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COMMISSION ON GENETIC RESOURCES FOR FOOD AND AGRICULTURE

Item 6 of the Provisional Agenda

INTERGOVERNMENTAL TECHNICAL WORKING GROUP ON ANIMAL GENETIC RESOURCES FOR FOOD AND AGRICULTURE

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THE ROLE OF GENETIC RESOURCES FOR FOOD AND AGRICULTURE IN CLIMATE CHANGE ADAPTATION AND MITIGATION

TABLE OF CONTENTS

Paragraphs

I. INTRODUCTION

1. The Commission on Genetic Resources for Food and Agriculture (Commission), at its last session, requested FAO to prepare a scoping study on the role of genetic resources for food and agriculture (GRFA) in adaptation to and mitigation of climate change, including knowledge gaps, taking into account the forthcoming special reports on terrestrial and marine systems by the Intergovernmental Panel on Climate Change (IPCC) and other available relevant sources, including examples from different regions and subsectors.[1]

2. The Commission further requested its Intergovernmental Technical Working Groups to review the study.

II. SCOPING STUDY ON THE ROLE OF GENETIC RESOURCES FOR FOOD AND AGRICULTURE IN ADAPTATION TO AND MITIGATION OF CLIMATE CHANGE

3. The draft text of the scoping study on the role of genetic resources for food and agriculture in adaptation to and mitigation of climate change is presented in *Appendix* to this document.

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[1] CGRFA-17/19/Report, paragraph 29.

APPENDIX

SCOPING STUDY ON THE ROLE OF GENETIC RESOURCES FOR FOOD AND AGRICULTURE IN ADAPTATION TO AND MITIGATION OF CLIMATE CHANGE

TABLE OF CONTENTS

Pages

ABBREVIATIONS

AnGR	animal genetic resources for food and agriculture
APFORGEN	Asia Pacific Forest Genetic Resources Programme
AqGR	aquatic genetic resources for food and agriculture
ASTI	Agricultural Science and Technology Indicators
BDA	breeding, delivery and adoption
BREEDCAFS	Breeding Coffee for Agroforestry Systems
CBD	Convention on Biological Diversity
CCAFS	CGIAR Research Program on Climate Change, Agriculture and Food Security
CGIAR	Consultative Group on International Agricultural Research
CIAT	International Center for Tropical Agriculture
CIMMYT	International Maize and Wheat Improvement Center
CIP	International Potato Centre
CSBs	community seed banks
CWRs	crop wild relatives
DAD-Net	Domestic Animal Diversity Network
DIIVA	Diffusion and Impact of Improved Varieties in Africa
DSI	digital sequence information
DTMA	Drought Tolerant Maize for Africa
DTMASS	Drought Tolerant Maize for Africa Seed Scaling
EU	European Union
EUFGIS	European Information System on Forest Genetic Resources
EUFORGEN	European Forest Genetic Resources Programme
EURISCO	European Search Catalogue for Plant Genetic Resources
EX-ACT	FAO’s Ex-Ante Carbon-balance Tool
FAO	Food and Agriculture Organization of the United Nations
FGR	forest genetic resources
GIS	geographic information system

GLIS	Global Information System (of the International Treaty on Plant Genetic Resources for Food and Agriculture)
GRFA	genetic resources for food and agriculture
GRIN	Germplasm Resources Information Network
ICARDA	International Center for Agricultural Research in the Dry Areas
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IAEA	International Atomic Energy Agency
IFPRI	International Food Policy Research Institute
IITA	International Institute of Tropical Agriculture
IMTA	integrated multitrophic aquaculture
INDCs	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
IPNV	infectious pancreatic necrosis virus
IRRI	International Rice Research Institute
ITPGRFA	International Treaty on Plant Genetic Resources for Food and Agriculture
LAFORGEN	Latin American Forest Genetic Resources Network
LIFEGENMON	Life for European Forest Genetic Monitoring System Project
MVD	Mutant Variety Database
NAPs	National Adaptation Plans
NAPAs	National Adaptation Programmes of Action
NARES	National Agricultural Research and Extension Systems
NDCs	Nationally Determined Contributions
NGO	non-governmental organization
PGRFA	plant genetic resources for food and agriculture
POMS	Pacific oyster mortality syndrome
QTL	quantitative trait locus/loci
REDD+	reducing emissions from deforestation and forest degradation
SADC	Southern African Development Community

SBSTTA	Subsidiary Body on Scientific, Technical and Technological Advice
SDG	Sustainable Development Goal
SAFORGEN	Sub-Saharan African Forest Genetic Resources Programme
SIAC	Strengthening Impact Assessment in the CGIAR
SoW-AqGR	*The State of the World's Aquatic Genetic Resources for Food and Agriculture*
TALENs	transcription activator-like effector nucleases
TRIVSA	Tracking Improved Varieties in South Asia
UNFCCC	United Nations Framework Convention on Climate Change
WIEWS	World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture
ZFNs	zinc-finger nucleases

I. INTRODUCTION

Background

The impacts of anthropogenic climate change are visible around the globe. Climate projections predict increases in temperature, in the frequency and severity of droughts (reducing the availability of irrigation water and increasing salinity of arable land) and in the unpredictability of precipitation (IPCC, 2018; Messerer *et al.*, 2018). The severity of these impacts varies greatly across agricultural systems. A greenhouse, for example, is less vulnerable than a pastoralist system, as environmental conditions such as heat and precipitation can be controlled. Aside from direct effects, climate change is expected to lead to changes in ecosystems including shifts in the ranges of pests and diseases and to new host–parasite associations (Hoberg and Brooks, 2015). Globally, 7.9 percent of species are predicted to face extinction due to climate change (Urban, 2015).

Farmers, livestock keepers, fisherfolk and forest dwellers have adapted their production systems to changing environmental conditions over millennia, and genetic resources have been fundamental to this adaptation (FAO, 2015a). As the pace of climate change is increasing, it is more important than ever to conserve, characterize and sustainably use genetic resources for food and agriculture. Species diversity and genetic diversity within species increases the likelihood that production systems will be able to cope with and adapt to changing environmental conditions (FAO, 2015a). Systems with large interspecies or intraspecies diversity are more resilient to biotic and abiotic stresses, as the diversity reduces the impacts of these stresses and supports the recovery and adaptation of the production systems (FAO, 2019a).

Adaptation strategies centred around genetic resources can include modifying a given population through breeding or shifting to the use of a different species, variety or breed. Breeding offers a way not only to improve a variety or breed's ability to cope with climate change impacts but also to improve resource-use efficiency, for example reducing the amount of water, fertilizer or pesticides used and hence the carbon footprint of production. Production system-level interventions include elements of diversification that increase resilience to climate-related impacts.

In the first two decades after the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, little attention was given to genetic resources for food and agriculture (GRFA) in international climate change discussion, largely because the global approach of the Convention meant that there was no specific place to discuss them. With the creation of the Korinivia joint work programme on agriculture there is now an opportunity to have more substantive discussions under the UNFCCC on GRFA and climate change. In order to promote the understanding of the roles of GRFA in ecosystem function and resilience in the context of climate change, the Commission on Genetic Resources for Food and Agriculture adopted a Programme of Work on Climate Change and Genetic Resources for Food and Agriculture at its Fourteenth Regular Session in 2013 (FAO, 2013a).

In 2011, FAO published background study papers on the state of knowledge, risks and opportunities related to climate change and plant, animal, forest, aquatic, micro-organism and invertebrate genetic resources (Asfaw and Lipper, 2011; Beed *et al.*, 2011; Cock *et al.*, 2011; Jarvis *et al.*, 2010; Loo *et al.*, 2011; Pilling and Hoffmann, 2011; Pullin and White, 2011). To further raise awareness of the issue, FAO published *Coping with climate change – the role of genetic resources for food and agriculture* (FAO, 2015a), which summarized the studies. In order to support countries in their efforts to integrate GRFA into climate change adaptation planning, FAO also published the *Voluntary Guidelines to Support the Integration of Genetic Diversity into National Climate Change Adaptation Planning* (FAO, 2015b).

The reporting process for *The State of the World's Biodiversity for Food and Agriculture* (FAO, 2019a) involved inviting countries to report on the effects of climate change on biodiversity and its role in the supply of ecosystems services. Where countries were able to provide information, they generally reported that these effects are negative. Pest and disease regulation, natural-hazard regulation, water cycling, habitat provisioning and pollination were the ecosystem services most frequently reported to be affected by climate change.

The UNFCCC Guidelines for National Adaptation Plans (NAPs) provide advice on establishing a national planning process, but because they are not specific to any sector, the UNFCCC invited agencies and partners to submit sector-specific supplementary technical guidelines to support developing countries in preparing their NAPs (Least Developed Countries Expert Group, 2012). In 2017, FAO published *Addressing agriculture, forestry and fisheries in national adaptation plans. Supplementary guidelines* in response to this request (FAO, 2017a). In 2020, FAO published *Addressing fisheries and aquaculture in National Adaptation Plans* (Brugere and De Young, 2020) and *Addressing forestry and agroforestry in National Adaptation Plans – Supplementary guidelines* (Meybeck *et al.*, 2020).

In recent years, the interlinkages between agriculture, biodiversity and climate change have become more prominent in the global policy arena. In 2017, the Parties to the UNFCCC established the Koronivia Joint Work on Agriculture, a landmark decision recognizing the role of agriculture in tackling climate change (UNFCCC, 2017). In the same year, the FAO Strategy on Climate Change was adopted (FAO, 2017b). The strategy makes ample reference to biodiversity and, more specifically, to GRFA.

In 2018, the Intergovernmental Panel on Climate Change (IPCC) published the special report *Global warming of 1.5 °C*, which predicts that impacts of climate change on terrestrial, marine, freshwater and coastal biodiversity and ecosystems will increase if global warming is not limited to 1.5 ºC, and that their capacity to provide services to humans will be reduced (IPCC, 2018). In August and September 2019, respectively, the IPCC published the special reports *Climate change and land* and *The ocean and cryosphere in a changing climate*, which address, *inter alia*, the effect of climate change on agriculture, forestry, fisheries and aquaculture, as well as options for mitigation and adaptation (IPCC, 2019a,b). While the report on *Climate change and land* addresses plant and animal breeding as options for adaptation and mitigation, the other reports focus mainly on ecosystem or production system-level adaptation.

In November 2019, the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) of the Convention on Biological Diversity (CBD) considered the document *Biodiversity and climate change* (CBD, 2019).

Although the attention given to agriculture in the climate change policy arena has increased in recent years, GRFA are still not receiving the attention they deserve given their enormous importance. There are also considerable knowledge gaps in this field, in particular with regard to breeding for climate change adaptation and mitigation. For instance, a 2017 review of 50 National Adaptation Programmes of Action (NAPAs) found that the majority did not incorporate agricultural biodiversity (Bedmar Villanueva, Halewood and Noriega, 2017).

With this context in mind, the Commission on Genetic Resources for Food and Agriculture, at its Seventeenth Regular Session, held in February 2019, requested FAO to prepare a scoping study on the role of genetic resources for food and agriculture in adaptation to and mitigation of climate change. The intention was that the study would, *inter alia*, address knowledge gaps, take into account the IPCC's special reports on terrestrial and marine systems and other relevant sources, and include examples from different regions and subsectors. The present study was prepared in response to this request.

Scope

The main focus of the study is the state of current use of genetic resources in climate change adaptation and mitigation efforts. Each chapter explores the impacts of climate change on genetic resources and also considers the significance of genetic resources to climate change adaptation and mitigation. The UNFCCC defines adaptation as "adjustments in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts" and mitigation as "efforts to reduce emission and enhance sinks" (UNFCCC, 2019).

The study is based on scientific literature and reports by FAO and other international organizations, as well as on Nationally Determined Contributions (NDCs) submitted by countries to the UNFCCC. FAO has analysed the information related to agriculture and land use found in 169 NDCs, representing 195 countries, submitted to the UNFCCC as of 1 October 2020. To date, FAO has published a series of regional-level analyses of the representation of agriculture and land use in the NDCs, including Eastern

Africa (FAO, 2017c), Europe and Central Asia (FAO, 2019b), Asia (FAO, 2020a) and the Pacific (FAO, 2020b), Latin America (FAO, 2020c) and the Caribbean (FAO, 2020d). The methodology adopted to run the analysis is described in detail in the recent FAO publication by Crumpler *et al.* (2020). FAO will produce a global NDC update report that will cover new or updated NDCs submitted by countries from 2020 onwards. In addition to reviewing scientific literature and reports, explorative interviews were conducted with experts from private breeding companies in the crop and livestock sectors in order to gain an overview of current trends in breeding and of how climate change is being taken into account in breeding efforts. Additionally, experts from various research institutions were contacted in order to obtain in-depth information about their ongoing projects.

In order to gain information from national coordinators for the management of animal genetic resources and a wide variety of other stakeholders around the world, members of the Domestic Animal Diversity Network (DAD-Net)[2] were asked to answer questions on the role of animal genetic resources in climate change adaptation and mitigation. DAD-Net is an e-mail-based network operated by FAO that provides an informal forum for the discussion of issues relevant to the management of animal genetic resources.

