of the studies. The pest incidence depends upon the combination of crops and the range of the pests. Yusuf (2005) found that the parasitism rate by indigenous parasitoids of *Maruca vitrata* larvae in the intercropping system was significantly higher than those in other cropping systems. The 'push–pull' method developed in East Africa for maize stemborers, which involves the use of plant species as trap crops to attract stemborers away from the cereal plants and as intercrops to repel pests, might also be used in cowpea-cereal cropping systems in West Africa if appropriate crop combinations for local conditions are employed (Adati *et al.*, 2007).

Biological control. Studies in the 1980s and 1990s focused on the interactions between pests and their natural enemies. Conservation of indigenous natural enemies provides the basis for pest regulation in cowpea ecosystems. Research on biological control is continuing at IITA. Natural enemies of key pests in West Africa include parasitoids, predators and other organisms that feed on insects, mites and other arthropod pests (Adati *et al.*, 2007).

Botanical or microbial insecticides. Conventional insecticides can cause environmental damage and may suppress the ecosystem service of pest regulation by reducing the populations of the natural enemies of pests. For this reason, the use and selection of chemical insecticides should be done in a careful and rational way. Extracts of several plants, particularly neem (*Azadirachta indica*), have been found to have insecticidal and repellent effects and can be used as alternatives to conventional insecticides. The aqueous seed (kernel) extract and kernel oil of neem were reported to be effective in deterring insect pests, and positive results have been reported for the use of neem extract against storage pests. As neem seed extract has higher levels of active ingredient than the leaves, there have been fewer findings on the use of leaf extracts that can be used in the field (Adati *et al.*, 2007). However, neem seeds are only available during one season, and the preparation for seed use is labour intensive. Private sector interest is needed to produce local, affordable, effective, and ready-to-use bio-pesticides (Adati *et al.*, 2007).

Many other botanical extracts have been tested for post-harvest pest include chili peppers (*Capsicum*) (Belmain and Stevenson, 2001), sweet basil *Ocimum* species (Kéita *et al.*, 2001), several *Mentha* species (Raja *et al.*, 2001), and tobacco extracts in pre-harvest operations (Opolot *et al.*, 2006).

Microbial insecticides can also serve as alternatives to chemical insecticides. Fungi that feed on insects, mites and other arthropod pests (e.g. *Metarhizium anisopliae* and *Beauveria bassiana*) have shown promise in suppressing populations of cowpea pests such as *Aphis* craccivora and *Maruca vitrata* (Ekesi *et al.*, 2000; Tumuhaise *et al.*, 2015).

Insecticide use should be kept to a minimum and applied in combination with other IPM strategies. This also prevents pests from developing pesticide resistance. The objective of **resistance management** is to prevent or slow the accumulation of resistant individuals in pest populations and preserve the effectiveness of available pesticides (FAO, 2012). A key principle of IPM is to use pesticides only when absolutely necessary, and use alternative pest management techniques whenever possible (FAO, 2012). Farmers should make decisions on whether to apply chemical pesticides based on a sound understanding of economic threshold levels. The use of economic threshold levels improves decision-making by using partial economic analyses on the impact of a control practice (e.g. applying insecticides). An overall analysis requires knowledge of the agroecosystem, natural enemies, weather, plant health, and the ability to compensate for damage (FAO, 2020).

Weeds tend to be suppressed by the rapid growth and spreading habit of traditional cowpea varieties. Both drilled and broadcast cowpea plantings shade the soil to block out weeds (Bowman *et al.*, 1998). Cowpea intercrops cover the inter-row space and help to control weeds for cereal crops and reduce weeding labour (Pradhan *et al.*, 2018). However, there may be a need to weed the field during initial growth stages when cowpea plants are small and cannot shade weeds.

3.4 Climate change mitigation approaches

A range of options exist to enable cowpea production systems to support climate change mitigation and contribute to global efforts to reach **SDG 13** particularly as measured by **SDG Indicator 13.2.2**, the reduction of national GHG emissions. The options available for mitigation strategies in cowpeas production systems can improve carbon sequestration in the agricultural ecosystem and reduce GHG emissions. These options increase resource use efficiency and prevent soil erosion and nutrient losses. Key elements for mitigation strategies include the diversification of crop production, integrated soil fertility and nutrient management, and sustainable mechanization. Agronomic practices including the combined application of rhizobia inoculant, phosphorus and organic manure can also be part of a mitigation strategy. Many of these strategies deliver co-benefits to the environmental and human health, and may also generate greater economic returns for farmers and farming communities.

Because legumes can fix atmospheric nitrogen and reduce the need for farmers to apply chemical nitrogen fertilizers that are a source of nitrous oxide, their cultivation have been promoted as a method of reducing GHG emissions. Also, sustainable agriculture systems that use conservation agriculture practices, which includes crop rotation and the use of cover crops such as legumes, increase soil carbon sequestration. For this reason, cowpea cultivation inherently contributes to climate change mitigation (Sánchez-Navarro *et al.*, 2020)

3.4.1. Increasing soil carbon sequestration

Increasing soil organic matter content requires enhancing carbon inputs and minimizing carbon losses. Climatic conditions (e.g. precipitation, temperature) and soil aeration influence the decomposition of organic matter. The deep rooting systems of cowpeas can also contribute to carbon sequestration by redistributing carbon to deeper soil layers, making it less susceptible to decomposition.

Actions

Diversification of crop production as part of conservation agriculture systems can increase carbon sequestration and nitrogen use efficiency (Corsi *et al.* 2012; Sapkota *et al.*, 2017). Diversification and intensification of crop production system to include legumes in the crop rotation avoids leaving fields fallow and contributes to biological nitrogen fixation, which can reduce farmers' reliance on chemical fertilizers and lower nitrous oxide and carbon dioxide emissions. When perennial, biennial, and annual legumes are used as intercrops and relay crops, the results can lead to increases in both yield and income.

Biological nitrogen fixation and the reduced use of chemical fertilizers contribute to the economy-wide target of improving global resource efficiency in consumption and production (**SDG Target 8.4**), and reduces the release of chemicals into the air, water and soil, which minimizes their impacts on human health and the environment (**SDG Target 12.4**).

Improved yields and incomes contribute directly to the target of doubling agricultural productivity and incomes of small-scale food producers (**SDG Target 2.3**).

Increasing soil organic carbon content helps to stabilize the soil and protect it from erosion, which contributes to reaching the target of a land degradation-neutral world (**SDG Target 15.3**).

Integrated soil fertility and nutrient management can reduce land degradation and the mining of nutrients from the soil that can result from unsustainable intensified agricultural production systems. The application of inorganic and organic fertilizer, which includes recycled organic resources such as green manure and farmyard manure, on the basis of crop needs can accumulate carbon in the soil and reduce GHG emissions. In wheat-legumes multiple cropping systems, crop rotations combined with manure and nitrogen-phosphorus fertilizer could increase both wheat and faba bean grain yields (Agegnehu and Amede, 2017). In intensified systems, the management of soil organic carbon is essential for sustainable crop production. Fertilization recommendations should be adjusted in accordance with the considered cropping systems and the type of soil. Improving soil organic carbon enhances soil quality, reduces soil erosion and degradation, limiting carbon dioxide and nitrous oxide emissions (Kukal *et al.*, 2009).

3.4.2. Reducing GHG emissions

Reducing carbon dioxide emissions in crop production is primarily achieved by lowering direct emissions from operations and avoiding the mineralization of soil organic carbon.

There are several negative environmental impacts associated with the use of inorganic and organic fertilizers (e.g. water eutrophication, air pollution, soil acidification, and the accumulation of nitrates and heavy metals in the soil) (Mosier *et al.*, 2013). Rising concerns about environmental problems associated with the increasing use of nitrogen fertilizers around the world has created a larger role for legume cultivation (Kulkarni *et al.*, 2018).

Improved efficiency in the use of nutrients and fertilizers not only lowers GHG emissions, it also reduces nutrient pollution in terrestrial, freshwater and marine ecosystems, and enhances related ecosystems services (**SDG Targets 15.1, 6.3, 14.1**).

This increased efficiency can also have beneficial impacts on human health by reducing illnesses associated with air, water and soil pollution and contamination (**SDG Target 3.9**).

Actions

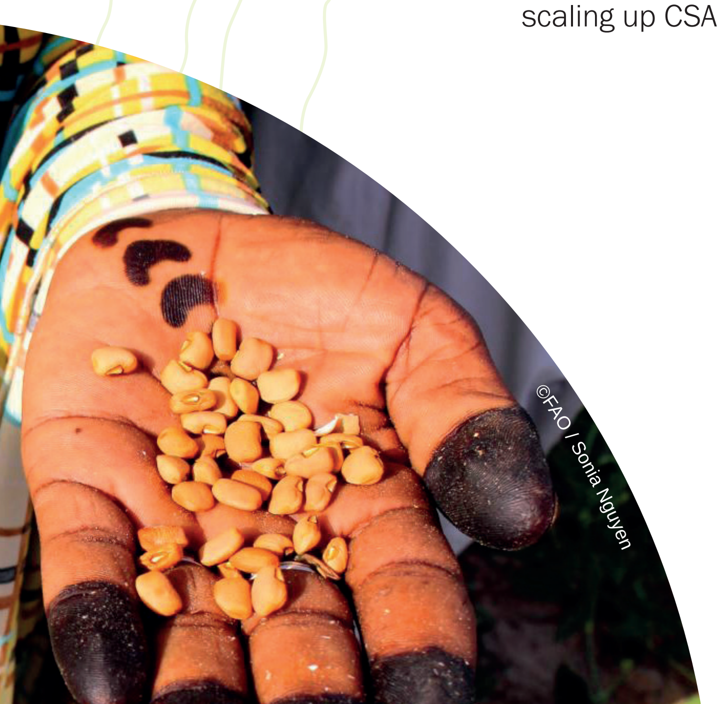
Sustainable mechanization, the use of smaller tractors, making fewer passes across the field, and reduced working hours, when combined with conservation agriculture reduces carbon dioxide emissions. These actions also minimize soil disturbance, and reduce soil erosion and degradation that are common in tillage-based crop systems (FAO, 2017). For intercrop systems, jab planters are effective.

Combined application of rhizobia inoculant, phosphorus and organic manure can improve grain yield of cowpea and reduce applications of inorganic fertilizers. In savanna soils, low concentrations of phosphorus and organic matter are the major constraints to productivity. The application of phosphorus fertilizer and organic manure could improve cowpea response to *Bradyrhizobium* inoculation (Ulzen *et al.*, 2020). This method can be a cost-effective fertilization option for risk-averse small-scale farmers.

3.5 Enabling policy environment

The transition to CSA, which involves the scaling up of specific climate-smart practices demands strong political commitment, as well as coherence and coordination among the various sectors dealing with climate change, agricultural development and food security. Before designing new policies, policymakers should systematically assess the effects of current agricultural and non-agricultural agreements and policies on the objectives of CSA while considering other national development priorities. They should exploit synergies between the three objectives of climate-smart agriculture (sustainable production, adaptation, and mitigation), as well as address potential trade-offs and if possible avoid, reduce or compensate for them. Understanding the socio-economic and gender-differentiated barriers and incentive mechanisms that affect the adoption of CSA practices is critical for designing and implementing supportive policies.

In addition to supportive policies, the enabling environment also encompasses fundamental institutional arrangements; stakeholder involvement and gender considerations; infrastructure; credit and insurance; and farmers' access to weather information, extension and advisory services, and input/output markets. The laws, regulations and incentives that underpin the enabling environment establish the foundation for sustainable climate-smart agricultural development. The development of institutional capacity is essential to support farmers and extension services, and reduce the risks that may discourage and prevent farmers from investing in proven new practices and technologies to enable them to adapt to the impacts of climate change. Institutions are a key organizing force for farmers and decision-makers and are critical for scaling up CSA practices.



3.6 Conclusion

Cowpea production systems will need to adapt to ensure they continue to contribute to food security, rural livelihoods and sustainable food systems under a changing climate. The specific adaptation and mitigation approaches will vary according to location. In cowpea producing regions, there are a wide variety of agro-ecological conditions, microclimates within the soil, climate risks and socio-economic contexts. It is crucial to collect data and information to determine the best course of action and adapt practices to local needs. This information allows for a continuous learning process and can also feed into the improvement of future policies. Close coordination and collaboration among stakeholders at all levels are needed to build an enabling environment that gives farmers opportunities to adopt targeted measures to enhance the productivity, resilience and sustainability of cowpea production in the face of climate change.

The precise challenges that will be created by climate change on cowpea production systems remains uncertain. These challenges will vary from one farming communities to another, but it is certain that they will be especially daunting for countries already coping with high levels of food insecurity. However, there is a clear way forward to meeting these challenges. Options include the adoption of context-specific good agronomic practices, such as conservation agriculture, efficient water and nutrient management and IPM. These options will complement the gains that can be made through the cultivation of improved varieties.

3.7 References

Abberton, M., Batley, J., Bentley, A., Bryant, J., Cai, H., Cockram, J., Costa de Oliveira, A., Cseke, L. J., Dempewolf, H., de Pace, C., Edwards, D., Gepts, P., Greenland, A., Hall, A. E., Henry, R., Hori, K., Howe, G. T., Hughes, S., Humphreys, M.,& Yano, M. 2016. Global agricultural intensification during climate change: A role for genomics. *Plant Biotechnology Journal*, 14(4):1095-1098. https://doi.org/10.1111/pbi.12467

Adati, T., Tamò, M., Yusuf, S. R., Downham, M. C. A., Singh, B. B. & Hammond, W. 2007. Integrated pest management for cowpea-cereal cropping systems in the West African savannah. *International Journal of Tropical Insect Science*, 27(3-4), 123-137. https://doi.org/10.1017/S1742758407883172

Addae, P. C., Ishiyaku, M. F., Tignegre, J. B., Ba, M. N., Bationo, J. B., Atokple, I. D. K., Abudulai, M., Dabiré-Binso, C. L., Traore, F., Saba, M., Umar, M. L., Adazebra, G. A., Onyekachi, F. N., Nemeth, M. A., Huesing, J. E., Beach, L. R., Higgins, T. J. V., Hellmich, R. L., Pittendrigh, B. R. & Peairs, F. 2020. Efficacy of a cry1Ab Gene for Control of Maruca vitrata (Lepidoptera: Crambidae) in Cowpea (Fabales: Fabaceae). *Journal of Economic Entomology*, 113(2):974-979, https://doi.org/10.1093/jee/toz367

Agunbiade, T. A., Sun, W., Coates, B. S., Traore, F., Ojo, J. A., Lutomia, A. N., Bello-Bravo, J., Miresmailli, S., Huesing, J. E., Agyekum, M., Tamò, M. & Pittendrigh, B. R. 2018. Insect pests and integrated pest management techniques in grain legume cultivation. In S. Sivasankar, ed. *Achieving sustainable cultivation of grain legumes, Volume 1: Advances in breeding and cultivation techniques*, pp. 1-24. London, Burleigh Dodds Science Publishing.

Agegnehu, G. & Amede, T. 2017. Integrated Soil Fertility and Plant Nutrient Management in Tropical Agro-Ecosystems: A Review. *Pedosphere*, 27 (4):662-680. https://doi.org/10.1016/S1002-0160(17)60382-5

Ahamefule, E. H. & Peter, P. C. 2014. Cowpea (*Vigna unguiculata* L. Walp.) response to phosphorus fertilizer under two tillage and mulch treatments. **Soil and Tillage Research**, 136:70-75. https://doi.org/10.1016/j.still.2013.09.012

Ajeigbe, H.A., Mohammed, S.G., Adeosun, J.O. & Ihedioha, D. I. 2010. *Farmers' guide to increased productivity of improved legume–cereal cropping systems in the savannas of Nigeria*. Ibadan, IITA.

Ajetomobi, J. & Abiodun, A. 2010. Climate change impacts on cowpea productivity in Nigeria. *African Journal of Food, Agriculture, Nutrition and Development*, 10(3). https://doi.org/10.4314/ajfand.v10i3.54082

Andow, D. A. 1991. Vegetational diversity and arthropod population response. *Annual Review of Entomology*, 36(1):561-586. https://doi.org/10.1146/annurev.en.36.010191.003021

ARCC (African and Latin American Resilience to Climate Change).2014. *A Review of Fifteen Crops Cultivated in the Sahel.* USAID.

Ba, M. N., Huesing, J. E., Tamò, M., Higgins, T. J. V., Pittendrigh, B. R. & Murdock, L. L. 2018. An assessment of the risk of Bt-cowpea to non-target organisms in West Africa. *Journal of Pest Science*, 91:1165-1179. https://doi.org/10.1007/s10340-018-0974-0

Batley, J. & Edwards, D. 2016. The application of genomics and bioinformatics to accelerate crop improvement in a changing climate. *Current Opinion in Plant Biology*, 30:78-81. https://doi.org/10.1016/j.pbi.2016.02.002

Belmain, S. & Stevenson, P. 2001. Ethnobotanicals in Ghana: Reviving and modernising age-old farmer practice. *Pesticide Outlook*, 12, 233-238. https://doi.org/10.1039/b110542f

Bowman, G., Shirley, C. & Cramer, C. 1998. *Managing Cover Crops Profitably*, second edition, Sustainable Agriculture Network.

Cairns, J. E., Sonder, K., Zaidi, P. H., Verhulst, N., Mahuku, G., Babu, R., Nair, S. K., Das, B., Govaerts, B., Vinayan, M. T., Rashid, Z., Noor, J. J., Devi, P., San Vicente, F. & Prasanna, B. M. 2012. Maize production in a changing climate: impacts, adaptation, and mitigation strategies. *Advances in Agronomy*, 114:1-58. https://doi.org/10.1016/B978-0-12-394275-3.00006-7

Cairns, J. E., Hellin, J., Sonder, K., Araus, J. L., MacRobert, J. F., Thierfelder, C. & Prasanna, B. M. 2013. Adapting maize production to climate change in sub-Saharan Africa. *Food Security,* 5(3):345-360. *https://doi.org/10.1007/s12571-013-0256-x*

CGIAR. 2019. The genetic improvement of cowpea: Develop high-yielding varieties. In: *CGIAR: News* [online]. [Cited 18 June 2021]. https://www.cgiar.org/news-events/news/the-genetic-improvement-of-cowpea-develop-high-yielding-varieties/

Casas, N.M. 2017. *Crop weather and climate vulnerability profiles.* Dublin, Concern Worldwide.

CONAB (Companhia Nacional de Abastecimento). 2018. Observatório Agrícola - Acompanhamento da safra brasileira de grãos, Vol. 5 -SAFRA 2017/18 - No. 6 -Sexto levantamento Março 2018. Brasília.

Corsi, S, Friedrich, T., Kassam, A., Pisante, M. & de Moraes Sà, J. 2012. *Soil Organic Carbon Accumulation and Greenhouse Gas Emission Reductions from Conservation Agriculture: A review of evidence*. Integrated Crop Management, Vol. 16. Rome, FAO.

Dhankher, O. P. & Foyer, C. H. 2018. Climate resilient crops for improving global food security and safety. *Plant Cell and Environment*, 41(5):877-884. https://doi.org/10.1111/pce.13207

Dumet D., Adeleke, R. & Faloye B. 2008. Regeneration guidelines: cowpea. In: M.E., Dulloo, I. Thormann I., M.A. Jorge & J. Hanson, eds. Crop specific regeneration guidelines [CD- ROM]. CGIAR System-wide Genetic Resource Programme, Rome, Italy.

Ekesi, S., Akpa, A. D., Onu, I. & Ogunlana, M. O. 2000. Entomopathogenicity of *Beauveria* bassiana and Metarhizium anisopliae to the cowpea aphid, *Aphis* ckoch (Homoptera: Aphididae). *Archives of Phytopathology and Plant Protection*, 33(2):171-180. https://doi.org/10.1080/03235400009383341

FAO. 2012. Guidelines on Prevention and Management of Pesticide Resistance. Rome. (also available at www.fao.org/publications/card/en/c/8dcf273c-c907-4e71-b5e5-8753a861de87/).

FAO. 2013. **Climate-Smart Agriculture Sourcebook**, first edition. Rome. (also available at www.fao.org/3/i3325e/i3325e.pdf).

FAO. 2016. Save and grow in practice: maize, rice and wheat - A guide to sustainable cereal production. Rome. (also available at www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1263072/).

FAO. 2017. Climate-Smart Agriculture Sourcebook, second edition [online]. [Cited 18 June 2021] http://www.fao.org/climate-smart-agriculture-sourcebook/about/en/

FAO. 2019. Sustainable Food Production and Climate Change. (also available at www.fao.org/3/ca7223en/CA7223EN.pdf).

FAO. 2020. What is Integrated Pest Management? In: FAO: *Plant Production and Protection Division* [online]. [Cited 18 June 2021]. http://www.fao.org/agriculture/crops/thematic-sitemap/theme/spi/scpi-home/managing-ecosystems/integrated-pest-management/ipm-what/en/#

FAO. 2021. FAOSTAT. *In: FAO* [online]. [Cited 24 July 2020]. http://faostat.fao.org

Fatokun, C.A., Togola, A., Ongom, P., Lopez, K. & Boukar, O. 2020. Cowpea receives more research support In: Research Program on Grain Legumes and Dryland Cereals: News Stories[online]. [Cited 15 August 2020]. https://www.cgiar.org/news-events/news/cowpea-receives-more-research-support/

Gaikwad, D. G. & Thottappilly, G. 1988. Occurrence of Southern Bean Mosaic Virus on Cowpea in Senegal. *Journal of Phytopathology,* 121(4)366-369. https://doi.org/10.1111/j.1439-0434.1988.tb00981.x

Gomez, C. 2004. *Cowpea: Post-harvest Operations.* Rome, FAO.

Guzzetti, L., Fiorini, A., Panzeri, D., Tommasi, N., Grassi, F., Taskin, E., Misci, C., Puglisi, E., Tabaglio, V., Galimberti, A. & Labra, M. 2020. Sustainability perspectives of *Vigna unguiculata* L. Walp. cultivation under no tillage and water stress conditions. *Plants*, 9(1):48. https://doi.org/10.3390/plants9010048

Hall, A. E. 2004. Breeding for adaptation to drought and heat in cowpea. *European Journal of Agronomy*, 21(4):447-454. https://doi.org/10.1016/j.eja.2004.07.005

Hall, A. E. 2012. Phenotyping cowpeas for adaptation to drought. *Frontiers in Physiology*, 3:155 https://doi.org/10.3389/fphys.2012.00155

Hall, A E, Ismail, A. M., Ehlers, J. D., Marfo, K. O., Cisse, N., Thiaw, S. & Close, T. J. 2002. Breeding cowpea for tolerance to temperature extremes and adaptation to drought. In C.A. Fatokun, S.A. Tarawal, B.B. Singh, P.M. Kormawa, & M. Tamo, eds. *Challenges and opportunities for enhancing sustainable cowpea production: Proceedings of the world cowpea conference III held at IITA, Ibadan, Nigeria, 4-8 September 2000*, pp.14-21. Ibadan, Nigeria, IITA.

ICRISAT. 2020. Government and research bodies expand seeds support to over 10 000 Nigerian smallholders to shield agriculture from Covid-19. In: *ICRISAT: ICRISAT Happenings Newsletter* [online]. [Cited 18 June 2021]. www.icrisat.org/government-and-research-bodies-expand-seeds-support/

IITA. 2019. Cowpea. In: *IITA:Crops* [online]. [Cited 15 August 2020]. https://www.iita.org/cropsnew/cowpea/

Jackai, L. 1982. A field screening technique for resistance of cowpea (Vigna unguiculata) to the pod-borer Maruca testulalis (Geyer) (Lepidoptera: Pyralidae). *Bulletin of Entomological Research,* 72(1), 145-156. https://doi.org/10.1017/S0007485300050379

Jackai, L. 1990. Screening of Cowpeas for Resistance to Clavigralla tomentosicollis Stål (Hemiptera: Coreidae). *Journal of Economic Entomology*, 83(2):300-305. https://doi.org/10.1093/jee/83.2.300

Javaid, I., Dadson, R. B., Hashem, F. M., Joshi, J. M. & Allen, A. L. 2005. Effect of insecticide spray applications, sowing dates and cultivar resistance on insect pests of cowpea in the Delmarva Region of the United States. *Journal of Sustainable Agriculture*, 26:3, 57-68. https://doi.org/10.1300/J064v26n03_07

Jayathilake, C., Visvanathan, R., Deen, A., Bangamuwage, R., Jayawardana, B. C., Nammi, S. & Liyanage, R. 2018. Cowpea: an overview on its nutritional facts and health benefits. In *Journal of the Science of Food and Agriculture,* 98(13);4793-4806. https://doi.org/10.1002/jsfa.9074

Kamara, A. Y., Omoigui, L. O., Kamai, N., Ewansiha, S. U. & Ajeigbe, H. A. 2018. *Improving cultivation of cowpea in West Africa*. In S. Sivasankar, D. Bergvinson, P.M. Gaur, S. Kumar, S. Beebe, & M. Tamo, eds. *Achieving sustainable cultivation of grain legumes. Volume 2: Improving cultivation of particular grain legumes*, pp.235-252. Burleigh Dodds Series in Agricultural Science (36). Cambridge, UK, Burleigh Dodds Science Publishing Limited. https://doi.org/10.19103/as.2017.0023.30

Karungi, J., Adipala, E., Ogenga-Latigo, M. W., Kyamanywa, S. & Oyobo, N. 2000. Pest management in cowpea. Part 1. Influence of planting time and plant density on cowpea field pests infestation in eastern Uganda. *Crop Protection*, 19(4):231-236. https://doi.org/10.1016/S0261-2194(00)00013-2

Kéita, S. M., Vincent, C., Schmit, J. P., Arnason, J. T. & Bélanger, A. 2001. Efficacy of essential oil of Ocimum basilicum L. and O. gratissimum L. applied as an insecticidal fumigant and powder to control Callosobruchus maculatus (Fab.) [Coleoptera: Bruchidae]. *Journal of Stored Products Research*, 37(4):339-349. https://doi.org/10.1016/S0022-474X(00)00034-5

Kole, C., Muthamilarasan, M., Henry, R., Edwards, D., Sharma, R., Abberton, M., Batley, J., Bentley, A., Blakeney, M., Bryant, J., Cai, H., Cakir, M., Cseke, L. J., Cockram, J., de Oliveira, A. C., de Pace, C., Dempewolf, H., Ellison, S., Gepts, P., Greenland, A., Hall, A., Hori, K., Howe, G.T., Hughes, S., Humphreys, M.W., Iorizzo, M., Ismail, A.M., Marshall, A., Mayes, S., Nguyen, H.T., Ogbonnaya, F.C., Ortiz, R., Paterson, A.H., Simon, P.W., Tohme, J., Tuberosa, R., Valliyodan, B., Varshney, R.K., Wullschleger, S.D., Yano, M. & Prasad, M. 2015. Application of genomics-assisted breeding for generation of climate resilient crops: Progress and prospects. *Frontiers in Plant Science*, 6:563. https://doi.org/10.3389/fpls.2015.00563

Kukal, S. S., Rasool, R. & Benbi, D. K. 2009. Soil organic carbon sequestration in relation to organic and inorganic fertilization in rice-wheat and maize-wheat systems. *Soil and Tillage Research*, 102(1):87-92. https://doi.org/10.1016/j.still.2008.07.017

Kulkarni, K. P., Tayade, R., Asekova, S., Song, J. T., Shannon, J. G. & Lee, J. D. 2018. Harnessing the potential of forage legumes, alfalfa, soybean, and cowpea for sustainable agriculture and global food security. *Frontiers in Plant Science*. 9:1314. https://doi.org/10.3389/fpls.2018.01314

Kurukulasuriya, P. & Mendelsohn, R. 2006. *Crop selection: adapting to climate change in Africa*. CEEPA *Discussion Paper No. 26*. Centre for Environmental Economics and Policy in Africa, University of Pretoria.

Lucas, M. R., Ehlers, J. D., Huynh, B. L., Diop, N. N., Roberts, P. A. & Close, T. J. 2013. Markers for breeding heat-tolerant cowpea. *Molecular Breeding*, 31:529–536. https://doi.org/10.1007/s11032-012-9810-z

Moroke, T. S., Schwartz, R. C., Brown, K. W. & Juo, A. S. R. 2011. Water use efficiency of dryland cowpea, sorghum and sunflower under reduced tillage. *Soil and Tillage Research*, 112(1):76-84. https://doi.org/10.1016/j.still.2010.11.008

Mosier, A., Syers, J.K. & Freney, J. R. 2013. *Agriculture and the nitrogen cycle: assessing the impacts of fertilizer use on food production and the environment*. SCOPE Report, No. 65. Washington, D.C., Island Press.

Mousavi-Derazmahalleh, M., Bayer, P. E., Hane, J. K., Valliyodan, B., Nguyen, H. T., Nelson, M. N., Erskine, W., Varshney, R. K., Papa, R. & Edwards, D. 2019. Adapting legume crops to climate change using genomic approaches. *Plant Cell and Environment.*, 42(1):6-19. https://doi.org/10.1111/pce.13203

Oghiakhe, S., Jackai, L. E. N. & Makanjuola, W. A. 1995. Evaluation of cowpea genotypes for field resistance to the legume pod borer, Maruca testulalis, in Nigeria. *Crop Protection*, 14(5):389-394. https://doi.org/10.1016/0261-2194(95)98918-L

Opolot, H. N., Agona, A., Kyamanywa, S., Mbata, G. N. & Adipala, E. 2006. Integrated field management of cowpea pests using selected synthetic and botanical pesticides. *Crop Protection*, 25(11):1145-1152. https://doi.org/10.1016/j.cropro.2005.03.019

Paul, A. 2020. Legume Farmer Fab Labs Design Seeds That Work For Family Farms, Women And The Market. In: ICRISAT: *ICRISAT Happenings Newsletter* [online]. [Cited 18 June 2021]. https://www.icrisat.org/legume-farmer-fab-labs-design-seeds-that-work-for-family-farms-women-and-the-market/

Plaza-Bonilla, D., Cantero-Martínez, C., Bareche, J., Arrúe, J. L., Lampurlanés, J. & Álvaro-Fuentes, J. 2017. Do no-till and pig slurry application improve barley yield and water and nitrogen use efficiencies in rainfed Mediterranean conditions? *Field Crops Research*, 203:74-85. https://doi.org/10.1016/j.fcr.2016.12.008

Pradhan, A., Chan, C., Roul, P. K., Halbrendt, J. & Sipes, B. 2018. Potential of conservation agriculture (CA) for climate change adaptation and food security under rainfed uplands of India: A transdisciplinary approach. *Agricultural Systems,* 163:27-35. https://doi.org/10.1016/j.agsy.2017.01.002

Raja, N., Albert, S., Ignacimuthu, S. & Dorn, S. 2001. Effect of plant volatile oils in protecting stored cowpea Vigna unguiculata (L.) Walpers against Callosobruchus maculatus (F.) (Coleoptera: Bruchidae) infestation. *Journal of Stored Products Research*, 37(2):127-132. https://doi.org/10.1016/S0022-474X(00)00014-X

Sánchez-Navarro, V., Marcos-Pérez, M. & Zornoza, R. 2020. A comparison between vegetable intercropping systems and monocultures in greenhouse gas emissions under organic management. *22nd European Geosciences Union (EGU) General Assembly, held online 4-8 May, 2020*.

Sangakkara, U. R., Frehner, M. & Nösberger, J. 2001. Influence of soil moisture and fertilizer potassium on the vegetative growth of mungbean (Vigna radiata L. Wilczek) and cowpea (Vigna unguiculata L. Walp.). *Journal of Agronomy and Crop Science*, 186(2);73-81. https://doi.org/10.1046/j.1439-037X.2001.00433.x

Sapkota, T. B., Jat, M. L., Aryal, J. P., Jat, R. K. & Khatri-Chhetri, A. 2015. Climate change adaptation, greenhouse gas mitigation and economic profitability of conservation agriculture: Some examples from cereal systems of Indo-Gangetic Plains. *Journal of Integrative Agriculture,* 14(8):1524-1533. https://doi.org/10.1016/S2095-3119(15)61093-0

Sapkota, T. B., Jat, R. K., Singh, R. G., Jat, M. L., Stirling, C. M., Jat, M. K., Bijarniya, D., Kumar, M., Yadvinder-Singh, Y. S., Saharawat, Y. S. & Gupta, R. K. 2017. Soil organic carbon changes after seven years of conservation agriculture in a rice–wheat system of the eastern Indo-Gangetic Plains. *Soil Use and Management*, 33(1):81-89. https://doi.org/10.1111/sum.12331

Semenov, M. A. & Halford, N. G. 2009. Identifying target traits and molecular mechanisms for wheat breeding under a changing climate. *Journal of Experimental Botany,* 60(10):2791-2804. https://doi.org/10.1093/jxb/erp164

Singh, B. B. & Tarawali, S. A. 1997. Cowpea and its improvement: key to sustainable mixed crop/livestock farming systems in West Africa. In C. Renard, ed., *Crop Residues in Sustainable Mixed Crop/Livestock Farming Systems*, pp. 79–100. ICRISAT

Singh, B. B., Ajeigbe, H. A., Tarawali, S. A., Fernandez-Rivera, S. & Abubakar, M. 2003. Improving the production and utilization of cowpea as food and fodder. *Field Crops Research*, 84(1-2):169-177. https://doi.org/10.1016/S0378-4290(03)00148-5

Singh, B. B. & Ajeigbe, H. 2007. Improved cowpea-cereals-based cropping systems for household food security and poverty reduction in West Africa. *Journal of Crop Improvement*, 19(1-2):157-172.
https://doi.org/10.1300/J411v19n01_08

Singh, B. B. ., Musa, A., Ajeigbe, H. A. & Tarawali, S. A. 2011. Effect of feeding crop residues of different cereals and legumes on weight gain of Yankassa rams. *International Journal of Livestock Production*, 2(2):17-23.

Singh, B. B. 2014. *Cowpea: The Food Legume of the 21st Century*. Madison, Wisconsin, USA, Crop Science Society of America.
https://acsess.onlinelibrary.wiley.com/doi/book/10.2135/2014.cowpea

Singh, B. B. 2016. Genetic enhancement for yield and nutritional quality in cowpea [Vigna unguiculata (L.) Walp.]. *Indian Journal of Genetics and Plant Breeding,* 76(4):568-582.
https://doi.org/10.5958/0975-6906.2016.00073.0

Sivasankar, S., ed. 2018. *Achieving sustainable cultivation of grain legumes, Volume 1: Advances in breeding and cultivation techniques*. London, Burleigh Dodds Science Publishing.
https://doi.org/10.1201/9781351114424

Timko, M.P. & Singh, B.B. 2008. Cowpea, a Multifunctional Legume. In P.H. Moore, R. Ming, eds. *Genomics of Tropical Crop Plants, Plant Genetics and Genomics: Crops and Models, vol 1*, pp 227-258. New York, NY, Springer.

Tumuhaise, V., Ekesi, S., Mohamed, S. A., Ndegwa, P. N., Irungu, L. W., Srinivasan, R. & Maniania, N. K. 2015. Pathogenicity and performance of two candidate isolates of Metarhizium anisopliae and Beauveria bassiana (Hypocreales: Clavicipitaceae) in four liquid culture media for the management of the legume pod borer Maruca vitrata (Lepidoptera: Crambidae). *International Journal of Tropical Insect Science*, 35(1):34-47.
https://doi.org/10.1017/S1742758414000605

Ulzen, J., Abaidoo, R. C., Ewusi-Mensah, N. & Masso, C. 2019. Combined application of inoculant, phosphorus and organic manure improves grain yield of cowpea. *Archives of Agronomy and Soil Science*, 66(10):1358-1372. https://doi.org/10.1080/03650340.2019.1669786

Wyckhuys, K. A. G., Lu, Y., Morales, H., Vazquez, L. L., Legaspi, J. C., Eliopoulos, P. A. & Hernandez, L. M. 2013. Current status and potential of conservation biological control for agriculture in the developing world. *Biological Control*, 65(1):152-167. https://doi.org/10.1016/j.biocontrol.2012.11.010

Yusuf S. R. 2005. Infestation and damage by *Maruca vitrata* Fabricius (Lepidoptera: Pyralidae) on some cowpea lines under different cropping systems in Kano, Nigeria. Abubakar Tafawa Balewa University, Bauchi. (PhD thesis)

4. Sustainable maize production

Adapting production systems to changing climatic conditions and reducing environmental impacts

H. Jacobs, S. Corsi, C. Mba, M. Taguchi, J. Kienzle,
H. Muminjanov, B. Hadi, F. Beed, P. Lidder and H. Kim

©FAO / Marco Salustro

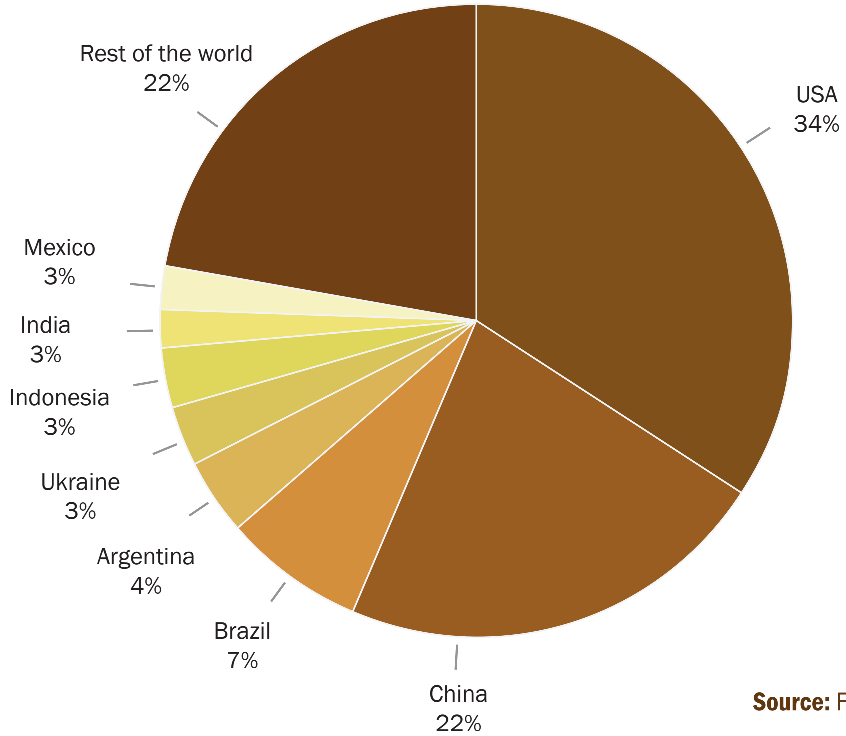
©FAO / Sergey Kozmin

4.1 Introduction

Maize is one of the world's most widely cultivated crops because of its adaptability and the many ways it can be used as a source of food, feed, fiber and fuel. It is crucial for food security, particularly in developing countries. The negative impacts of climate change on maize yields have already been observed in various regions. These impacts are expected to become more pronounced and will have profound consequences for farmers' livelihoods and food security. This briefing note describes climate change adaptation and mitigation approaches that are available to support a transition to more sustainable and resilient maize production systems. It also highlights synergies with the 2030 Agenda for Sustainable Development. Strong political commitment, supportive institutions and investments are essential to bring these climate-smart solutions to farmers and enable their widespread adoption. Increased uptake of these approaches will in turn enhance yield and income stability, ensure food security, and contribute to building resilient, sustainable and low-emission food systems.

Maize (*Zea mays*) is the one of the world's most important cereals. This multipurpose crop can be used for food, feed, fodder and in various industrial processes. It ranks behind only wheat and rice as the crop most directly consumed by people as food. In developed countries, over 70 percent of maize is used for animal feed; only three percent is eaten by people. This stands in stark contrast to the situation in sub-Saharan Africa where 77 percent of maize is used for food and only 12 percent for feed (Shiferaw *et al.*, 2011).

Figure 1: Share of maize production by country (tonnes), 2018



Source: FAO, 2021

In large parts of sub-Saharan Africa, maize is the principal staple crop, accounting for an average of 30 percent of consumed calories in southern Africa in 2017 (FAO, 2021).

Maize is one of the most widely produced and highly traded crops in the world by volume. However, only a few countries produce the majority of the world's supply. In 2018, the top-ranking countries in order of maize production were the United States, China, Brazil, Argentina, Ukraine, Indonesia, India and Mexico. The total world production in 2018 was about 1.2 billion tonnes of grain from 194 million ha (FAO, 2021).

Between 2010 and 2050, demand for maize is projected to double in developing countries (Shiferaw *et al.* 2011; Nelson *et al.*, 2010). It is clear that maize production is fundamental to food and nutritional security of millions of small-scale farmers and their families and consumers all over the world.

This brief, which serves as a companion to the Climate-smart Agriculture (CSA) Sourcebook (FAO, 2017), summarizes the best practices for maize production systems under different climate change scenarios. It is intended to provide a reference for policymakers, researchers and other groups and individuals working to support sustainable crop production and intensification. Written in plain language with case studies, this brief provides a checklist of actionable interventions that could be adopted to enhance or sustain the productivity of maize production systems that are at risk from climate change.

The strategies for sustainable maize production presented in this brief address the three pillars of CSA: sustainably increasing agricultural productivity and incomes; adapting and building resilience to climate change; and reducing and/or removing greenhouse gas (GHG) emissions, where possible. The strategies can serve to both adapt maize production systems to increased biotic and abiotic stresses that result from changing climatic conditions, and reduce the GHG emissions from these systems. This maize-focused brief is one in a series of crop-specific briefs for CSA.

4.2 Impacts of climate change and projections for maize

Maize is a versatile annual crop with wide genetic diversity. It is a crop that can produce hybrids with high yields and varying degrees of adaptability to a wide range of climate conditions. The crop is cultivated in a range of agro-climatic zones in latitudes between 40° S to 52° N; at altitudes from sea-level to over 3 800 m; and under temperatures in the range of 21 °C and 30 °C, with 25°C to 30 °C being considered optimal.[3] Global mean yields of maize are estimated to have decreased by 4.1 percent during the period 1981–2010 (Iizumi *et al.*, 2018). However, there is a marked geographical pattern in changes in yields, with increases projected at the middle and high latitudes, and yield losses occurring at lower latitudes. An increase in temperature of 2 °C would result in a greater reduction in maize yields in sub-Saharan Africa than a 20 percent decrease in precipitation (Lobell *et al.*, 2011).

Tigchelaar *et al.* (2018) determined that, with a few exceptions (e.g. some locations in western Europe and China), maize yields would decline everywhere in response to 2 °C increase in temperature. Declines would be especially noted in the southeastern United States, eastern Europe, and southeastern Africa.

Reductions in maize yield, particularly in developing countries, may lower the incomes of small-scale farmers (**Target 2.3**), affecting local and national food security (**SDG 2, Targets 2.1 and 2.2**).

These reductions may also hinder efforts to end poverty (**SDG 1**) and reduce inequalities (**SDG 10**), and will particularly affect the most vulnerable and marginalized members of society, including subsistence farmers.

The warming climate increases the metabolic rates of insect pests and the growth of their population, which could potentially increase yield losses from pests that feed on plant material (herbivory). An increase of 2 °C in temperatures is associated with a 31 percent higher median yield loss in maize due to insect pests compared to the current losses. The global distribution of future additional losses is not uniform, with higher additional losses predicted in temperate regions (Deutsch *et al.* 2018).

A 2018 FAO report projected that climate change would cause yields of staple crops to decline of 5 percent by 2050 compared to 2012 (FAO, 2018). (The projection did not account for the potential effects of carbon dioxide fertilization – a higher rate of photosynthesis resulting from increased levels of atmospheric carbon dioxide). These reductions are expected to have a greater impact on developing countries. Recent studies have indicated that

3 Ecological requirements for different stages of plant growth are available from the FAO Land and Water website at: http://www.fao.org/land-water/databases-and-software/crop-information/maize/en/.

yield loss for each degree increase in global mean temperature is potentially largest for maize (Zhao *et al.*, 2017). Impact estimates for changes in yields in the four major maize producing countries that are responsible for two-thirds of global maize production are: United States of America - between −10.3 and +5.4 percent per degree Celsius; China - between −8.0 and +6.1 percent per degree Celsius; Brazil - between −5.5 and +4.5 percent per degree Celsius; and India between −5.2 and + 4.5 percent per degree Celsius.

Impacts of maize production on climate change. In addition to being affected by climate change, maize production also generates GHG emissions. In maize production systems, the primary sources of GHG emissions are associated with conventional crop production practices. These practices include conventional tillage, which leads to a loss of soil organic carbon; the use of nitrogen fertilizers and pesticides, which contribute to GHG emissions of non-carbon dioxide GHGs (e.g. nitrous oxide); and direct emissions from agricultural operations (e.g. electricity consumption for irrigation and fuel consumption in agricultural machinery). These impacts and approaches for their mitigation are discussed in Section III.

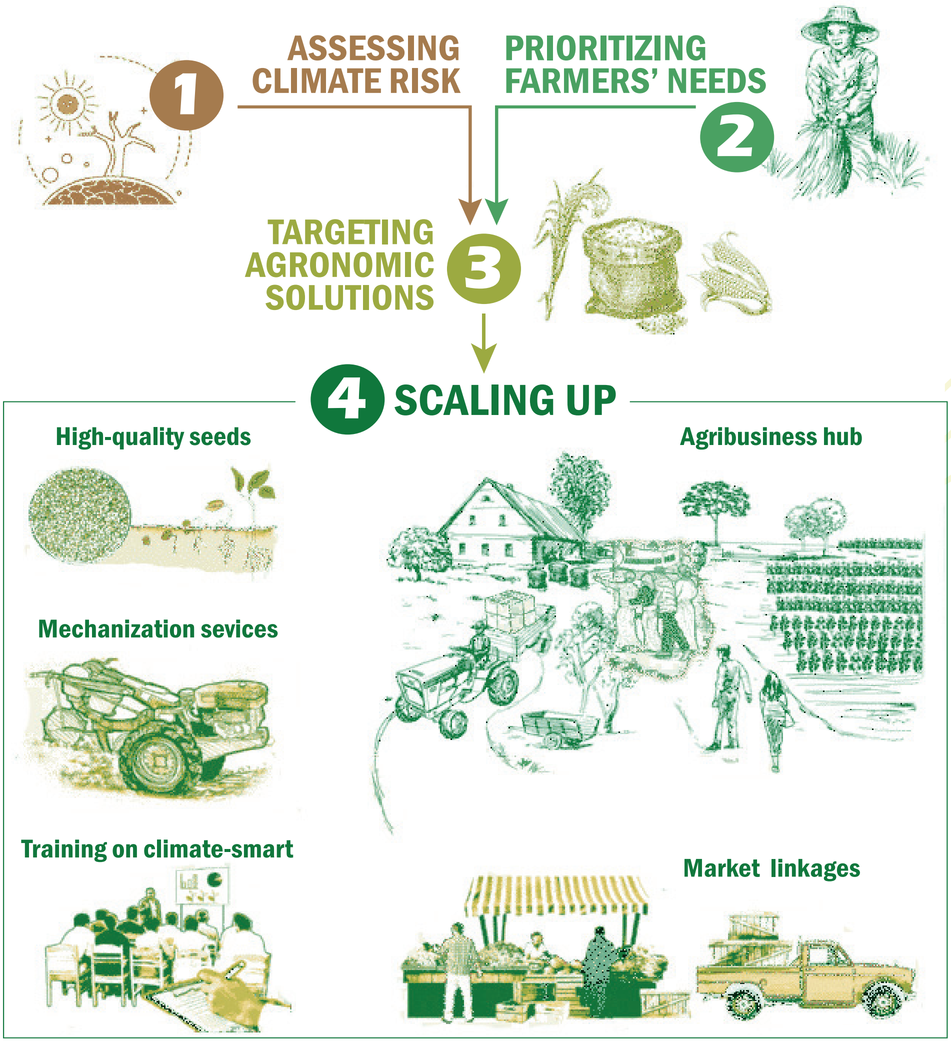
4.3 Climate change adaptation approaches

Higher temperatures, shifts in rainfall regimes, changes in the distribution patterns of maize pests and more frequent and more extreme weather events, (e.g. heat waves and cyclones) are examples of the challenges that maize farmers will face as climate changes. Maize production systems need to become more resilient to climate hazards, and the adaptive capacities of maize farmers need to be strengthened. Progress in this area will contribute to achieving Sustainable Development Goal (SDG) 13 (Climate Action), particularly in reaching SDG Target 13.1. Key approaches for reaching these objectives include conservation agriculture, the use of improved crops and varieties, efficient water management, and integrated pest management. Enabling policies and legislation are instrumental to enable farmers to adopt these climate-smart practices. Extension and climate information services, and farmers' access to specific technologies and inputs are also critical. Public-private partnerships that support local seed systems, which provide small-scale farmers with access to affordable improved seed, are an example of the type of institutional arrangement that is required

FAO works with countries to reduce the impacts of climate change on crop productivity and the contributions crop production systems make to climate change. Based on lessons learned in the field, FAO (2019) has proposed a four-step approach to climate change adaptation and mitigation:

1) assess climate risk;
2) prioritize farmers' needs;
3) target agronomic solutions; and
4) scale up successful interventions.

Figure 2: The Save and Grow approach



Source: FAO, 2019

The FAO 'Save and Grow' approach to sustainable crop production intensification relates to step 3 in this four-step sequence. The 'Save and Grow' approach consists of practices that include conservation agriculture; the use of improved crops and varieties; efficient water management; and integrated pest management (IPM). This section describes in greater detail the application of these practices in maize-based production systems.

4.3.1. Conservation agriculture

Conservation agriculture is a sustainable agronomic management system that combines zero or reduced tillage, the maintenance of soil surface cover with mulch or cover crops, and the diversification of crop production (Cairns *et al.*, 2013; FAO, 2016; 2017). Disturbing the soil with farm machinery causes organic matter to decompose rapidly, which reduces soil fertility and damages soil structure.

Actions

Enhancing the water regulation capacities of agricultural soils increases water use efficiency (**Target 6.4**), enhances water quality (**Target 6.3**) and improves access to safe drinking water (**Target 6.1**), ultimately contributing to ensuring the availability and sustainable management of water resources (**SDG 6**).

Zero-tillage or direct seeding involves the precise placement of maize seeds by drilling or opening a seed line through the previous crop's residues without the mechanical preparation of the seedbed. It enhances soil organic matter content (Sapkota *et al.*, 2017), which improves water infiltration and retention, increases water use productivity, and reduces erosion (Sapkota *et al.*, 2015). Recommended **sustainable mechanization equipment** includes two-wheeled tractors, jab planters and mechanized direct seeders (Sims and Kienzle, 2015; FAO, 2016).

Cover crops and mulch on the soil surface conserve soil moisture, reduce erosion, increase water infiltration and suppress weeds. Integrating nitrogen-fixing green manure cover crops maximizes nitrogen fixation and improves nitrogen use efficiency, which can enable farmers to reduce their use of external inputs over the long term. Different green manure cover crop species of edible and nonedible legumes (perennial, biennial and annual) can be used in combinations to maintain a supply of crop nutrients and strengthen the overall production system.

Because crop residues decompose slowly, and the microorganisms that drive the decomposition process require nitrogen, conservation agriculture can temporarily keep nitrogen from the soil and make it unavailable to plants (Verhulst *et al.*, 2014; Vanlauwe *et al.*, 2014). In the first years, after converting to conservation agriculture, farmers can compensate for this by increasing the application of nitrogen fertilizer (mineral or organic).

Improved nutrient management, erosion protection and diversification of cropping and farming systems all contribute to building more sustainable and resilient food systems (**SDG Target 2.4**) and to ensuring the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services (**SDG Target 15.1**).

Diversification is also a strategy to achieve higher levels of economic productivity (**SDG Target 8.2**).

Minimizing nutrient losses from the use of fertilizers contributes to the reduction of marine pollution from land-based activities (**SDG Target 14.1**).

Diversification of crop production should be promoted to avoid maize monocultures and continuous cropping. In maize production systems, the soil must be replenished with abundant amounts of nitrogen, which can be partly supplied by including legumes in the crop rotation. Growing different crops in succession reduces and prevents soil erosion caused by floods and drought; controls weeds, pests and diseases; and decreases the need for fertilizers and herbicides. Crop species and varieties and their combinations should be adapted to each farming system. Cultivating legumes (e.g. velvet pea, cowpea, pigeon pea, chickpea, climbing bean and soybean) in rotation with maize can enrich the soil with nitrogen and can produce a higher yield. Maize-legume systems are suitable for both rainfed and irrigated cultivation in temperate and sub-tropical areas. These systems can be implemented using three general methods:

- **intercropping**, which involves planting maize and legumes simultaneously in the same row or alternating rows;
- **relay cropping**, which involves planting maize and legumes on different dates but cultivating them together for a part of their life cycle; and
- **rotation**, which involves planting maize after the legumes have been harvested.

Diversification of the production system

In addition to adopting measures aimed at adapting specialized crop-based systems to changing climatic conditions, diversifying production through the integration of livestock and tree species is a widespread practice for coping with change, especially in small-scale farming systems. Agricultural systems that integrate crop and livestock production and agroforestry are common in the tropics. Integrated crop livestock systems produce over 90 percent of the world's milk supply and 80 percent of the meat from ruminant animals (Herrero *et al.*, 2013). These systems also provide most of the staple crops consumed in developing countries, including between 41 and 86 percent of the maize, rice, sorghum and millet, as well as 75 percent of milk, and 60 percent of the meat (Herrero *et al.*, 2010). One example is the integrated maize-livestock system in Latin America that incorporates *Brachiaria* grass.

Box 1: Integrated maize-livestock systems in Latin America

Many livestock farmers in Latin America have adopted a sustainable livestock production system that integrates forages with cereals to improve the quantity and quality of feed, and increase ruminant productivity. Brazilian farmers are incorporating *Brachiaria* into a direct-seeded maize system to replace soybean monocropping. *Brachiaria* is a grass that grows well in poor soils, tolerates heavy grazing and is resistant to pests and diseases. It has an ample root system that restores soil structure and helps prevent soil compaction. Zero-tillage systems using *Brachiaria* produce up to three cereal crops a year. The forages produce large amounts of biomass in the dry season that can be grazed or used as green manure. Relay cropping *Brachiaria* with maize makes better use of the whole farm area and causes less pasture degradation.

Source: FAO, 2016

4.3.2. Improved crops and varieties

The cultivation of climate-resilient maize varieties has been shown to increase yields, reduce yield variability and ultimately increase food security and nutrition (Cairns and Prasanna, 2018). There has been significant progress in the development of climate-resilient maize varieties over the last decade. For example elite heat-tolerant maize varieties have been developed and released in South Asia, and over 70 000 tonnes of seeds of drought-tolerant maize varieties have been sold in 13 sub-Saharan countries (Cairns and Prasanna, 2018).

It is necessary to integrate modern tools and strategies in maize breeding and increase the pace, precision and efficiency of the processes (Cairns and Prasanna, 2018). Strengthening seed systems is also important. Farmers acquire seeds for important food security crops like maize from formal systems and/or informal systems (FAO, 2017). Farmers often have limited purchasing capacity and market access. Consequently, seed enterprises, especially the community-based enterprises that cater to resource-poor farmers, need to be given information on new varieties. They must also be provided with adequate and reliable supplies of early-generation (breeder and foundation) seed in order to deliver improved varieties to farmers in a timely manner and at affordable prices (Atlin *et al.*, 2017; Cairns and Prasanna, 2018). This also requires appropriate government policies and seed laws (Cairns and Prasanna, 2018).

Actions

Breeding for climate-related traits is an important adaptive measure for all types of farms. Each of the past three decades have been significantly warmer than the previous, and old varieties are becoming increasingly unsuitable for current conditions (Atlin *et al.*, 2017). One way to address this constraint is to reduce the length of the breeding cycle so that improved varieties can be developed more rapidly (Atlin *et al.*, 2017; Cairns and Prasanna, 2018). There is large variation in the types of maize varieties cultivated by small-scale farmers. In southern and eastern Africa, hybrids are the dominant form, and hybrid use is also increasing rapidly in Ghana and Nigeria. Many

> The use of landraces and crop wild relatives in plant breeding contributes to maintaining the genetic diversity in cultivated plants (**SDG Target 2.5**).

farmers in Southern Africa and Latin America grow several varieties at once, including hybrids and open-pollinated varieties. A decision on what type of climate-resilient variety to breed (i.e. hybrid vs. open-pollinated) must be based on the prevailing farming practices in the region or country.

Forging public-private partnerships to improve seed supply is becoming increasingly important. The seed of maize hybrids is typically produced by the private sector, while seed of the open-pollinated varieties is produced by non-governmental organizations and community-based organizations (FAO, 2016). Brazil, China and International Maize and Wheat Improvement Center (CIMMYT) have established public-private partnerships in which improved maize lines are provided to the private sector for the production and marketing of hybrid seed in exchange for funding or other research support (FAO, 2016). Partnerships led by CIMMYT have been operating successfully for several years in Africa (see Box 2).

Switch crop varieties or species. Switching to maize varieties that are more resilient to climatic stress is a valid climate change adaptation strategy. However, in some cases, it may be possible and necessary to shift to a different new crop. For example, in eastern and southern Africa, cassava is a potential alternative to maize, as it can be grown in marginal soils and tolerates heat and drought (Jarvis *et al.*, 2012).

Box 2: Partnerships for improved maize varieties

The **Drought Tolerant Maize for Africa (DTMA)** and the **Stress Tolerant Maize for Africa (STMA)** projects, jointly implemented by CIMMYT and International Institute of Tropical Agriculture (IITA), led to the development and commercialization of several improved maize varieties in sub-Saharan Africa. Grain yields under moderate drought stress increased by at least one tonne per hectare. In addition to drought tolerance, the new varieties and hybrids also have resistance to major diseases affecting maize in sub-Saharan Africa. The DTMA and STMA projects strengthened the capacity of African seed companies and national research institutions. These projects engaged government officials in policy dialogue to help foster competitive seed markets and give producers greater access to quality seed at affordable prices. The **Accelerated Genetic Gains for Maize and Wheat Improvement (AGG)** project, which started in April 2020, builds on the foundation established by the DTMA and STMA projects.

For information on DTMA, go to:
www.cimmyt.org/projects/drought-tolerant-maize-for-africa-dtma/

For information on STMA, go to:
www.cimmyt.org/projects/stress-tolerant-maize-for-africa-stma/

4.3.3. Efficient water management

Efficient water management in maize cropping systems, which can be achieved, for example, through efficient irrigation technologies and management, contributes to ensuring the sustainable management of water resources (**SDG 6**), and to increasing water use efficiency in particular (**Target 6.4**).

Maize generally needs rainfall of between 500 mm and 1 200 mm over the course of the growing season. Because it is mainly grown as a rainfed crop, maize is highly vulnerable to fluctuations in rainfall and temperatures. The impacts of changing precipitation patterns will be particularly pronounced when combined with higher temperatures that affect evapotranspiration and increase moisture loss. Adapting to these changes will require a combination of sound agronomic and soil management practices. This will include retaining residues on crop surface and reducing tillage; making better use of irrigation technologies if they are available; and achieving a balanced use of surface and groundwater resources.

Actions

Shift planting dates. Increased climate variability and change in the beginning and/or the end of the growing season requires shifting planting dates. Another option is cultivating new varieties to cope with changes in the length of the growing season or avoid situations where the levels of moisture and temperature are not appropriate for the stage the crop has reached in its development (FAO, 2017).

Broad bed and furrow. For maize in rainfed areas, CIMMYT and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) have promoted a method of permanent raised-bed systems that enhance water productivity. This 'broad bed and furrow' system is a soil and moisture conservation and drainage technology for clay soils that are frequently waterlogged during the rainy season. Crops are planted using precision seeders on sloping beds that conserve water and channel excess runoff to tanks for later use.

Conservation agriculture practices (see Section II) can be used to enhance water-holding capacity and reduce evaporation losses. Maintaining sufficient levels of soil organic matter also helps bolster water productivity (FAO, 2016).

4.3.4. Integrated pest management

Pests and diseases

The pests and diseases that inflict the most damage to maize are southern rust, fall armyworm, *Fusarium* and *Gibberella* stalk rots, African corn borer and viral diseases (e.g. maize lethal necrosis disease). Increased rainfall and humidity in sub-Saharan Africa and Asia are expected to reduce maize yields by increasing the number, severity and distribution of fungal diseases (FAO, 2016). Higher temperatures are associated with increased feeding capacity of individual pests and larger populations (Deutsch *et al.*, 2018). Additionally, the distribution ranges of some key maize pests are likely to expand as temperatures increase (Diffenbaugh *et al.*, 2008; Kocmánková *et al.*, 2011).