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[2] https://dgroups.org/fao/dad-net

II. ANIMAL GENETIC RESOURCES FOR FOOD AND AGRICULTURE

2.1 Introduction

Domesticated farm animals support the livelihoods of hundreds of millions of livestock keepers around the world, including an estimated 70 percent of the world's rural poor (FAO, 2015c). Livestock not only provide food products such as milk, meat and eggs but also provide fibre, fertilizer, fuel, transportation and draught power. Although there are more than 30 terrestrial species of domesticated farm animals, global livestock production relies heavily on a small group of species (FAO, 2017e). Animal genetic resources (AnGR) include over 8 800 livestock breeds, but single breeds such as Holstein dairy cattle and the commercial Leghorn chicken make up a large proportion of the production volume, in particular in commercialized production systems (FAO, 2017d).

Climate change impacts livestock both directly – through heat and drought stress brought about by changing temperatures and precipitation patterns – and indirectly – through changes in the availability and quality of feed and changes in the ranges of pests and pathogens (IPCC, 2019a). AnGR can play an important role in climate change adaptation. Different breeds have different tolerances of stress induced by climate change; adapted breeds may be able to support livelihoods and food security in spite of changing environmental conditions. Climate change has implications not only for the survival of domesticated mammals and birds but also for the maintenance of their diversity (FAO, 2015a).

2.1.1 The impact of climate change on animal genetic resources for food and agriculture[3]

Increasing temperatures, variation in precipitation and changing atmospheric CO_2 concentrations are the main factors through which livestock systems are affected by climate change (IPCC, 2019a). Many critical factors in livestock production such as water availability and animal health and reproduction are severely affected by temperature (IPCC, 2019a). Heat stress affects production and fertility, increases water requirements, reduces appetite and feed intake and increases mortality (FAO, 2015a). Heat stress in poultry, for example, negatively affects fat deposition and the chemical composition of meat, thus reducing meat quality and yield; birds' immune responses are weakened, making them more susceptible to pathogens (Lara and Rostagno, 2013). It has been projected that heat stress will lead to a 2.8 percent fall in milk yields in Europe by the end of the century (Hempel *et al.*, 2019).

Impacts of climate change will vary across livestock systems, breeds and regions (IPCC, 2019a). High-output breeds are generally not well adapted to high temperatures, high humidity and poor feed quality (FAO, 2017d). While industrial livestock production systems with controlled conditions can mitigate some of the impacts of climate change, for instance by cooling sheds or buying feed from outside the local area, they are dependent on the continuous availability of water, power and diverse feedstuffs. Small-scale producers who have adopted high-output breeds may struggle to obtain these inputs (FAO, 2015a, 2017a). Indirect impacts of climate change such as the rising costs of water and feed and the destruction of infrastructure by extreme weather events will severely affect industrial livestock production systems (IPCC, 2019a; Lopez-I-Gelats, 2014; Rivera-Ferre *et al.*, 2016).

Animals in extensive livestock systems are directly exposed to the local climate. If climatic changes occur rapidly, breeds may not be able to adapt and their productivity may fall (FAO, 2017d). This may force livestock keepers to change the breeds or species they raise, migrate to more suitable areas or give up livestock production entirely (ibid.). It has been hypothesized that drought episodes have had an important role in the species shift from cattle to small ruminants and camels observed in Western African Sahel over recent decades (Hoffmann, Boettcher and Leroy, 2015).

Pastoral systems are very vulnerable to climate change and will be affected by changes in pasture productivity, lower animal growth rates and productivity, damage to reproductive functions, increased pest and disease pressure, and loss of biodiversity (IPCC, 2019a). In pastoral, mixed and extensive systems, the impacts of climate change on livestock productivity are closely linked to impacts on rangelands and pastures (IPCC, 2019a). Changes in atmospheric CO_2 concentrations, rainfall and temperature are projected to lead to changes in herbage growth and quality and in pasture composition

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[3] This section draws from the IPCC Special Report on Climate Change and Land (IPCC, 2019).

(Herrero *et al.*, 2016). Reduced quality of forage can in turn lead to an increase in methane (CH_4) emissions (IPCC, 2019a). Pastoral communities that are already vulnerable due to low livestock productivity are projected to be most severely affected by environmental degradation caused by climate change (Godde *et al.*, 2020).

Climate change will exacerbate extreme climatic events such as droughts, floods and hurricanes, which have the potential to kill a large number of animals or even cause the extinction of entire breeds (FAO, 2017d). Coastal regions are particularly affected by extreme weather events. In a study of farmers' perceptions of the threats posed by climate change in coastal Bangladesh, 90 percent of participating households indicated that cyclones were the predominant climate risk that they faced (Aryal *et al.*, 2020). Floods not only cause direct injury and death to animals but also spread animal pests and diseases (Bakare *et al.*, 2020).

Changes in climate will affect the survival, range and occurrence of pests and vector-borne diseases, and alter their biology, for example leading to more generational cycles (IPCC, 2019a). Increases in temperature and in the variation of rainfall are the main factors affecting livestock diseases (Rojas-Downing *et al.*, 2017). Because of the complexity of host–pathogen interactions, impacts of climate change on livestock pests and diseases will be hard to predict. Vector-borne diseases are particularly sensitive to climate change, as warming in regions that were previously too cold for specific vectors may allow them to spread (Abdela and Jilo, 2016). Pests and diseases may also be indirectly affected by climate change through changes in water storage and irrigation (Bett *et al.*, 2017).

Bluetongue is a vector-borne viral disease that leads to sheep mortality and is transmitted by insect vectors, particularly biting *Culicodes* midges (World Organisation for Animal Health, 2020a). A study modelling the impact of climate change on the spread of bluetongue found that its distribution is likely to expand, particularly in central Africa, the United States of America and western parts of the Russian Federation (Samy and Peterson, 2016).

Rift Valley fever (RVF) is a vector-borne viral disease that is mostly transmitted by mosquitoes; it primarily affects domesticated animals but can also infect humans and in a small percentage of severe cases can lead to death (WHO, 2020; World Organisation for Animal Health, 2020b). As the distribution of mosquitoes is affected by temperature and precipitation, the distribution of the disease is projected to change in the future. In the United Republic of Tanzania, for example, the risk of outbreaks is projected to increase in the western parts of the country and decrease in the southern part (Mweya, Mboera and Kimera, 2017). In Baringo County in Kenya, climate change is projected to extend the range of RVF vectors significantly (Ochieng *et al.*, 2016).

Animal African trypanosomiasis (AAT) is one of the most serious cattle diseases in sub-Saharan Africa. It is caused by unicellular parasites called trypanosomes and transmitted by haematophagous insects, generally tsetse flies. The disease causes anaemia and weight loss and is often lethal. It therefore has a high economic impact (Shaw *et al.*, 2014). The effects of climate change on AAT incidence are complex. The range of tsetse flies is expected to decline or to shift as temperatures increase, with some areas becoming too hot and some areas that were formerly too cold becoming suitable (Easter, Killion and Carter, 2018; Lord *et al.*, 2018; Moore *et al.*, 2012). However, AAT occurs more frequently in long dry seasons, possibly because of the increased mobility of cattle during such seasons and the consequent increased exposure to vectors (Kimaro, Toribio and Mor, 2017; Majekodunmi *et al.*, 2013). Moreover, low nutritional status during the dry season leaves animals weakened and may lead to clinical signs of trypanosomiasis in animals that would be subclinically infected if they were in good health (Mochabo *et al.*, 2005). Temperature changes lead to the secretion of stress hormones, which depress the immune system and thus have the potential to facilitate the spread of pathogens (Bett *et al.*, 2017).

2.1.2 Characterization and conservation of animal genetic resources for food and agriculture

Genetic and phenotypic characterization of AnGR can be used to support climate change adaptation. When phenotypic characteristics of breeds relating to their performance and survival in various environments are known, breeds can be chosen to fit the environments in which they are to be raised. Genetic characterization can be used to make breeding more targeted and produce animals that are better adapted to the adverse effects of climate change.

Studies that genetically characterize AnGR can provide insights into the diversity and the phylogenetic history of breeds (Mosweu *et al.*, 2020). This knowledge can be used to help design effective breeding programmes and conservation strategies (Madilindi *et al.*, 2019).

Native AnGR are still insufficiently characterized and many are at risk of extinction (FAO, 2015a). There is an urgent need to step up efforts to characterize such breeds and the production environments in which they are kept, paying attention to characteristics that are relevant to climate change adaptation. Conservation strategies may need to be reviewed in view of the additional threats posed by climate change and the need to ensure the survival of breeds that may be of particular importance in climate change adaptation.

2.2 Adaptation

Many livestock keepers, particularly in mountainous and arid regions, are experienced in adapting their production to harsh and fluctuating environments, for example by raising several species or breeds and migrating to where fodder is available (FAO, 2017b). However, the increasing pace of climate change may make it impossible for livestock keepers to adapt their husbandry practices or find suitable land for their animals (ibid.).

As climate change impacts vary greatly by location, adaptation to climate change needs to be site-specific. Options for adaptation to climate change include breeding for improved resilience or for specific climate-related traits and cross-breeding with heat- and disease-tolerant breeds (Rivera-Ferre *et al.*, 2016).

Breeds that have been kept over many generations in adverse environments tend to have become adapted to the local conditions and to have developed characteristics that may be valuable in climate change adaptation (Ahmed, Sara and Semir Bechir Suheil, 2017).

Most modern breeding efforts focus on breeds kept in industrial production systems, while those kept in extensive systems receive less attention (FAO, 2015c). Although African cattle breeds have many traits that make them suitable candidates for use in climate change adaptation, there are few breeding programmes aimed at improving the performance of such breeds (Mwai *et al.*, 2015).

Scientific advances have contributed to a better understanding of the links between specific genes and tolerance of the impacts of climate change, and this knowledge can be used to improve the targeting and speed of breeding efforts (FAO, 2017b). Crossing traditional dryland-adapted breeds with exotic breeds may have the potential to increase production (Fre, 2018).

Global exchange of AnGR consists largely of the movement of high-output breeds from industrialized countries to developing countries, while there is also some movement of tropically adapted cattle between South Asia, Latin America and Africa, and grazing animals from developing countries to dry areas of Australia and the United States of America (FAO, 2015c).

Breeding for tolerance to emerging diseases can also support adaptation to climate change. African Zebu and European taurine breeds, for example, do not usually survive AAT without treatment, while West African taurine breeds such as N'Dama, Somba and Baoule are trypanotolerant (Berthier *et al.*, 2015). Trypanotolerance is of particular importance given that some strains of trypanosomes have been found to be resistant to trypanocidal drugs (Mulandane *et al.*, 2018; Tchamdja *et al.*, 2017). While the exact genetic mechanisms underlying trypanotolerance have not yet been identified, knowledge of which genes play a role in response to trypanosome infection is increasing (Bahbahani and Hanotte, 2015; Tijjani *et al.*, 2019; Wang *et al.*, 2016). The West Africa Livestock Innovation Centre (WALIC) is working on genetic improvement of trypanotolerant breeds such as N'Dama cattle, West African Dwarf goat and Djallonke sheep (WALIC, 2020).

In Ethiopia, the International Livestock Research Institute and its partners implemented a project that involved communities in phenotyping the local goats. The project found that adaptation traits such as drought tolerance were generally considered to be less of a priority for selection than production-related traits or coat colour. Specific village selection schemes were designed to maintain adaptability and hardiness while at the same time improving productivity (Dessie *et al.*, 2014).

The ability to tolerate extreme climatic conditions varies greatly between species and breeds (FAO, 2015a). For example, naked-neck chickens have a better heat dissipation mechanism then normally feathered chickens, and perform better in terms of growth under heat stress (Islam and Nishibori, 2009; Rajkumar *et al.*, 2011).

Climate models can be useful to predict the potential future ranges of livestock breeds and species. For example, FAO's Breed Distribution Model models the suitable area for about 8 800 livestock breeds recorded in the Domestic Animal Diversity Information System (DAD-IS)[4] under current and expected future climatic conditions based on various climate models (FAO, 2020e).

Some breeds may not be able to adapt to future climatic changes in the locations where they have traditionally been raised. For example, Petit and Boujenane (2018) determined the climatic domains of the major sheep breeds of Morocco and found that they are adapted to specific climatic conditions and that at least one out of the six may not be able to adapt to the projected changes in climate in the area where it occurs.

While there are no global data available on how many livestock keepers are adapting to climate change by changing species or breeds, some studies have found that this adaptation strategy is used (Marshall, 2014). There is some evidence that cattle are being replaced by camelids or small ruminants in an attempt to adapt to dryer climate in some parts of the world. For example, in some regions of Ethiopia, the cattle population decreased while the camel increased between 1993 and 2013 (Yosef *et al.*, 2013). In the region ranging from western Eritrea to eastern Sudan, decades of drought, combined with displacement due to conflict, has led Beni-Amer pastoralists, who traditionally raised cattle, to adopt multispecies herding of sheep, goats and camels (Fre, 2018). In Ethiopia, surveys found that while rainfall in some areas had declined by 15 to 20 percent, the cattle population had declined by 50 to 70 percent and the dromedary population had increased by 10 to 200 percent, depending on the district (FAO, 2015c).

Adopting a different species may increase resilience to climate change, but it may also have less welcome consequences. Browsers such as goats feed on shrubs and trees more than sheep and cattle do (Estell *et al.,* 2012) and can thus help adapt production systems to dryer conditions, although they may not always be well matched to local environments and livelihood requirements. Similarly, switching to a more adapted breed may sustain the livelihoods of farmers, but it may increase the risk that the replaced breeds become extinct (FAO, 2017b; Yosef *et al.*, 2013).