Actions

Integrated pest management (IPM) is an ecosystem approach to crop production and protection that was developed in response to the widespread overuse of pesticides. In IPM, farmers use natural methods based on field observation to manage pests. Methods include biological control (i.e. the use of natural enemies of pests); the use of resistant varieties; habitat and cultural modification (i.e. the removal and introduction of certain elements from the cropping environment to reduce its suitability for pests). The rational and safe application of selective pesticides is used as a last resort (FAO, 2016). IPM capitalizes on natural pest management mechanisms that maintain a balance between pests and their natural enemies. Examples of non-chemical methods include use of resistant varieties (Cairns *et al.*, 2012); manipulating habitat around production fields to provide additional food and shelter to conserve natural enemies (Wyckhuis *et al.*, 2013); applying mineral or edible oils to maize whorls and silks, and biopesticides for fall armyworm. Inter-row cultivation can be effective in fighting weed infestations and also helps the soil retain moisture (FAO, 2017).

> IPM, which emphasizes the minimal use of harmful chemical pesticides, contributes to the sustainable management of terrestrial ecosystems (**SDG Target 15.1**) and reduces marine pollution from land-based activities (**SDG Target 14.1**).
>
> The successful implementation of IPM, which can prevent infestations that can severely damage crops and cause famine, contributes to **SDG Target 2.1**.
>
> IPM contributes to the sound management of chemicals throughout their life cycle and reduces their release into the air, water and soil, which minimizes impacts on human health and the environment (**SDG Target 12.4**).
>
> IPM can also benefit human health by reducing illnesses caused by air, water and soil pollution and contamination (**SDG Target 3.9**).

Fall armyworm in Africa: a guide for integrated pest management (Prasanna *et al.*, eds., 2018), which compiles currently available, scientifically validated strategies to control fall armyworm, is an important guide for managing this pest. There is an urgent need to generate awareness among farming communities about the life stages of the fall armyworm. This involves scouting for the pest, as well as its natural enemies; understanding the correct stages in its life cycle for pest control; and implementing low-cost agronomic practices and other landscape management practices for sustainable management of the pest. These strategies build on the research and field experience of countries (Brazil and the United States of America) that have dealt with infestations of fall armyworm. As much of the available evidence on fall armyworm control methods in Africa is preliminary, the Guide presents the best management strategies that have either been validated or are in the process of validation in Africa. Future editions of the Guide, which is a living document that is updated regularly, will reflect the rapidly evolving African experience with fall armyworm and provide opportunities to expand and refine local IPM approaches in light of new knowledge and tools.

Box 3: The push-pull system

The IPM push-pull system in East Africa has been adopted across Ethiopia, Kenya, Uganda, and the United Republic of Tanzania. The system harnesses the complex chemical interactions within systems where maize is intercropped with the leguminous plant Desmodium, and Napier grass is planted as a border around the field. Desmodium produces chemicals that attract predators of stem borers, which are the larva of an indigenous moth and one of the most damaging maize pests. The chemicals give a false distress signal to the moths that the area is already infested. The chemicals 'push' the moths to lay eggs in places where there is less competition for food. Chemicals produced by the Napier grass 'pull' the moths toward them and release a sticky substance that traps larvae as they feed on the stems. Napier grass also attracts stem borer predators. This method works in the same way for the parasitic weed, Striga, with Desmodium serving as a 'false host'. The push-pull system has been proven to work extremely well compared to maize planted in monocultures. The system also provides soil cover to retain soil moisture and prevent erosion.

Source: FAO, 2016

4.4 Climate change mitigation approaches

A range of options exist to enable maize production systems to support climate change mitigation and contribute to global efforts to reach **SDG 13**, particularly as measured by **SDG Indicator 13.2.2**, reduction of national GHG emissions. The options available for mitigation strategies in maize can improve carbon sequestration in the agricultural ecosystem and reduce GHG emissions. These options increase resource use efficiency and prevent soil erosion and nutrient losses. Key elements for mitigation strategies include the diversification of crop production, agroforestry, precision farming, sustainable mechanization and a reduced reliance on chemical fertilizers. Many of these strategies deliver co-benefits to the environment and human health, and may generate greater economic returns for farmers and farming communities.

To reduce GHG in maize production systems, the following strategies should be used.

4.4.1. Increasing soil carbon sequestration

Increasing soil organic matter content requires enhancing carbon inputs and minimizing carbon losses. Climatic conditions (e.g. precipitation and temperature) and soil aeration influence the decomposition of organic matter.

Actions

The diversification of crop production as part of conservation agriculture can increase carbon sequestration (Gonzalez-Sanchez *et al.*, 2019) and nitrogen use efficiency (Corsi *et al.*, 2012; Sapkota *et al.*, 2017). Conventional maize monoculture production depletes soil nutrients. Maize intercropping and relay cropping have multiple benefits. For example, they protect against soil erosion for a greater portion of the year and produce additional root biomass that increases organic matter in the soil.

The efficient use of nitrogen contributes to the economy-wide target of improving global resource efficiency in consumption and production (**SDG Target 8.4**).

Nitrogen use efficiency contributes to the sound management of chemicals throughout their life cycle and reduces their release into the air, water and soil, which minimizes their impacts on human health and the environment (**SDG Target 12.4**).

Erosion protection in agricultural landscapes contributes to achieving a land degradation-neutral world (**SDG Target 15.3**).

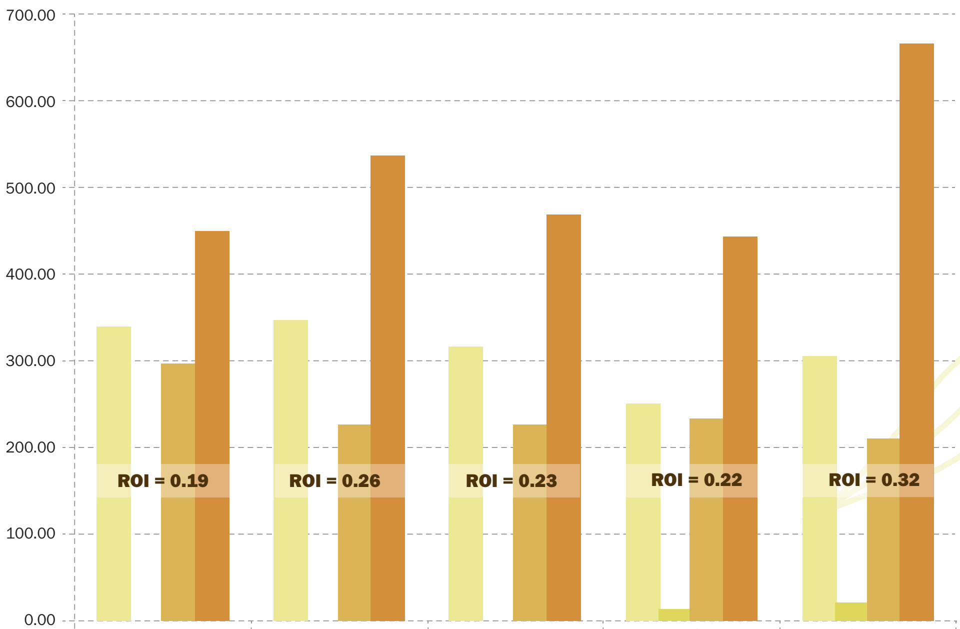
Improved yields and incomes contribute directly to the target of doubling agricultural productivity and the incomes of small-scale food producers (**SDG Target 2.3**).

The diversification and intensification of the cropping system to include legumes and perennials in the crop rotation help reduce, and ideally avoid, the time the fields are left fallow.

A number of studies have questioned the efficacy of conservation agriculture in increasing soil carbon stock, arguing that it has only a small effect on soil carbon sequestration and that its impact on climate change mitigation should not be overestimated (Powlson *et al.*, 2014; Corbeels *et al.*, 2020). Increasing soil organic carbon through conservation agriculture may be a feasible option, but a site-specific assessment of the effectiveness of the various management options (e.g. cover crops, zero-tillage) is required. Recent model forecasts for future climate scenario indicate that conservation agriculture systems have a higher potential to sequester carbon in the soil, particularly when cover crops are used (Valkama *et al.*, 2020).

As mentioned in Section II, maize-legume systems are important for biological nitrogen in the soil and can reduce farmers' reliance on chemical fertilizers, which lowers nitrous oxide emissions. When perennial, biennial, and annual legumes are used as intercrops and relay crops with maize the results can lead to increases in both higher yield and income. Ideally farmers combine these practices with the use of adapted varieties and the efficient application of fertilizers.

Figure 3: Return on investment of maize-legume systems



	Farmer practice	Maize - Velvet bean intercrop + Gliricidia	Maize - Pigeon pea intercrop + Gliricidia	Maize - Cowpea intercrop + Gliricidia	Maize - Climbing bean intercrop + Gliricidia
Maize Yield (kgha-1)	341.00	347.08	316.15	250.08	305.46
Climbing beans Yield (kgha-1)				12.69	20.38
Total Input Cost (US$)	298.46	228.08	228.08	233.85	210.77
Net Production Income (US$)	451.77	535.46	467.46	443.23	665.08

Source: Field data from the FAO project “Building the Basis for implementing the Save and Grow approach - Regional strategies on sustainable and climate-resilient intensification of cropping systems”

Figure 3 displays results from FAO fieldwork in Zambia of the project, Implementing the Save and Grow approach, showing the return on investment of various maize-legume systems.

Green manure cover crops provide multiple benefits. They increase soil organic matter and suppress weeds in maize fields (FAO, 2016). Even when green manure crops are not edible (e.g. *Mucuna pruriens*), they should be prioritized because they produce large amounts of biomass that reduce the costs and disadvantages associated with the use of fertilizers and weed control measures. As noted in Section II, one example of **integrated maize-livestock systems** uses the grass *Brachiaria*. A chemical mechanism in the roots of one *Brachiaria* species inhibits the release of nitrous oxide emissions.

Agroforestry is the term for land-use systems and technologies in which woody perennials (e.g. trees, shrubs, palms or bamboos) and crops or grasses and/or animals are deliberately grown on the same parcel of land in some form of spatial and temporal arrangement (Choudhury and Jansen, 1999).

By reducing the pressure on natural forest, agroforestry can contribute to curbing deforestation (**SDG Target 15.2**).

Economic opportunities that arise from agroforestry contribute to improving the livelihoods of small-scale food producers (**SDG Target 2.3**) and can support subsistence farmers in overcoming poverty (**SDG Target 1.1**).

When properly designed and managed, agroforestry systems can be effective carbon sinks. By providing products and services that would otherwise be sourced from forests (e.g. woodfuel, timber), agroforestry can also strengthen local livelihoods and reduce pressure on natural forests.

Box 4: Agroforestry

Agroforestry practices have helped farmers in southern Africa overcome a lack of crop residues, produce feed and maintain a constant cover over the soil. An example is the integration of nitrogen-fixing trees, such as Faidherbia albida and Gliricidia sepium into maize production systems. These deciduous legume trees lose their nitrogen-rich leaves at the beginning of maize production cycle and then grow them back at the end of the rainy season. This prevents competition for light with maize plantlets, which can be grown directly under the leafless trees. The decaying leaves from the trees provide the soil with up to twice as much organic matter and nitrogen, and the new leaves reduce evapotranspiration during the drier period.

Source: FAO, 2016

Increasing soil organic carbon content helps to stabilize the soil and protect it from erosion, which contributes to reaching the target of a land degradation-neutral world (**SDG Target 15.3**).

Need-based and organic fertilizer applications (e.g. green manure, farmyard manure) serve to accumulate carbon in the soil and reduce GHG emissions. The management of soil organic carbon is essential for sustainable agriculture. Improving soil organic carbon enhances soil quality, reduces soil erosion and degradation and reduces carbon dioxide and nitrous oxide emissions (Kukal *et al.*, 2009).

4.4.2. Reducing GHG emissions

Reducing carbon dioxide emissions in crop production is primarily achieved by lowering direct emissions from operations and avoiding the mineralization of the soil organic carbon. Better fertilizer management and improved efficiency in the use of fertilizers, particularly fertilizers containing nitrogen and sulfur that release nitrous oxide and sulfur dioxide, can reduce the emissions of non-carbon dioxide GHGs.

There are several other negative environmental impacts associated with the excessive use of inorganic and organic fertilizers (e.g. water eutrophication, air pollution, soil acidification, and the accumulation of nitrates and heavy metals in the soil) (Mosier *et al.*, 2013).

Nitrogen fertilizers are the most frequently used type of inorganic fertilizers. Almost half of the world's population relies on nitrogen fertilizer for food production, and 60 percent of global nitrogen fertilizer is used for producing the three major cereals: rice, wheat and maize (Ladha *et al.*, 2005). However, excessive use of nitrogen fertilizer can put ecosystems and human health at risk. Adopting improved agronomic practices and developing improved varieties that increase nitrogen use efficiency in maize can significantly reduce farmers' reliance on chemical inputs.

Improved efficiency in the use of nutrients and fertilizers not only lowers GHG emissions, it also reduces nutrient pollution in terrestrial, freshwater and marine ecosystems, and enhances related ecosystems services (**SDG Targets 15.1, 6.3, 14.1**).

This increased efficiency also facilitates the sound management of chemicals throughout their life cycle and reduces their release to air, water and soil, which minimizes their impacts on human health and the environment (**SDG Target 12.4**).

This can also have beneficial impacts on human health by reducing illnesses associated with air, water and soil pollution and contamination (**SDG Target 3.9**).

Actions

Sustainable mechanization, the use of smaller tractors, making fewer passes across the field and reduced working hours, when combined with conservation agriculture, lower carbon dioxide emissions, minimize soil disturbance, and reduce soil erosion and degradation (FAO, 2017).

The cultivation of varieties with higher fertilizer use efficiency can reduce losses in fertilizer nutrients. These losses have been estimated (on average) to be up to 50 percent of applied nitrogen and 45 percent of phosphorus (FAO, 2016). There is considerable genetic variability among maize varieties for nitrogen use efficiency (Lafitte and Edmeades 1997; Bertin and Gallais 2001; Gallais and Hirel 2004; Gallais and Coque 2005).

Precision farming encompasses an increasing range of high-tech approaches that include GPS technology and environmental information to optimize the application of fertilizers and other inputs according to site-specific requirements (Balafoutis *et al.*, 2017). Precision farming, which takes into consideration spatial

Utilizing GPS-enabled precision farming, sustainable mechanization, and improved varieties contributes to the transfer, dissemination and diffusion of environmentally sound technologies to developing countries (**SDG Target 17.7**).

and temporal needs of the fields, can reduce GHG emissions, while maintaining yields and minimizing the use of water, chemicals and labour. These crop and site specific application methods improve fertilizer use efficiency and reduce the excess application of fertilizers that increases nitrous oxide emissions and lead to nitrogen leaching. These methods can also enhance carbon sequestration by reducing tillage. Precision technology can also decrease GHG emissions by reducing the use of farm equipment in sowing, fertilizing, spraying, weeding and irrigation management.

Applying biochar to the soil can be a sustainable option for sequestering carbon and enhancing soil fertility (Mukherjee and Zimmerman, 2013). The application of biochar may be able to reduce nitrous oxide emissions through its capacity for reducing the availability of nitrates to organisms (denitrifiers) that consume the nitrogen and release it to the atmosphere (Felber *et al.*, 2014).

Biofertilizer application can reduce methane and carbon dioxide emissions in rice paddy fields (Kantha *et al.*, 2015). The beneficial microbes contained in biofertilizers can improve the activity of bacteria that oxidize methane. Further research is required to identify the type of microorganisms that are most beneficial for maize in terms of sustainable agricultural productivity and environmental management.

4.5 Enabling policy environment

The transition to CSA, which involves the scaling up of specific climate-smart practices, demands strong political commitment, as well as coherence and coordination among the various sectors dealing with climate change, agricultural development and food security. Before designing new policies, policymakers should systematically assess the effects of current agricultural and non-agricultural agreements and policies on the objectives of CSA while considering other national development priorities. They should exploit synergies between the three objectives of climate-smart agriculture (sustainable production, adaptation and mitigation) as well as address potential trade-offs and possibly avoid, reduce or compensate for them. Understanding the socio-economic and gender-differentiated barriers and incentive mechanisms that affect the adoption of CSA practices is critical for designing and implementing supportive policies.

In addition to supportive policies, the enabling environment also encompasses fundamental institutional arrangements; stakeholder involvement and gender considerations; infrastructure; credit and insurance; and farmers' access to weather information, extension and advisory services, and input/output markets. The laws, regulations and incentives that underpin the enabling environment establish the foundation for sustainable climate-smart agricultural development. The development of institutional capacity is essential to support farmers and extension services, and reduce the risks that may discourage and prevent farmers from investing in proven new technologies and practices to enable them to adapt to the impacts of climate change and other shocks. Institutions are a key organizing force for farmers and decision-makers, and are critical for scaling up CSA practices.

4.6 Conclusion

Maize production systems will need to adapt to ensure they continue to contribute to food security, rural livelihoods and sustainable food systems under a changing climate. The specific adaptation and mitigation approaches will vary according to location. In the world's maize producing regions, there are a wide variety of agro-ecological conditions, microclimates within the soil, climate risks and socio-economic contexts. It is crucial to collect data and information to determine the best course of action and adapt practices to local needs. This information allows for a continuous learning process and can feed into the improvement of future policies. Close coordination and collaboration among stakeholders at all levels are needed to build an enabling environment that enables farmers to adopt targeted measures to enhance the productivity, resilience and sustainability of maize production in the face of climate change.

The precise challenges that will be created by climate change on maize production systems remain uncertain. These challenges will vary from one farming community to another, but it is certain that they will be especially daunting for countries already coping with high levels of food insecurity. However, there is a clear way forward to meeting these challenges. Options include the adoption of context-specific good agronomic practices, such as conservation agriculture; efficient water and nutrient management; and IPM. These options will complement the gains that can be made through the cultivation of improved varieties.

4.7 References

Atlin, G. N., Cairns, J. E. & Das, B. 2017. Rapid breeding and varietal replacement are critical to adaptation of cropping systems in the developing world to climate change. *Global Food Security*, 12:31-37. https://doi.org/10.1016/j.gfs.2017.01.008

Balafoutis, A., Beck, B., Fountas, S., Vangeyte, J., van der Wal, T., Soto, I., Gómez-Barbero, M., Barnes, A. & Eory, V. 2017. Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. *Sustainability*, 9(8):1339. https://doi.org/10.3390/su9081339.

Bertin, P. & Gallais, A. 2001. Genetic variation for nitrogen use efficiency in a set of recombinant inbred lines II - QTL detection and coincidences. *Maydica*, 46(1):53-68.

Cairns, J. E., Sonder, K., Zaidi, P. H., Verhulst, N., Mahuku, G., Babu, R., Nair, S. K., Das, B., Govaerts, B., Vinayan, M. T., Rashid, Z., Noor, J. J., Devi, P., San Vicente, F. & Prasanna, B. M. 2012. Maize production in a changing climate: impacts, adaptation, and mitigation strategies. *Advances in Agronomy*, 114:1-58. https://doi.org/10.1016/B978-0-12-394275-3.00006-7

Cairns, J. E., Hellin, J., Sonder, K., Araus, J. L., MacRobert, J. F., Thierfelder, C. & Prasanna, B. M. 2013. Adapting maize production to climate change in sub-Saharan Africa. *Food Security*, 5(3):345-360. https://doi.org/10.1007/s12571-013-0256-x

Cairns, J. E. & Prasanna, B. M. 2018. Developing and deploying climate-resilient maize varieties in the developing world. *Current Opinion in Plant Biology*. https://doi.org/10.1016/j.pbi.2018.05.004

Choudhury, K. & Jansen, J. 1998. *Terminology for Integrated Resources Planning and Management*. Rome, FAO.

Corbeels, M., Cardinael, R., Powlson, D. S., Chikowo, R. & Gérard, B. 2020. Carbon sequestration potential through conservation agriculture in Africa has been largely overestimated. Comment on:"Meta-analysis on carbon sequestration through conservation agriculture in Africa". *Soil and Tillage Research, 196*, 104300.

Corsi, S, Friedrich, T., Kassam, A., Pisante, M. & de Moraes Sà, J. 2012. Soil Organic Carbon Accumulation and Greenhouse Gas Emission Reductions from Conservation Agriculture: A review of evidence. *Integrated Crop Management*, Vol. 16. Rome, FAO.

Deutsch, C. A., Tewksbury, J. J., Tigchelaar, M., Battisti, D. S., Merrill, S. C., Huey, R. B. & Naylor, R. L. 2018. Increase in crop losses to insect pests in a warming climate. *Science*, 361:916-919. https://doi.org/10.1126/science.aat3466

Diffenbaugh, N.S., Krupke, C.H., White, M.A. & Alexander, C.E. 2008. Global warming presents new challenges for maize pest management. *Environmental Research Letters*, 3(4):044007-9. https://doi:10.1088/1748-9326/3/4/044007.

FAO. 2016. Save and grow in practice: maize, rice and wheat - A guide to sustainable cereal production. Rome. (also available at www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1263072/).

FAO. 2017. Climate-Smart Agriculture Sourcebook, second edition [online]. [Cited 18 June 2021] http://www.fao.org/climate-smart-agriculture-sourcebook/about/en/

FAO. 2018. *The future of food and agriculture – Alternative pathways to 2050*. Rome. (also available at www.fao.org/global-perspectives-studies/resources/detail/en/c/1157074/).

FAO. 2019. Sustainable Food Production and Climate Change. (also available at www.fao.org/3/ca7223en/CA7223EN.pdf).

FAO. 2021. FAOSTAT. In: FAO [online]. [Cited 24 July 2020]. http://faostat.fao.org

Felber, R., Leifeld, J., Horak, J. & Neftel, A. 2014. Nitrous oxide emission reduction with greenwaste biochar: comparison of laboratory and field experiments. *European Journal of Soil Science*, 65:128-138.

Gallais, A. & Hirel, B. 2004. An approach to the genetics of nitrogen use efficiency in maize. Journal of Experimental Botany, 55(396):295-306. https://doi.org/10.1093/jxb/erh006

Gallais, A. & Coque, M. 2005. Genetic variation and selection for nitrogen use efficiency in maize: A synthesis. *Maydica*, 50(3):531-547.

Gonzalez-Sanchez, E. J., Veroz-Gonzalez, O., Conway, G., Moreno-Garcia, M., Kassam, A., Mkomwa, S., Ordóñez-Fernández, R., Triviño-Tarradas, P. & Carbonell-Bojollo, R. 2019. Meta-analysis on carbon sequestration through Conservation Agriculture in Africa. *Soil and Tillage Research*, 190, 22-30. https://doi.org/10.1016/j.still.2019.02.020.

Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J., Peters, M., van de Steeg, J., Lynam, J., Rao, P.P., Macmillan, S., Gerard, B., McDermott, J., Seré, C. & Rosegrant, M. 2010. Smart investments in sustainable food production: revisiting mixed crop–livestock systems. *Science*, 327: 822-825.

Herrero, M., Havlík, P., Valin, H., Notenbaert, A.M., Rufino, M., Thornton, P.K., Blummel, M., Weiss, F. & Obersteiner, M. 2013. Global livestock systems: biomass use, production, feed efficiencies and greenhouse gas emissions. *Proceedings of the National Academy of Sciences*, 110(52): 20888-20893.

Iizumi, T., Shiogama, H., Imada, Y., Hanasaki, N., Takikawa, H. & Nishimori, M. 2018. Crop production losses associated with anthropogenic climate change for 1981–2010 compared with preindustrial levels. *International Journal of Climatology*, 38(14):5405–5417. https://doi.org/10.1002/joc.5818

Jarvis, A., Ramirez-Villegas, J., Campo, B. V. H. & Navarro-Racines, C. 2012. Is Cassava the Answer to African Climate Change Adaptation? *Tropical Plant Biology*, 5(1):9–29. https://doi.org/10.1007/s12042-012-9096-7

Kantha, T., Kantachote, D. & Klongdee, N. 2015. Potential of biofertilizers from selected Rhodopseudomonas palustris strains to assist rice (Oryza sativa L. subsp. indica) growth under salt stress and to reduce greenhouse gas emissions. *Annals of Microbiology*, 65:2109-2118. https://doi.org/10.1007/s13213-015-1049-6

Kocmánková, E., Trnka, M., Eitzinger, J., Dubrovský, M., Štěpánek, P., Semerádová, D., Balek, J., Skalák, P., Farda, A., Juroch, J. & Žalud, Z. 2011. Estimating the impact of climate change on the occurrence of selected pests at a high spatial resolution: A novel approach. *The Journal of Agricultural Science*, 149(2):185-195. https://doi:10.1017/S0021859610001140

Kukal, S. S., Rasool, R. & Benbi, D. K. 2009. Soil organic carbon sequestration in relation to organic and inorganic fertilization in rice-wheat and maize-wheat systems. *Soil and Tillage Research*, 102(1):87-92. https://doi.org/10.1016/j.still.2008.07.017

Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J. & van Kessel, C. 2005. Efficiency of Fertilizer Nitrogen in Cereal Production: Retrospects and Prospects. *Advances in Agronomy*, 87:85-156. https://doi.org/10.1016/S0065-2113(05)87003-8

Lafitte, H. R. & Edmeades, G. O. 1997. Temperature effects on radiation use and biomass partitioning in diverse tropical maize cultivars. *Field Crops Research*, 49(2-3):231-247. https://doi.org/10.1016/S0378-4290(96)01005-2

Lobell, D. B., Bänziger, M., Magorokosho, C. & Vivek, B. 2011. Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change*, 1:42-45. https://doi.org/10.1038/nclimate1043

Mosier, A., Syers, J.K. & Freney, J. R. 2013. *Agriculture and the nitrogen cycle: assessing the impacts of fertilizer use on food production and the environment*. SCOPE Report, No. 65. Washington, D.C., Island Press.

Nelson, G.C. Rosegrant, M.W., Palazzo, A., Gray, I., Ingersoll, C., Robertson, R., Tokgoz, S., Zhu, T., Sulser, T.B., Ringler, C., Msangi, S. & You, L. 2010. *Food Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options.* Washington, D.C., International Food Policy Research Institute (IFPRI). https://doi.org/10.2499/9780896291867

Powlson, D. S., Stirling, C. M., Jat, M. L., Gerard, B. G., Palm, C. A., Sanchez, P. A. & Cassman, K. G. 2014. Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change*, 4(8):678-683.

Prasanna, B., Huesing, J. E., Eddy, R. & Peschke, V. M., eds. 2018. *Fall Armyworm in Africa: a Guide for Integrated Pest Management.* Mexico, CDMX, CIMMYT.

Sapkota, T. B., Jat, M. L., Aryal, J. P., Jat, R. K. & Khatri-Chhetri, A. 2015. Climate change adaptation, greenhouse gas mitigation and economic profitability of conservation agriculture: Some examples from cereal systems of Indo-Gangetic Plains. *Journal of Integrative Agriculture*, 14(8):1524-1533. https://doi.org/10.1016/S2095-3119(15)61093-0

Sapkota, T. B., Jat, R. K., Singh, R. G., Jat, M. L., Stirling, C. M., Jat, M. K., Bijarniya, D., Kumar, M., Yadvinder-Singh, Y. S., Saharawat, Y. S. & Gupta, R. K. 2017. Soil organic carbon changes after seven years of conservation agriculture in a rice–wheat system of the eastern Indo-Gangetic Plains. *Soil Use and Management*, 33(1):81-89. https://doi.org/10.1111/sum.12331

Shiferaw, B., Prasanna, B. M., Hellin, J. & Bänziger, M. 2011. Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. *Food Security*, 3, (article 307). https://doi.org/10.1007/s12571-011-0140-5

Sims, B. & Kienzle, J. 2015. Mechanization of Conservation Agriculture for Smallholders: Issues and Options for Sustainable Intensification. *Environments*, 2(2):139-166. https://doi.org/10.3390/environments2020139

Tigchelaar, M., Battisti, D. S., Naylor, R. L. & Ray, D. K. 2018. Future warming increases probability of globally synchronized maize production shocks. *Proceedings of the National Academy of Sciences of the United States of America*, 115(26):6644-6649. https://doi.org/10.1073/pnas.1718031115

Valkama, E., Kunypiyaeva, G., Zhapayev, R., Karabayev, M., Zhusupbekov, E., Perego, A., Schillaci, C., Sacco, D., Moretti, B., Grignani, C. & Acutis, M. 2020. Can conservation agriculture increase soil carbon sequestration? A modelling approach. *Geoderma*, 369(30):114298.

Vanlauwe, B., Wendt, J., Giller, K. E., Corbeels, M., Gerard, B. & Nolte, C. 2014. A fourth principle is required to define conservation agriculture in sub-Saharan Africa: the appropriate use of fertilizer to enhance crop productivity. *Field Crops Research,* 155:10-13

Verhulst, N., François, I., Grahmann, K., Cox, R. & Govaerts, B. 2014. *Nitrogen use efficiency and optimization of nitrogen fertilization in conservation agriculture*. CIMMYT.

Wyckhuys, K. A. G., Lu, Y., Morales, H., Vazquez, L. L., Legaspi, J. C., Eliopoulos, P. A. & Hernandez, L. M. 2013. Current status and potential of conservation biological control for agriculture in the developing world. *Biological Control*, 65(1):152-167.
https://doi.org/10.1016/j.biocontrol.2012.11.010

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., Huang, M. *et al.*. 2017. Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences of the United States of America*, 114(35): 9326–9331.
https://doi.org/10.1073/pnas.1701762114

5. Sustainable rice production

Adapting production systems to changing climatic conditions and reducing environmental impacts

H. Jacobs B. Hadi, C. Mba, S. Corsi, M. Taguchi,
H. Muminjanov, J. Kienzle, F. Beed, P. Lidder and H. Kim

5.1 Introduction

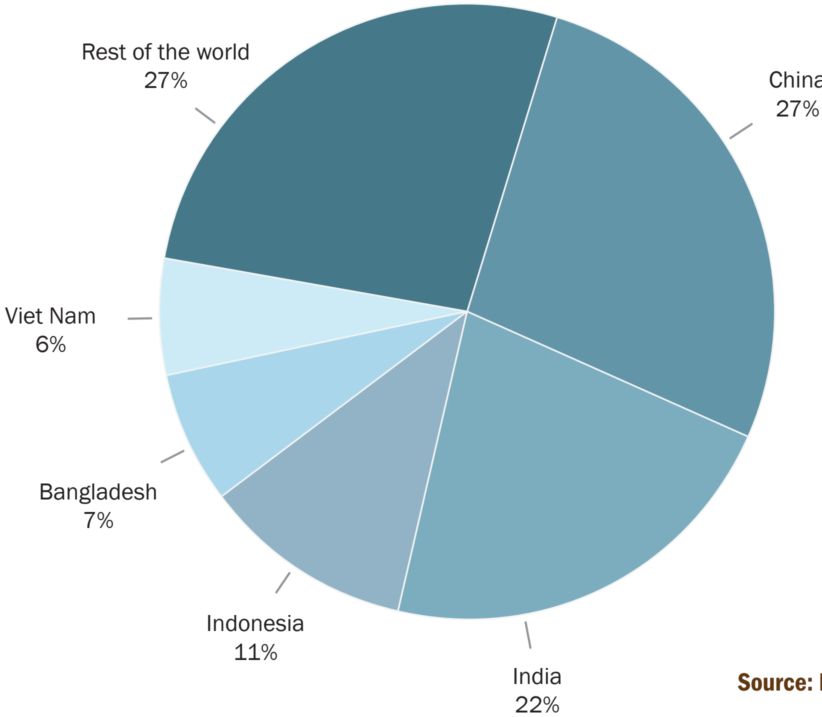
Rice is one of the most widely cultivated staple crops globally because it can be grown under a range of diverse conditions. It is crucial for food security, particularly in developing countries. However, the negative impacts of climate change on rice production can already be observed in a number of regions. These impacts, which are expected to become even more pronounced, will have consequences on farmers' livelihoods and food security. This briefing note describes approaches to climate change adaptation and mitigation that can support a transition to more sustainable and resilient rice production systems. It also highlights the synergies these approaches share with the Sustainable Development Goals (SDGs) in 2030 Agenda for Sustainable Development. Strong political commitment, supportive institutions and investments are essential to give farmer access to these climate-smart approaches and enable their widespread adoption. Increased uptake of these approaches will in turn enhance yields, provide more stable incomes, ensure food security, and contribute to building resilient, sustainable and low-emission food systems.

Rice is a staple food for more than 3.5 billion people. The rice species, *Oryza sativa*, is cultivated worldwide and has two major subspecies: *japonica* which is short-grained and grown mainly in temperate regions; and indica which is long-grained and grown mainly in tropical regions. *Oryza glaberrima* is grown in parts of West Africa (FAO, 2016). Rice is produced in a wide range of locations under a variety of climatic conditions, from very wet areas to dry areas. In 2018, the total global rice production was about 763 million tonnes on 166 million ha. China, India, Indonesia, Bangladesh, and Viet Nam are the top rice producing countries (FAO, 2021). Rice constitutes a high portion of the total planted area in South, Southeast, and East Asia. In both Asia and Africa, it is primarily a smallholder crop.

Cultivated rice is generally considered a semiaquatic annual grass. Rice has the ability to withstand anaerobic soil conditions (i.e. with no oxygen present in the soil), but can also adapt to aerobic conditions even in mountainous regions. In the tropics, rice (ratoon rice) can survive as a perennial, producing new grass shoots (tillers) from nodes after harvest (GRiSP, 2013). In many irrigated areas, rice is grown as a monoculture, completing two crop cycles per year. However, rice is also grown in rotation with a range of other crops. For example, between 15 to 20 million ha are under rice-wheat cultivation (GRiSP, 2013). More than 90 percent of the world's rice production is harvested from irrigated or rainfed lowland rice fields. Upland rice production is not as common, but does occur in the Lao People's Democratic Republic, eastern India and Viet Nam, Latin America and Central and West Africa. Traditionally, lowland rice seedlings have been raised in a seedbed and then transplanted into puddled soil with standing water. This has been done to help control weeds and pests, shorten the duration in the field, and adapt to a limited water supply, as seedlings are grown separately and at a higher density (GRiSP, 2013).

Broadcasting seed is also a common traditional practice. Recently there has been a gradual shift from transplanting seedlings to direct seeding across South and Southeast Asia because it frees farmers from having to maintain nurseries (Kumar and Ladha, 2011).

Figure 1: Share of rice production by country (tonnes), 2018



Source: FAO, 2021

The impacts of climate change, including rising sea levels, seawater intrusion in mega-deltas during the dry season, and increased frequency of storms and dry spells, are severely threatening rice production. Rising sea levels have the potential to cause food security crises in the rice-based agricultural systems in coastal regions (e.g. the river deltas in Bangladesh, Myanmar and Viet Nam), which have accounted for half the total increase in rice production in recent decades (FAO, 2016). Compounding this problem is the fact that high-yielding rice varieties generally do not tolerate major abiotic stresses (e.g. higher temperatures, drought and salinity) (FAO, 2016).

This brief, which serves as a companion to the Climate-smart Agriculture (CSA) Sourcebook (FAO, 2017), summarizes best practices for rice production systems under climate change scenarios. It is intended to provide a reference for policymakers, researchers and other groups and individuals working to support the intensification of sustainable crop production. In plain language and with case studies, the brief provides a checklist of actionable interventions that could be adopted to enhance or sustain the productivity of rice production systems that are at risk from climate change. The strategies can serve to adapt rice production systems to increased biotic and abiotic stress that result from changing climatic conditions and to reduce GHG emissions from these systems. This rice-focused brief is one in a series of crop-specific briefs for CSA.

5.2 Impacts of climate change and projections for rice

Without effective adaptation and genetic improvement, and if there are no carbon dioxide fertilization effects (an increased rate of photosynthesis resulting from increased levels of atmospheric carbon dioxide), every 1 °C increase in global mean temperature has been predicted, on average, to reduce global yields of rice by 3.2 percent (Zhao *et al.*, 2017). Negative climate change impacts in 2050 are projected to be large for oilseeds and rice, but more moderate for coarse grains and wheat. The Agricultural Model Intercomparison and Improvement Project (AgMIP) and the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) undertook a global gridded crop model ensemble analysis of projected crop yields under Representative Concentration Pathway (RCP) 8.5, a high-emission scenario that was adopted by the Intergovernmental Panel on Climate Change (IPCC) (Rosenzweig *et al.*, 2014). Projections indicated mainly large yield declines for soybean and rice (larger than for maize and wheat) when assuming no carbon dioxide fertilization effects (Wiebe *et al.*, 2015).

Estimates on the impacts of climate change on rice production differ among major rice producing countries (e.g. Indonesia, Bangladesh, and Viet Nam). When estimates for these countries were averaged across all methods of rice cultivation, temperature change was predicted to have minor impacts on rice production (Zhao *et al.*, 2017). For India, however, large temperature impacts on rice production were predicted, with an average of between −6.6 to +3.8 percent change per degree Celsius (Zhao *et al.*, 2017). In an analysis of yield variability resulting from climate in major crops for the 1981–2010 period, Iizumi and Ramankutty (2016) found increased yield variability for rice in Bangladesh, southern China, Indonesia and Myanmar.

Simulations produced by the General Large-Area Model (GLAM)-Rice for five Southeast Asian countries (Cambodia, the Lao People's Democratic Republic, Myanmar, Thailand, and Viet Nam) identified Cambodia as the country where the rice yield decrease would be the largest in the absence of adequate adaptation to climate change. By the 2080s, Cambodia would experience an approximately 45 percent reduction under RCP 8.5 relative to the baseline period of 1991–2000 (Chun *et al.*, 2016). However, when model simulations considered elevated levels of carbon dioxide, it was projected that improved irrigation could largely increase rice yields by between 8.2 to 42.7 percent in the 2080s under RCP 8.5

compared to a scenario without irrigation (Chun *et al.*, 2016). Rising global temperatures might even favour increased rice production in the northern regions of some countries (e.g. China), or enable the completion of two crops cycles per year in areas where only one can be completed currently (RICE, 2021).

Impacts of rice production on climate change. In addition to being affected by climate change, rice production also contributes to GHG emissions. Wetland rice is a significant source of the major GHGs: methane, carbon dioxide, and nitrous oxide (Harriss *et al.*, 1985; Bouwman, 1989; Solomon *et al.*, 2007; Lee, 2010; FAO, 2016). After non-dairy cattle, rice cultivation is the largest producer of methane, emitting 0.5 gigatonnes of carbon dioxide equivalents annually (FAO, 2021). In Southeast Asia, rice fields contribute as much as 11 percent of the emissions from the agriculture sector (FAO, 2019a).

Anaerobic decomposition of rice residue in paddy fields emits methane into the atmosphere, and these emissions combined with the emissions from livestock accounts for almost half of global methane emissions (FAO, 2016). The amount of methane emitted from rice paddy fields is influenced by the water regime and organic inputs. Soil conditions, tillage practices, fertilizer use, residue management, and the rice variety have relatively little influence. Flooding generally provides conditions that result in continuous methane emissions. Rainfed rice areas with an intermittent supply of water emit less methane than areas that are continuously flooded (GRiSP, 2013).

©FAO / Sarah Elliot

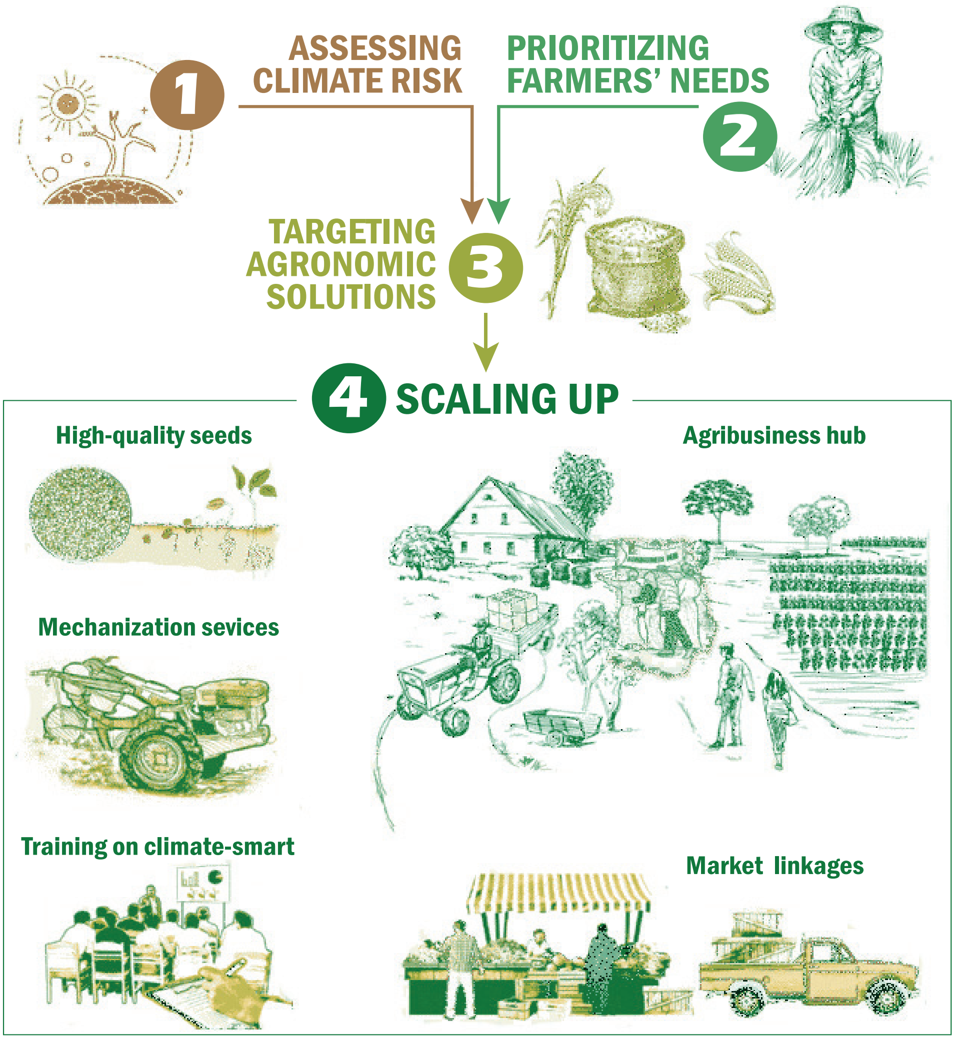
5.3 Climate change adaptation approaches

Higher temperatures, shifts in rainfall regimes, changes in the distribution patterns of rice pests and more frequent and more extreme weather events (e.g. heat waves and cyclones), are examples of the challenges that rice farmers will face as the climate changes. Rice production systems need to become more resilient to these climate hazards and the adaptive capacity of rice farmers need to be strengthened. Progress in this area will contribute to achieving **Sustainable Development Goal (SDG) 13** (Climate Action) particularly to reaching **SDG Target 13.1**. Key approaches to reaching these objectives include conservation agriculture, the use of improved crops and varieties, efficient water management, and integrated pest management. Enabling policies and legislation are instrumental to enable farmers to adopt these climate-smart practices, as are extension and climate information services. It is critical to increase farmers' access to specific technologies, provide them with training and capacity development through farmer field schools on integrated pest management, and involve them in research and experiential learning.

FAO works with countries to reduce both the impacts of climate change on crop productivity and the contributions of crop production systems make to climate change. Based on lessons learned in the field, FAO (2019a) has proposed the 4-step approach to climate change adaptation and mitigation:

1) assess climate risk;
2) prioritize farmers' needs;
3) target agronomic solutions; and
4) scale up successful interventions.

Figure 2: The Save and Grow approach



Source: FAO, 2019

The FAO 'Save and Grow' approach to sustainable crop production intensification relates to step 3 in this four-step sequence.

The 'Save and Grow' approach consists of practices that include conservation agriculture; the use of improved crops and varieties; efficient water management; and integrated pest management (IPM). This section describes in greater detail the application of these practices in rice-based production systems. First, an overview is provided of the practices for establishing a rice crop through direct seeding and dry seeding.

Direct seeding. In many areas, the practice of transplanting rice seedlings into puddled soil has been replaced by direct seeding. In this practice seeds may be broadcast on puddled fields or drill-seeded with no prior tillage. Direct seeding, which produces similar yields, reduces the amount of water used for irrigation. It makes for faster and easier planting, and eliminates the need to prepare nurseries for the seedlings, which reduces labour. Direct seeding also enables the crop to reach maturity more quickly, and lowers methane emissions. In India, pre-monsoon dry seeding of rice through surface mulch has served as an alternative for farmers who previously had left the land fallow (FAO, 2016). In general, **zero-tillage** practices have been taken up at a faster rate for maize and wheat than for rice. However, several trials of zero-tillage, dry-seeded rice have shown that puddling is not necessary for high yields. FAO posits that increased use of zero-tillage rice would further reduce the use of irrigation water (World Bank, 2007).

Dry seeding has traditionally been a method for adapting to drought in rainfed lowland ecosystems. Transplanting of rice into puddled soil is intensive in terms of labour, water and energy, and damages soil structure. However, farmers in irrigated rice systems have been switching to dry seeding with zero-tillage. This practice has been shown to use up to one-third less irrigation water and reduce production costs. Rice is directly seeded with 2- or 4-wheel tractors or with seed drills drawn by a power tiller.

The adoption rates of dry seeding vary throughout Asia. This is partly because much of the rice grown in tropical Asia is produced in the wet season when soil is too saturated for other staple crops. Other factors, such as farmers' lack of access to proper equipment also hinder adoption (FAO 2016). However, in many areas the onset of the rainy season is fluctuating and becoming increasingly unpredictable. More erratic rainfall patterns in the early rainy season make it difficult for farmers to time the preparation of the seedlings for the transplanting. Consequently, to overcome the risk of late season drought, it may be advantageous to plant rice by dry seeding, which can be done much earlier than is possible for conventional transplanting or even wet seeding, which needs ponded water for puddling. This is particularly true when the rainy season ends much earlier, which may become more common as the climate changes. It has also been shown that dry seeded rice plants develop earlier and grow larger than transplanted plants. Dry seeding can also be used as an approach to avoid the negative impacts of increasing floods since earlier planting using dry seeding may mitigate the submergence that occurs under heavy rainfall in flood-prone low-lying areas (Y. Kato, personal communication, 2020).

5.3.1. Conservation agriculture

Conservation agriculture is a sustainable agronomic management system that combines zero- or reduced tillage, the maintenance of soil surface cover with mulch or cover crops, and the diversification of crop production (FAO 2016, FAO 2017; Cairns *et al.* 2013).

Actions

Diversification of crop production and sustainable mechanization. Crop rotation is one of the key principles in conservation agriculture systems. Diversification should be promoted to reduce biotic and abiotic stress, conserve soil and water, reduce weed infestations and create additional sources of income. Rice-based systems are becoming increasingly diverse. For example, the area under rice-maize crop rotation is expanding, and drained rice paddies are now used to plant zero-tillage potatoes on raised beds. In West Africa, farmers are relay cropping rice with vegetables, and in Uganda, farmers grow velvet beans, a legume that fixes nitrogen in the soil, before the rice crop since most soils lack nitrogen. In Indonesia rice bunds are planted with *Sesbania* trees, which improve nutrient levels in the soil and increase crop productivity (FAO, 2016).

It is recommended to grow at least one leguminous, oilseed or other non-rice crop in each annual crop cycle (Le, 2016). Due to the changing profitability of crops, small-scale farmers often grow 4 to 6 crops over a 2 to 3 years cycle. These crops will have diverse seeding depths, seed sizes, row spacing, and fertilizer application rates (Haque *et al.*, 2017). To manage this diversity, the use of **sustainable mechanization** equipment is recommended. The versatile multi-crop planter (VMP) has been used in South Asia, where it has successfully addressed the challenges of diverse crop rotation systems and the need to maintain a high cropping intensity. For upland rice agricultural ecosystems, where soil erosion is a main problem, conservation agriculture with appropriate weed management is important.

Diversification of rice production systems, which includes intercropping with other cereals, as well as annual and perennial legumes, and the integration of rice production with aquaculture, provides multiple benefits.

This diversification contributes to more sustainable and resilient food systems (**SDG Target 2.4**), and supports the sustainable management of terrestrial ecosystems (**SDG Target 15.1**).

Diversification is also a strategy to achieve higher levels of economic productivity (**SDG Target 8.2**) and creates income opportunities for small-scale farmers (**SDG Target 2.**3).

Sustainable mechanization is critical for the adoption of rice-based systems that involve intercropping, crop rotations and the cultivation of multiple crops. It contributes to the transfer, dissemination and diffusion of environmentally sound technologies to developing countries (**SDG Target 17.7**).

Strip based non-puddling transplanting. In conventional systems, most farmers prepare puddled fields where they transplant rice seedlings. However, in conservation agriculture systems, strip based non-puddled transplanting or direct seeding is recommended. There are two methods for transplanting rice seedlings into non-puddled soils that keep soil disturbance to a minimum. In the first method strips are prepared using a versatile multi-crop planter in non-saturated soil. The field is then flooded for 18 to 24 hours to soften the soil, and then the rice seedlings are transplanted into the strip either manually or with a walk-behind transplanter. In the second method an experimental rice transplanter is used that incorporates a narrow strip tillage mechanism (Haque and Bell, 2019).

Non-puddling of the soil for rice cultivation also favours the growth of dryland crops during the dry season as there are fewer problems associated with waterlogging problems and the soil structure is not broken by puddling.

Improved agronomic practices, including direct seeding, and the management of soil fertility and nutrients, contribute to increasing the productivity and incomes of small-scale farmers (**SDG Target 2.3**).

Crop stubble retention. In conventional tillage systems, rice stubble may hinder the establishment of subsequent crops. In many areas, farmers prefer to burn large amounts of stubble. Under conservation agriculture, crop stubble is retained on the soil surface to improve soil health and structure, reduce soil temperature, minimize weed infestations, conserve water, and reduce GHG emissions (FAO, 2016).

Box 1: Diversified rice farming systems

Rice-wheat farming systems are the most widespread cropping systems in the Indo-Gangetic Plain, covering 13.5 million hectares and producing 80 million tonnes of rice and 70 million tonnes of wheat annually (FAO, 2016). Although the Green Revolution was a success that saved as many as one billion people from the threat of famine, its approach has proven to be unsustainable, as it was based on intensification of fertile land. It did not extend to marginal areas, and as a result subsistence farmers received little benefit. To address this situation, rice-wheat systems were introduced in the 1990s by the Rice-Wheat Consortium, a CGIAR initiative affiliated with national agriculture research centres. The systems produce rice during the summer monsoon and wheat during the short winter, using laser-assisted levelling of land, permanent bed planting, and the dry seeding of rice. Long-duration varieties of rice are replaced with short-duration varieties. Dry direct seeding reduces water use, energy costs and labour requirements.

Rice-maize systems have expanded quickly in Asia over the last two decades and now cover more than 3.3 million hectares of land. In South and Southeast Asia, millions of rice farmers grow maize in the dry season with high-yielding hybrids that consume less water and generate higher incomes. The most rapid expansion has taken place in Bangladesh, where farmers started growing maize to sell as feed to the poultry industry (FAO, 2016).

5.3.2. Improved crops and varieties

The cultivation of resistant varieties is a means to combat abiotic and biotic stresses (Ali *et al.*, 2017). Improved rice varieties have been developed by two CGIAR centres, the International Rice Research Institute (IRRI) and the AfricaRice Centre, in collaboration with national agricultural research and extension systems. These improved varieties have been released in many countries over the past five decades. Together IRRI and the AfricaRice Centre safeguard about 152 000 accessions of rice germplasm (RICE, 2021; IRRI, 2021; AfricaRice, 2020). These accessions are repositories of traits that can be harnessed to progressively improve the adaptation of the rice crop to the impacts of climate change. The development of improved varieties can now take advantage of increasingly available efficiency-enhancing breeding methodologies. Research on low GHG-releasing varieties has been conducted, including studies in India which found that fields planted with IR-36 and Aghoni varieties emitted the least methane (Gogoi *et al.*, 2008). Recent studies in China have found that high-yielding cultivars may actually emit less methane in conditions of high soil organic carbon content (Jiang *et al.*, 2017).

Actions

The use by farmers of crop varieties that match local conditions is an important adaptive practice. In Africa, where the adoption of improved crop varieties and the use of their quality seeds are extremely low, climate change is projected to have negative impacts across all scenarios if farmers continue using current varieties. Positive impacts are more likely if they adopt improved varieties (FAO, 2016). The widespread adoption of the improved varieties developed through the breeding programmes, especially by IRRI and the Africa Rice Centre, and their national counterparts should contribute significantly to enhancing the adaptation of rice production systems to climate change. In this regard, farmers need to use the quality seeds of the varieties that are resistant to the prevailing biotic and abiotic stresses, and well adapted to the local agricultural ecosystem and production systems. Pre-release and off-season seed multiplication of early generation seeds could be a way to increase the efficiency of seed production. This would make the seeds available to farmers in a timely manner and at affordable prices. The seed systems must be context-specific. It is particularly important to include community-based quality seed production, including production by small and medium-scale enterprises, that can cater to resource-poor farmers who source their seeds mostly from informal channels that lack quality assurance safeguards.

The use of landraces and crop wild relatives in plant breeding contributes to maintaining the genetic diversity in cultivated plants (**SDG Target 2.5**).

The adoption of improved crop varieties through technology transfer is fundamental for climate change adaptation strategies (**SDG Target 13.1**)

Strengthening the collaboration between formal and informal seed systems for improved seed supply contributes to the promotion of effective public-private and civil society partnerships (**SDG Target 17.17**) and creates opportunities for decent rural employment (**SDG Target 8.5**).

The outputs of research and development in the genetic improvement of rice, which farmers may adopt as means to adapt rice production systems to climate change, include varieties that have been developed to meet a number of issues rice farmers face.

- **Lodging** (the bending over of the stems near ground level)
  The IRRI-developed Green Revolution semi-dwarf rice variety, IR8, has stiff stems that resist strong winds and rain and yield up to 10 times more than the local varieties (IRRI, 2016).
- **Drought**
  Drought is common in several rice-growing regions, and additional research is needed to develop drought-tolerant varieties (FAO, 2016). IRRI scientists have identified several key regions of the rice genome that confer drought tolerance and plan to introduce drought tolerance into popular high-yielding rice varieties (IRRI Rice Knowledge Bank, 2021). The NERICA series of rice varieties developed by the Africa Rice Centre were crosses between the *Oriza sativa* and *Oriza glaberrima*. These varieties combined the hardiness *O. glaberrima*, including its resistance to abiotic stresses, with the high yield of the former *O. sativa* (WARDA, 2001; 2002). The hardy features of the upland NERICA series of rice varieties include drought tolerance. This trait contributes significantly to their superior yields under the moisture limiting rainfed conditions, with frequent drought spells, in which rice is grown in sub-Saharan Africa.
- **Flood and submergence**
  Most high yielding rice varieties are vulnerable to flood-induced loss because the plants are damaged if completely submerged for an extended period of time. Several flood-tolerant landraces have been developed across Asia, including deep-water varieties that are able to grow rapidly to survive (IRRI Rice Knowledge Bank, 2021). Improved rice varieties with enhanced tolerance to short-term flash floods and long-term stagnant flooding are becoming increasingly available to farmers (Kato et al., 2019). IRRI collaborated with the University of California at Davis, in the United States of America, to breed submergence-tolerant rice varieties, which have been released in several Asian countries, including Bangladesh, India, Indonesia and the Philippines (Bailey-Serres and Voesenek, 2010; Ismail et al., 2013; Rumanti et al., 2018). Dubbed the 'scuba' rice, these varieties had yield advantages of between 1 and 3 tonnes per ha over check cultivars after 10 to 15 days of complete submergence under floodwater. Once submerged, these plants become dormant and conserve their energy until the floodwater receded. This adaptive trait results from the activation of the SUB1A gene, which had been introgressed into these improved varieties; an accomplishment made possible by molecular breeding (IRRI Rice Knowledge Bank, 2021).

- **Salinity**
  Rice productivity in salt-affected areas can be poor. IRRI scientists identified a major region of the rice genome called Saltol that confers salt tolerance, and have developed more than 100 salinity-tolerant elite lines (IRRI Rice Knowledge Bank, 2021).
- **Heat and cold**
  Temperatures in excess of 35 degrees reduce rice production, as do low temperatures. IRRI research shows that an increase in nighttime temperature by 1 °C may reduce rice yields by about 10 percent (RICE, 2021). In some cases, the impact of high temperatures can be mitigated through early sowing or using early maturing varieties that can avoid high temperatures during the grain filling stage (Korres et al., 2017). Varieties that produce high yield in a shorter growing season reduce their exposure to late season heat stress. In South Asia, the planting of earlier maturing rice varieties in the monsoon season has allowed for the earlier planting of subsequent wheat, maize and other dry season crops (FAO, 2016). Rice germplasm from extremely warm regions can be used to select traits that allow for the development of high temperature stress-tolerant rice varieties (Wyckhuys et al., 2013). IRRI has worked with South Korea's Rural Development Administration to develop a cold-tolerant breeding line through the Germplasm Utilization Value Added (GUVA) Project, a breeding programme for developing high-yielding, high-quality and high-value temperate japonica rice varieties adapted to tropical regions. GUVA has developed photo-insensitive japonica rice varieties with cold tolerance (IRRI, 2019).
- **Pests and diseases**
  IRRI has developed rice varieties that are resistant to major pests and diseases including blast, sheath blight, bacterial blight and tungro virus.
- **Perenniality**
  Perennial rice varieties are being developed mainly in China and tested in a number of Asian and African countries. Perennial rice systems reduce soil disturbance and labour.

Where possible, incorporate shorter duration varieties to reduce exposure to heat stress, water scarcity and salinity (seawater intrusion), which often occur in the latter part of dry season (Won *et al.*, 2020).

Box 2: AfricaRice

AfricaRice, a CGIAR agricultural research center, has developed 'New Rice for Africa' (Nerica) varieties and has helped to distribute them to farmers. Nerica varieties are hybrids that combine high yield and other traits from Asian rice with African varieties that are resistant to the parasitic weed *Striga*. In West Africa, most rice is grown on slopes and valley bottoms that lack sufficient irrigation and drainage. AfricaRice is promoting a 'smart valleys' development approach that uses simple structures such as bunds and basic irrigation and drainage infrastructure. IRRI is also combining different race-specific genes into the same rice variety to confer resistance to blast fungus. In China, glutinous rice planted with a blast-resistant hybrid prevents the establishment of fungus inoculum and greatly reduces pesticide use (FAO, 2016).

5.3.3. Efficient water management

Seasonal water needs for rice paddy fields can be 2 to 3 times greater than for other cereals. The amount can range from 400 mm per field in heavy clay soils to more than 2 000 mm in sandy or loamy soils with deep groundwater tables, with an average of about 1 300 mm for irrigated rice in Asia (GRiSP, 2013). Competition for water from domestic and industrial users is reducing rice cultivation in some Asian countries (FAO, 2016). However, growing rice without flooding can reduce water use by up to 70 percent (Oda and Nguyen, 2020). Some rice farmers have reduced the flooding of fields, which lowers methane emissions, however the adoption of alternate wetting and drying is still limited globally.

Actions

Increasing the efficiency of water use in irrigated rice production can be done through the following actions.

- **Laser-assisted precision land levelling** is a laser-guided technology used to level fields by removing soil from high points and placing it in low points of the field (IRRI GHG Mitigation in Rice, 2021). This can save water and increase productivity. It also reduces the risk that any fertilizer that has been applied will be washed by rain. This technique was introduced in the Indo-Gangetic Plain and uses laser-guided tractors operated by private contractors. It has proven to be more precise and more affordable compared to the standard practice of levelling using wooden boards and scrapers, which wasted water and produced lower yields (FAO, 2016).

Improved water management in rice cropping systems includes precision land levelling and adjusted irrigation regimes. These practices contribute to ensuring the sustainable management of water resources (**SDG 6**), and increasing water use efficiency in particular (**Target 6.4**).

- **Peripheral bunding** improves rainwater use, reduces dependence on canal water supplies, and reduces the risk of fertilizer being washing away by heavy rains.
- **Dry-seeding with zero-tillage and intermittent irrigation** reduce water use (Kumar and Ladha, 2011; FAO, 2016).

System of rice intensification (SRI) and alternate wetting and drying. In these two methods, fields in lowland areas are not watered for up to 10 days, which reduces water use and expenses on fuel for pumping water. These practices can enable farmers to shift from cultivating a single rice crop to completing two crop cycles each year. By allowing dry periods and decreasing the level of flooding, these practices can reduce water consumption by approximately 50 percent compared to flooded rice fields (Wassmann et al., 2011).