Some examples of adaptation actions as reported by by stakeholders from around the world via DAD-Net are presented in Box 1.

2.2.1 The use of animal genetic resources for food and agriculture for climate change adaptation in the nationally determined contributions

A number of countries mention the improved management of livestock as an adaptation action. Most of these mention very general actions such as promoting sustainable livestock management, while some countries focus on improving animal health and welfare or pasture management or on technical changes such as ventilation of livestock housing.

A few countries refer to breeding or to the diversification of AnGR. Ethiopia, for example, intends to increase the capacity of breeding programmes to deal with the emergence and expansion of diseases and pests. Burkina Faso plans the establishment of five livestock breeding intensification zones within the country. Sudan mentions breed improvement. Belize aims to increase access to drought-tolerant breeds.

In terms of diversification, countries either mention the adoption of resilient breeds or diversification of the species kept. Namibia, for example, mentions the use of drought-resistant breeds. In the Republic of Moldova, focus is laid on the introduction of livestock species that are resilient to extreme temperatures and the adaptation of livestock diets to conditions imposed by climate change. Burundi focuses on enabling activities such as the raising of multiple species of animals. Uganda mentions

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[4] http://www.fao.org/breed-distribution-model/en/

expanding the diversification of livestock keeping. Chad plans to promote the genetic diversity of various livestock species. The Lao People's Democratic Republic plans to diversify animal populations in areas threatened by flooding and drought.

Box 1. Submissions received through the Domestic Animal Diversity Network (DAD-Net)

The Domestic Animal Diversity Network (DAD-Net) is an e-mail-based network that provides an informal forum for the discussion of issues relevant to the management of animal genetic resources (AnGR). In order to gain information from a wide variety of stakeholders around the world, members of the network were asked to answer questions on the role of AnGR in climate change adaptation and mitigation. They were asked whether the livestock masterplan or other livestock policy in their country takes climate change into account and whether they knew of a breeding programme that takes climate change adaptation or mitigation into account. They were further asked whether breeding was targeting specific traits related to climate resilience, or general robustness. Selected answers provided by the respondents are presented below. Several respondents from Africa noted that they would be interested in participating in training or events on this topic should FAO organize them.

Algeria[5]

In Algeria, breeding for climate change adaptation or mitigation is currently not included in livestock sector policies, but there is ongoing research on heat tolerance and pest and disease resistance in local poultry and sheep breeds (Ahmed, Sara and Semir Bechir Suheil, 2017). In order to facilitate breeding of local poultry breeds, researchers at the University of Tlemcen have created an association that brings together breeders, master's students, doctoral students and researchers. A national association for the endangered local Hamra sheep breed has been created to support the breed's development.

The Gambia[6]

The open nucleus breeding programme implemented by the West Africa Livestock Innovation Centre (WALIC) aims to increase milk and meat production in local breeds without losing their adaptedness to trypanosomiasis and other environmental stresses and thereby contribute to climate change adaptation. The livestock breeds under this programme are N'Dama cattle, Djallonke sheep and the West African Dwarf goat.

Indonesia[7]

Indonesian cattle breeds are known for being well adapted to the local humid environment and low-quality feed, and can maintain their reproduction rates in such conditions. The Breeding Programme of the Directorate General of Livestock and Animal Health of the Ministry of Agriculture utilizes indigenous or local breeds to produce frozen semen to be used for artificial insemination. The frozen semen is distributed to smallholder farmers and used for breeding. There are several breeding centres across the country that work towards the improvement of local breeds such as Aceh cattle, Pesisir cattle and Bali cattle and exotic breeds such as Simmental and Brahman crosses. The bulls produced by the breeding centres are distributed to farmer groups that need to improve their cows or sent to national and regional artificial insemination centres to produce frozen semen. The Indonesian Centre for Animal Research and Development (ICARD) works on the development of breeds that are adapted to hot and humid environments − for example the Pogasi Agrinak, which is selected from Ongole cattle. Simultaneously, the breeding of sheep and goats that are well adapted to hot and humid environments produced the Compass Agrinak, Bahtera Agrinak and Boerka Galaksi, which were released as new breeds in 2014 and 2019. New breeds of chicken such as KUB chicken, Sensi Agrinak, Ulu and IPB D1 chicken have been developed using local genetic resources. Research on new breeds of duck for egg and meat production has led, respectively, to the development of the Mojomaster Agrinak and Alabimaster Agrinak and the PmP Agrinak.

Mauritius[8]

In Mauritius, the local Creole cattle breed has been shown to be more heat tolerant and feed efficient than imported breeds (Poillot, Leclesio and Wong Yon Cheong, 1976). A nucleus of Creole cattle and local goats is being conserved at the Food and Agriculture Research and Extension Institute (FAREI) for use in breeding programmes. Where mitigation is concerned, greater emphasis is being laid on the rearing of small ruminants to reduce greenhouse-gas emissions. The Ministry of Agro-Industry and Food Security recognizes that climate change has

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[5] Provided by Semir Bechir Suheil Gaouar, University of Tlemcen, Algeria.

[6] Provided by Olawale F. Olaniyan, School of Agriculture and Environmental Sciences, West Africa Livestock Innovation Centre, The Gambia.

[7] Provided by Bess Tiesnamurti, Indonesian Center for Animal Research and Development.

[8] Provided by Krishnawotee Dowluth, Ministry of Agro-Industry and Food Security and Micheline Seenevassen Pillay, Food and Agriculture Research and Extension Institute (FAREI), Mauritius.

an impact on agriculture, and adaptation and mitigation measures are addressed in the Strategic Plan 2016−2020 for the Food Crop Livestock and Forestry Sectors. The strategic plan proposes measures that promote adaptation by encouraging farmers to produce small animals such as turkeys, ducks and rabbits and encouraging the public to consume these types of meat (Ministry of Agro-Industry and Food Security of Mauritius, 2016).

South Africa[9]

In South Africa, links between climate change and animal breeding are continuously being studied. There is a network of quantitative geneticists that have a special interest in quantifying improved efficiency when indigenous and/or exotic cattle breeds are used in cross-breeding systems. Preweaning and postweaning growth and fertility traits are also analysed. A number of scientific publications have been published. Scholtz *et al.* (2016), for example, proposed short- and long-term drought-adaptation strategies such as considering alternative feed sources, restricting livestock movement during the hottest hours of the day and breeding for more drought-resistant animals and forage varieties.

Switzerland[10]

The Swiss National Strategic Plan for Animal Breeding 2030 prioritizes support for animal breeding for resource efficiency, reduced environmental impact and adaptability to the locations in which animals are reared, and recognizes climate change as a major driver (BLW, 2018). Breeding of cattle, pigs, sheep and goats aims to extend the functional life of animals. In the case of cattle, research is being done on reducing methane emissions, and in the future, climate-related traits such as environmental adaptability, robustness, metabolic efficiency and feed efficiency will be taken into account.

2.3 Mitigation

Livestock production systems are responsible for 14.5 percent of anthropogenic greenhouse-gas emissions, with cattle being the major source of methane emissions, and thus contributing substantially to climate change (Gerber *et al.*, 2013). Economic development has been found to correlate with an increase in meat consumption, and rising cattle numbers in recent decades have contributed to rising greenhouse-gas emissions from agriculture (Sans and Combris, 2015; Tubiello, 2018). In industrialized countries, however, where meat consumption per capita is generally high, a growing number of consumers are choosing to reduce their consumption of animal products (Graça, Godinho and Truninger, 2019; Malek, Umberger and Goddard, 2019). Although concerns about the environmental impact motivate some consumers to reduce their meat consumption, there may also be other motivations, such as concerns about animal welfare (Graça, Godinho and Truninger, 2019).

The main way in which AnGR can be used to promote mitigation is in reducing emissions from livestock systems rather than in increasing the removal of carbon from the atmosphere. Increasing efficiency can substantially decrease emissions. In Europe, for example, livestock production increased between 1990 and 2002, while CH_4 and N_2O emissions were reduced by 8 percent over this period as a result of intensification (European Environment Agency, 2019; Rivera-Ferre *et al.*, 2016).

Most mitigation options currently used in the livestock sector are production-system level interventions such as reducing enteric methane through improved feeding practices, reducing nitrous oxide emissions through manure management and promoting carbon sequestration through pasture management (IPCC, 2019a). Beef production accounts for 41 percent of emissions from livestock production, and therefore mitigation actions often target beef production (Gerber *et al.*, 2013).

Targeted breeding of lower-emitting animals has the potential to reduce methane emissions from livestock production systems (Hristov *et al.*, 2013; IPCC, 2019a). Reductions of emissions from livestock production can also be achieved through breeding for feed conversion efficiency (Rivera-Ferre *et al.*, 2016). This plays a particularly important role in the reduction of emissions from non-ruminant species such as pigs and poultry (Forabosco, Chitchyan and Mantovani, 2017). Commercial breeding goals for these species have significantly expanded since the 1970s, and the focus has shifted from productivity to other traits such as feed efficiency and robustness (Neeteson-van Nieuwenhoven, Knap and Avendaño, 2013).

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[9] Provided by Anette Theunissen, Vaalharts Research Station, South Africa.

[10] Provided by Melissa Raemy, Federal Office for Agriculture, Switzerland.

Interventions at production-system level can also contribute to reducing emissions. Improving animal health, for example, can significantly improve productivity and fertility and reduce mortality, thereby reducing emissions per unit of product (ADAS UK Ltd, 2015). Dietary manipulation can help reduce methane and nitrogenous emissions and increase feed efficiency (FAO, 2017d). For example, Niderkorn *et al.* (2019) found that feeding sheep pure chicory led to lower methane emissions than feeding them pure ryegrass or mixtures of ryegrass, chicory and white clover.

Choosing species according to the environment in which they are raised has the potential to increase productivity (IPCC, 2019a). Changing from ruminant to monogastric species (e.g. from cattle to pigs or poultry) is an effective way of reducing methane emissions; however, certain non-ruminant species compete with humans for food, while ruminant species can feed on feed that is inedible to humans (e.g. grass and shrubs) (Gill, Smith and Wilkinson, 2010; Ripple *et al.*, 2014; Rivera-Ferre *et al.*, 2016).

Reducing the number of low-producing animals and replacing them with fewer but higher-yielding cross-bred animals could help mitigate greenhouse-gas emissions by improving efficiency (IPCC, 2019a). However, such strategies may be difficult to implement in some production systems (ibid.).

Dual-purpose cattle breeds used for milk and meat production can lead to a decrease in greenhouse-gas emissions on farm, as fewer animals are needed for production, but can increase greenhouse-gas emissions per kg of protein, milk or meat produced, because the yield of one product or the other tends to be smaller than from single-purpose cattle (Schader *et al.*, 2014). The appropriate choice of breed choice will depend on the production system and the production objectives. A study in Switzerland found that greenhouse-gas emissions from dual-purpose cattle were lower than those obtained by raising specialized dairy cattle and compensating for the associated decline in meat production by increasing suckler-calf production (Probst *et al.*, 2019). The study, however, also found that even lower emissions could be obtained by keeping specialized dairy cows and using sexed semen to breed herd replacements and beef-breed semen to produce offspring to be reared for meat, although the use of dual-purpose animals was concluded to be judicious for mountain and organic production (ibid.).

2.3.1 The use of animal genetic resources for food and agriculture for climate change mitigation in the nationally determined contributions

When countries mention the livestock sector in their proposed mitigation actions, they usually refer to the production of biogas from manure, reduction of enteric methane production through feed management and the use of feed additives, and in some cases the adoption of management practices such as those associated with organic or climate-smart livestock production. A few countries, however, mention the management of AnGR (i.e. genetic improvement, appropriate choice of breeds, etc.) as a mitigation strategy.

Bhutan, for example, refers to the improvement of livestock breeds and the conservation of native genetic diversity. In particular, the improvement of yak and cattle breeds through the selection of superior bulls from local populations on the basis of pedigree and/or progeny performance and the distribution of bulls from other areas to introduce new bloodlines and reduce inbreeding and artificial insemination with imported semen are mentioned. Togo also mentions the promotion of local breeds. Pakistan mentions the development and adoption of new breeds of cattle that produce more milk and meat and have lower methane emissions from enteric fermentation. Thailand mentions improving animal breeding to enhance production efficiency. Albania, the Democratic People's Republic of Korea, Togo and Uganda also mention livestock breeding as a mitigation action. Myanmar mentions decreasing the number of ruminant animals.

A few countries mention diversification in livestock production systems. Nicaragua, for example, mentions the inclusion of trees on livestock ranches. Chad mentions the development of the agrosilvopastoral sector.

FAO's *Regional Analysis of the Nationally Determined Contributions of Eastern Africa − Gaps and Opportunities in the Agriculture Sectors* (FAO, 2017c) found that the coverage of policies and measures aiming to improve livestock breeding was insufficient.

2.4 Conclusions and recommendations

Climate change is already affecting AnGR in many parts of the world. Most studies on the impact of climate change on AnGR focus on species in a given area, and in some cases on specific breeds. A substantial amount of literature focuses on the impact of climate change on livestock pests and diseases. While there are some studies on the impacts of climate change on rangelands and livestock production at a global level, they have received less attention than impacts on crop production (IPCC, 2019a). Similarly, there are more studies quantifying or modelling the impact of climate change on crop pests and diseases than there are doing the equivalent for livestock pests and diseases.