SRI is a climate-smart, agroecological system that was developed in 1983 in Madagascar to increase rice productivity by changing the management of plants, soil, water and nutrients. The system spread throughout rice growing regions with the help of Cornell University (Cornell University, 2020). SRI is based on four main interacting principles: (1) early, quick and healthy plant transplanting and establishment; (2) reduced plant density to allow for root and canopy growth; (3) improved soil conditions through enrichment with organic matter; and (4) reduced and controlled water application. These principles can be adapted to specific agroecological and socio-economic conditions and have been adapted for rainfed and irrigated rice as well as for other crops, such as wheat and sugarcane. Benefits include increased yields; reduced water need for irrigation, which helps to decrease methane emissions; and savings on fertilizer and seed (FAO, 2016). One disadvantage to SRI is that more labour is required; a constraint that could be addressed with technological innovations. SRI is not necessary to grow rice near the optimal yield potential, but it may meet the needs of farmers in areas with poor soils with potential for iron toxicity (Dobermann, 2004). Under SRI, soil moisture is kept at a lower level than under conventional practices, which reduces methane emissions. The system also emphasizes the importance of using organic fertilizers over synthetic nitrogen fertilizers, which reduces nitrous oxide emissions. The combination of intermittent irrigation and the application of organic material improves the soil nearest to the plant root system (rhizosphere) and increases yield (Lin et al., 2011).

Box 3: Rice-fish integrated farming systems.

In Asia, farming fish in paddy fields control rice pests, fertilizes the rice crop and improve diets. FAO has estimated that rice-fish farming can generate up to 400 percent more income than rice monoculture (FAO, 2016). Aquaculture practiced in the trenches surrounding rice fields increases the nutrient supply to the plants and provides farmers with an additional source of protein (FAO, 2016).

Rice-fish farming is an ancient practice that is now being promoted as an option for improving water and land use efficiency, diversifying farm production and supporting climate change mitigation and adaptation (FAO, 2019a). Rice-fish farming contributes to climate change mitigation by replacing fertilizers for rice production with fish feces, and by lowering the artificial feed and energy needed for fish production. Fish are also beneficial for weed control; sometimes more effective than herbicides or manual weeding (FAO, 2016). The system contributes to climate change adaptation by enabling the production of resistant aquatic animals (e.g. shrimp and brackish water fish) during the dry season when it is often impossible to cultivate rice. It uses improved irrigation systems that supply water during drought or the dry season. However, the adoption rate of rice-fish farming systems is lower outside China due to a number of obstacles including the limited availability of low-cost pesticides, a lack of awareness of the benefits of these systems, and farmers' limited access to credit for making investments in fish production.

Alternate wetting and drying (AWD). AWD, which is a water-saving regime that is often used in SRI, reduces irrigation water consumption without decreasing yield (IRRI Rice Knowledge Bank, 2021). Fields are alternately flooded and dried for between 1 and 10 days depending on the specific local conditions. In this way, AWD reduces the duration of flooding, which lowers costs for pumping water, improves the quality of the soil structure, and allows farmers to intercrop rice with other crops. AWD is most effective in lowland areas with finer textured soils that hold moisture and often have good potential for continuous cropping. However, it is difficult to implement in rotations with paddy rice and upland crops, such as maize. AWD also enables the absorption of zinc and nitrogen and the reuse of nutrients by subsequent crops. AWD can also be used for climate change mitigation, as it has been shown to reduce methane emissions from rice production with no reduction in yield. According to FAO (2019b), AWD is accepted as the most promising practice for reducing GHG emissions from irrigated rice, as on average it reduces water use by 30 percent, fuel use by 30 percent and methane emissions by 40 percent. During the dry phases, the methane-producing bacteria are inhibited. AWD practices also reduce consumption of nitrogen fertilizer and chemical pesticides, which minimizes nitrous oxide emissions and lowers the indirect emissions that result from the production of inputs (IRRI GHG Mitigation in Rice, 2021).

Upland rice is cultivated in dry soil, and irrigation is only used when necessary. The cultivation of upland rice uses varieties that are adapted to well-drained and non-puddled soils in rainfed areas that are subject to water scarcity. Yields of upland rice can be 75 to 80 percent of the yields obtained from flooded rice cultivation, but require 50 to 70 percent less water and less labour (FAO, 2016). With intensive water, nutrient and weed management, grain yield is equivalent to that of conventional flooded rice, particularly in temperate regions (e.g. East Asia and Brazil). Upland rice is often called aerobic rice (Kato and Katsura, 2014).

5.3.4. Integrated pest management

Pests, pathogens and diseases.

The impacts of climate change on pests and pathogens depend highly on the species and location. An increase in surface temperature affects plant-eating insects by increasing their metabolism rate (i.e. the amount of plant tissue consumed) and the growth rate of their populations. In some tropical areas, the growth rate of insect population may decrease as temperatures rise. However, the increased metabolism rate associated with increased temperature will affect the final yield loss. In temperate regions, both the size of insect populations and their metabolic rates are expected to increase as temperatures rise, which will contribute to higher increase in yield loss. When average global surface temperatures increase by 2 °C, the median overall increase in yield losses from pests is projected to be 19 percent for rice, amounting to 92 megatonnes per year (Deutsch *et al.*, 2018). A study has found a positive correlation between increasing maximum temperature with population levels of certain rice pests, such as rice leaffolder (Ali *et al.* 2019).

As the global temperature rises, areas at higher latitudes will start to record temperature ranges that allow new pests and pathogens to survive. There has already been an indication of potential range expansion for some rice pests associated with warming climate (Osawa *et al.* 2018). In a simulation study covering climate change scenarios between 2010 and 2069, the ability of rice leaf blast to infect rice plants across the Indo-Gangetic Plain is expected to increase during the winter months due to higher temperatures. However, during the same period, this ability is estimated to remain stable or even decrease during the monsoon season (Viswanath *et al.* 2017). A modelling exercise for rice yield loss from diseases in the United Republic of Tanzania showed a declining trend in yield loss due to leaf blast and an increase due to bacterial leaf blight over the next 30 years (Duku *et al.* 2015).

Rodents, which are found in lowland irrigated rice crops, may pull up transplanted plants, destroy young seedlings and feed on plants as they ripen. Several non-chemical methods may be used to control rodents. These methods include keeping the height of rice bunds to less than 30 cm to prevent burrowing; keeping areas around the field, villages, and grain stores clean; coordinating consistent planting times with neighbours (IRRI Rice Knowledge, 2021). Trap barrier systems have also proven successful in trapping rodents in irrigated rice fields. These systems are used in fields that are planted earlier than surrounding fields, thereby attracting rodents from a wider area.

Insects. Planthoppers, leafhoppers, leaffolders and stem borers are among the most destructive insect pests for rice. Planthoppers and leafhoppers cause direct plant damage by removing the sap from leaves and stems. Leafhoppers attack all the aerial parts of the plant, while planthoppers primarily attack the basal portion of the plant. Planthopper feeding causes the plant to become yellow, and at high population densities the plant becomes completely dry. Green leafhoppers extract plant sap and spread the viral disease tungro and diseases caused by other viruses (e.g. the yellow dwarf, yellow-orange leaf, transitory yellowing, and dwarf viruses). Stem borers are an important group of insects that can damage rice at any stage of the plant's development by feeding upon tillers. Stem borer infestations in rice fields often involve multiple species of borers. Leafholder larvae spin silk from one leaf edge to the other. As the silk shrinks, the leaf folds, and the larvae feed on the green tissues from within the fold, causing the leaf to dry and impeding photosynthetic activity (FAO, 2016).

Golden apple snail. Two invasive snail species, Pomacea canaliculata and Pomacea maculata, commonly known as golden apple snails, damage rice crops. In the 1980s, these snails were introduced to Asia from South America as potential food for people. The snails, which eat the young and emerging rice plants, spread through water distribution pathways and during flooding events, and can hibernate in mud for up to six months (IRRI Rice Knowledge Bank, 2021).

Prevalent rice diseases include bacterial blight, bacterial leaf streak, bacterial sheath brown rot, rice blast, and sheath blight. Planting disease-resistant varieties is often the best and most cost-effective strategy for diseases (IRRI Rice Knowledge Bank, 2021).

Actions

Integrated pest management (IPM) is an ecosystem approach to crop production and protection that was developed in response to the widespread overuse of pesticides. In IPM, farmers use natural methods based on field observation to manage pests. Methods include biological control (i.e. using natural enemies of pests), use of resistant varieties, and habitat and cultural modification (i.e. removal and introduction of certain elements from the cropping environment to reduce its suitability for pests). The rational and safe application of selective pesticides is used as a last resort (FAO, 2016).

Agronomic measures that farmers can use to manage rice pests include monitoring planthopper numbers and their natural predators in rice fields; planting resistant varieties; optimizing fertilizer use and seeding timing; and removing infected plants. For golden apple snails, IPM strategies include encouraging natural predators, handpicking the snails, cultivating toxic plants, limiting the availability of water, and conducting mass collection campaigns. In rice production areas that are integrated with aquaculture, the fish feed on insect pests, fungi and weeds, and lessen the need for chemical controls (FAO, 2016).

IPM, which emphasizes the minimal use of harmful chemical pesticides, contributes to the sustainable management of terrestrial ecosystems (**SDG Target 15.1**) and reduces marine pollution from land-based activities (**SDG Target 14.1**).

The successful implementation of IPM contributes to prevent infestations that can severely damage crops and cause famine (**SDG Target 2.1**).

IPM contributes to the sound management of chemicals throughout their life cycle and reduces their release into the air, water and soil, which minimize impacts on human health and the environment (**SDG Target 12.4**).

IPM can also benefit human health by reducing illnesses caused by air, water and soil pollution and contamination (**SDG Target 3.9**).

Training through farmer field schools (FFSs). The FFS approach is an efficient methodology for sharing IPM principles with farmers and establishing a learning process suitable for solving practical problems. For over 30 years, FAO FFSs have improved the skills of over 4 million of farmers in more than 90 countries. The approach has benefited from experiences gained through the implementation of FFSs on IPM of rice pests and diseases in Southeast Asia. The need to promote ecological literacy, which underpins sound IPM was first recognized in Indonesia. It was in this setting that the FFS approach was developed. The excessive use of insecticides had decimated natural enemies in the rice ecosystem, which led to secondary outbreaks of planthoppers. These outbreaks were of major concern to governments as they seriously threatened rice production and self-sufficiency. Managing the planthoppers and other pests in rice requires an understanding of all elements and interactions in the ecosystem as the crop develops. Farmers attending FFS usually reduce insecticide use and report increased yields (FAO, 2016).

Training farmers on IPM through the farmer field school approach supports them in acquiring new technical and vocational skills (**SDG Target 4.4**).

Gender-sensitive seed systems improve equal access to seeds and promote the empowerment of women (**SDG Target 5.b**).

The FFS approach enhances understanding of complex agricultural ecosystems. Communities are encouraged to change practices and take a lead role in improving the production system and charting a pathway to the future. FFS are based on observing, analysing and understanding local agricultural ecosystems. All activities are discovery-based - ‘the field is the book'. Activities, which aim at meeting local needs, are based on a thorough understanding of biological synergies and ecosystem functions. Characterized by 'grass-roots labs' and innovation, FFS ensure a continuous process for updating the information base needed to cope with climate change. The key focus of the learning process is defined according to the local context and specific local climatic conditions. The analysis of cropping systems and weather patterns are integrated into the FFS learning cycle to identify risks and promising options for adaptation. FFS can measure rainfall and temperature, interact with meteorological centres and evaluate crop water requirements.

Box 4: Farmer–researcher collaboration and experiential learning on SRI in Senegal.

An FFS experience in Senegal tested different crop management systems for irrigated rice over the course of three seasons of adaptive research trials in three locations in the middle Senegal River Valley. The objectives were to assess the agronomic and socio-economic viability of recommended management practices compared to SRI and farmers' practices. During the 2008 dry season, the recommended management practices increased yields over farmers' practices by 2.3 tonnes per ha (a 44 percent increase), and SRI increased yields by 2.6 tonnes per ha (a 50 percent increase) across all sites. Farmers analysed their experiences in post-experiment meetings. They appreciated the potential for SRI to increase yield and save water, but found it labour demanding, especially for weed management that coincided with horticultural activities. The farmers described the higher rate of herbicide application in recommended management practices to be costly. They noted that, because of poorly functioning agro-chemical markets, herbicide volumes larger than those typically used in farmers' practices are difficult to obtain. To modify the recommended management systems to fit farmers' needs and assets, the FFS collaboratively developed a fourth, 'farmer adapted practice' that blended recommended management practices and SRI. The farmer adapted practice used intermittent irrigation during the late vegetative stage (i.e. before the first tillers appear), adopted the recommended crop density and intermediate seedling age, and then carried out a single round of mechanical weeding, which was followed by localized herbicide application. Farmers compared this practice against the initial recommended management practices over the course of the following seasons. Though no yield differences were found between recommended management practices, SRI and the farmer adapted practice, each yielded significantly more tonnes per ha than the initial farmers' practices. The farmer adapted practice also reduced labour requirements without increasing weed biomass compared to recommended management practices or SRI. It used 40 percent less herbicide than the recommended management practices and 10 percent less herbicide than the initial farmers practices. The farmer adapted practice increased the net profit potential and decreased economic risk. Before the 2009 dry season trials, the Government of Senegal eliminated herbicide subsidies, doubling their cost. The recommended management practices yielded 2.9 tonnes per ha more than the initial farmers' practices; SRI 3.0 tonnes per ha more; and the farmer adapted practice 3.1 tonnes per ha more. The farmer adapted practices again reduced weeding labour and herbicide requirements and lowered production risk across all sites (Krupnik et al., 2012).

Direct seeding helps prevent the mixing of weed seeds into the root zone, and increases the resilience of the system. It can be especially useful in Africa when combined with upland Nerica rice varieties (FAO, 2016). One method for dry direct seeding is using high seeding rates, which enables the canopy to close quickly, which helps to suppress weeds compared to low seeding rates. A low seeding rate may foster weed growth since plants take more time to close their canopy (Ahmed *et al.*, 2014). It has also been shown that increasing rice residues suppresses the seedling emergence of various weed species. For other species, increasing residues can lessen weed biomass or slow seedling emergence and growth (FAO, 2016)

AWD reduces certain pests and diseases. However, it should be evaluated on a case-by-case basis since it may increase the presence of other pests and weeds. It may also help to prevent mosquito infestation and the development of other water-borne diseases due to the reduction in flooding frequency (Allen and Sander, 2019).

Box 5: Rice Doctor

Rice Doctor is a diagnostic tool that helps farmers and agricultural extension workers diagnose more than 80 crop problems caused by pests, diseases and abiotic stresses. The Rice Doctor supports a visual diagnosis and provides guidance for the prevention and management of problems by offering access to global knowledge and information.

Rice Doctor is available at:
http://www.knowledgebank.irri.org/decision-tools/rice-doctor

5.4 Climate change mitigation approaches

A range of options exist to enable rice production systems to support climate change mitigation and contribute to global effort to reach **SDG 13**, particularly as measured by **SDG Indicator 13.2.2**, reduction of national GHG emissions. The options available for mitigation strategies in rice production systems reduce GHG emissions, particularly methane emissions resulting from anaerobic decomposition of organic material and nitrous oxide emissions associated with the application of nitrogen fertilizers. Key elements for these mitigation strategies include the use of mid-season drainage, intermittent drainage and dry seeding to reduce methane emissions from continuous flooding; the use of short-duration varieties; laser land levelling, machine transplanting and sustainable mechanization; alternative rice straw management options, and site-specific nutrient management, and the application of biochar and biofertilizers. Many of these strategies deliver co-benefits to the environment and human health and may generate greater economic returns for farmers and farming communities.

5.4.1. Reducing GHG emissions

In addition to the critical issue of methane emissions from anaerobic decomposition, it is also necessary to examine the impacts of nitrogen fertilizers. Nitrogen fertilizers are the most frequently used type of inorganic fertilizers. Almost half of the world population relies on nitrogen fertilizer for food production, and 60 percent of global nitrogen fertilizer is used for producing the three major cereals: rice, wheat and maize (Ladha *et al.*, 2005). However, excessive use of nitrogen fertilizer can put ecosystems and human health at risk. There are several negative environmental impacts associated with the use of inorganic and organic fertilizers (e.g. water eutrophication, air pollution, soil acidification, the accumulation of nitrates and heavy metals in the soil, Mosier *et al.*, 2013). In particular, fertilizers containing nitrogen and sulfur can lead to nitrous oxide and sulfur dioxide emissions.

Improved efficiency in the use of nutrients and fertilizers not only lowers GHG emissions, but also reduces nutrient pollution in terrestrial, freshwater and marine ecosystems, and enhances ecosystems services (**SDG Targets 15.1, 6.3, 14.1**).

This increased efficiency contributes to the sound management of chemicals throughout their life cycle and reduces their release into the air, water and soil, which minimizes their impacts on human health and the environment (**SDG Target 12.4**).

Improved efficiency in the use of nutrients and fertilizers can also have beneficial impacts on human health by reducing illnesses associated with air, water and soil pollution and contamination (**SDG Target 3.9**).

Actions

Mid-season drainage and intermittent drainage reduce methane emissions. Mid-season drainage is a common practice in irrigated regions of China and Japan (GRiSP, 2013). However, these practices can increase carbon dioxide and nitrous oxide emission rates (Miyata *et al.*, 2000; Saito *et al.*, 2005; Wassmann *et al.*, 2011). Carbon dioxide and nitrous oxide emissions have been shown to increase under intermittent drainage regimes and reach higher levels than under continuous flooding (FAO, 2016). This is because drainage makes oxygen available for the production of nitrous oxide from nitrification or denitrification (Xiong *et al.*, 2007). When nitrogen fertilizer is applied at high rates, there is a risk that increased nitrous oxide emissions will offset any methane emission reductions. For this reason, water management practices should be combined with efficient fertilizer applications (Wassman *et al.*, 2011). Nitrogen fertilizers increase crop growth but also affect methane-producing microbes (methanogens) and methane-consuming microbes (methanotrophs). Higher methane emissions per kg of nitrogen have been correlated with increases in crop yield achieved through the application of nitrogen fertilizers. This is because there is an increase in biomass that is rich in carbon in the soil (carbon substrates) that supports methane-producing microbes (Banger *et al.*, 2012).

Short-duration rice varieties. Traditional rice varieties take 160 to 200 days to harvest, whereas improved short duration varieties can be harvested in 90 to 110 days (IRRI GHG Mitigation in Rice, 2021). This reduces the amount of time that methane emissions are produced, and in some cases creates new opportunities to cultivate an additional crop, which can increase carbon sequestration and increase incomes.

Laser land levelling reduces GHG emissions by saving on energy, reducing cultivation time, and improving efficiency in the use of inputs (IRRI GHG Mitigation in Rice, 2021).

Machine transplanting instead of manual transplanting reduces GHG emissions due to the reduction of cultivation time and improved water use efficiency. It is most effective when used in combination with laser land levelling to reduce the amount of time and water needed for irrigation. Improved plant establishment can increase yields, resulting in a lower emission per yield unit (IRRI GHG Mitigation in Rice, 2021).

Dry seeding rice reduces methane emissions because the soils remain aerobic for a substantial portion of the season.

Sustainable mechanization, when combined with conservation agriculture, reduces carbon dioxide emissions, minimizes soil disturbance, and curtails soil erosion and degradation that are common in tillage-based crop system (FAO 2017). Box 6 describes the no-till planter, which has been shown to reduce GHG emissions in rice-wheat farming systems.

Box 6: The Happy Seeder in rice-wheat farming systems on the Indo-Gangetic Plain

The Happy Seeder is a tractor-mounted no-till planter that can drill wheat seed through heavy loads of rice residues. The Happy Seeder then deposits the residues over the sown area as mulch. The International Maize and Wheat Improvement Center (CIMMYT) has found that systems that make use of the Happy Seeder have the most profitable and scalable residue management practices, proving to be on average 10 to 20 percent more profitable than burning. These systems are able to reduce GHG emissions by 78 percent per hectare compared to all burning options. The burning of residues, which has been widely practiced for rice cultivation, significantly contributes to air pollution and short-lived climate pollutants (CIMMYT, 2019).

Rice straw management options. Straw is a by-product of harvesting rice paddies. Incorporating the straw into the soil can delay soil preparation for the next crop, and removing it from the field is labour intensive, so the straw is often burned in the fields. This practice generates methane, nitrous oxide and sulfur dioxide emissions. It also produces air pollutants such as coarse dust particles and fine particles, which affect air quality. However, rice residues can be managed using in-field and off-field options. Because the incorporation of rice straw into paddy soil has the potential to increase emissions due to its slow rate of decomposition, researchers developed a technology to accelerate decomposition using fungal inoculums (Goyal and Sindhu, 2011; Ngo *et al.*, 2012). A machine has been introduced that combines harvesting with the chopping of rice straw and the spraying of inoculums into the chopped straw. Off-field, rice straw can be removed and used for mushroom and energy production, biochar production, and livestock feed (IRRI Rice Knowledge Bank, 2021).

Replacing the burning of rice stubble with alternative management options, including using it as a soil amendment, livestock fodder or bioenergy feedstock, reduces air pollution, benefiting human health and the environment (**SDG Target 3.9; SDG Target 15.1**).

These options also contribute to increasing the share of renewable energy (**SDG Target 7.2**) as well as reducing waste through the recycling of by-products (**SDG Target 12.5**).

Site-specific nutrient management. Fertilizer use efficiency has been improved using site-specific nutrient management, a strategy that optimizes the use of existing soil nutrients and fills gaps with mineral fertilizer (FAO, 2016). As part of this approach, IRRI and partners have introduced a low-cost plastic 'leaf colour chart,' which allows rice farmers to determine optimal timing for the application of urea fertilizer. The farmers compare the colour of rice leaves to the colour panels corresponding to specific crop nitrogen deficits. This chart has helped reduce urea use by about 20 percent with no decline in yields. The more efficient use of nitrogen reduces nitrous oxide emissions and the indirect emissions of GHGs that result from the production of nitrogen fertilizer. Based on site-specific nutrient management principles, a web-based decision support tool named Rice Crop Manager (RCM) was recently developed by IRRI to calculated field-specific nutrient management in the Philippines (Buresh *et al.*, 2019). Calibrated algorithms calculate nitrogen, phosphorus, and potassium fertilizers required for a target yield. The algorithms and procedures developed can also

be used to enhance nutrient management decision support tools for rice in other countries.

Biochar application can help reduce methane emissions by 10 to 60 percent depending on the type of soil (FAO, 2019b). Continuous applications of biochar can improve nitrogen use efficiency and increase the grain yield in rice (Huang *et al.*, 2018). Applying biochar is a promising approach because, depending on the type of feedstock used and the temperatures needed to produce the biochar, it can significantly reduce nitrous oxide emissions from rice paddies. It can also increase soil pH by more than 11 percent and rice yield by more than 16 percent (Awad *et al.*, 2018).

Biofertilizer application can reduce methane and carbon dioxide emissions in rice paddy fields (Kantha *et al.*, 2015). Organic and saline flooded rice fields contribute to global warming due to their low productivity and methane emissions. However, beneficial micro-organisms contained in biofertilizers can have positive impact on methane emissions by improving the activity of methane-oxidizing bacteria. Among the various biofertilizers available, purple non-sulfur bacteria (e.g. *Rhodopseudomonas palustris*) have been identified as being non-toxic to plants, and having the potential to enhance rice yields and reduce methane and carbon dioxide emissions.

Box 7: Thailand Nationally Appropriate Mitigation Action (NAMA) on Rice

Thailand is the fourth largest emitter of rice-related GHG emissions. In Thailand, 55 percent of agricultural GHG emissions come from rice cultivation, contributing 27.8 million tonnes of carbon dioxide equivalents. To reduce emissions and support national mitigation goals, the Thai Ministry of Agriculture developed the Thai Rice NAMA, which was financed by the NAMA Facility and went into effect in August 2018. The objective is to introduce 100 000 rice farmers in central Thailand to low-emission farming techniques by 2023 and decrease GHG emissions by 29 percent compared to the business-as-usual scenario. The country, which plans to use AWD to achieve mitigation goals, first began adopting this practice to reduce water consumption following a severe drought in 2013. Farmers are combining AWD with laser land leveling and reducing water use by about 30 percent by installing perforated plastic tubes that shows when the water level in the soils has receded to the point where reflooding is needed. They are also replacing traditional techniques of burning rice straw with a system of machine-based straw and stubble management, in which organic material is collected to be sold and used as livestock feed or for bioenergy production. Site-specific nutrient management based on soil analyses will be used to reduce nitrous oxide emissions. (NAMA Facility, 2019)

5.5 Enabling policy environment

The transition to CSA, which involves the scaling up of specific climate-smart practices, demands strong political commitment, as well as coherence and coordination among the various sectors dealing with climate change, agricultural development and food security. Before designing new policies, policymakers should systematically assess the effects of current agricultural and non-agricultural agreements and policies on the objectives of CSA, while considering other national development priorities. They should exploit synergies between the three objectives of climate-smart agriculture (sustainable production, adaptation and mitigation), as well as address potential trade-offs and if possible avoid, reduce or compensate for them. Understanding the socio-economic and gender-differentiated barriers and incentive mechanisms that affect the adoption of CSA practices is critical for designing and implementing supportive policies.

In addition to supportive policies, the enabling environment also encompasses fundamental institutional arrangements; stakeholder involvement and gender considerations; infrastructure; credit and insurance; and farmers' access to weather information, extension and advisory services, and input/output markets. The laws, regulations and incentives that underpin the enabling environment establish the foundation for sustainable climate-smart agricultural development. The development of institutional capacity is essential to support farmers and extension services, and reduce the risks that may discourage and prevent farmers from investing in proven new practices and technologies to enable them to adapt to the impacts of climate change. Institutions are a key organizing force for farmers and decision-makers and are critical for scaling up CSA practices.

Governance platforms and initiatives for sustainable rice production. Stakeholder engagement and multi-stakeholder platforms are important elements in the creation of an enabling policy environment. The following initiatives and platforms provide the foundations for sustainability in rice production. They support governments, and connect public and private sectors with research institutions and international organizations that are working to advance the adoption of climate-smart practices.

The Sustainable Rice Platform (SRP) is a multi-stakeholder platform established in 2011 and convened by The United Nations Environment Programme (UNEP) and IRRI. SRP promotes resource efficiency and sustainability in trade flows, production and consumption operations, and supply chains in the global rice sector. It provides private, nonprofit and public actors with sustainable production standards and outreach mechanisms that contribute to increasing the global supply of affordable rice, improving livelihoods for rice producers and reducing the environmental impact of rice production. The SRP has created the Standard for Sustainable Rice Cultivation (Standard 2.1), the world's first voluntary sustainability standard for rice. The Standard has 46 requirements structured under eight themes each of which is aimed at reaching a specific sustainability impact. The standard is designed for farm-level impacts and has a set of 12 quantitative performance indicators to measure progress (SRP, 2021).

The Sustainable Rice Landscapes Initiative, which was launched in 2018 during the 6th Assembly of the Global Environment Facility (GEF), builds on the work of the SRP. The Initiative, which works within the context of GEF-7 programme, is intended to meet the growing global demand for sustainable rice through a public-private partnership working to achieve the SDGs, meet national GHG reduction targets, restore degraded landscapes, and conserve biodiversity. It is a partnership of FAO, the German Government's development agency (GIZ), IRRI, SRP, UNEP and the World Business Council for Sustainable Development (WBCSD), and cooperate with governments and value chain actors at landscape and policy levels to promote the adoption of proven climate-smart best practices (FAO, 2020).

The Coalition for African Rice Development (CARD) is a consultative group of donors, and regional and international organizations that provide policy support to countries in sub-Saharan Africa so that they can reach rice self-sufficiency. The goal of the second phase of CARD (2018-2030) is to support the efforts of African countries to double rice production from 28 to 56 million tonnes per year by 2030. CARD supports member countries in preparing their national rice development strategy (NRDS). The second phase has adopted the RICE approach, which reflects four main components: Resilience, Industrialization, Competitiveness and Empowerment. The second phase will maintain its focus on value chain development and cross-cutting activities that build capacities and establish strong partnerships with the private sector (CARD, 2021).

5.6 Conclusion

Rice production systems need to adapt to ensure they continue to contribute to food security, rural livelihoods and sustainable food systems under a changing climate. The specific adaptation and mitigation approaches will vary according to location. In the world's rice producing regions, there are a wide variety of agroecological conditions, microclimates within the soil, climate risks and socio-economic contexts. It is crucial to collect data and information to determine the best course of action and adapt practices to local needs. This information allows for a continuous learning process and can feed into the improvement of future policies. Close coordination and collaboration among stakeholders at all levels are needed to build an enabling environment that gives farmers opportunities to adopt targeted measures to enhance the productivity, resilience and sustainability of rice production in the face of climate change.

The precise challenges that will be created by climate change on rice production systems remain uncertain. These challenges will vary from one farming communities to another, but it is certain they will be especially daunting for countries already coping with high levels of food insecurity. However, there is a clear way forward to meeting these challenges. Options include the adoption of context-specific good agronomic practices, such as conservation agriculture; efficient water and nutrient management and IPM. These options will complement the gains that can be made through the cultivation of improved varieties.

5.7 References

AfricaRice. 2020. AfricaRice Center, Côte d'Ivoire. (Accessed 24 July 2020). http://eservices.africarice.org/argis/search.php.

Ahmed, S., Salim, M. & Chauhan, B. S. 2014. Effect of weed management and seed rate on crop growth under direct dry seeded rice systems in Bangladesh. *PLoS ONE*, 9(7):e101919. https://doi.org/10.1371/journal.pone.0101919

Ali, S. A., Tedone, L. & de Mastro, G. 2017. Climate variability impact on wheat production in Europe: Adaptation and mitigation strategies. In M. Ahmed & C. Stockle C., eds. *Quantification of Climate Variability, Adaptation and Mitigation for Agricultural Sustainability*, pp 251-321. Springer, Cham. https://doi.org/10.1007/978-3-319-32059-5_12

Allen J.M, & Sander B.O. 2019. *The Diverse Benefits of Alternate Wetting and Drying (AWD)*. Los Baños, Philippines, International Rice Research Institute. https://cgspace.cgiar.org/bitstream/handle/10568/101399/AWD_Co-benefits v2.pdf

Awad, Y. M., Wang, J., Igalavithana, A. D., Tsang, D. C., Kim, K. H., Lee, S. S. & Ok, Y. S. 2018. Biochar effects on rice paddy: meta-analysis. *Advances in Agronomy*, 148:1-32. https://doi.org/10.1016/bs.agron.2017.11.005

Bailey-Serres, J. & Voesenek, L. 2010. Life in the balance: a signaling network controlling survival of flooding. *Current Opinion in Plant Biology*, 13(5): 489– 494

Banger, K., Tian, H., & Lu, C. 2012. Do nitrogen fertilizers stimulate or inhibit methane emissions from rice fields? *Global Change Biology*, 18(10):3259-3267. https://doi.org/10.1111/j.1365-2486.2012.02762.x

Bouwman, A. F. 1989. The role of soils and land use in the greenhouse effect. *Netherlands Journal of Agricultural Science*, 37:13-19.

Buresh, R. J., Castillo, R. L., Torre, J. C. D., Laureles, E. V., Samson, M. I., Sinohin, P. J. & Guerra, M. 2019. Site-specific nutrient management for rice in the Philippines: Calculation of field-specific fertilizer requirements by Rice Crop Manager. *Field Crops Research*, 239:56-70. https://doi.org/10.1016/j.fcr.2019.05.013

Cairns, J. E., Hellin, J., Sonder, K., Araus, J. L., MacRobert, J. F., Thierfelder, C. & Prasanna, B. M. 2013. Adapting maize production to climate change in sub-Saharan Africa. *Food Security*, 5(3):345-360. https://doi.org/10.1007/s12571-013-0256-x

CARD. 2021. *Coalition for African Rice Development (CARD), Rice for Africa* [online]. [Cited 18 June 2021]. https://riceforafrica.net/

Chun, J. A., Li, S., Wang, Q., Lee, W. S., Lee, E. J., Horstmann, N., Park, H., Veasna, T., Vanndy, L., Pros, K. & Vang, S. 2016. Assessing rice productivity and adaptation strategies for Southeast Asia under climate change through multi-scale crop modeling. *Agricultural Systems*, 143:14-21. https://doi.org/10.1016/j.agsy.2015.12.001

Cornell University. 2020. *The System of Rice Intensification - SRI Online* [online]. [Cited 18 June 2021]. http://sri.ciifad.cornell.edu/

CIMMYT. 2019. Happy Seeder can reduce air pollution and greenhouse gas emissions while making profits for farmers. In: *CIMMYT: Press Releases* [online]. [Cited 18 June 2021]. https://www.cimmyt.org/news/happy-seeder-can-reduce-air-pollution-and-greenhouse-gas-emissions-while-making-profits-for-farmers/

Deutsch, C. A., Tewksbury, J. J., Tigchelaar, M., Battisti, D. S., Merrill, S. C., Huey, R. B. & Naylor, R. L. 2018. Increase in crop losses to insect pests in a warming climate. *Science*, 361:916-919. https://doi.org/10.1126/science.aat3466

Dobermann, A. 2004. A critical assessment of the system of rice intensification (SRI). *Agricultural Systems*, 79(3):261-281. https://doi.org/10.1016/S0308-521X(03)00087-8

FAO. 2016. *Save and grow in practice: maize, rice and wheat - A guide to sustainable cereal production.* Rome. (also available at www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1263072/).

FAO. 2017. *Climate-Smart Agriculture Sourcebook, second edition* [online]. [Cited 18 June 2021] http://www.fao.org/climate-smart-agriculture-sourcebook/about/en/

FAO. 2019a. *Sustainable Food Production and Climate Change*. (also available at www.fao.org/3/ca7223en/CA7223EN.pdf).

FAO. 2019b. *Rice Landscapes & Climate Change: Workshop Report* (October 10-12, 2018). Bangkok. (also avaialble at www.fao.org/3/CA3269EN/ca3269en.pdf)

FAO. 2020. The Sustainable Rice Landscape Initiative. In: *FAO: Regional Office for Asia and the Pacific* [online]. [Cited 18 June 2021]. http://www.fao.org/asiapacific/partners/networks/rice-initiative/fr/

FAO. 2021. FAOSTAT. *In: FAO* [online]. [Cited 24 July 2020]. http://faostat.fao.org

Gogoi, N., Baruah, K. & Gupta, P. K. 2008. Selection of rice genotypes for lower methane emission. *Agronomy for Sustainable Development*, 28:181-186. https://doi.org/10.1051/agro:2008005

Goyal, S. & Sindhu, S. S. 2011. Composting of Rice Straw Using Different Inocula and Analysis of Compost Quality. *Microbiology Journal*, 1(4):126-138. https://doi.org/10.3923/mj.2011.126.138

GRiSP (Global Rice Science Partnership). 2013. *Rice almanac, 4th edition*. Los Baños, Philippines, International Rice Research Institute.

Haque, Md. E. & Bell, R. W. 2019. Partially mechanized non-puddled rice establishment: on-farm performance and farmers' perceptions. *Plant Production Science*, 22(1):23-45. https://doi.org/10.1080/1343943X.2018.1564335

Haque, M. M., Biswas, J. C., Kim, S. Y. & Kim, P. J. 2017. Intermittent drainage in paddy soil: ecosystem carbon budget and global warming potential. *Paddy and Water Environment,* 15:403-411. https://doi.org/10.1007/s10333-016-0558-7

Harriss, R. C., Gorham, E., Sebacher, D. I., Bartlett, K. B. & Flebbe, P. A. 1985. Methane flux from northern peatlands. *Nature*, 315:652–654. https://doi.org/10.1038/315652a0

Kato, Y. & Katsura, K. 2014. Rice adaptation to aerobic soils: Physiological considerations and implications for agronomy. *Plant Production Science*. 17(1):1-12. https://doi.org/10.1626/pps.17.1

Kato, Y., Collard, B. C. Y., Septiningsih, E. M. & Ismail, A. M. 2019. Increasing flooding tolerance in rice: Combining tolerance of submergence and of stagnant flooding. *Annals of Botany*,124(7):1199-1209 https://doi.org/10.1093/aob/mcz118

Krupnik, T. J., Shennan, C., Settle, W. H., Demont, M., Ndiaye, A. B. & Rodenburg, J. 2012. Improving irrigated rice production in the Senegal River Valley through experiential learning and innovation. *Agricultural Systems*, 109: 101-112. https://doi.org/10.1016/j.agsy.2012.01.008

Lin, X., Zhu, D. & Lin, X. 2011. Effects of water management and organic fertilization with SRI crop practices on hybrid rice performance and rhizosphere dynamics. *Paddy and Water Environment*, 9:33-39. https://doi.org/10.1007/s10333-010-0238-y

Iizumi, T. & Ramankutty, N. 2016. Changes in yield variability of major crops for 1981-2010 explained by climate change. *Environmental Research Letters,* 11(3):034003. https://doi.org/10.1088/1748-9326/11/3/034003

IRRI. 2016. The Rice that Changed the World – Celebrating 50 Years of IR8. *Rice Today* (Special supplement focusing on IR8). IRRI.

IRRI. 2019. Where in the world is IRRI? South Korea. In: *IRRI*: News [online]. [Cited 18 June 2021]. https://www.irri.org/country-month-south-korea-may-2019

IRRI. 2021. International Rice Genebank. In: *IRRI* [online]. [Cited 24 July 2020]. https://www.irri.org/international-rice-genebank

IRRI Rice Knowledge Bank. 2021. *Rice Knowledge Bank* [online]. [Cited 18 June 2021]. http://www.knowledgebank.irri.org/

IRRI GHG Mitigation in Rice. 2021. *GHG Mitigation in Rice: Information Kiosk*. [online]. [Cited 18 June 2021]. https://ghgmitigation.irri.org/

Ismail, A., Singh, U., Singh, S., Dar, M. & Mackill, D. 2013. The contribution of submergence-tolerant (Sub1) rice varieties to food security in flood-prone rainfed lowland areas in Asia. *Field Crops Research*. 152:83-93.

Jiang, Y., van Groenigen, K. J., Huang, S., Hungate, B. A., van Kessel, C., Hu, S., Zhang, J., Wu, L., Yan, X., Wang, L., Chen, J., Hang, X., Zhang, Y., Horwath, W. R., Ye, R., Linquist, B. A., Song, Z., Zheng, C., Deng, A. & Zhang, W. 2017. Higher yields and lower methane emissions with new rice cultivars. *Global Change Biology*. 23(11):4728-4738. https://doi.org/10.1111/gcb.13737

Huang, M., Fan, L., Chen, J. & Zou, Y. 2018. Continuous applications of biochar to rice: Effects on nitrogen uptake and utilization. *Scientific Reports*, 8 (article number 11461). https://doi.org/10.1038/s41598-018-29877-7

Kantha, T., Kantachote, D. & Klongdee, N. 2015. Potential of biofertilizers from selected Rhodopseudomonas palustris strains to assist rice (Oryza sativa L. subsp. indica) growth under salt stress and to reduce greenhouse gas emissions. *Annals of Microbiology*. 65:2109-2118 https://doi.org/10.1007/s13213-015-1049-6

Korres, N. E., Norsworthy, J. K., Burgos, N. R. & Oosterhuis, D. M. 2017. Temperature and drought impacts on rice production: An agronomic perspective regarding short- and long-term adaptation measures. *Water Resources and Rural Development*, 9:12-27. https://doi.org/10.1016/j.wrr.2016.10.001

Kumar, V. & Ladha, J. K. 2011. Direct Seeding of Rice. Recent Developments and Future Research Needs. *Advances in Agronomy*, 111:297-413. https://doi.org/10.1016/B978-0-12-387689-8.00001-1

Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J. & van Kessel, C. 2005. Efficiency of Fertilizer Nitrogen in Cereal Production: Retrospects and Prospects. *Advances in Agronomy*, 87:85-156.
https://doi.org/10.1016/S0065-2113(05)87003-8

Le, T. 2016. Effects of climate change on rice yield and rice market in vietnam. Journal of Agricultural and Applied Economics. *Journal of Agricultural and Applied Economics*, 48(4): 366–382.
https://doi.org/10.1017/aae.2016.21

Lee, Y. 2010. Evaluation of No-tillage Rice CoverCrop Cropping Systems for Organic Farming. *Korean Journal of Soil Science and Fertilizer,* 43(2):2002-208.

Miyata, A., Leuning, R., Denmead, O. T., Kim, J. & Harazono, Y. 2000. Carbon dioxide and methane fluxes from an intermittently flooded paddy field. *Agricultural and Forest Meteorology,* 102(4):287-303.
https://doi.org/10.1016/S0168-1923(00)00092-7

Mosier, A., Syers, J.K. & Freney, J. R. 2013. *Agriculture and the nitrogen cycle: assessing the impacts of fertilizer use on food production and the environment*, SCOPE Report, No. 65. Washington, D.C. Island Press.

NAMA Facility. 2019. *Thai Rice NAMA. Better Rice* [online]. [Cited 18 June 2021]. http://stories.nama-facility.org/better-rice

Ngo, P. T., Rumpel, C., Doan, T. T. & Jouquet, P. 2012. The effect of earthworms on carbon storage and soil organic matter composition in tropical soil amended with compost and vermicompost. *Soil Biology and Biochemistry*, 50: 214-220.
https://doi.org/10.1016/j.soilbio.2012.02.037

Oda, M. & Nguyen, H. C. 2020. Methane emissions in triple rice cropping: patterns and a method for reduction. *F1000Research*.
https://doi.org/10.12688/f1000research.20046.3

Osawa, T., Yamasaki, K., Tabuchi, K., Yoshioka, A., Ishigooka, Y., Sudo, S. & Takada, M.B. 2018. Climate-mediated population dynamics enhance distribution range expansion in a rice pest insect. *Basic and Applied Ecology*. 30: 41-51. https://doi.org/10.1016/j.baae.2018.05.006

RICE (CGIAR Research Program on Rice). 2021. *Ricepedia: the online authority on rice*. [online]. [Cited 18 June 2021].
http://ricepedia.org/challenges/climate-change

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müller, C., Arneth, A., Boote, K. J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T. A. M., Schmid, E., Stehfest, E., Yang, H. & Jones, J. W. 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences of the United States of America*, 111 (9):3268-3273. https://doi.org/10.1073/pnas.1222463110

Rumanti, I.A., Hairmansis, A., Nugraha, Y., Nafisah, Susanto, U., Wardana, P., Subandiono, R.E., Zaini, Z., Sembiring, H., Khan, N.I., Singh, R.K., Johnson, D.E., Stuart, A.M. & Kato, Y. 2018. Development of tolerant rice varieties for stress-prone ecosystems in the coastal deltas of Indonesia. Field Crops Research, 223:75-82.

Saito, M., Miyata, A., Nagai, H. & Yamada, T. 2005. Seasonal variation of carbon dioxide exchange in rice paddy field in Japan. *Agricultural and Forest Meteorology*, 135(1-4):93-109. https://doi.org/10.1016/j.agrformet.2005.10.007

SRP. 2021. *Sustainable Rice Platform* [online]. [Cited 18 June 2021]. http://www.sustainablerice.org

WARDA (West African Rice Development Association). 2001. *NERICA: Rice for Life.* Bouaké, Côte d'Ivoire, WARDA.

WARDA. 2002. *NERICA on the Move: A symbol of hope for rice farmers in Africa*. Bouaké, Côte d'Ivoire, WARDA.

Wassmann, R., Jagadish, S. V. K., Peng, S. B., Sumfleth, K., Hosen, Y. & B.O. Sander. 2011. Rice Production and Global Climate Change: Scope for Adaptation and Mitigation Activities. In: *Advanced Technologies of Rice Production for Coping with Climate Change: 'No Regret' Options for Adaptation and Mitigation and Their Potential Uptake*, 67-76. FAO and IRRI. http://books.irri.org/LP16_content.pdf

Wiebe, K., Lotze-Campen, H., Sands, R., Tabeau, A., van der Mensbrugghe, D., Biewald, A., Bodirsky, B., Islam, S., Kavallari, A., Mason-D'Croz, D., Müller, C., Popp, A., Robertson, R., Robinson, S., van Meijl, H., & Willenbockel, D. 2015. Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environmental Research Letters*, 10:085010. https://doi.org/10.1088/1748-9326/10/8/085010

Won, P. L. P., Liu, H., Banayo, N. P. M., Nie, L., Peng, S., Islam, M. R., Sta. Cruz, P., Collard, B. C. Y. & Kato, Y. 2020. Identification and characterization of high-yielding, short-duration rice genotypes for tropical Asia. *Crop Science*, 60(5):2241-2250.

World Bank. 2007. *World Development Report 2008: Agriculture for Development.* Washington, DC.

Wyckhuys, K. A. G., Lu, Y., Morales, H., Vazquez, L. L., Legaspi, J. C., Eliopoulos, P. A. & Hernandez, L. M. 2013. Current status and potential of conservation biological control for agriculture in the developing world. *Biological Control*, 65(1):152-167. https://doi.org/10.1016/j.biocontrol.2012.11.010

Xiong, Z.-Q., Xing, G.-X. & Zhu, Z.-L. 2007. Nitrous Oxide and Methane Emissions as Affected by Water, Soil and Nitrogen. *Pedosphere*, 17(2):146-155. https://doi.org/10.1016/s1002-0160(07)60020-4

Zhao, C. *et al.* 2017. Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences of the United States of America*. 114(35):9326-9331. https://doi.org/10.1073/pnas.1701762114

6. Sustainable wheat production

Adapting production systems to changing climatic conditions and reducing environmental impacts

H. Jacobs, S. Corsi, C. Mba, W. Hugo, M. Taguchi,
J. Kienzle, H. Muminjanov, B. Hadi, P. Lidder and H. Kim

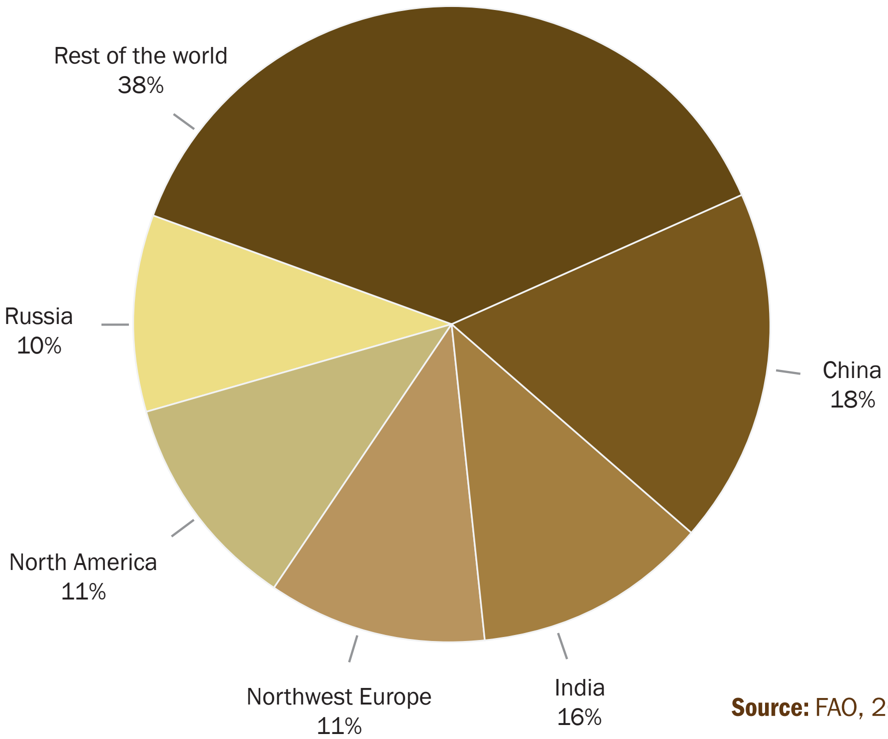
6.1 Introduction

Wheat is one of the world's most widely cultivated staple crops due to its agronomic adaptability and ease of storage. It is crucial for food security, particularly in developing countries. However, the negative impacts of climate change on wheat yields are already being observed in a number of regions. These impacts, which are expected to become even more pronounced, will have consequences on farmers' livelihoods and food security. This briefing note describes approaches for climate change adaptation and mitigation that can support a transition to more sustainable and resilient wheat production systems. It also highlights the synergies these approaches share with the Sustainable Development Goals (SDGs) in the 2030 Agenda for Sustainable Development. Strong political commitment, supportive institutions and investments are essential to give farmers access to these climate-smart approaches and enable their widespread adoption. Increased uptake of these approaches will in turn enhance yields, provide more stable incomes, ensure food security, and contribute to building resilient, sustainable and low-emission food systems.

Wheat, which is grown on 220 million hectares, is cultivated on more land than any other crop (FAO, 2021; Ali *et al.*, 2017). Wheat can tolerate a wide range of temperatures and precipitation levels, and grows on a number of types of soils. The most common wheat species are bread wheat (*Triticum aestivum*) and durum wheat (*Triticum turgidum*). Both species play an important role in feeding the world (Ali *et al.*, 2017).

By 2050, demand for wheat is predicted to increase by 50 percent from current levels (CIMMYT, n.d.). Declining wheat productivity and rising wheat prices will have the most profound impact on countries that have high rates of poverty and depend on wheat for food security. As climate change potentially drives production into higher latitudes, the livelihoods of small-scale farmers, particularly in the global South, will become increasingly at risk (FAO, 2016).

Figure 1: Share of wheat production by country/region (tonnes), 2015-2017



Source: FAO, 2021

China, India, the Russian Federation, North America and Northwest Europe are ranked as the top wheat producing countries and regions. Globally, wheat is second only to rice as a source of calories, and is the most important source of protein. Wheat supplies up to half of all calories in North Africa and West and Central Asia (WHEAT, n.d.).

This brief, which serves as a companion to the Climate-smart Agriculture (CSA) Sourcebook (FAO, 2017), summarizes best practices for wheat production systems under climate change scenarios. It is intended to provide a reference for policymakers, researchers and other groups and individuals working to support sustainable crop production intensification. In plain language and with case studies, the brief lays out a checklist of actionable interventions that could be adopted to enhance or sustain the productivity of wheat production systems that are at risk from climate change.

The strategies for sustainable wheat production presented in this brief address the three pillars of CSA: sustainably increasing agricultural productivity and incomes; adapting and building resilience to climate change; and reducing and/or removing greenhouse gas (GHG) emissions, where possible. The strategies can be used to adapt wheat production systems to increased biotic and abiotic stress that result from changing climatic conditions, and reduce GHG emissions from these systems. This wheat-focused brief is one in a series of crop-specific briefs on CSA.

6.2 Impacts of climate change and projections for wheat

Climate change, which is being driven by increasing concentrations of carbon dioxide and other GHGs in the atmosphere, is having a number of observable impacts, such as drought and higher temperatures, and these impacts are predicted to reduce crop yields and affect global food production (Abraha and Savage, 2006; Ali *et al.*, 2017). Generally, reduced yields result from a combination of factors, including adverse extreme temperatures, disease threats (e.g. wheat rusts), decreased soil fertility and declining efficiency in the use of inputs in conventional cropping systems. This combination of factors is increasing the demand for new crop varieties (FAO, 2016).

Several studies have shown that higher temperatures may shorten the growing season. This would give plants less time to produce grain and accumulate biomass, leading to smaller grains and lower yields (Giannakopoulos *et al.*, 2009; Battisti and Naylor, 2009; Supit *et al.*, 2010; Lobel *et al.*, 2010). As temperatures increase, warmer regions are likely to suffer more yield loss than cooler regions (Liu *et al.*, 2016). Sapkota *et al.* (2014) concluded that due to higher temperature and solar radiation, wheat yields were about 5.2 percent lower over their study period (1981–2009) than they would have been in the absence of global warming. A 2016 study using several models predicts global yield losses of between 4.1 and 6.4 percent for a 1 °C increase in temperature, with a mean yield loss of 5.7 percent (Asseng *et al.*, 2017; Liu *et al.*, 2016). Actual farm yield data collected over a 30-year period from Sonora, Mexico showed a decline of 9 percent for every 1 °C increase in the average night temperature from February to April (H. Braun, personal communication, 2020).

Reductions in wheat yield, particularly in developing countries, may compromise lower the incomes of small-scale farmers (**Target 2.3**), affecting local and national food security (**SDG 2, Targets 2.1 and 2.2**).

These reductions may also hinder efforts to end poverty (**SDG 1**) and reduce inequalities (**SDG 10**). They will particularly affect the most vulnerable and marginalized members of society, including subsistence farmers.

The International Center for Agriculture Research in the Dry Areas (ICARDA) and the International Maize and Wheat Improvement Center (CIMMYT) predict that by 2050 higher temperatures will reduce wheat yields in developing countries by approximately 20 to 30 percent. The McKinsey Global Institute (2020) has projected that by 2030, wheat farmers will be 11 percent more likely to see a 10 percent or greater yield decline in any given year compared with the present, and the same decrease is predicted to be 23 percent more likely by 2050. However, Challinor *et al.* (2014) posit that if adaptation measures are implemented, even with a 2 °C to 3 °C increase in local temperatures, most yield loss in wheat may be avoided and even reversed in tropical regions and in a wide range of temperate regions.

Increased atmospheric concentration of carbon dioxide

There is little clarity regarding the impacts of elevated levels of carbon dioxide on the yield and the nutritional attributes of wheat. However, some experiments under controlled environments and modeling exercises, suggest that the increased concentration of carbon dioxide in the atmosphere could increase photosynthesis rates and productivity in C3 plants (i.e. plants that produce a three-carbon compound during photosynthesis) such as wheat (Ali *et al.*, 2017). This increase could partly negate the impacts of climate change on wheat production. However, the increased concentration of carbon dioxide in the atmosphere may reduce the nutritional quality of wheat. For example, when wheat is cultivated under elevated concentrations of carbon dioxide in the atmosphere, the grains may have less protein, zinc and iron (IPCC, 2019). Crop response to elevated carbon dioxide will most likely depend on environmental and crop management factors (Rosenzweig and Tubiello, 2007). More research in this area is needed.

Impacts of wheat production on climate change

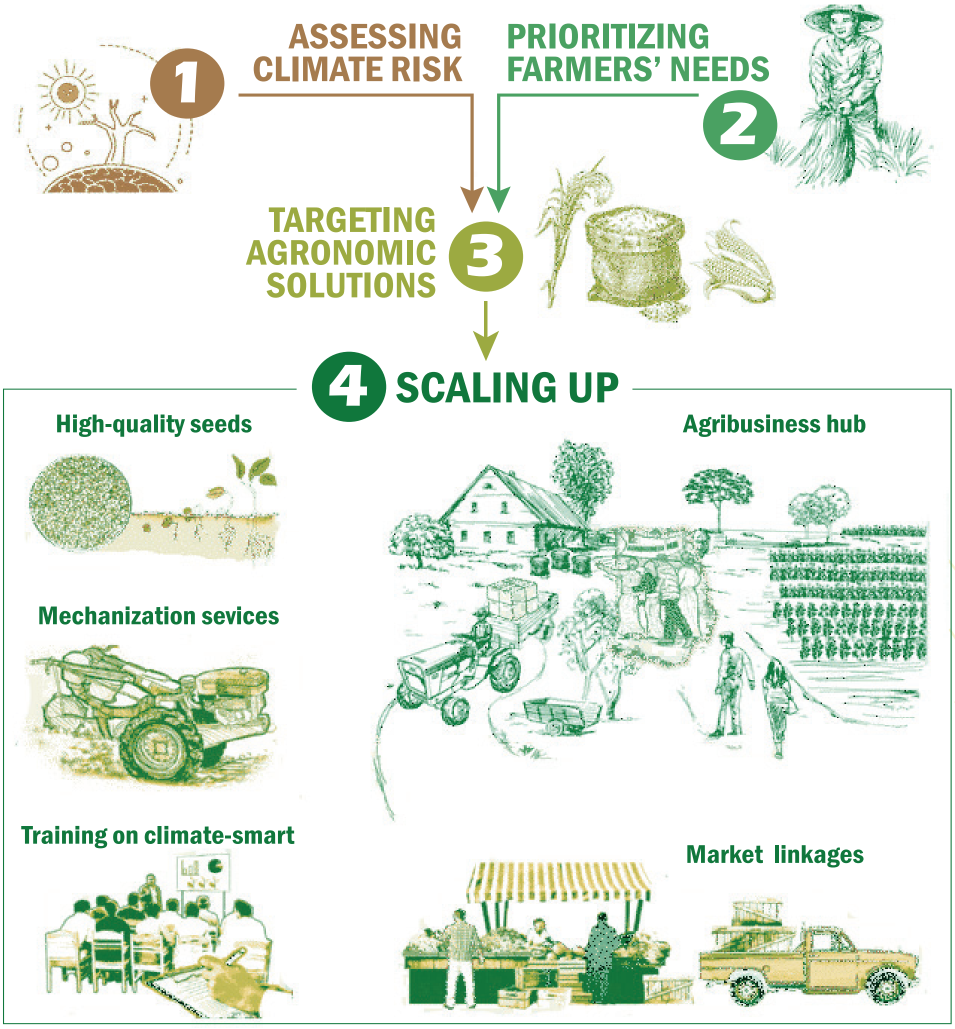
In addition to being affected by climate change, wheat production also contributes to GHG emissions. In wheat production systems, the primary sources of GHG emissions are associated with conventional crop production practices. These practices include conventional tillage, which leads to a loss of soil organic carbon; the use of nitrogen fertilizers and pesticides, which contribute to emissions of non-carbon dioxide GHGs (e.g. nitrous oxide); and emissions from agricultural operations (e.g. electricity consumption for irrigation and fuel consumption in agricultural machinery). These impacts and approaches for their mitigation are discussed in Section III.

6.3 Climate change adaptation approaches

FAO works with countries to reduce the adverse impacts of climate change on crop productivity and the contributions crop production systems make to climate change. Based on lessons being learned in the field, FAO (2019) has proposed a four-step approach to climate change adaptation and mitigation:

1) assess climate risk;
2) prioritize farmers' needs;
3) target agronomic and breeding solutions; and
4) scale up successful interventions.

Figure 2: The Save and Grow approach



Source: FAO, 2019

The FAO 'Save and Grow' approach to sustainable crop production intensification relates to step 3 in this four-step sequence.

The 'Save and Grow' approach consists of a set of practices that include conservation agriculture; the use of improved crops and varieties; efficient water management; and integrated pest management (IPM). This section describes in greater detail the application of these practices in wheat-based production systems.

6.3.1. Conservation agriculture

Conservation agriculture is a sustainable agronomic management system that combines zero or reduced tillage, the maintenance of soil surface cover with mulch or cover crops, and the diversification of cropping systems (Cairns *et al.*, 2013; FAO, 2016; 2017). Disturbing the soil with farm machinery causes organic matter to decompose rapidly, which reduces soil fertility and damages soil structure.

It should be noted that conservation agriculture may act as a catalyst for specific pests and diseases (e.g. the fungal diseases tan spot and *Septoria*, as well as snails, slugs, and mice), which may create a barrier to the adoption of conservation agriculture by small-scale farmers. However, the problems associated with pests and diseases are treatable and decrease over time as the long-term benefits of conservation agriculture accrue (Thierfelder *et al.*, 2018). Training farmers in effective treatments for pests and diseases involves discussions and feedback from agronomists and extension workers, particularly during the approximately 5-year transition phase that is required to make a shift to conservation agriculture. If conservation agriculture is to be adopted as a principal strategy, a greater emphasis needs to be placed on training (Leake, 2003).

In the Indo-Gangetic Plain, which spans 2.25 million square km across South Asia, from Bangladesh through India and Nepal to Pakistan, and constitutes the breadbasket for 1.8 billion people, intensive rice-wheat and maize-wheat systems that have used conservation agriculture have contributed to significant improvements in the physical and chemical properties of soil (Jat *et al.*, 2009; FAO, 2016). Wheat farmers there who use zero-tillage and reduced tillage achieve higher yields and increase soil and water conservation. Conservation agriculture, crop diversification and the application of biofertilizers deliver many co-benefits in term of pest management (Murrell, 2017).

Enhancing the water regulation capacities of agricultural soils increases water use efficiency (**Target 6.4**), enhances water quality (**Target 6.3**) and improves access to safe drinking water (**Target 6.1**), ultimately contributing to ensuring the availability and sustainable management of water resources (**SDG 6**).

Actions

Zero-tillage or direct seeding involves the placement of wheat seeds by drilling or opening a seed line through the previous crop's residues without the mechanical preparation of the seedbed. It enhances soil organic matter content (Sapkota *et al.*, 2017), which improves water infiltration and retention, increases water use productivity, and reduces erosion (Sapkota *et al.*, 2015). Recommended **sustainable mechanization equipment** includes tractors (both two-wheeled and four-wheeled), and mechanized direct seeders that include precision fertilizer applicators (Sims and Kienzle, 2015; FAO, 2017).

Cover crops or mulches on the soil surface conserve soil moisture, reduce erosion, increase water infiltration and suppress weeds. Integrating nitrogen-fixing green manure cover crops maximizes nitrogen fixation and improves nitrogen use efficiency, which can enable farmers to reduce their use of external inputs over the long term. Different green manure cover crop species of edible and nonedible legumes (perennial, biennial and annual) can be used in combinations to maintain a supply of crop nutrients and strengthen the overall production system.