While many countries acknowledge the importance of climate change adaptation and mitigation in livestock production, few refer to AnGR management specifically as an adaptation and mitigation option in their national livestock strategies and NDCs. Specific targets and actions need to be developed to ensure that AnGR fulfil their potential in climate change adaptation and mitigation.

Adaptation to and mitigation of climate change are rarely primary breeding goals, but feed efficiency and the tolerance of climate-related stresses, such as heat or the effects of pests and diseases, are generally selected for in breeding programmes. There are a number of notable regional breeding programmes in Africa and Europe that focus on climate-related traits such as drought and disease tolerance and feed efficiency. Such initiatives should be prioritized in the allocation of funds, as they not only support the adaptation of agriculture to climate change but also contribute to the sustainable use of AnGR.

Many local breeds are known to be hardy and well adapted to difficult conditions, thus making them ideal candidates for use in climate change adaptation. In many developing countries, however, the endangered status of some locally adapted breeds and the lack of structured breeding programmes hinder their use. Conservation efforts need to be strengthened so that locally adapted breeds remain available for use in climate change adaptation. There is some evidence that cross-breeding locally adapted and exotic breeds can produce animals that are both more productive and well adapted to local climates. However, cross-breeding needs to be carefully planned so that cross-bred animals are well matched to production environments and that locally adapted breeds are not put at risk of extinction.

In some parts of the world, livestock keepers are adapting to climate change by adopting different breeds or species. Again, such introductions need to be carefully planned, taking into account the productivity of the introduced breed or species under local conditions, along with possible environmental impacts and impacts on AnGR diversity.

The use of AnGR in climate change mitigation focuses on the reduction of emissions from livestock production through increased efficiency. Breeding for better feed conversion rates and the use of dual-purpose breeds can contribute to lowering emissions.

In conclusion, there is great potential for AnGR to be used in climate change adaptation and mitigation, but efforts need to be scaled up to keep up with the rapid pace of climate change and further reduce the negative effects that livestock production has on the global climate. Possible implications of adaptation and mitigation measures for the conservation of AnGR need to be carefully considered, and measures need to be specifically adapted to local contexts.

III. AQUATIC GENETIC RESOURCES FOR FOOD AND AGRICULTURE

3.1 Introduction

Aquatic genetic resources for food and agriculture (AqGR) underpin fisheries and aquaculture, but in turn are often highly dependent on the state of the wider aquatic ecosystem, including wild relative genetic resources. Capture fisheries rely on continuous recruitment within wild populations, and therefore on healthy ecosystems that provide breeding and spawning grounds. As the domestication of aquatic species in aquaculture only became widespread during the twentieth century, and breeding techniques are still being developed or refined for many species, farmed types of cultured species are often genetically very similar to their wild relatives. In many cases, aquaculture still relies on wild stocks as seed or broodstock (FAO, 2019c).

3.1.1 The impact of climate change on aquatic ecosystems and fisheries

Aquatic ecosystems account for the planet's largest carbon and nitrogen fluxes and act as one if its most important carbon sinks (Gruber *et al.*, 2019; Ocean & Climate Platform, 2019). Oceans absorb about two gigatonnes more CO_2 per year than they release into the atmosphere, and have taken up about a third of the anthropogenic CO_2 released since the beginning of the industrial revolution (IPCC, 2019b). However, uptake may fluctuate or decrease with warming temperatures (Landschützer *et al.*, 2014). Calcium carbonate in the bodies of some aquatic micro-organisms and in the skeletal structures of marine invertebrates falls to the ocean floor and is stored in sediments, significantly contributing to global carbon storage (Pullin and White, 2011). The uptake of CO_2 by the water causes ocean acidification, which in turn compromises the ability of calcifying organisms to build their skeletons and shells, and makes them vulnerable to dissolution, thus disrupting the process of carbon storage in marine sediments (IPCC, 2019b).

Other impacts of climate change on marine environments include increases in water temperature, sea-level rise, storms, changes in currents and hypoxia (the depletion or absence of oxygen) (Howes *et al.*, 2015). Seasonally occurring hypoxia is expected to become more severe and affect larger areas, and in extreme cases oxygen levels may fall too low to support most marine life (Phillips and Pérez-Ramírez, 2017). Environmental changes of these kinds lead to shifts in population ranges, including modifications in dispersal patterns, and to changes in species interactions (Poloczanska *et al.*, 2016). Storms and rising sea levels are threatening coastal communities and affecting artisanal fishing.

Another important impact of climate change on marine environments is coral bleaching. Rising temperatures affect the symbiosis between corals and zooxanthellae, the algae that provide the corals with feed and oxygen (Kemp *et al.*, 2012). An increase in water temperature of 1 °C or more over a prolonged period of time impairs the algae's ability to photosynthesize, which causes bleaching and subsequent death of the corals (Heron, Eakin and Douvere, 2017). This has severe repercussions for many marine species, especially those that have an obligatory relationship to coral. The composition of coral-reef communities is also changing due to climate pressures; phase shifts – abrupt decreases in coral abundance with simultaneous increases in non-reef-building organisms, such as algae and soft corals – are occurring in many reefs around the world (IPCC, 2019b; Kleypas, 2019). Negative impacts on tropical reef fishes, conchs and spiny lobsters, caused by loss of nursery and adult habitats, increasing surface temperature and ocean acidification, have been observed (FAO, 2018b; Oxenford and Monnereau, 2017).

Kelp forests, mangroves and seagrass meadows are referred to as "blue carbon" ecosystems because of their ability to sequester carbon from the ocean and the atmosphere (Nelleman *et al*., 2009). They also provide habitats for diverse communities of aquatic organisms. If they fail to adapt, these habitats and their associated ecosystem services will be disrupted and may disappear completely (FAO, 2017b). Mangrove forests act as natural barriers against storms and waves and can thus protect coastal areas from climate change-driven extreme events. Seagrasses not only provide habitat for many small marine animals, they also bind sediments, dissipate wave energy and reduce the velocity of currents, and thus play an important role in coastal protection (FAO, 2019a; Hyndes *et al.*, 2016; Wilson and Forsyth, 2018). The loss of seagrass meadows entails the erosion of carbon stocks formerly bound in the ocean floor, turning it from a carbon sink to a carbon source (Marbà *et al.*, 2015). Kelp forests are composed of high-density stands of brown macro-algae and provide habitat for many aquatic species, protect shorelines and play an important role in nutrient cycling (Krumhansl *et al.*, 2016; Laffoley and Grimsditch, 2009).

Coral reefs, seagrass meadows and kelp forests have a low to moderate capacity to adapt and will be at high risk at 1.5 °C of global warming (IPCC, 2019b). Indirect effects, such as increased grazing pressure caused by the spread of tropical species to higher latitudes, also have negative consequences for seagrass meadows and coral reefs (ibid.).

Harmful algal blooms in coastal areas have become more frequent and more intense since the 1980s as a result of both climatic drivers (e.g. ocean warming and oxygen loss) and non-climatic drivers (e.g. increased riverine nutrient runoff) (IPCC, 2019b). These blooms can negatively affect coastal communities and food security; examples have included significant economic losses for the tuna industry in Mexico and the death of over 40 000 tonnes of cultivated salmon in Chile (Díaz *et al.*, 2019; García-Mendoza *et al.*, 2018; IPCC, 2019b).

Marine heat waves can severely affect some commercially significant species. For example, in February and March 2011, a marine heat wave off the southwestern coast of Western Australia had detrimental effects on Roe's abalone (*Haliotis roei*), with mortality rates of up to 99.8 percent in the northern part of the fishery (FAO, 2019c). Sensitivity to marine heat waves has also been found in the bivalve *Anomalocardia flexuosa*, which is an important source of food and income along its distribution range on the eastern shores of South America and the Caribbean (Carneiro *et al.*, 2020; Silva-Cavalcanti, Costa and Alves, 2018).

The distribution of marine species is more sensitive to temperature changes than that of terrestrial species (Sunday *et al.*, 2015). Fish production is predicted to increase at high latitudes and decrease at low and mid latitudes (as species there are already at the upper limit of their thermal tolerance), with considerable regional variations (Barange *et al.*, 2014).

Climate change will also have an impact on freshwater availability, which in turn will affect both farmed and wild AqGR. Rivers will be affected by changing precipitation and evaporation patterns, and the increasing frequency of droughts will increase the risk that small lakes and rivers will dry out, thus disrupting waterbody connectivity and fish migration (FAO, 2017b). Increases in temperature will continue to negatively affect coldwater fish, such as trout, causing them to migrate upstream and thus shrinking their ranges (Eby *et al.*, 2014; IPCC, 2019b).

Changes in the cryosphere have a significant impact on downstream watersheds. Glacier recession in the mountains of coastal Alaska has led to the creation of new stream systems that have been, and could potentially continue to be, colonized from the sea by salmon species; however, this effect will cease once glaciers have diminished to a point where runoff is reduced (Milner *et al.*, 2017; Schoen *et al.*, 2017). Glacier recession is thought to be the driver behind seasonal reductions of fish habitat and the marked decline or extinction of fish stocks in the high-altitude watershed of the Cordillera Blanca in Peru (Bury *et al.*, 2011).[11]

Extreme events such as storms and heavy rainfalls, which are expected to increase in frequency and intensity as a result of climate change, also affect freshwater and marine (especially coastal) ecosystems. Flooding caused by extreme rainfall can temporarily merge separated water bodies and facilitate the spread of invasive species (FAO, 2015a). Runoff increases turbidity and siltation, which can lead to the eradication of aquatic species that require very clear water and the physical burial of some organisms (Pullin and White, 2011; FAO, 2017b). The effects of climate change on phytoplankton, which feed many aquatic species, are hard to determine at a global scale, as turbidity lowers light penetration and reduces their abundance and activity, but rising CO_2 levels increase their activity (Cavicchioli *et al.*, 2019; FAO, 2017b).

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[11] This paragraph is adapted from IPCC (2019b).

3.1.2 The impact of climate change on aquaculture

Although the domestication of aquatic species in aquaculture became widespread only during the twentieth century, aquaculture is the fastest growing food-production sector and is expected to play the main role in meeting the rising demand for aquatic food in the future given that production from capture fisheries has plateaued since the 1980s (FAO, 2018b; Nash, 2011). Aquaculture is affected by direct and indirect climate change drivers such as eutrophication, hypoxia, salinity intrusion, increased risk of disease incidence, increased frequency of extreme weather events (e.g. floods), and reduced access to freshwater because of declines in precipitation (FAO, 2018a).

While warming may lead to increased growth rates, exposure to high temperature negatively affects the reproductive development of female salmonids such as rainbow trout (*Oncorhynchus mykiss*) and Arctic charr (*Salvelinus alpinus*) (Pankhurst and King, 2010). Increased water temperature can lead to a higher incidence of some diseases (de Kantzow *et al.*, 2016).

In the Sundarban delta in India, freshwater aquaculture has been threatened by salinity intrusion associated with coastal flooding caused by sea-level rise and the increased frequency of cyclones and storm surges (Dubey *et al.*, 2017). In Bangladesh, shrimp farming is affected by many climate impacts, including flooding, which can lead to the escape of shrimp or the intrusion of predatory fish, as well as to increased salinity, which can increase disease incidence (Ahmed and Diana, 2015). In China, a marine heatwave led to mass mortality of farmed sea cucumbers in 2018 (Li, 2018). In the United Kingdom, aquaculture is likely to be affected by an increase in the incidence of diseases and by increased temperatures (Collins *et al.*, 2020).

Fifty percent of the 92 countries that provided reports as inputs to *The State of the World's Aquatic Genetic Resources for Food and Agriculture* (SoW-AqGR) indicated that climate change would have a negative or strongly negative impact on farmed type genetic resources (FAO, 2019c). Reported effects are summarized in Table 1 and Figure 1. There was a relatively high degree of uncertainty regarding the impacts of climate change on farmed types, mainly due to the lack of scientific information on how climate-driven changes, in particular temperature rise, would affect aquaculture species. In the warm tropics, where species may already be cultured at the upper end of their temperature tolerance range, the impacts of climate change on aquaculture can be particularly marked. Only 15 percent of responding countries believed that climate change would have a positive effect on farmed types. Factors mentioned included better growth rate with slightly higher temperature, and opportunities to use lagoons for the cultivation of marine species due to increased salinity.

Table 1. Reported impacts of climate change on farmed AqGR

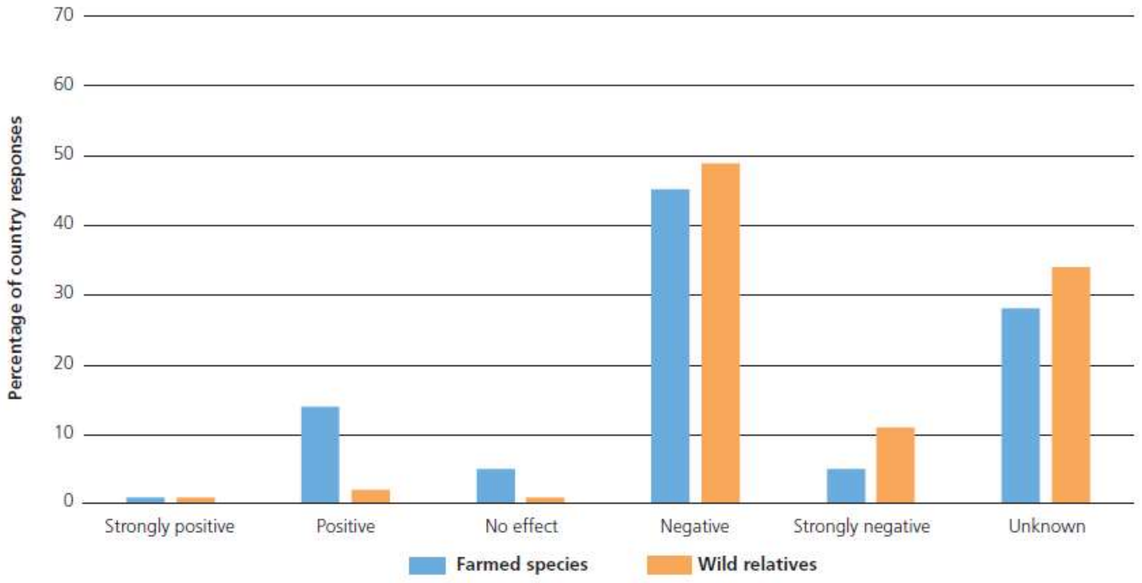
Impact	*Countries*
Increased sea temperatures affecting grow-out	Australia, Chile, Finland
Increased incidence of stress and disease mainly as a result of temperature rise but also of changes in water availability and water quality	Bangladesh, Canada, Guatemala, Honduras, Malaysia, Morocco, Philippines
Water shortages drying out ponds or reservoirs impacting production or choice of broodstock for the next crop	Colombia, Malawi, Nigeria, Sri Lanka, Uganda, Zambia
Water levels in reservoirs reduced to the anoxic "dead zone", with water-quality issues and temperature rises	Cuba, Ghana
Delayed rains and seasonal shifts affecting grow-out season, deteriorating water quality and increasing disease outbreaks	Venezuela (Bolivarian Republic of)
Combination of high temperature and increased salinity impacting brackish-water culture	Costa Rica

Temperature and seasonal impacts on reproductive capacity, with impacts on hatchery production	Benin, Lao People's Democratic Republic
Establishment of invasive species in areas that were previously too cold	Suckermouth catfish (*Hypostomus plecostomus*) in Guatemala; grass carp (*Ctenopharyngodon idella*) and common carp (*Cyprinus carpio*) in Sweden.
Extreme weather events impacting aquaculture facilities	Viet Nam
Increased flooding events affecting water quality	Belize, Benin, Sri Lanka
Increased flooding events impacting production facilities	United Republic of Tanzania
Abandonment of aquaculture due to low productivity because of the impact of climate change	Senegal

Source: FAO (2019c).

Sixty percent of countries that provided reports for the SoW-AqGR considered that climate change would have a negative impact on the wild relatives of farmed species (FAO, 2019c). Impacts mentioned included shifts in species distribution because of changes in temperature or salinity, effects of acidification on estuarine and marine shellfish, and drying out of dry-season refuges and breeding areas. Thirty-four percent of responding countries reported that the impacts of climate change were unknown. Countries noted that there was inadequate understanding of how climate change would affect the complex interactions between wild relatives, their predators and preys and other ecosystem components and of how it would affect reproduction and other physiological mechanisms. A few countries reported that climate change-related effects were expected to benefit wild AqGR, for example by providing an opportunity for brackish-water species to expand their ranges in delta areas or for range expansion among species that prefer warmer waters. It was also noted that the disappearance of wild stocks in certain regions would drive the development of aquaculture for these species.

Figure 1: Country responses on the effect of climate change on aquatic genetic resources of farmed species and their wild relatives



Source: FAO (2019c).

3.2 Adaptation

AqGR are fundamental to the adaptation of fisheries and aquaculture to climate change. Most adaptation of wild and farmed aquatic organisms occurs through natural selection, although in aquaculture and culture-based fisheries, adaptation can also be achieved by selective breeding or by introducing a new species (FAO, 2015a). In order to be useful in climate change adaptation, AqGR need to have adequate genetic variation in traits related to tolerance of the impacts of climate change (Pullin and White, 2011). The success of adaptation measures depends on effective characterization and monitoring, which are, to date, not done systematically in many countries (FAO, 2019c). It may seem that marine species can move more freely than terrestrial species, and thus have greater potential to adapt to climate change via migration. However, there are many barriers, such as temperature, salinity or the lack of suitable breeding and spawning grounds, that can hinder their dispersal.

3.2.1 The role of aquatic genetic resources for food and agriculture in the adaptation of fisheries and aquatic ecosystems to climate change

Capture fisheries are production systems in which many variables cannot be controlled, and therefore potential interventions to promote the adaptation of species to climate change are limited. Adaptation is occurring through natural selection. However, changes in climate may become too fast or too drastic for species to be able to adapt naturally (Klerks, Athrey and Leberg, 2019; Manhard, Joyce and Gharrett, 2017; Muñoz *et al.*, 2015). Restocking with wild or hatchery-reared fish that have specific traits such as tolerance to higher temperatures is possible, but can have large and irreversible effects on surviving wild populations, such as the loss of local genetic diversity and the risk of disease or parasite introduction (FAO, 2015a, 2018a). For example, hatchery-raised Pacific salmon lack genetic diversity, and thus spawning with wild populations can reduce the genetic fitness of these populations and compromise their ability to cope with stresses such as increased temperature (FAO, 2018a).

A 2016 review of the agriculture sectors in the Intended Nationally Determined Contributions (INDCs) found that 55 percent of countries (72 out of 131) mention fisheries or aquaculture when outlining their adaptation actions, and an additional 12 countries refer exclusively to the protection and restoration of marine resources (FAO, 2016). Adaptation actions mostly focus on policy development, resilience building and disaster risk management, improving legal and institutional frameworks, diversifying livelihoods, technological adaptations such as switching to different fishing gear or smartphone-based early-warning systems for extreme weather events, and ecosystem-based approaches to natural-resources management and conservation.

There are some examples of adaptation measures that involve the management of biodiversity, for example coral-reef, seagrass and mangrove restoration (FAO, 2018a). Several countries, particularly in East Africa, stress the importance of conserving and restoring marine, freshwater and coastal ecosystems and their biodiversity in their NDCs (FAO, 2017c). For example, the restoration of mangrove forests is used to promote carbon sequestration and prevent coastal erosion in Myanmar, to provide habitat for fish and other marine species in Senegal, and is mentioned by a number of other countries (FAO, 2016). In Mauritius, expansion of the protected areas network for the rehabilitation of seagrass meadows and coral reefs is named as a priority adaptation action; in Malawi, emphasis is placed on the protection of fish spawning and breeding sites (ibid.). Mexico's NDC mentions the implementation of a scheme for the conservation and recovery of coastal and marine ecosystems such as coral reefs, mangroves, seagrass meadows and sand dunes to increase carbon capture and strengthen coastal protection. Restoring coastal ecosystems not only supports the adaptation of coastal communities but also has mitigation co-benefits. Despite their roles in coastal protection and habitat provisioning, restoration of seagrass meadows has generally received less attention than the restoration of mangroves and coral reefs (Wilson and Forsyth, 2018).

Some adaptation measures focus on reducing the negative impacts of human activities on coastal processes, sediment dynamics and essential habitat to enhance the general resilience of ecosystems that support fisheries (FAO, 2018a). In freshwater ecosystems, habitat management focuses on physical properties such as restoring connectivity or reducing turbidity rather than genetic resources management (Arlinghaus *et al.*, 2015).

Wild aquatic populations can be conserved in marine, brackish and freshwaters by designating protected areas and managing them effectively or introducing other effective area-based conservation measures (FAO, 2015a; Maxwell *et al.*, 2020). Monitoring how populations are coping with changed climatic conditions is also important (FAO, 2015a). Area-based efforts can be supported by moving AqGR to other *in situ* sites or into *ex situ* collections (ibid). Interventions at the level of marine ecosystems, such as coral-reef restoration or the adoption of an ecosystem approach to fisheries and aquaculture, can help increase the resilience of marine and coastal ecosystems, but they are not systematically used to support the adaptation of fisheries to climate change (FAO, 2019a; Ferrario *et al.*, 2014).

Fishing quotas and allocations can act as barriers to adaptation, as climate change may mean that existing quotas no longer coincide with geographical distribution of the targeted species (FAO, 2018a). Fishery reserves and marine protected areas currently protect nursery and spawning grounds for many commercially important species, but climate change is likely to shift the location of such grounds and affect their ecological functions, leading to the need to revise protected areas and take action to ensure that their connectivity is maintained, and highlighting the need to consider climate projections when planning management measures (Erisman and Asch, 2015; FAO, 2018a). Likewise, the timing of closed seasons aimed at protecting species' main spawning periods will need to change to match changes in phenologies (FAO, 2018a).

Coral species and coral-reef ecosystems vary in their capacity to adapt to the impacts of climate change. Some coral species have been shown to possess traits that could help them adapt to changing environmental conditions such as ocean acidification and increasing temperatures (Camp *et al.*, 2018; Cornwall *et al.*, 2018; Drake *et al.*, 2018; Gintert *et al.*, 2018; Wall *et al.*, 2017). Epigenetic mechanisms[12] may be playing a role in the ability of some corals and their symbionts to acclimatize to changing conditions (Li *et al.*, 2018; Liew *et al.*, 2017, 2018; Torda *et al.*, 2017). However, it has not yet been established whether these effects will enable corals and their associated biota to adapt to global warming beyond 1.5 °C compared to pre-industrial levels.

As traditional conservation approaches such as the designation of marine protected areas are insufficient to address climate change impacts on coral reefs, active restoration interventions have been developed, and significant advances in reef restoration techniques have been made in the past two decades (Barton, Willis and Hutson, 2017; Lirman and Schopmeyer, 2016). These interventions include the direct transplantation of corals and the farming of coral colonies in underwater nurseries, sometimes referred to as the "coral gardening" approach (Forrester *et al.*, 2019). In the latter case, corals are cultured for up to several years and subsequently transplanted to degraded reef sites together with coral-associated biota (Lohr and Patterson, 2017; Montoya-Maya *et al.*, 2016; Ng, Toh and Chou, 2016; Rachmilovitz and Rinkevich, 2017).

There are a number of adaptation interventions that are still at the "proof-of-concept" stage, such as assisted evolution, the development of corals that are resistant to climate change impacts through the acceleration of natural evolution processes, for example by translocating corals from warmer to cooler regions to foster thermal-tolerance traits (Van Oppen *et al.*, 2015). Other such interventions include assisted coral chimerism, inoculating corals with symbionts and coral microbiome manipulation (McIlroy and Coffroth, 2017; van Oppen *et al.*, 2017; Rinkevich, 2019). A small number of quantitative trait loci (QTLs) associated with thermal and bleaching tolerance have been identified, and while there is no QTL-guided breeding of corals to date, breeding experiments are being conducted with corals that have survived bleaching events (Bay and Palumbi, 2014; FAO, 2019a; Jin *et al.*, 2016).[13]

Although active restoration can contribute to reef rehabilitation in all major reef regions, there is limited evidence as to how resistant restored corals are to further climate change-driven effects, in particular rising sea levels, or as to whether restoration options will be ineffective if global warming exceeds 1.5 °C relative to pre-industrial levels (IPCC, 2018; Perry *et al.*, 2018; Rinkevich, 2014; Shaish *et al.*, 2010). Additionally, coral restoration is costly, and as long as the underlying drivers of ocean acidification and

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[12] Epigenetic mechanisms are heritable phenotype changes that do not involve alterations in the DNA sequence.

[13] A more detailed review of assisted evolution methods for reef-building corals can be found in *The State of the World's Biodiversity for Food and Agriculture* (FAO, 2019a).

temperature increase are not mitigated, its potential remains limited (Bayraktarov *et al.*, 2019).[14] The cost of restoring aquatic and coastal ecosystems are lowest for mangroves, higher for salt marshes and highest for seagrass beds and coral reefs, partly because of the technical difficulties involved in planting organisms underwater (IPCC, 2019b).

3.2.2 The role of aquatic genetic resources for food and agriculture in the adaptation of aquaculture to climate change

Adapting aquaculture to climate change is more straightforward than adapting capture fisheries, as the former is a managed production system. Over 600 species are raised in aquaculture around the world, and this diversity can be used to adapt production systems to various climate change impacts (FAO, 2017e, 2019c).

Selective breeding of species used in aquaculture is not widespread to date, with only an estimated 10 percent of global aquaculture production using improved farmed types originating from well-managed selective breeding programmes (FAO, 2019c). Furthermore, 45 percent of countries that provided reports as inputs to the SoW-AqGR indicated that genetic improvement does not currently contribute to aquaculture production to any significant extent (ibid.). Selective breeding is estimated to have the potential to increase food production from farmed aquatic populations by 5.4 percent per year (Gjedrem, Robinson and Rye, 2012). Selective breeding of fish usually targets traits such as fast growth, food-conversion efficiency and disease resistance, but it can also improve traits that enhance resilience to specific impacts of climate change, for example temperature or salinity tolerance (FAO, 2017d, 2019c). Because of the relatively high levels of genetic variation retained in many recently domesticated species, and the medium to high levels of heritability of many commercially important traits, it can be anticipated that selection for tolerance to climate change-related effects such as rising temperatures is feasible.