The diversification of the cropping system should be promoted to avoid wheat monocultures and continuous cropping. In wheat production systems, the soil must be replenished with abundant amounts of nitrogen, which can be supplied by including legumes in the crop rotation. Growing different crops in succession reduces and prevents soil erosion caused by floods and drought; controls weeds, pests and diseases; and decreases the need for fertilizers and herbicides. Crop species and varieties and their combinations should be adapted to each farm system. Rotation of wheat with grain legumes (e.g. lentils, chickpeas, and faba beans) and forage legumes (e.g. vetch, berseem clover and species of Medicago) are used in rainfed production areas and in soils with low nitrogen levels. Wheat-legume systems are suitable for temperate, sub-tropical rainfed and irrigated farming systems in different agroecological zones. These systems can be implemented using three general methods:

- **intercropping**, which involves planting wheat and legumes simultaneously in the same row or alternating rows;
- **relay cropping**, which involves planting wheat and legumes on different dates but cultivating them together for a part of their life cycle; and
- **rotation**, which involves planting wheat after the legumes have been harvested.

Improved nutrient management, erosion protection and the diversification of cropping and farming systems all contribute to building more sustainable and resilient food systems (**SDG Target 2.4**) and to ensuring the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services (**SDG Target 15.1**).

Minimizing nutrient losses from the use of fertilizers contributes to the reduction of marine pollution from land-based activities (**SDG Target 14.1**).

Diversification is also a strategy to achieve higher levels of economic productivity (**SDG Target 8.2**).

Box 1: Diversified wheat farming systems

Wheat production systems (wheat-legume, wheat-maize, rice-wheat, and wheat-cotton systems).
Wheat is grown in rotation with other crops in all production regions. (FAO, 2016).

Wheat-legume systems. Farmers in dry areas can use fields that are commonly left fallow in the summer to grow legume crops. This leads to a more productive use of land, enhances soil fertility and improves water use efficiency. Choosing the right legume is important, as legume species differ in their ability to fix and accumulate nitrogen in the soil, their production of dry matter, and the quality of their residues (FAO, 2016). Crop residues should be retained on the soil surface, and zero-tillage should be adopted to conserve soil structure, moisture and nutrients.

Wheat-maize intercropping is useful where conditions allow for only annual, one-season cropping patterns. Due to high water consumption levels, however, it is important to employ zero-tillage and reduced tillage to conserve water. In India, the most productive wheat-maize systems use zero-tillage and permanent raised beds that are drill seeded through crop residues.

Wheat-maize double cropping systems. Planting maize using zero-tillage after harvesting wheat is a common practice in the valleys of China, Turkey and Central Asia as well as South America, especially in Argentina and Uruguay.

Rice-wheat farming systems are common across the Indo-Gangetic Plain. After the Green Revolution, rice and wheat yields began to decline as soils became increasingly depleted after decades of intensive cultivation. To address this situation, rice-wheat cropping systems that conserve resources were introduced in the 1990s by the Rice-Wheat Consortium, a CGIAR initiative affiliated with national agriculture research centres. Later, other national and international research organizations and universities started designing, developing and promoting conservation agriculture for the sustainable intensification of rice-wheat systems. The rice-wheat crop rotation, which is the most widespread cropping system in the Indo-Gangetic Plain, covers 13.5 million hectares and produces 80 million tonnes of rice and 70 million tonnes of wheat annually (FAO, 2016). The systems produce rice during the summer monsoon and wheat during the short winter. Wheat is planted after rice using a tractor-drawn seed drill, which plants the seeds directly into unploughed fields with a single pass. The 'Happy Seeder', a commonly known technology, uses laser-assisted leveling of land and permanent bed planting for the dry seeding of rice and surface seeding of wheat.

Wheat-cotton rotation systems are used in Egypt, India, Pakistan, Tajikistan, Turkey and Uzbekistan. The late harvesting time for cotton can delay wheat planting in South Asia, which then subjects the crop to heat stress. Relay planting of wheat in the standing cotton crop enables wheat sowing to be moved up and can boost yields by up to 40 percent (FAO, 2016).

6.3.2. Improved crops and varieties

The use of landraces and crop wild relatives in plant breeding contributes to maintaining the genetic diversity in cultivated plants (**SDG Target 2.5**).

Improved varieties that produce high yields, resist pests and diseases, and tolerate biotic and abiotic stresses are developed by the continuous incorporation of new desirable traits in crop breeding. These traits may be found in germplasm collections that include landraces or farmers' varieties and wild relatives. The cultivation of resistant varieties is a way to combat abiotic and biotic stresses (Ali *et al.*, 2017). Wheat landraces in particular have important traits for conferring drought and heat tolerance. These landraces are also sources of the increased biomass and larger grains, and should be used in breeding to develop well-adapted, nutritious and productive varieties. Proof of concept has already been shown through breeding approaches that have enabled wheat varieties to acquire these traits as well as other stress-adaptive traits (Reynolds *et al.*, 2017). An example are varieties that provide a cooler canopy, which is associated with more vigorous root growth, and for which a genetic base has been established (Pinto and Reynolds, 2015). It should be noted that there are sometimes trade-offs between traits for abiotic or biotic stresses tolerance and traits that increase crop growth and yield (Da Silva *et al.* 2020).

Actions

Cultivating crop varieties that match local conditions is an important adaptive practice for all types of crop production systems. This can involve growing familiar crop varieties and **incorporating new heat-tolerant varieties**. Where possible, it is recommended to **incorporate crop varieties that produce high yields in a shorter growing season** to reduce exposure to late season heat stress.

Improving the salt tolerance of wheat varieties is critical. Crop species and varieties that are more salt tolerant are becoming increasingly important. Breeding for salt tolerant crops can be beneficial for farmers working on naturally salty soils that need to be prepared for cultivation. Salt tolerant varieties can also help to remove salt from the soil. However, the presence of salt in the soil is often the result of poor engineering, drainage and water quality, or a combination of these factors. Saline soils are growing challenge that demand solutions that involve more than salt tolerant crops. Increasing salt tolerance should not enable the continued use of unsustainable irrigation practices that may end up further increasing soil salinity.

Root systems are especially important in rainfed wheat production, which depends on moisture stored in the soil. Traits that are beneficial in rainfed wheat production systems include: deeper root systems; increased root length density in medium and deep soil layers; reduced root length density in topsoil; and increased root hair growth, which decreases resistance of water movement from the soil to the root (Wasson *et al.*, 2012). Soil-borne diseases (e.g. root lesion nematodes and crown rot) that affect the root system or the base of the stem can cause even greater damage under drought stress or limited moisture availability (see Section IV). Breeding for resistance, which is a promising approach in this area, is being done by the CIMMYT-Turkey Soil-Borne Pathogens Program, a research center established in 2017 with the support of the Turkish Ministry of Agriculture and Forestry. A major element of the Program's work on root diseases involves screening the high-yielding, adapted durum and spring wheat germplasm developed at CIMMYT-Mexico to identify novel forms of resistance to multiple soil-borne pathogens and map their genetic basis (Australian Government Grains Research and Development Programme, 2016; CIMMYT, 2017).

Box 2: CIMMYT Global Wheat Program

The CIMMYT Global Wheat Program is an extremely important source of climate-resilient, high-yielding and pest-tolerant wheat varieties for Africa, Asia, and Latin America. CIMMYT works with ICARDA and the CGIAR Research Program on Wheat (WHEAT), sharing advanced lines and associated data. The wheat research program uses the latest molecular breeding tools, bioinformatics, and precise phenotyping approaches to develop genetically diverse wheat varieties. The Wheat Molecular Breeding laboratory develops tools for breeders around the world. Heat-tolerant wheat has been released in several countries. A CIMMYT-supported wheat improvement network is exploring the development of high-yielding wheat varieties that can cope with increasingly hot summers (FAO, 2016).

Increasing farmers' access to improved varieties is essential. To foster this process, CIMMYT and ICARDA have helped national partners accelerate the testing and release of varieties that are adapted to local conditions, produce high yields, and are resistant to abiotic and biotic stress. National-level programmes and famer groups can accelerate this process and support large-scale production (Joshi *et al.*, 2011; FAO, 2016).

6.3.3. Efficient water management

Wheat generally needs between 450 and 650 mm of precipitation over the course of the growing period (Doorenbos and Pruitt, 1977). However, several areas where wheat is cultivated receive as little as 330 mm. Typically, 600 litres of water are needed to produce one kg of wheat. In reality, most irrigated wheat production systems, such as those in Asia, require roughly 900 litres to produce one kg (Pimentel *et al.*, 1997). In areas where irrigation systems are inefficient, up to 1 200 litres per kg may be needed (Braun, personal communication, 2020). As the competition for irrigation water increases, it is expected that water will be diverted from wheat to higher value crops and other sectors of the economy, which may force wheat cultivation into rainfed areas and less productive lands (FAO, 2016).

Efficient water management in wheat cropping systems, which can be achieved, for example, through efficient irrigation technologies and management, contributes to ensuring the sustainable management of water resources (**SDG 6**), and to increasing water use efficiency in particular (**Target 6.4**).

Actions

Shifting planting dates may be required to adapt to increased climate variability and change in the beginning and/or the end of the growing season. Another option is cultivating new varieties to cope with changes in the length of the growing season or avoid situations where the levels of moisture and temperature are not an appropriate match for the stage the crop has reached in its development (FAO, 2017; Ali *et al.*, 2017).

Supplemental irrigation involves adding small amounts of stored water when rainfall is insufficient at critical stages in crop growth to increase and stabilize yields (FAO, 2016).

Raised-bed planting with furrow irrigation, which carries water to the soil between two rows of crops, improves water use efficiency, and increases soil porosity and water infiltration (Sayre, 1998; Solh *et al.*, 2014). Raised-bed planting also increases yields in areas where soil salinity is a problem.

Conservation agriculture practices (see Section I) can be used to enhance the capacity of the soil to retain moisture and reduce moisture loss from evaporation. Maintaining sufficient levels of soil organic matter also helps increase water productivity (FAO, 2016).

Sprinkler irrigation and subsurface irrigation are efficient techniques that can be used in combination with other conservation agriculture practices to avoid disturbing the soil and improve water use efficiency.

Drip irrigation provides greater water use efficiency than surface irrigation (Salvador *et al.*, 2011). By enhancing soil moisture, drip irrigation can also increase wheat yield compared to basin irrigation in areas where water availability is limited (Fang *et al.*, 2018). Currently, drip irrigation systems for wheat may not be economical due to installation costs, but this may change if water shortages increase. In any case, drip irrigation currently allows for the conservation of more water for irrigated wheat than any other irrigation method.

6.3.4. Integrated pest management

Pests and diseases. Increased rainfall and humidity are expected to affect the timing of wheat pests and diseases during the growing season, and influence their population dynamics (e.g. their ability to survive over winter, changes in the number of generations) and their geographic distribution (Juroszek and von Tiedemann, 2013; Vaughan, Backhouse and Del Ponte, 2016). Wheat rusts have a long history and are increasingly appearing in new regions. The strong return of wheat stem rusts in the late 1990s and 2000s, particularly the emergence of the new race, Ug99, in Africa, prompted researchers to develop resistant varieties (Bhattacharya, 2017). Due to coordinated action among wheat researchers and donors, it was possible to confine stem rust epidemics to East Africa. Today, most varieties released in at-risk areas are resistant, which stands in stark contrast to 1998, the year Ug99 was first detected, when more than 80 percent of the world's wheat varieties were susceptible.

Wheat rust (e.g. wheat stripe, leaf and stem rusts) have threatened global wheat production since wheat was first domesticated (Figueroa *et al.*, 2018). Tan spot is another important disease that affects the leaves of wheat and is present in major wheat growing countries. Tan spot is caused by the fungus *Pyrenophora tritici-repentis* (Ptr), which can survive in infected crop residue from one season to the next, and can be dispersed over long distances (Abdullah *et al.*, 2017). Because of these traits, tan spot has a particularly strong impact on wheat grown under monoculture systems. Tan spot can also become a problem in wheat crops grown under conservation agriculture (Cotuna *et al.* 2015). Wheat blast, which can cause devastating losses, was first identified in Brazil but has now spread throughout South America. It was confirmed in Bangladesh in 2016 (Figueroa *et al.*, 2018) and reached Africa (Zambia) in 2018 (Tembo *et al.*, 2020). Bunt and smut diseases are other important fungal diseases, but can be effectively controlled through seed treatment.

Septoria (Septoria tritici blotch (STB) and Septoria nodorum blotch) diseases are important wheat diseases that cause significant losses in yield. STB is characterized by necrotic lesions on leaves and stems that develop after infected cells collapse. STB epidemics are associated with frequent rains and moderate temperatures, specific cultural practices, the cultivation of susceptible wheat varieties and the availability of inoculum (Eyal *et al.*, 1997; Curtis, Rajaram and Macpherson, eds. 2002).

Soil-borne diseases are globally significant, but they largely under-researched and often are not recognized. Specifically, cyst and lesion nematodes, and root and crown rots can cause significant damage particularly under drought conditions and in soils with nutrient imbalances (Braun, personal communication, 2020).

The warming climate increases the metabolic rates of insect pests and the growth of their populations, which could potentially increase yield losses from pests that feed on plant material (herbivory). A 2 °C increase in temperature is associated with a 46 percent higher median yield loss in wheat due to insect pests compared to the current losses. The global distribution of future additional losses is not uniform, with higher additional losses predicted in temperate regions (Deutsch *et al.*, 2018). As the global temperature increases, areas in higher latitudes will start to record temperature ranges that allow new pests and pathogens to survive. There is already an indication of a pole-ward expansion of the ranges of many crop pests and diseases that has been associated with global climate change (Bebber *et al.*, 2013).

Several major wheat pests (e.g. sunn pest, aphids, leaf beetles) damage crops all over the world (Miller and Pike, 2002). Sunn pests extract fluids from wheat stems, leaves and developing grains, and when feeding on kernels they reduce kernel weight and quality (Miller and Pike, 2002). Aphids can be found in all wheat production areas and can cause considerable damage by secreting a substance that promotes mold growth. However, wheat crops can often tolerate relatively low levels of infestation. Cereal leaf beetles, which feed on young leaves, affect most cereal crops, but prefer wheat. Biological control (i.e. using natural enemies of pests) has been a successful strategy in combatting wheat pest infestations (Miller and Pike, 2002).

IPM, which emphasizes the minimal use of harmful chemical pesticides, contributes to the sustainable management of terrestrial ecosystems (**SDG Target 15.1**) and reduces marine pollution from land-based activities (**SDG Target 14.1**).

The successful implementation of IPM, which can prevent infestations that can severely damage crops and cause famine, contributes to **SDG Target 2.1**.

IPM contributes to the sound management of chemicals throughout their life cycle and reduces their release into the air, water and soil, which minimizes impacts on human health and the environment (**SDG Target 12.4**).

IPM can also benefit human health by reducing illnesses caused by air, water and soil pollution and contamination (**SDG Target 3.9**).

Actions

Integrated pest management (IPM) is an ecosystem approach to crop production and protection that was developed in response to the widespread overuse of pesticides. In IPM, farmers use natural methods based on field observation to manage pests. Methods include biological control (i.e. the use of natural enemies of pests), the use of resistant varieties, and habitat and cultural modification (i.e. the removal or introduction of certain elements from the cropping environment to reduce its suitability for pests). The rational and safe application of selective pesticides is used as a last resort (FAO, 2016). IPM capitalizes on natural pest management mechanisms that maintain a balance between pests and their natural enemies. Manipulating the habitat around the fields to provide additional food and shelter for the natural enemies of pests is a non-chemical method that can be used for most crops (Wyckhuys *et al.*, 2013). For wheat, crop management practices to combat pests include early or delayed planting; targeted ground spraying; the cultivation of flowering plants that attract natural predators; the application of biopesticides and the release of arthropod biocontrol agents; and crop rotations (FAO, 2016).

IPM can be promoted through farmer field schools. Field schools provide an excellent forum where farmers can share their experiences with IPM strategies for wheat pests and learn by doing.

Septoria diseases can be combatted by cultivating resistant varieties and not planting crops too early. Soil management practices should not leave wheat stubble and debris on the soil surface, as this can increase the probability of epidemics under favorable climatic conditions. In some cases, the removal of this debris for use as feed combined with crop rotations with a non-wheat crop can help to prevent outbreaks (Curtis, Rajaram and Macpherson, eds. 2002). Fungicides applied to crop foliage can also be used to control outbreaks.

Soil-borne diseases. Cultural practices to control soil-borne diseases include delayed planting and the optimized application of nitrogen to reduce late season water stress. Planting crops in rotation, keeping fallow land clean, and cultivating trapping crops can also serve to control soil-borne diseases. Host plant resistance is the most efficient and economical approach to reducing yield losses caused by soil-borne disease (Dababat *et al.*, 2018).

6.4 Climate change mitigation approaches

A range of options exist to enable wheat production systems to support climate change mitigation and contribute to global efforts to achieve SDG 13 particularly as measured by SDG Indicator 13.2.2, reduction of national GHG emissions. The options available for mitigation strategies in wheat production system can improve carbon sequestration in the agricultural ecosystem and reduce GHG emission. These options increase resource use efficiency and prevent soil erosion and nutrient losses. Key elements for these mitigation strategies include the diversification of crop production, agroforestry, precision farming, sustainable mechanization and a reduced reliance on chemical fertilizers. Many of these strategies deliver co-benefits to the environment and human health, and may generate greater economic returns for farmers and farming communities.

Crop production practices, such as conventional tillage and the application of chemical fertilizers and pesticides, contribute to GHG emissions. The implementation of improved practices is essential for reducing these emissions and mitigating climate change. Where possible, wheat production systems can contribute to reducing emissions by adopting the following strategies.

6.4.1. Increasing soil carbon sequestration

Increasing soil organic matter content requires enhancing carbon inputs and minimizing carbon losses. Climatic conditions (e.g. precipitation and temperature) and soil aeration influence the decomposition of organic matter.

Actions

The diversification of crop production as part of conservation agriculture can increase carbon sequestration and improve nitrogen use efficiency (Corsi *et al.*, 2012, Sapkota *et al.*, 2017). Conventional wheat monoculture production depletes soil nutrients. Wheat intercropping and relay cropping has multiple benefits. For example, they protect against soil erosion for a greater portion of the year and produce additional root biomass that increases organic matter in the soil. The diversification and intensification of the crop production system by including legumes and perennials in the crop rotation avoids leaving fields fallow and contributes to soil carbon sequestration. As mentioned in Section II, wheat-legume systems fix nitrogen in the soil and can reduce farmers' reliance on chemical fertilizers, which reduces nitrous oxide emissions. When perennial, biennial, and annual legumes are used as intercrops and relay crops with wheat, the results can lead to both higher yield and income. Ideally, famers would combine these practices with the use of adapted varieties and integrated plant nutrient management.

The efficient use of nitrogen contributes to the economy-wide target of improving global resource efficiency in consumption and production (**SDG Target 8.4**).

Nitrogen use efficiency contributes to the sound management of chemicals throughout their life cycle and reduces their release into the air, water and soil, which minimizes their impacts on human health and the environment (**SDG Target 12.4**).

Erosion protection in agricultural landscapes contributes to achieving a land degradation-neutral world (**SDG Target 15.3**).

Improved yields and incomes contribute directly to the target of doubling agricultural productivity and the incomes of small-scale food producers (**SDG Target 2.3**).

The rice-wheat farming system of the Indo-Gangetic Plain, described in Section II, is another example of a diversified system that can mitigate climate change. In this system, a combination of zero-tillage and the partial retention of residues increase biomass production, grain yields and soil organic carbon, and allows farmers to use the residues for other purposes (Sapkota *et al.* 2017).

Agroforestry is the term for land-use systems and technologies in which woody perennials (e.g. trees, shrubs, palms or bamboos) and crops or grasses and/or animals are deliberately grown on the same parcel of land in some form of spatial and temporal arrangement (Choudhury and Jansen, 1999).

When properly designed and managed, agroforestry systems can be effective carbon sinks. By providing products and services that would otherwise be sourced from forests (e.g. woodfuel and timber), agroforestry can also strengthen local livelihoods and reduce pressure on natural forests.

By reducing the pressure on natural forest, agroforestry can contribute to the sustainable management of forests and curb deforestation (**SDG Target 15.2**).

Economic opportunities that arise from agroforestry contribute to improving the livelihoods of small-scale food producers (**SDG Target 2.3**) and can support subsistence farmers in overcoming poverty (**SDG Target 1.1**).

Integrated soil fertility and nutrient management can reduce land degradation and the mining of nutrients from the soil that result from unsustainable intensified agricultural production systems. The application of inorganic and organic fertilizer, which includes recycled organic resources (e.g. green manure and farmyard manure), on the basis of crop needs, can accumulate carbon in the soil and reduce GHG emissions. In wheat-legume multiple cropping systems, crop rotations combined with manure and nitrogen-phosphorus fertilizer could increase the yield for both wheat and faba bean (Agegnehu and Amede, 2017). In intensified systems, the management of soil organic carbon is essential for sustainable crop production. Fertilization recommendations should be adjusted in accordance with the cropping systems that are being considered and the type of soil. Improving soil organic carbon enhances soil quality, reduces soil erosion and degradation, which in turn reduces carbon dioxide and nitrous oxide emissions (Kukal *et al.* 2009). The Rice-Wheat Consortium created a leaf colour chart for rice farmers to indicate the best times for fertilization and has adapted it for wheat farmers. When the chart was introduced to wheat farmers in the Indo-Gangetic Plains, they were able to reduce their fertilizer applications by up to 25 percent with no reduction in yields (FAO, 2016).

Increasing soil organic carbon content helps to stabilize the soil and protect it from erosion, which contributes to achieving the target of a land degradation-neutral world (**SDG Target 15.3**).

Applying biochar to the soil can be a sustainable option for sequestering carbon and enhancing soil fertility (Mukherjee and Zimmerman, 2013). In durum wheat, the application of biochar could increase biomass production and grain yields by 30 percent without affecting the grain's nitrogen content (Vaccari *et al.*, 2011). In addition, converting agricultural residues to biochar can be an effective method for reducing carbon dioxide emissions.

6.4.2. Reducing GHG emissions

Reducing carbon dioxide emissions in crop production is primarily achieved by lowering direct emissions from operations and avoiding the mineralization of soil organic carbon. Better fertilizer management and improved efficiency in the use of fertilizers, particularly fertilizers containing nitrogen and sulfur that release nitrous oxide and sulfur dioxide, can reduce the emissions of non-carbon dioxide GHGs. There are several negative environmental impacts associated with the use of inorganic and organic fertilizers (e.g. water eutrophication, air pollution, soil acidification, and the accumulation of nitrates and heavy metals in the soil) (Mosier *et al.*, 2013).

Nitrogen fertilizers are the most frequently used type of inorganic fertilizers. Almost half of the world's population relies on nitrogen fertilizer for food production, and 60 percent of global nitrogen fertilizer is used for producing the three major cereals: rice, wheat and maize (Ladha *et al.*, 2005). However, excessive use of nitrogen fertilizer can put ecosystems and human health at risk. Adopting

Improved efficiency in the use of nutrients and fertilizers not only lowers GHG emissions, it also reduces nutrient pollution in terrestrial, freshwater and marine ecosystems, and enhances related ecosystems services (**SDG Targets 15.1, 6.3, 14.1**).

This increased efficiency also facilitates the sound management of chemicals throughout their life cycle and reduces their release into the air, water and soil, which minimizes their impacts on human health and the environment (**SDG Target 12.4**).

This can also have beneficial impacts on human health by reducing illnesses associated with air, water and soil pollution and contamination (**SDG Target 3.9**).

improved agronomic practices and developing improved varieties that increase nitrogen use efficiency in wheat production can significantly reduce farmers' reliance on chemical inputs.

Actions

Sustainable mechanization, the use of smaller tractors, making fewer passes across the field, and reduced working hours, when combined with conservation agriculture, reduce the combustion of fossil fuels and lower GHG emissions. These actions also minimize soil disturbance, and reduce soil erosion and degradation (FAO, 2017). Box 3 describes the no-till planter "Happy Seeder", which has been shown to reduce GHG emissions in rice-wheat farming systems.

Box 3: The Happy Seeder in rice-wheat farming systems on the Indo-Gangetic Plain

The Happy Seeder is a tractor-mounted no-till planter that can drill wheat seed through heavy loads of rice residues. The Happy Seeder then deposits the residues over the sown area as mulch. CIMMYT has found that systems that make use of the Happy Seeder have the most profitable and scalable residue management practices, proving to be 10 to 20 percent on average more profitable than burning. The systems are able to reduce GHG emissions by 78 percent per hectare compared to burning options. The burning of residues, which has been widely practiced for rice cultivation, contributes significantly to air pollution and short-lived climate pollutants.

Source: CIMMYT, 2019; Shyamsundar *et al.*, 2019.

The cultivation of varieties with higher fertilizer use efficiency can reduce losses in fertilizer nutrients. These nutrient losses have been estimated (on average) to be up to 50 percent of applied nitrogen and 45 percent of phosphorus (FAO, 2016). There is considerable genetic variability among wheat varieties for nitrogen use efficiency. The nitrogen level in the soil is also important for the genetic expression of uptake and utilization efficiency in wheat (Curtis, Rajaram and Macpherson, eds. 2002; Ortiz-Monasterio R. *et al.*, 1997).

Applying nitrogen fertilizers at specific stages of crop growth can increase fertilizer use efficiency in wheat. If the nitrogen fertilizer is applied all at once during the sowing process (basal application), the nitrogen does not remain in the soil for the crop's entire growing cycle. Some of the nitrogen may be washed away by rain or though irrigation (nitrate leaching). However, if the same amount of nitrogen is divided into two or three applications during the crop cycle, the amount that is successfully absorbed by the plant increases and less is released into the environment. When the supply of nitrogen in the soil is low, applying one dose of nitrogen late in the season can also improve the grain protein concentration (Rossmann *et al.*, 2019).

Precision farming encompasses an increasing range of high-tech approaches that include precision land leveling, precision planting and precision nutrient management. For example, GPS, GIS or remote sensing technologies and environmental information are being used to develop a decision support system for farmers that allows them to optimize the application of fertilizers, pesticides and other inputs to meet precise site-specific requirements (Balafoutis *et al.*, 2017). Decision support systems, which take into consideration spatial and temporal needs of the fields, can reduce GHG emissions while maintaining yields and minimizing the use of water, chemicals and labour. Additionally, some sophisticated combine harvesters now have yield monitors, many of which are linked to GPS. These monitors can calculate and record the yield of biomass or grain, measuring areas consisting of few square meters. This data is used to create a yield map that can be loaded into the planting machine for the following season. This can enable the farmer to apply precise amounts of fertilizer that will vary according to demands indicated on the yield map from the previous crop. These crop- and site-specific application methods improve fertilizer use efficiency and reduce the excess application of fertilizers that increase nitrous oxide emissions and lead to nitrogen leaching. These methods can also enhance carbon sequestration by reducing tillage. Precision technologies can also decrease GHG emissions by reducing the use of farm equipment in sowing, fertilizing, spraying, weeding and irrigation management.

Utilizing GPS-enabled precision farming, sustainable mechanization, and improved varieties contributes to the transfer, dissemination and diffusion of environmentally sound technologies to developing countries (**SDG Target 17.7**).

Precision management of nutrients and water (Sapkota *et al.* 2014; Jat *et al.*, 2015) contributes to both climate change adaptation and mitigation (IPCC, 2019). Precision nutrient management has increased productivity and reduced the contribution wheat production systems in northwest India make to climate change. Zero-tillage systems combined with site-specific nutrient management, which enhances use of existing soil nutrients and fills gaps with mineral fertilizer, can increase nutrient use efficiency and yields and decrease GHG emissions (FAO, 2016). Micronutrients (e.g. calcium, magnesium, sulphur, iron and zinc) play an important role in improving the health of the soil, increasing crop productivity and enhancing the nutritional content of wheat. The precision application of fertilizers that contain these micronutrients improves crop's nutritional quality, increases yield, and builds the crop's resilience to pests, diseases and drought. Efficient fertilizer management has been

Box 4: Sensor-based nitrogen management

In Mexico, fertilizer use efficiency has improved through the use of a hand-held Normalized Difference Vegetative Index (NDVI) sensor and a nitrogen fertilization algorithm, which measure the vigour of wheat crops and optimize nitrogen applications to meet crop requirements. Fertilizer applications guided by optical sensors help to adjust the amount of nitrogen fertilizer needed at different stages of the crops' development. Nutrient Expert® is a nutrient decision support tool based on the principles of site-specific nutrient management. It takes into account variations in the growing environment that are affected by climate, soil type, cropping system, and crop management practices, to provide farmers with recommendations for balanced application of nutrients based on crop requirement in individual farmers' fields, considering specific site information. This tool is joint development of wheat stakeholders in India including representatives from national research and extension system, private industries, CIMMYT, and International Plant Nutrition Institute (IPNI). (Pampolino *et al.*, 2012). Using recommendations from Nutrient Expert®, improved nutrient management strategies were used in the Indo-Gangetic Plain with conservation agriculture to reduce fertilizer applications while producing higher wheat yields and reducing off-farm environmental impacts (Sapkota *et al.* 2014; FAO, 2016).

identified as a cost-effective mitigation option because it reduces the cost of production, increases crop yield and at the same time lowers GHG emissions (Sapkota *et al.*, 2019).

The application of biofertilizers, such as plant growth promoting bacteria (PGPB), to the soil is another promising approach for integrated management systems (Di Benedetto *et al.*, 2017). PGPB have the ability to mobilize nutrients (mineral or organic) that are otherwise bound to the soil and make these nutrients available to the plants. They can also fix atmospheric nitrogen into the soil and convert it into forms the plants can use. Further research is required to identify the type of bacteria that are the most appropriate PGPB for wheat in terms of sustainable agricultural productivity and environmental management. This research would need to consider the ways biological fixation increases the availability of nutrients around the roots, the expansion of the surface area of the roots, and the potential symbiotic relationships with the host.

6.5 Enabling policy environment

The transition to CSA, which involves the scaling up of specific climate-smart practices, demands strong political commitment, as well as coherence and coordination among the various sectors dealing with climate change, agricultural development and food security. Before designing new policies, policymakers should systematically assess the effects of current agricultural and non-agricultural agreements and policies on the objectives of CSA while considering other national development priorities. They should exploit synergies between the three objectives of climate-smart agriculture (sustainable production, adaptation and mitigation), as well as address potential trade-offs and possibly avoid, reduce or compensate for them. Understanding the socio-economic and gender-differentiated barriers and incentive mechanisms that affect the adoption of CSA practices is critical for designing and implementing supportive policies.