A variety of genome-based biotechnologies can be applied to the improvement of farmed AqGR, but their use is not widespread. QTL mapping can be used to identify genes underpinning specific traits, thus enabling the implementation of marker-assisted selection (FAO, 2019c). Genomic selection has also started to be incorporated into some commercial breeding programmes (Zenger *et al.*, 2019).

Genetic techniques such as gene transfer, gene editing, crossbreeding and hybridization could potentially be used to create fish that are more climate-resilient. For example, hybrids between Nile tilapia (*Oreochromis niloticus*) and blue tilapia (*O. aureus*) are particularly tolerant of cold temperatures and salinity (Bartley, Rana and Immink, 2000; Wohlfarth, Hulata and Halevy, 1990). However, there are issues regarding fertility and a risk of genetic pollution of native populations in the case of escapes from aquaculture into natural waterbodies.

Climate change is expected to lead to more disease outbreaks, and disease-control methods used for terrestrial livestock, for example vaccination and biosecurity measures such as quarantining, cannot be applied to wild aquatic species, and show limited success in farmed ones (Figueroa *et al.*, 2017).

There have been a few successful breeding programmes for disease resistance in aquatic species. The discovery of a QTL linked to resistance to infectious pancreatic necrosis virus (IPNV), which leads to over 90 percent mortality during two specific growth stages in farmed Atlantic salmon, allowed for selection of individuals carrying the resistant allele and led to a rapid decline in IPNV outbreaks in aquaculture (Moen *et al.*, 2015). QTL associated with disease resistance have also been studied in Pacific salmon (Miller *et al.*, 2014). Another example is the development in Australia of Pacific oysters (*Crassostrea gigas*) resistant to Pacific oyster mortality syndrome (POMS), a marine herpesvirus that causes mass mortality (Australian Seafood Industries, 2017). Because higher water temperatures correlate with higher incidence of and mortality due to the virus, climate change is exacerbating its effects on the Pacific oyster (de Kantzow *et al.*, 2016).

Although aquaculture is often mentioned as an alternative to capture fisheries in the context of climate change, cultured species may face suboptimal physiological conditions, particularly with respect to

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[14] The section on coral-reef adaptation is adapted from IPCC (2019b).

temperature (FAO, 2018a). Moreover, increasing the use of waterbodies and coastal areas for aquaculture may increase outbreaks of known and new pathogens or parasites, highlighting the need for genetically improved farmed types that are resistant or tolerant and the need to be able to change between farmed species (ibid).

Before they can be widely applied, the properties, roles and risks of genetic technologies and their application to AqGR need to be better understood (FAO, 2019c). Long-term breeding programmes are needed to expand the impact of genetic improvement on aquaculture (ibid.). The EU-funded five-year project FISHBOOST is one such initiative.[15] Twenty-six partners from the public and private sectors are working towards the improvement of six finfish species – Atlantic salmon, common carp, European seabass, gilthead seabream, rainbow trout and turbot – through selective breeding, while maintaining levels of genetic variation in farmed types. The genetic improvement is aimed at increasing disease resistance and production efficiency, and attention is also given to optimizing breeding schemes and the development of genomic tools for aquaculture. While disease resistance and higher resource-use efficiency are traits that are relevant in climate change adaptation and mitigation, the latter were not specific objectives of the breeding programme.

Generally, countries do not mention genetic improvement of AqGR as an adaptation measure in their NDCs. One exception is Sri Lanka, which mentions cryopreservation of fish sperm for breeding, the conversion of existing open-air breeding facilities into indoor facilities to allow control of temperature impacts, and the development of temperature-tolerant species.

Species diversification is one option for the adaptation of aquaculture: selecting the species showing the best production results under specific farming conditions (FAO, 2018a). Some fish such as anguilid eels, catfish and snakeheads, for example, are hypoxia-tolerant.

Production system-level adaptations mentioned in the country reports submitted for the SoW-AqGR include adjusting stocking and harvesting cycles in order to adapt to changing and less reliable seasonal weather, and the development of production systems that use freshwater more efficiently (FAO, 2019c). It is important to find an appropriate balance between the diversification of aquaculture into new species and the adaptation of existing cultured species to new or changing environments. These two approaches often compete for resources (e.g. research and development funding) and the introduction of new species involves considerable expense on the development of culture systems, which may be equivalent to or more than the costs of developing a breeding programme to adapt an existing cultured species. Furthermore, introducing new species outside of their natural range bears the risk of their escaping into the wild and potentialy becoming invasive.

3.3. Mitigation

As noted above, blue carbon ecosystems have the potential to sequester carbon from the atmosphere and the ocean, thus directly mitigating climate change. Generally, greenhouse-gas emmisions from aquaculture, while varying between different systems, are lower than those for most other forms of animal protein production and comparable with those for chicken production (Willett *et al.,* 2019). Greenhouse-gas emissions from aquaculture and fisheries have the potential to be substantially reduced, mainly by reducing energy use, using renewable energy sources and improving the efficiency of resource use (FAO, 2018a). AqGR can contribute to increased resource-use efficiency in various ways, for example via the use of species with efficient feeding habits in aquaculture. Choosing herbivorous or omnivorous species rather than carnivorous ones also lowers the ecological footprint of aquaculture.

3.3.1 The role of aquatic genetic resources for food and agriculture in mitigating the effects of climate change in aquatic ecosystems

Well-managed aquatic ecosystems can significantly contribute to climate change mitigation, in particular through carbon sequestration (FAO, 2017d). Vegetated marine habitats can store up to 1 000 tonnes of carbon per hectare in the ocean floor, which is much more than can be stored in most terrestrial ecosystems (IPCC, 2019b). Restoration or rehabilitation actions have the potential to sequester 226±39

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[15] For more information, see http://www.fishboost.eu/

grams of carbon per square metre per year in the case of mangroves and 138±38 grams of carbon per square metre per year in the case of seagrass ecosystems (McLeod *et al.*, 2011). It is estimated that macroalgae sequester approximately 173 Tg carbon per year globally (Krause-Jensen and Duarte, 2016). Quantifying the exact benefits of restoration measures is difficult, because the quantity of carbon stored is highly variable and site specific.

Globally, around 160 mangrove restoration projects have been documented (Worthington and Spalding, 2018). Twelve countries mention mangrove restoration as a mitigation action in their NDCs. Ten countries have included seagrass restoration or protection in their NDCs, in five cases specifically as mitigation actions. There are a number of seagrass restoration projects globally. However, they are costly and challenging. For example, the Novagrass eelgrass restoration project in Denmark found that replanting eelgrass from seeds had no success in Danish waters, mainly because of seeds being buried by lugworms too deeply to germinate, seeds being washed away by waves and seedlings being uprooted by drifting macroalgae (Delefosse and Kristensen, 2012; Kuusemäe *et al.*, 2016; Valdemarsen *et al.*, 2010). The project turned to transplanting mature shoots instead, which has led to the successful restoration of several areas of about one hectare each.[16] The number of ongoing seagrass restoration projects globally is hard to estimate, as many efforts go unreported, especially if they are conducted by non-governmental organizations (NGOs) or if the transplanting is unsuccessful.[17] In order for restoration measures to be successful, it is vital to address the factors causing loss and degradation (IPCC, 2019b).

3.3.2 The role of aquatic genetic resources for food and agriculture in mitigating the effects of climate change in aquaculture

Breeding has the potential to increase the productivity, feed-conversion efficiency and health of aquatic organisms and thereby reduce emissions. However, concerted breeding efforts are not widespread to date (see Section 3.1) (Sae-Lim *et al.*, 2017).

Diversified aquaculture systems not only have the benefit of being more resilient to climate change impacts, they can also mitigate some of the negative impacts monocultures have on the environment. Integrated crop–aquaculture production systems, such as the raising of fish in rice fields, have lower greenhouse-gas emissions and have the potential to sequester carbon (FAO, 2017d). Converting 25 percent of the global aquaculture area to integrated aquaculture–agriculture ponds, for instance, has the potential to sequester 95.4 million tonnes of carbon per year (Ahmed *et al.*, 2017).

Integrated multitrophic mariculture, whereby effluents from fish are used as a nutrient source for macroalgae and filter-feeding shellfish, can significantly enhance the resource efficiency of mariculture systems (SAPEA, 2017; Wang *et al.*, 2013). Shell-building aquatic organisms such as mussels bind carbon present in the water into their shells, and therefore contribute to carbon sequestration. However, the carbon sequestration effect may be offset by the greenhouse-gas emissions involved in their production (Aubin *et al.*, 2018).

Another diversified aquaculture system that contributes to climate change mitigation is integrated mangrove–shrimp farming. The system involves integrating shrimp ponds with mangroves rather than clearing mangroves to make way for aquaculture and thereby contributes to carbon sequestration (Ahmed, Thompson and Glaser, 2018). A FAO project that evaluated the carbon footprint of integrated mangrove–shrimp farming compared to other shrimp-farming systems is described in Box 2.

Non-fed aquaculture systems such as oyster and mussel farming are relatively sustainable forms of aquculture and have the additional benefit of tying up carbon in the shells where it is usually retained post-harvest (The Fish Site, 2004). Similarly, natural shellfish reefs can also act as carbon sinks. Many such reefs have been lost as a result of overharvesting, and restoration of these habitats could recreate these carbon sinks, as well as promote biodiversity, improve fishery resources and deliver a range of other ecosystem services (Fodrie *et al.*, 2017).

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[16] Personal communication with Erik Kristensen. For more information, visit https://www.novagrass.dk/en/purpose/

[17] Personal communication with Robert J. Orth.

Where the potential role of aquatic plants grown for food is concerned, one study found that water spinach (*Ipomoea aquatica*) had a lower carbon footprint than other vegetables such as tomato and Chinese cabbage (Yan, Pan and Chen, 2012). Algae can provide up to 15 percent of the protein requirements of farmed fish without compromising growth and feed utilization (FAO, 2009). Most species of aquatic macrophytes have little potential as fish feeds, with the possible exception of duckweed, which has been shown to be a suitable replacement for less-sustainable feeds such as soybean meal (Pullin and White, 2015; Zuberi, Aslam and Nazir, 2017).

Box 2. Integrated mangrove–shrimp farming for blue carbon and blue growth in Viet Nam

Viet Nam is the world's third largest producer of farmed shrimp after China and Indonesia. In the country's southern provinces, production focuses mainly on the intensive and semi-intensive culture of whiteleg shrimp (*Penaeus vannamei*). The rapid development of shrimp aquaculture has come at the cost of the destruction of coastal mangrove forests. The Government of Viet Nam is supporting the diversification of shrimp farming systems and practices to ensure the sustainability of the sector. Integrated mangrove–shrimp farming is an alternative to intensive shrimp monoculture and reduces greenhouse-gas emissions. Although government institutions and non-governmental organizations have been working on different aspects of the practice, there has been lack of coordinated efforts to promote mangrove−shrimp farming and there are knowledge gaps regarding its environmental benefit. FAO implemented a project aimed at improving knowledge of how the carbon balance of integrated mangrove–shrimp systems compares to that of intensive shrimp farming, and to promote the scaling up of integrated mangrove−shrimp farming for blue carbon and blue growth in Bac Lieu and CaMau provinces by improving farming techniques and training extension officers and farmers.

Greenhouse-gas emissions from the different farming systems were calculated using FAO's EX-Ante Carbon-balance Tool (EX-ACT),[18] with data on shrimp production and agricultural and energy inputs obtained from a 2017 survey of 71 households operating integrated mangrove–shrimp systems (extensive systems) in Cà Mau and Bạc Liêu, intensive farming systems in Ben Tre and mixed systems (combining intensive and semi-intensive production) in Bac Liêu.

The intensive and mixed systems were found to emit 5.2 and 6.9 tonnes of CO_2 equivalent[19] per tonne of shrimp production respectively, while the extensive system developed from the conversion of mangrove forests into shrimp ponds was found to emit 86.0 tonnes of CO_2 equivalent per tonne of shrimp production, making it the practice with the highest impact on the environment. The conversion of mudflats to integrated mangrove–shrimp farming, however, sequesters 9.5 tonnes of CO_2 equivalent per tonne of shrimp production. Therefore, integrated mangrove–shrimp production has the potential to transform shrimp aquaculture from a greenhouse-gas source to a sink. These results show the advantage of reconciling shrimp aquaculture and blue carbon conservation in mangrove ecosystems.

The project developed good practices for integrated mangrove–shrimp farming and trained selected coastal communities. The project also supported the development of a national project proposal for upscaling of integrated mangrove–shrimp farming in southern Viet Nam. The project is now working on improving techniques for integrated mangrove–shrimp farming and on building the capacity of farmers and extension officers to scale up the practice.

Source: Based on Miao (2018) and unpubished project documents (TCP/VIE/3502 and LOA.FAVIE.50/2017).

The farming of marine macroalgae (seaweeds), particularly in the tropics, contributes significantly to carbon sequestration (Duarte *et al*., 2017; Mazarrasa *et al*., 2014). Because of their ability to take up CO_2, seaweeds can mitigate the effect of ocean acidification locally, thereby protecting the shells of molluscs from dissolution (Kaladharan, Amalu and Revathy, 2019; Young and Gobler, 2018).