In addition to supportive policies, the enabling environment also encompasses fundamental institutional arrangements; stakeholder involvement and gender considerations; infrastructure; credit and insurance; and farmers' access to weather information, extension and advisory services, and input/output markets. The laws, regulations and incentives that underpin the enabling environment establish the foundation for sustainable climate-smart agricultural development. The development of institutional capacity is essential to support farmers and extension services, and reduce the risks that may discourage and prevent farmers from investing in proven new practices and technologies to enable them to adapt to the impacts of climate change and other shocks. Institutions are a key organizing force for farmers and decision-makers and are critical for scaling up CSA practices.

6.6 Conclusion

Wheat production systems need to adapt to ensure they continue to contribute to food security, rural livelihoods and sustainable food systems under a changing climate. The specific adaptation and mitigation approaches will vary according to location. In the world's wheat producing regions, there are a wide variety of agroecological conditions, microclimates within the soil, climate risks and socio-economic contexts. It is crucial to collect data and information to determine the best course of action and adapt practices to local needs. This information allows for a continuous learning process and can feed into the improvement of future policies. Close coordination and collaboration among stakeholders at all levels are needed to build an enabling environment that gives farmers opportunities to adopt targeted measures to enhance the productivity, resilience and sustainability of wheat production in the face of climate change.

The precise challenges that will be created by climate change on wheat production systems remain uncertain. These challenges will vary from one farming communities to another, but it is certain that they will be especially daunting for countries already coping with high levels of food insecurity. However, there is a clear way forward to meeting these challenges. Options include the adoption of context-specific good agronomic practices, such as conservation agriculture; efficient water and nutrient management; and IPM. These options will complement the gains that can be made through the cultivation of improved varieties.

6.7 References

Abdullah, S., Sehgal, S. K., Jin, Y., Turnipseed, B. & Ali, S. 2017. Insights into tan spot and stem rust resistance and susceptibility by studying the pre-green revolution global collection of wheat. *Plant Pathology Journal*, 33(2):125-132. https://doi.org/10.5423/PPJ.OA.07.2016.0157

Abraha, M. G. & Savage, M. J. 2006. Potential impacts of climate change on the grain yield of maize for the midlands of KwaZulu-Natal, South Africa. *Agriculture, Ecosystems and Environment*, 115 (1-4): 150-160. https://doi.org/10.1016/j.agee.2005.12.020

Agegnehu, G. & Amede, T. 2017. Integrated soil fertility and plant nutrient management in tropical agro-ecosystems: a review. *Pedosphere*, 27(4):662-680.

Ali, S. A., Tedone, L. & de Mastro, G. 2017. Climate variability impact on wheat production in Europe: Adaptation and mitigation strategies. In M. Ahmed & C. Stockle C., eds. *Quantification of Climate Variability, Adaptation and Mitigation for Agricultural Sustainability*, pp 251-321. Springer, Cham. https://doi.org/10.1007/978-3-319-32059-5_12

Asseng, S., Cammarano, D., Basso, B., Chung, U., Alderman, P. D., Sonder, K., Reynolds, M. & Lobell, D. B. 2017. Hot spots of wheat yield decline with rising temperatures. *Global Change Biology*, 23(6):2464-2472 https://doi.org/10.1111/gcb.13530

Australian Government Grains Research & Development Program. 2016. Genetic resources screened for disease resistance. In: *GroundCover, Issue 122* [online]. [Cited 18 June 2021] https://grdc.com.au/resources-and-publications/groundcover/ground-cover-issue-122-may-jun-2016/genetic-resources-sceened-for-disease-resistance

Balafoutis, A., Beck, B., Fountas, S., Vangeyte, J., van der Wal, T., Soto, I., Gómez-Barbero, M., Barnes, A. & Eory, V. 2017. Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. *Sustainability*, 9(8):1339. https://doi.org/10.3390/su9081339

Battisti, D. S. & Naylor, R. L. 2009. Historical warnings of future food insecurity with unprecedented seasonal heat. *Science*, 323:240-244. https://doi.org/10.1126/science.1164363

Bebber, D. P., Ramotowski, M. A. T. & Gurr, S. J. 2013. Crop pests and pathogens move polewards in a warming world. *Nature Climate Change*, 3:985-988. https://doi.org/10.1038/nclimate1990

Bhattacharya, S. 2017. Wheat rust back in Europe. *Nature*, 509:15-16. https://doi.org/10.1038/509015a

Cairns, J. E., Hellin, J., Sonder, K., Araus, J. L., MacRobert, J. F., Thierfelder, C. & Prasanna, B. M. 2013. Adapting maize production to climate change in sub-Saharan Africa. *Food Security*, 5(3):345-360. https://doi.org/10.1007/s12571-013-0256-x

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R. & Chhetri, N. 2014. A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, 4(4):287-291. https://doi.org/10.1038/nclimate2153

Choudhury, K. & Jansen, J. 1998. *Terminology for Integrated Resources Planning and Management*. Rome, FAO.

CIMMYT. 2017. Establishing a soil borne pathogen research center in Turkey. In: *CIMMYT: News* [online]. [Cited 18 June 2021] https://www.cimmyt.org/news/establishing-a-soil-borne-pathogen-research-center-in-turkey/

CIMMYT. 2019. Happy Seeder can reduce air pollution and greenhouse gas emissions while making profits for farmers. In: *CIMMYT: News* [online]. [Cited 18 June 2021] https://www.cimmyt.org/news/happy-seeder-can-reduce-air-pollution-and-greenhouse-gas-emissions-while-making-profits-for-farmers/

CIMMYT. n.d. Wheat Research. In: *CIMMYT: Our Work* [online]. [Cited 18 June 2021] https://www.cimmyt.org/work/wheat-research/

Corsi, S., Friedrich, T., Kassam, A., Pisante, M. & de Moraes Sà, J. 2012. *Soil Organic Carbon Accumulation and Greenhouse Gas Emission Reductions from Conservation Agriculture: A review of evidence*. Integrated Crop Management, Vol. 16. Rome, FAO.

Cotuna, O., Paraschivu, M., Paraschivu, A. M. & Sărățeanu, V. 2015. The influence of tillage, crop rotation and residue management on tan spot (*Drechslera tritici repentis.* Died. Shoemaker) in winter wheat. *Research Journal of Agricultural Science*, 47:13-21.

Curtis, B. C., Rajaram, S. & Macpherson, H. G., eds. 2002. *Bread Wheat: Improvement and Production*. FAO Plant Production and Protection Series, No. 30. Rome, FAO.

Dababat, A. A., Erginbas-Orakci, G., Toumi, F., Braun, H. J., Morgounov, A. & Sikora, R. A. 2018. IPM to control soil-borne pests on wheat and sustainable food production. *Arab Journal of Plant Protection*, 36(1):37-44. https://doi.org/10.22268/AJPP-036.1.037044

Da Silva A.C., De Freitas Lima M., Barbosa Eloy N., Thiebaut F., Montessoro P., Silva Hemerly A. & Cavalcanti Gomes Ferreira P. 2020. The Yin and Yang in plant breeding: the trade-off between plant growth yield and tolerance to stresses. *Biotechnology Research and Innovation*, 3(1):73-79 https://doi.org/10.1016/j.biori.2020.02.001.

Deutsch, C. A., Tewksbury, J. J., Tigchelaar, M., Battisti, D. S., Merrill, S. C., Huey, R. B. & Naylor, R. L. 2018. Increase in crop losses to insect pests in a warming climate. *Science*, 361:916-919. https://doi.org/10.1126/science.aat3466

Di Benedetto, N.A., Corbo, M.R., Campaniello, D., Cataldi, M.P., Bevilacqua, A., Sinigaglia, M. & Flagella, Z. 2017. The role of plant growth promoting bacteria in improving nitrogen use efficiency for sustainable crop production: a focus on wheat. *AIMS microbiology*, 3(3):413-434. https://10.3934/microbiol.2017.3.413

Doorenbos, J. & Pruitt, W. O. 1977. Crop water requirements. FAO *Irrigation and Drainage Paper 24*. Rome, FAO.

Eyal, Z., L., S. A., M., P. J. & van Ginkel, M. 1997. The Septoria Diseases of Wheat: Concepts and Methods of Disease Management. In *Rust Diseases of Wheat: Concepts and methods of disease management*. Mexico, D.F., CIMMYT.

Fang, Q., Zhang, X., Shao, L., Chen, S. & Sun, H. 2018. Assessing the performance of different irrigation systems on winter wheat under limited water supply. *Agricultural Water Management*, 196:133-143.

FAO. 2016. Save and grow in practice: maize, rice and wheat - A guide to sustainable cereal production. Rome. (also available at www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1263072/).

FAO. 2017. Climate-Smart Agriculture Sourcebook, second edition [online]. [Cited 18 June 2021] http://www.fao.org/climate-smart-agriculture-sourcebook/about/en/

FAO. 2019. Sustainable Food Production and Climate Change. (also available at www.fao.org/3/ca7223en/CA7223EN.pdf).

FAO. 2021. FAOSTAT. In: FAO [online]. [Cited 24 July 2020]. http://faostat.fao.org

Figueroa, M., Hammond-Kosack, K. E. & Solomon, P. S. 2018. A review of wheat diseases—a field perspective. In *Molecular Plant Pathology*, 19(6):1523-1536. https://doi.org/10.1111/mpp.12618

Giannakopoulos, C., le Sager, P., Bindi, M., Moriondo, M., Kostopoulou, E. & Goodess, C. M. 2009. Climatic changes and associated

impacts in the Mediterranean resulting from a 2 °C global warming. *Global and Planetary Change,* 68(3):209-224.
https://doi.org/10.1016/j.gloplacha.2009.06.001

IPCC. 2019. *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.* [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)].

Jat, M. L., Gathala, M. K., Ladha, J. K., Saharawat, Y. S., Jat, A. S., Kumar, V., Sharma, S. K., Kumar, V. & Gupta, R. 2009. Evaluation of precision land leveling and double zero-till systems in the rice-wheat rotation: Water use, productivity, profitability and soil physical properties. *Soil and Tillage Research*, 105(1):112-121.
https://doi.org/10.1016/j.still.2009.06.003

Jat, M., Singh, Y., Gill, G., Sidhu, H., Aryal, J., Stirling, C. & Gerard, B. 2015. *Laser-Assisted Precision Land Leveling Impacts in Irrigated Intensive Production Systems of South Asia*. In R Lal & B. A. Stewart, eds. Soil-Specific Farming: Precision Agriculture, pp.323-352. CRC Press Taylor and Francis. https://doi.org/10.1201/b18759-14

Joshi, A. K., Azab, M., Mosaad, M., Moselhy, M., Osmanzai, M., Gelalcha, S., Bedada, G., Bhatta, M. R., Hakim, A., Malaker, P. K., Haque, M. E., Tiwari, T. P., Majid, A., Kamali, M. R. J., Bishaw, Z., Singh, R. P., Payne, T. & Braun, H. J. 2011. Delivering rust resistant wheat to farmers: A step towards increased food security. *Euphytica*, 179:187-196.
https://doi.org/10.1007/s10681-010-0314-9

Juroszek, P. & von Tiedemann, A. 2013. Plant pathogens, insect pests and weeds in a changing global climate: A review of approaches, challenges, research gaps, key studies and concepts. *Journal of Agricultural Science*, 151(2):163-188. https://doi.org/10.1017/S0021859612000500

Kukal, S. S., Rasool, R. & Benbi, D. K. 2009. Soil organic carbon sequestration in relation to organic and inorganic fertilization in rice-wheat and maize-wheat systems. *Soil and Tillage Research*, 102(1):87-92.
https://doi.org/10.1016/j.still.2008.07.017

Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J. & van Kessel, C. 2005. Efficiency of Fertilizer Nitrogen in Cereal Production: Retrospects and Prospects. *Advances in Agronomy*, 87:85-156.
https://doi.org/10.1016/S0065-2113(05)87003-8

Leake, A. R. 2003. Integrated pest management for conservation agriculture. In L. García-Torres, J. Benites, A. Martínez-Vilela 6 A. Holgado-Cabrera, eds. *Conservation Agriculture*, pp. 271-279. Springer, Dordrecht.

Liu, B., Asseng, S., Müller, C. Ewert, F., Elliott, J., Lobell, D. B., Martre, P. *et al*. 2016. Similar estimates of temperature impacts on global wheat yield by three independent methods. *Nature Climate Change*, 6:1130-1136. https://doi.org/10.1038/nclimate3115

McKinsey Global Institute. 2020. *Climate Risk and response - Physical hazards and socioeconomic impacts.*

Miller, R. H. & Pike, K. S. 2002. Insects in wheat-based systems. In B. C. Curtis, S. Rajaram, & H. G. Macpherson, eds. *Bread Wheat Improvement and Production*. FAO Plant Production and Protection Series No. 30. Rome, FAO. http://www.fao.org/3/y4011e0q.htm#bm26

Mosier, A., Syers, J.K. & Freney, J. R. 2013. *Agriculture and the nitrogen cycle: assessing the impacts of fertilizer use on food production and the environment*. SCOPE Report, No. 65. Washington, D.C., Island Press.

Mukherjee, A. & Zimmerman, A. R. 2013. Organic carbon and nutrient release from a range of laboratory-produced biochars and biochar-soil mixtures. *Geoderma*, 193-194; 122-130. https://doi.org/10.1016/j.geoderma.2012.10.002

Murrell, E. G. 2017. Can agricultural practices that mitigate or improve crop resilience to climate change also manage crop pests? *Current Opinion in Insect Science*, 23:81-88. https://doi.org/10.1016/j.cois.2017.07.008

Ortiz-Monasterio R., J. I., Sayre, K. D., Rajaram, S. & McMahon, M. 1997. Genetic progress in wheat yield and nitrogen use efficiency under four nitrogen rates. *Crop Science*, 37(3):898-904 https://doi.org/10.2135/cropsci1997.0011183X003700030033x

Pampolino, M., Majumdar, K., Jat, M.L., Satyanarayana, T., Kumar, A., Shahi, V.B., Gupta, N. & Singh, V. 2012. Development and Evaluation of Nutrient Expert for Wheat in South Asia. *Better Crops*, 96(3):29-31.

Pimentel, D., Houser, J., Preiss, E., White, O., Fang, H., Mesnick, L., Barsky, T., Tariche, S., Schreck, J. & Alpert, S. 1997. Water Resources: Agriculture, the Environment, and Society. *BioScience*, 47(2):97-106.

Pinto, R. S., & Reynolds, M. P. 2015. Common genetic basis for canopy temperature depression under heat and drought stress associated with optimized root distribution in bread wheat. *Theoretical and Applied Genetics*, 128:575-585. https://doi.org/10.1007/s00122-015-2453-9

Reynolds, M. P., Pask, A. J. D., Hoppitt, W. J. E., Sonder, K., Sukumaran, S., Molero, G., Pierre, C. *et al*. 2017. Strategic crossing of biomass and harvest index—source and sink—achieves genetic gains in wheat. *Euphytica*, 213 (article 257). https://doi.org/10.1007/s10681-017-2040-z

Rosenzweig, C., & Tubiello, F. N. 2007. Adaptation and mitigation strategies in agriculture: An analysis of potential synergies. *Mitigation and Adaptation Strategies for Global Change*, 12:855-873. https://doi.org/10.1007/s11027-007-9103-8

Rossmann, A., Pitann, B. & Mühling, K.H. 2019. Splitting nitrogen applications improves wheat storage protein composition under low N supply. *Journal of Plant Nutrition and Soil Science*, 182(3):347-355. https://doi.org/10.1002/jpln.201800389

Salvador, R., Martínez-Cob, A., Cavero, J. & Playán, E. 2011. Seasonal on-farm irrigation performance in the EBRO basin (Spain): Crops and irrigation systems. *Agricultural Water Management*, 98 (4), 577-587.

Sapkota, T. B., Majumdar, K., Jat, M. L., Kumar, A., Bishnoi, D. K., McDonald, A. J. & Pampolino, M. 2014. Precision nutrient management in conservation agriculture based wheat production of Northwest India: Profitability, nutrient use efficiency and environmental footprint. *Field Crops Research*, 155:233-244. https://doi.org/10.1016/j.fcr.2013.09.001

Sapkota, T. B., Jat, M. L., Aryal, J. P., Jat, R. K. & Khatri-Chhetri, A. 2015. Climate change adaptation, greenhouse gas mitigation and economic profitability of conservation agriculture: Some examples from cereal systems of Indo-Gangetic Plains. *Journal of Integrative Agriculture*, 14(8):1524-1533. https://doi.org/10.1016/S2095-3119(15)61093-0

Sapkota, T. B., Jat, R. K., Singh, R. G., Jat, M. L., Stirling, C. M., Jat, M. K., Bijarniya, D., Kumar, M., Yadvinder-Singh, Y. S., Saharawat, Y. S. & Gupta, R. K. 2017. Soil organic carbon changes after seven years of conservation agriculture in a rice–wheat system of the eastern Indo-Gangetic Plains. *Soil Use and Management*, 33(1):81-89. https://doi.org/10.1111/sum.12331

Sapkota, T. B., Vetter, S. H., Jat, M. L., Sirohi, S., Shirsath, P. B., Singh, R., Jat, H. S., Smith, P., Hillier, J., & Stirling, C. M. 2019. Cost-effective opportunities for climate change mitigation in Indian agriculture. *Science of the Total Environment*, 655:1342-1354. https://doi.org/10.1016/j.scitotenv.2018.11.225

Sayre, K. D. 1998. *Ensuring the Use of Sustainable Crop Management Strategies by Small Wheat Farmers in the 21st Century.* Wheat Special Report No. 48. Mexico, D.F., CIMMYT. https://repository.cimmyt.org/xmlui/bitstream/handle/10883/1237/67141.pdf?sequence=1

Shyamsundar, P., Springer, N. P., Tallis, H., Polasky, S., Jat M. L., Sidhu, H. S., Krishnapriya, P. P. *et al.* 2019. Fields on fire: Alternatives to crop residue burning in India. *Science*, 365:536-538. https://doi.org/10.1126/science.aaw4085

Sims, B. & Kienzle, J. 2015. Mechanization of Conservation Agriculture for Smallholders: Issues and Options for Sustainable Intensification. *Environments*, 2(2):139-166. https://doi.org/10.3390/environments2020139

Solh, M., Braun, H-J. & Tadesse, W. 2014. *Save and Grow: Wheat. Paper prepared for the FAO Technical Consultation on Save and Grow: Maize, Rice and Wheat, Rome, 15–17 December 2014. Rabat, ICARDA*.

Supit, I., van Diepen, C. A., de Wit, A. J. W., Kabat, P., Baruth, B. & Ludwig, F. 2010. Recent changes in the climatic yield potential of various crops in Europe. *Agricultural Systems*, 103(9):683-694. https://doi.org/10.1016/j.agsy.2010.08.009

Tembo, B., Mulenga, R.M., Sichilima, S., M'siska, K.K., Mwale, M., Chikoti, P.C., Singh, P.K., He, X., Pedley, K.F., Peterson, G.L., Singh, R.P. & Braun H.J. 2020. Detection and characterization of fungus (Magnaporthe oryzae pathotype Triticum) causing wheat blast disease on rain-fed grown wheat (Triticum aestivum L.) in Zambia. *PLoS ONE*, 15(9):e0238724. https://doi.org/10.1371/journal.pone.0238724

Thierfelder, C., Baudron, F., Setimela, P. *et al.* 2018. Complementary practices supporting conservation agriculture in southern Africa. A review. *Agronomy for Sustainable Development*, 38 (article 16).

Vaccari, F. P., Baronti, S., Lugato, E., Genesio, L., Castaldi, S., Fornasier, F. & Miglietta, F. 2011. Biochar as a strategy to sequester carbon and increase yield in durum wheat. *European journal of agronomy*, 34(4):231-238.

Vaughan, M., Backhouse, D. & del Ponte, E. M. 2016. Climate change impacts on the ecology of Fusarium graminearum species complex and susceptibility of wheat to Fusarium head blight: A review. *World Mycotoxin Journal*, 9(5):685-700. https://doi.org/10.3920/WMJ2016.2053

Wasson, A. P., Richards, R. A., Chatrath, R., Misra, S. C., Prasad, S. V. S., Rebetzke, G. J., Kirkegaard, J. A., Christopher, J. & Watt, M. 2012. Traits and selection strategies to improve root systems and water uptake in water-limited wheat crops. *Journal of Experimental Botany*, 63(9):3485-3498. https://doi.org/10.1093/jxb/ers111

WHEAT (CGIAR Research Program on Wheat). n.d. WHEAT in the World. In: WHEAT [online]. [Cited 18 June 2021]
https://wheat.org/wheat-in-the-world/

Wyckhuys, K. A. G., Lu, Y., Morales, H., Vazquez, L. L., Legaspi, J. C., Eliopoulos, P. A. & Hernandez, L. M. 2013. Current status and potential of conservation biological control for agriculture in the developing world. *Biological Control*, 65(1):152-167.
https://doi.org/10.1016/j.biocontrol.2012.11.010

ANNEX 1

Summary of CSA practices recommended in these briefs and their contributions to SDGs and targets

H. Jacobs and T. Pirelli

Summary of CSA practices recommended in these briefs and their contributions to SDGs and targets

SDGs	CSA practices that contribute to the achievement of SDGs	Crops	Specific targets addressed
SDG 1: End poverty in all its forms everywhere	CSA contributes to restoring and conserving natural resources and ecosystems, may prevent yield reductions and contributes to ending poverty.	Wheat, maize	1
	By enhancing the efficient use of water, fertilizers and fuels, various CSA practices can reduce input requirements and production costs, which results in higher earnings for farmers.		1
	Diversifying agricultural production can contribute to creating new income opportunities and enhancing the resilience of farming systems to extreme weather events and other impacts of climate change.		1.1
	Economic opportunities created through agroforestry can support subsistence farmers in overcoming poverty.		
SDG 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture	The successful implementation of IPM can prevent infestations that severely damage crops and cause famine. Reversing trends in yield reductions through IPM, particularly in developing countries, can improve local and national food security. Introducing leguminous species, such as cowpea, into cropping systems and diets can improve access to nutritious food by all.	Rice, wheat, maize, coffee, cowpea	2.1
	Crop diversification through agroforestry, and the intercropping and the cultivation of leguminous species, creates new income opportunities for small-scale farmers and contributes to improving their livelihoods. The integration of crop and livestock production (e.g. cultivating cowpea to provide nutritious fodder) may generate additional income for small-scale farmers. Improved agronomic practices, including direct seeding, and the efficient management of soil, nutrients and water resources, reduce production costs and provide more stable yields, which ultimately contributes to increased productivity and higher incomes for small-scale farmers. Improved yields and incomes contribute directly to the target of doubling agricultural productivity and the incomes of small-scale food producers. Adapting coffee production to climate change is crucial to avoid severe economic impacts on the livelihoods of small-scale coffee producers.	Rice, wheat, maize, coffee, cowpea	2.3
	Improved nutrient management, erosion protection and the diversification of cropping and farming systems contribute to building more sustainable and resilient food systems.	Rice, wheat, maize, cowpea	2.4
	The use of landraces and crop wild relatives in plant breeding contributes to maintaining genetic diversity in cultivated plants and strengthens the resilience of farming systems.	Rice, wheat, maize, coffee, cowpea	2.5
SDG 3: Ensure healthy lives and promote well-being for all at all ages	IPM, improved efficiency in the use of nutrients, fertilizers, and water, and the reduced use of fossil fuels, can benefit human health by reducing illnesses caused by air, water and soil pollution and contamination. Replacing the burning of rice stubble with alternative management options (e.g. using it as a soil amendment, livestock fodder or bioenergy feedstock) reduces air pollution and benefits human health.	Rice, wheat, maize, coffee, cowpea	3.9
SDG 4: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	Training farmers on CSA practices, such as IPM, through farmer field schools and engaging them in research activities enables farmers to acquire new technical and vocational skills.	Rice, cowpea	4.4
SDG 5: Achieve gender equality and empower all women and girls	Gender-sensitive seed systems improve equality of access to seeds and promote the empowerment of women.	Rice, cowpea	5.b

SDGs	CSA practices that contribute to the achievement of SDGs	Crops	Specific targets addressed
SDG 6: Ensure availability and sustainable management of water and sanitation for all	Improving water management (e.g. precision land levelling and adjusted irrigation regimes in in rice cropping systems, and the use of efficient irrigation technologies and management in wheat, maize, coffee and cowpea cropping systems); enhancing the water regulation capacities of agricultural soils through conservation agriculture; improving erosion protection and water regulation through agroforestry and mulching in coffee plantations; and adopting water-saving processing practices for coffee berries and treatment of wastewater all contribute to ensuring the availability and sustainable management of water resources.	**Rice**, **wheat**, **maize**, **coffee**, **cowpea**	**6**
	Enhancing the water regulation capacities of agricultural soils improves access to safe drinking water.	**Maize**, **cowpea**	**6.1**
	Improved efficiency in the use of nutrients and fertilizers not only lowers GHG emissions, but also reduces nutrient pollution in terrestrial, freshwater and marine ecosystems, and enhances ecosystems services. Increasing the water regulation capacities of agricultural soils improves water quality. Water-saving processing practices for coffee berries and the treatment of wastewater contribute to improving water quality.	**Rice**, **wheat**, **maize**, **coffee**, **cowpea**	**6.3**
	Improving water management and enhancing the water regulation capacities of agricultural soils increase water use efficiency.	**Rice**, **wheat**, **maize**, **cowpea**	**6.4**
SDG 7: Ensure access to affordable, reliable, sustainable and modern energy for all	Replacing the burning of rice stubble with alternative management options (e.g. using it as feedstock for bioenergy production) reduces GHG emissions and contributes to increasing the share of renewable energy. Biogas production from coffee processing wastewater and its use as a biofuel reduce methane emissions and increase the share of renewable energy.	**Rice**, **coffee**	**7.2**
	Energy savings from reduced tillage and improved management of irrigation water increase energy efficiency in the agricultural sector.	**Cowpea**	**7.3**
SDG 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	Diversification of production systems through agroforestry and intercropping can increase economic productivity. Adapting coffee production to climate change is crucial to avoid severe economic impacts on coffee exporting countries. Cowpea provides nutritious fodder and can support the integration crop and livestock production, which creates opportunities to increase economic productivity.	**Rice**, **maize**, **coffee**, **cowpea**	**8.2**
	The efficient use of nitrogen and the reduced use of chemical fertilizers contribute to the economy-wide target of improving global resource efficiency in consumption and production.	**Wheat**, **maize**, **cowpea**	**8.4**
	Strengthening the collaboration between formal and informal seed systems for improved seed supply chains creates opportunities for decent rural employment. Cowpea provides nutritious fodder and can support the integration of crop and livestock production, which also creates opportunities for decent rural employment.	**Rice**, **cowpea**	**8.5**
SDG 12: Ensure sustainable consumption and production patterns	IPM and increased efficiency in the use of natural resources (e.g. water, nutrients) and fuels contribute to the sound management of chemicals throughout their life cycle and reduce the release of pollutants into the air, water and soil, minimizing their impacts on human health and the environment.	**Rice**, **wheat**, **maize**, **coffee**, **cowpea**	**12.4**
	Replacing the burning of rice stubble with alternative management options through the recycling of crop residues and by-products (e.g. bioenergy production, mulching) reduces waste generation. The recycling of bioenergy by-products (e.g. biochar, digestate) as soil amendments reduces waste and returns nutrients to the soil, which sequesters carbon and enhances soil fertility.	**Rice**, **coffee**, **maize**	**12.5**
	Water-saving processing practices for coffee berries and treatment of wastewater can contribute to sustainable consumption and production patterns, especially when accompanied by actions to promote sustainable consumer decisions and lifestyles.	**Coffee**	**12.8**

SDGs	CSA practices that contribute to the achievement of SDGs	Crops	Specific targets addressed
SDG 13: Take urgent action to combat climate change and its impacts	Conservation agriculture, the use of improved crop varieties, efficient water management, IPM, and the production of bioenergy from crop residues and wastewater from coffee processing are approaches that contribute to mitigating climate change and its impacts.	Rice, maize, coffee, cowpea	**13.1**
	Several options exist to enable wheat production systems to support climate change mitigation. These options can improve carbon sequestration in the agricultural ecosystem, reduce GHG emissions and increase resource use efficiency and prevent soil erosion and nutrient losses. They include the diversification of crop production, agroforestry, precision farming, sustainable mechanization and a reduced reliance on chemical fertilizers.	Wheat	**13.2.2**
SDG 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development	IPM, which emphasizes the minimal use of harmful chemical pesticides, reduces marine pollution from land-based activities. Improved efficiency in the use of nutrients and fertilizers reduces nutrient pollution in terrestrial, freshwater and marine ecosystems, and enhances ecosystems services. Water-saving processing practices for coffee berries and treatment of wastewater support the sustainable management of freshwater ecosystems.	Rice, wheat, maize, coffee, cowpea	**14.1**
SDG 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	The diversification of crop production systems, including intercropping with other cereals and annual and perennial legumes, as well as the integration of rice production with aquaculture, provides multiple benefits and supports the sustainable management of terrestrial ecosystems. IPM, improved nutrient management, and erosion protection achieved though conservation agriculture and mulching, contribute to a more sustainable use of terrestrial ecosystems. Water-saving processing practices for coffee berries and the treatment of wastewater support the sustainable management of freshwater ecosystems.	Wheat, maize, coffee, cowpea	**15.1**
SDG 17: Strengthen the means of implementation and revitalize the global partnership for sustainable development	Strengthening the collaboration between formal and informal seed systems to improve seed supply chains promotes effective public-private and civil society partnerships.	Rice, maize	**17.7**
	Utilizing GPS-enabled precision farming, adopting sustainable mechanization, and cultivating improved crop varieties contributes to the transfer, dissemination and diffusion of environmentally sound technologies to developing countries. Sustainable mechanization is critical for the adoption of rice-based systems that involve intercropping, crop rotations and the cultivation of multiple crops.	Rice, wheat, maize	**17.7**

Crops and climate change impact briefs

Climate-smart agriculture for more sustainable, resilient, and equitable food systems

with the financial support of the Italian ministry of Ecological Transition

MINISTERO DELLA TRANSIZIONE ECOLOGICA

ISBN 978-92-5-135510-7

9 789251 355107

CB8030EN/1/01.22