Some macroalgae have the potential to significantly reduce methane emissions from ruminant animals when added to their diets, with one study finding that methane emissions could be reduced by up to 60 percent by replacing 1 percent of the organic matter in the diet of dairy cows with macroalgae of the genus *Asparagopsis* (Roque *et al*., 2019). However, most studies to date have been conducted *in vitro*,

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[18] http://www.fao.org/tc/exact/ex-act-home/en/

[19] A CO_2 equivalent is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential, by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential. For more information, see https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Carbon_dioxide_equivalent

and *Asparagopsis* is not yet commercially produced on a large scale (Wozniacka, 2019). In spite of their significance as sources of human food, biofuels, pharmaceuticals and feed ingredients in aquaculture, production of farmed seaweeds is often not included in regular reporting to FAO (FAO, 2019c).

Biofuels can play an important role in the transition from fossil fuels to renewable energy sources. Microalgae are promising as biofuel sources as they grow quickly, have a high oil content and do not compete with food production the way land-based biofuel sources may do (Chye *et al.*, 2018). Because of the high costs of microalgal cultivation and harvesting, large-scale commercialization of algal biofuels is not economically feasible at present, but various methods of genetic editing and biorefining are being investigated (Lin *et al.*, 2019; Ziolkowska, 2020). Macroalgae production for biofuel is at an early stage of development, and many important parameters, such as the carbon balance and the cost of the produced fuel, have not yet been adequately assessed (Laurens, Chen-Glasser and McMillan, 2017). Algal production for biofuel is not considered by FAO to be a use of AqGR, and therefore the topic is not currently included in its work on AqGR.

In their NDCs, countries do not refer to the farming of microalgae or macroalgae or to the restoration of algal ecosystems such as kelp forests as a mitigation option. In summary, mitigation actions involving AqGR in aquaculture are mostly centred around aquatic plants including as component in integrated multitrophic aquaculture (IMTA) systems.

3.4 Conclusions and recommendations

AqGR are heavily affected by climate change, which in certain cases impairs their ability to provide ecosystem services. Although AqGR have the potential to significantly contribute to climate change adaptation and mitigation, aside from a few exceptions, they are to date not consistently managed to support adaptation and mitigation efforts. Given the tremendous importance of marine ecosystems as carbon sinks, their protection and restoration should be a high priority. While there are considerable efforts around the world to adapt and restore marine ecosystems, these measures are likely to be insufficient if global warming exceeds 1.5 °C and the drivers behind climate change are not addressed.

The impacts of climate change on AqGR are overwhelmingly negative, with rising temperatures, changing rainfall patterns and the increasing occurrence of extreme events being the most prominent threats. These changes in climate in turn have an impact on the range and incidence of pests and diseases. This has already had devastating effects on some AqGR and is expected to be an increasing threat in the future.

There has been a lot of research on the effects of climate change on AqGR at ecosystem or habitat level, in particular with regard to coral reefs. The impact of climate change has also been studied for some commercially relevant species. Knowledge of the impacts of climate change on AqGR is constantly increasing, but there are still knowledge gaps, as many countries do not assess the impact of climate change on aquatic species.

While mobile aquatic organisms may have the option of adapting to climate change by altering their range, sessile organisms such as corals and seagrasses do not have this option. The degradation of the aquatic ecosystems associated with these species in turn affects capture fisheries, as they provide habitat and breeding grounds for many commercially relevant species.

The *in situ* and *ex situ* conservation of AqGR is not carried out systematically, and needs to be expanded and complemented with characterization efforts, in particular regarding traits that can support adaptation to and mitigation of climate change, such as feed efficiency, temperature tolerance and disease resistance. While a number of countries mention the protection of marine and blue carbon ecosystems in their NDCs, only one country mentions *ex situ* conservation of fish sperm for breeding.

Breeding of AqGR, both plants and animals, is still in its infancy, and the traits targeted relate to optimizing production, for example faster growth rate and higher resource-use efficiency. In the case of aquatic animals, there are a few isolated examples of breeding targeted at increasing resistance to pests and diseases, some of which have increased or may increase in range or severity due to climate change, but adaptation to climate change is not commonly considered a key objective of breeding programmes.

Further research is needed to identify the genetic mechanisms responsible for these traits, and research findings need to be translated into action by establishing breeding programmes. Compared to terrestrial crop and livestock genetic resources, AqGR have the advantage of still having very high genetic diversity, and thus provide an ideal basis for genetic improvement. There is a need for long-term funding for breeding programmes and to develop breeding capacity, in particular in developing countries.

The vast majority of adaptation and mitigation measures involving AqGR are happening at ecosystem level. While there are a number of adaptation measures that include aquatic animals, mitigation measures focus almost exclusively on aquatic plants, with mangroves being the most prominent.

There is an urgent need to scale up mitigation efforts such as replanting of mangroves and seagrasses, and to promote sustainable aquaculture practices such as agri-aquaculture, integrated mangrove–shrimp farming and IMTA. Promoting carbon sequestration in blue carbon ecosystems, including through seagrass restoration and seaweed and microalgae production, has received little attention on the global policy agenda. Further research is needed to develop best practices and scale up restoration and production efforts.

The information system currently being developed by FAO’s Fisheries and Aquaculture Department as part of the follow-up process to SoW-AqGR provides a unique opportunity to include information on traits relevant to climate change adaptation and mitigation, and thereby collect comprehensive information on the AqGR held by member countries. The information system will also highlight knowledge gaps in terms of characterization and provide the opportunity to address them.

IV. FOREST GENETIC RESOURCES

4.1 Introduction

Forest genetic resources (FGR) are heritable materials maintained within and among trees and other woody plant species. They are crucial for the adaptation and the evolutionary processes of forests and trees, as well as for improving their resilience and productivity (FAO, 2014a). Forests provide a broad range of ecosystem services and harbour the majority of terrestrial biodiversity. Trees and other woody plants provide wood, fibre, fuel and foods that contribute to the livelihoods food security and nutrition of hundreds of millions of people. Other services they provide include air-quality regulation, climate regulation, natural-hazard regulation and water purification (FAO, 2019a).

Forest trees have high intraspecific genetic diversity, which can support their ability to adapt to climatic change. Forests, in fact, could provide over one-third of the cost-effective climate mitigation needed between now and 2030 to stabilize warming to below 2 °C (Griscom, 2017). What sets trees and forests apart from other species and ecosystems in climate change mitigation is that their potential to sequester carbon is already being realized by a number of countries around the world through tree planting and improved forest management.

Climate change is altering the frequency and intensity with which forests are affected by disturbances such as insect outbreaks, wildfires and storms. Greater incidence of intense cyclones, extreme droughts, fires and flooding due to increased rainfall has been observed in tropical forest ecosystems, but also in some temperate forests (FAO, 2014a). Successful adaptation and mitigation of climate change depends on proactive FGR management (Joyce *et al.*, 2018).

4.1.1 The impact of climate change on forest genetic resources

Predictions regarding the impact of climate change on forests and trees on farms vary. Though some authors consider that many trees have sufficient phenotypic plasticity and genetic diversity at the population level to withstand the negative effects of climate change, others predict severe impacts (Loo *et al.*, 2011, citing Hamrick, 2004; Mátyás, Vendramin and Fady, 2009; Rehfeldt *et al.*, 2001). Recent evidence suggests that, for a wide range of forest systems, warming and changes in precipitation are increasing tree mortality. Many areas have experienced declines in productivity due to heat stress, drought stress and pest outbreaks (FAO, 2015d). Current indications point to signs of climate stress, changes in fire regime, insect outbreaks and pathogen attacks (Settele *et al.,* 2014). The species composition of forests affects their ability to adapt to climate change, as tree species differ in their vulnerability (Sáenz-Romero *et al.*, 2019). If trees do not migrate sufficiently quickly in response to climatic changes, the consequent higher mortality rates and reduced gene pool may increase inbreeding in the surviving trees. The expected impacts of climate change on forests are likely to vary across regions and sites, from abrupt negative impacts to more subtle negative or positive impacts (FAO, 2014a).

New distribution ranges of tree species are difficult to predict, as data on both current distribution and future climatic conditions are required in order to make reliable predictions. There are reliable data on current species distributions in locations such as Europe, but assessing species distribution is often very difficult in tropical countries (Loo, 2016). The higher number of species, frequent changes in land use and already occurring impacts of climate change make spatial analyses and the prediction of changes in distribution ranges more difficult in these countries.[20]

Climate change will alter the distribution ranges of forest species, leading to expansion of the ranges of some species and reduction of those of others. Tree species' ranges in temperate regions are likely to shift towards the poles and higher elevations as a result of increasing temperature, while in the tropics, changes in precipitation will impact tree distribution (FAO, 2015a). In Australia, for example, climate change is expected to lead to changes in the range of different forest ecosystems, such as encroachment of rain forest into eucalypt woodlands and the establishment of trees in subalpine meadows (FAO, 2019d). Changes in temperature and precipitation may also alter the species composition of forests, and

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[20] Personal communication with Christopher Kettle, Bioversity International.

lead to divergences between the flowering periods of trees and the active periods of pollinator species, in turn limiting gene flow and reducing the size of tree populations, leaving them more vulnerable to the effects of climate change (ibid). Rising temperatures at high latitudes will lead to the thawing of permafrost and increase the disturbance of boreal forests by biotic stresses such as pests and diseases and abiotic stresses such as drought and fire (IPCC, 2019a).

Rising sea levels are threatening an increasing number of coastal forests (Fagherazzi *et al.*, 2019). Sea level rise and the intrusion of saline water influence the species composition of coastal forests, with the largest species shifts happening in the understory (Ogurcak *et al.*, 2019). In extreme cases, forests may not be able to adapt and may become ghost forests, stands of dead trees surrounded by marshlands (Kirwan and Gedan, 2019).

The frequency and magnitude of storms are expected to increase due to climate change and constitute a key driver of the destruction of forests (Gutmann *et al.*, 2018; Hall *et al.*, 2020). Although mangrove forests play an important role in protecting coasts from storms, flooding and erosion, studies suggest that they will also be impacted by sea level rise, leading to changes in their species composition and a reduction in their range (Ghosh, Kumar and Roy, 2017; Ghosh, Kumar and Kibet Langat, 2019; Mafi-Gholami, Zenner and Jaafari, 2020). Differential abilities to withstand storms and salinity are found more commonly across rather than within species, but the possibility of intraspecific selection needs to be further explored (Alfaro *et al*., 2014).

The ranges of forest pests and diseases are expected to shift, and climate-induced stress will leave trees more susceptible to infestations (FAO, 2015a). Increases in temperature can be expected to increase the ranges of some pests, thus exposing a larger area of forest to their effects (Bentz *et al.*, 2019). In Canada, for example, mountain pine beetle (*Dendroctonus ponderosae*) outbreaks have been linked to warmer winters, which reduce the pest's mortality rate (Natural Resources Canada, 2020a). Increases in mean annual temperatures of 1 to 4 °C will significantly increase the risk of outbreaks in high-latitude and high-elevation regions of Canada (Sambaraju *et al.*, 2012).

Increasing winter temperatures also facilitate the spread of invasive alien species. For instance, a study that modeled the potential range of the Asian longhorned beetle (*Anoplophora glabripennis*) − a pest of deciduous trees that is invasive in North America and Europe (Canadian Food Inspection Agency, 2020) − in future climates in Canada found that a large part of eastern Canada is likely to become suitable for the species, and that outbreaks will have severe economic impacts on the timber and maple-product industries (Pedlar *et al.*, 2019). The Asian longhorned beetle, along with the citrus longhorned beetle (*A. chinensis*), is also expected to spread through the Nordic countries as temperatures increase (Sjöman and Östberg, 2019).

Extended periods of drought will continue to exacerbate forest fires in dry forested regions such as those of Africa, Asia, Australia, North America, Latin America and southern Europe (Dupuy *et al.*, 2020; FAO, 2019d; IPCC, 2014b; Ruffault *et al.*, 2020; Strydom and Savage, 2017; Wang *et al.*, 2019). In Italy, for example, high temperatures and water stress due to low rainfall are expected to lead to higher incidence of forest fires across the country, with the worst impacts occurring in the centre and south, where the burnt area is projected to increase by 75 percent (Michetti and Pinar, 2019). Increased incidence of forest fires can lead to population isolation, and over time may affect genetic diversity, a process that can be exacerbated by the direct effects of climate change on tree fertility (Aravanopoulos and Alizoti, 2019)

Spatial modelling with geographic information system (GIS) mapping tools is increasingly used to monitor changes in forest area in order to examine the vulnerability of forests to the impacts of climate change. Based on such tools, Vinceti *et al.* (2013) calculated the future range of *Prunus africana*, a widely distributed but ecologically restricted species found in all of the Afromontane regions. The study found that, by 2050, the climate in about half of the current distribution range will become unsuitable for the species.

A study in Burkina Faso modelled the impact of various threats on food tree species and found that while overexploitation and cotton production are the most severe short-term threats, climate change will be the worst long-term threat (Gaisberger *et al.*, 2017). The study results enable decision-makers to take actions at the level of tree populations; recommendations include collection of seeds from the most threatened populations to ensure that they are not lost and can thus be used to maintain species' genetic diversity across their distribution ranges (ibid.).

Different tree species within the same area may be affected to different degrees by climate change. For example, the area suitable for sal (*Shorea robusta*), an economically important dipterocarp in South and Southeast Asia, is projected to decline by between 24 and 34 percent by 2070, while the area of garjan (*Dipterocarpus turbinatus*) is projected to decline by between 17 and 27 percent (Deb *et al.*, 2017). The main factor impacting the suitable area for these species was found to be precipitation (ibid.). Climate models can thus help inform conservation and management decisions.

Molecular studies can be used to complement field trials, which are lengthy and costly. For example, microarray analysis conducted by Perdiguero *et al.* (2013) on two Mediterranean pine species detected 113 drought-induced genes, including genes involved in the synthesis of abscisic acid, transcriptional regulators of drought-inducible pathways, and genes involved in late embryogenesis abundant protein synthesis. Shifts at such loci have been linked to global warming (ibid.).

4.1.2 Characterization, evaluation, monitoring and conservation of forest genetic resources

In order to understand the adaptation of forests to climate change, FGR need to be characterized both in terms of species distribution ranges and in terms of specific traits (FAO, 2017d). Identifying forests, species or populations with high genetic variety is crucial for the planning of tree breeding and of *in situ* and *ex situ* conservation measures (FAO, 2014a).

Provenance trials have been used to analyse the variation in traits related to the growth, physiology and phenology of seeds from different origins (FAO, 2017d). Some provenances within a given species may be better adapted than others to dry or humid environments, and therefore data from such trials can be used to choose the ideal seed source for a specific location and for the development of seed transfer guidelines (Adu-Bredu *et al.*, 2019).

Forest genetic monitoring can play an important role in identifying diversity losses and is crucial for successful conservation planning. Monitoring should include field measurement of growth traits and recording of the number of reproductively mature trees, seed quality and phenotypic traits crucial for reproduction and growth (Fussi *et al.*, 2016). Genetic monitoring also provides data on the effects of different forest management systems and conservation programmes (Kavaliauskas *et al.*, 2018).

Climate change also has implications for the conservation of FGR. Examples of *in situ* and *ex situ* conservation measures are shown in Table 2. Protected areas and conservation stands that are commonly used as *in situ* conservation sites will be impacted by climate change, and therefore conservation planning needs to take into account the implications of different climate change scenarios for the suitability of particular species for particular areas, and shift protected sites if necessary. In Europe, countries have established conservation stands for so-called "dynamic gene conservation"; a study found that by 2100 up to 65 percent of such stands will face conditions outside their climatic ranges (Schueler *et al.*, 2014). Seeds of threatened populations at the border of species' distribution ranges need to be collected and conserved *ex situ* before they go extinct locally in order to maintain the genetic diversity of the species (Gaisberger *et al.*, 2017).

The *ex situ* conservation of species that have orthodox seeds (seeds that remain viable if dried and stored at low temperature) is relatively straightforward, as the seeds can be kept in a seed bank. However, many forest species produce recalcitrant or intermediate seeds that do not cope well with desiccation and low temperatures. *Ex situ* conservation of these species therefore needs to be done in field gene banks, where, like in *in situ* conditions, they are vulnerable to the impacts of environmental factors such as those associated with climate change (FAO, 2017d). While *ex situ* collections are important in providing a backup of genetic diversity, they do not allow for the evolution or adaptation of germplasm to a changing climate. It is therefore necessary to consider climate change in both *in situ* and *ex situ* conservation.

Table 2. Types of conservation practices of FGR

<table>
<tr><th>In situ</th><th>Ex situ</th></tr>
<tr><td>Seed stands</td><td>Seed orchards</td></tr>
<tr><td>Protected areas (national parks, protected forests, conservation reserves, conservation units, ecoparks, etc.)</td><td>Field collections</td></tr>
<tr><td>Natural populations of tree species</td><td>Human-made conservation populations of tree species</td></tr>
<tr><td></td><td>Botanical gardens</td></tr>
<tr><td colspan="2">Cross-sectoral conservation programmes and initiatives (community-based, national, cross-border and international)</td></tr>
</table>

The regional networks APFORGEN (Asia Pacific Forest Genetic Resources Programme), EUFORGEN (European Forest Genetic Resources Programme), LAFORGEN (Latin American Forest Genetic Resources Network) and SAFORGEN (Sub-Saharan African Forest Genetic Resources Programme) promote the conservation and sustainable use of FGR and also consider emerging threats such as climate change.

EUFORGEN, for example, developed minimum requirements and data standards for genetic conservation units of forest trees across Europe that were used for creating EUFGIS (European Information System on Forest Genetic Resources), a georeferenced information system on the conservation of FGR in Europe (Koskela *et al.*, 2013). The data are provided and frequently updated by national focal points (ibid.).[21] The LIFEGENMON (Life for European Forest Genetic Monitoring System) project,[22] further developed genetic monitoring in European forests. In addition, the FORGER project, implemented from 2012 to 2016, aimed to integrateg and extendexisting knowledge to provide science-based recommendations on the management and sustainable use of FGR for European Union policy-makers, national stakeholders, forest managers and managers of natural areas.[23] Another European project, GenTree, was implemented from 2016 to 2020 and focused on developing tools and methods for FGR conservation and gaining a better understanding of how trees adapt to their environments (GenTree, 2016). Among other things, the project collected dendrochronological data that can be used to predict adaptability under different climate change scenarios (Martínez-Sancho *et al.*, 2020). While collection of data on the impacts of climate change in Europe is relatively well developed, there are still data gaps with regard to phenotypic plasticity, dispersal capabilities and physiological responses (Ruiz-Benito *et al.*, 2020).

There is a mismatch between the urgent need to collect, characterize and use FGR and the capacity available to do so. A review of tree seed systems in Asia, Africa and Latin America found that many countries lack capacity in terms of markets, technical information and access to high-quality germplasm (Nyoka *et al.*, 2015). In most countries, the importance of using high-quality tree germplasm is not sufficiently appreciated, and there is a need to raise awareness among farmers and policy-makers (ibid.). A study in Mexico found that the conservation, characterization and use of FGR for four species of Mexican pines were inadequate and that long-term efforts to develop FGR conservation were limited, mainly because forest tree species were not included in the main national conservation programme (Flores *et al.*, 2019). Both *in situ* and *ex situ* conservation approaches of FGR are playing vital parts in climate change mitigation, although their full potential is not yet being fully realized.

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[21] For more information, visit http://portal.eufgis.org/

[22] For more information visit http://www.lifegenmon.si/

[23] For more information visit https://cordis.europa.eu/project/id/289119

4.2 Adaptation

Trees are long-living organisms with high genetic variability in adaptive traits and can grow under a broad range of environmental conditions. Gene flow in wind-pollinated tree species can occur over more than 100 kilometres (FAO, 2017e). Drought tolerance, cold hardiness and resistance to pests and diseases are adaptive traits of considerable research interest and have been shown to vary across eco-geographic gradients (Alberto *et al.*, 2013).

Three natural phenomena influence the adaptation of forest ecosystems and forest genetic resources to climate change: migration, natural selection and genetic drift (Alfaro *et al.,* 2014 citing Futuyma, 2010, Kremer *et al.*, 2012 and Savolainen *et al.,* 2011). The pace of climate change may outstrip the capacity of natural selection to give rise to genotypes that are adapted to prevailing climatic conditions. If this happens, and populations are unable to migrate, extinctions will occur (Alfaro *et al.*, 2014).

Climate models can predict broad regional and national patterns of climate change with a degree of certainty, but making predictions at local level is difficult (FAO, 2015d). Forest resources are generally managed on medium- to long-term cycles in which the ability to make rapid changes is constrained, and this adds to the challenge involved in planning adaptation actions (ibid.).

Adaptation and conservation of forest genetic resources can be approached at three levels: genetic, species and ecosystem. With regard to the latter, climate change may result in a decrease in genetic and species diversity within a given ecosystem. Such changes are difficult to predict and have the potential to significantly decrease productivity (Alfaro *et al.,* 2014 citing Thornley and Cannell, 1996 and Wang *et al.*, 2012).

In areas where climate change leads to increased seasonality, as predicted to occur in the Mediterranean and Neotropics, for example, multidirectional selection pressure may mean that adaptation through natural selection becomes less efficient (Alfaro *et al.,* 2014 citing Jump and Peñuelas, 2005). Genetic diversity may not be wide and rich enough to allow the required changes to occur, and the loss of ecosystem functions may be inevitable (Mooney *et al.*, 2009).

Field trials relevant to climate change adapatation have been conducted mainly in boreal and temperate species and in some commercially important tropical species (Alfaro *et al.,* 2014 citing Aitken *et al.*, 2008 and Alberto *et al.*, 2013). However, relatively recent years have seen the inclusion of a broader range of tropical species, including several indigenous African fruit trees that have traits that are of considerable importance for climate change adaptation (Alfaro *et al.*, 2014). The information obtained from such studies will enhance breeding and afforestation programmes among African smallholders, enabling them to obtain appropriate types of forest reproductive materials for local use (Alfaro *et al.*, 2014 citing Sanou *et al.*, 2007).

Epigenetic effects are genetic alterations induced by environmental changes that do not alter the DNA sequence directly but can lead to changes in gene expression and thus influence how species respond to environmental changes (Loo, 2016). Recently, epigenetic phenomena have been recorded in some tree species, mostly conifers. In Norway spruce (*Picea abies*), the temperature during embryogenesis was found to influence the expression of genes responsible for the timing of bud burst (Carneros *et al.*, 2017; Yakovlev *et al.*, 2014). Epigenetic effects may help tree species to produce seeds that are adapted to new climatic conditions, and therefore to adapt within one generation.

Tree species can have a variety of adaptation strategies. A study of *Syzygium guineense* and closely related species in the Zambesian Floristic Region of south−central Africa found that the species adapted to drought stress in three different ways: retreat to wet refugial sites; occupation of high-disturbance habitats that require high phenotypic plasticity and hardiness; and avoidance of lethal disturbances by growing underground (Zigelski *et al.*, 2019). The study found weak genetic differentiation between different phenotypes and ecotypes in spite of their morphological and ecological differences (ibid.). As the fruits and leaves of *Syzygium guineense* are eaten as famine foods in seasons of food shortage, its adaptability can contribute to food security (Guinan and Lemessa, 2000).

4.2.1 Management of FGR for climate change adaptation

Various results from field experiments suggest that, in the past, a balance between divergent selection across contrasting sites and reproductive contact has sustained enough genetic diversity to support adaptation to changing environments (Kremer *et al.* 2010, cited in Alfaro *et al.,* 2014). It has been demonstrated that maintaining high genetic diversity within and among tree populations can increase ecosystem resilience, especially when trees are keystone species (Barbour *et al.*, 2009). Forest restoration projects could choose to encourage adaptation to rapidly changing conditions by admixing individuals from different populations to create new genetic combinations, although this would lead to substantial risk of outbreeding depression (North *et al.*, 2011; Breed *et al.*, 2013).

Information from old provenance trials can be reinterpreted in the context of climate change (Alfaro *et al.,* 2014 citing Aitken *et al.*, 2008 and Alberto *et al.*, 2013). Provenance trials can provide a range of data on the variation in quantitative traits such as frost hardiness, bud burst and bud set in a species' gene pool across variable environmental conditions. For example, southern provenances of Scots pine have been found to be better adapted than northern provenances to drought conditions (Seidel, Matiu and Menzel, 2019). Creating species distribution models can be highly useful in the selection of potential seed sources, particularly if complemented with genetic characterization data from the source populations (Thomas *et al.*, 2014 citing Soldati *et al.,* 2013, Azpilicueta *et al*., 2013).

In managed forests, efforts can be made to adapt to the threats of climate change. Increasing storm frequency in the Pacific region due to climate change has led to efforts to identify cyclone-resistant species such as *Endospermum medullosum* for large-scale planting. In Vanuatu, for example, the establishment of 20 000 ha of plantations of this species by 2034 has been planned (Alfaro *et al.*, 2014b). Planting or managing coastal forests as "bioshields" that can break the velocity of waves and wind during moderate storms can contribute to the protection of coastal communities (Jaisankar, Velmurugan and Swarnam, 2018).

Assisted migration, in other words the movement of species and populations to areas where current and predicted future climatic conditions better meet their needs, can contribute to the adaptation of forests to climate change (FAO, 2015a). For example, using seed sources from a region in the south of a planting site (in the Northern Hemisphere), or from a lower elevation in the case of mountainous regions, for reforestation ensures that the newly planted trees will be adapted to warmer climates (Alfaro *et al.*, 2014).

In Canada, many provinces have adapted seed transfer guidelines to account for future changes in climate and support assisted migration (Natural Resources Canada, 2020b). However, although it is considered important by experts, assisted migration is not yet widely practised and would require new approaches to international transfer of tree germplasm.

In developing countries, where official seed distribution channels may not have been established, community-based forest seed banks can contribute to the supply of locally adapted seeds. An FAO Action Against Desertification project in Téra, northwestern Niger, trained farmers in forest seed collection and the production of seedlings from native species. This enabled farmers to restore degraded land, as well as to gain an income from selling seeds to non-governmental organizations and other institutions for their own restoration efforts. Between 2016 and 2019, the union of 446 farmers sold 18 000 kg of quality seeds from over 20 native forest species in Niger and the neighboring countries of Burkina Faso, Chad and Nigeria, generating revenue of USD 140 700 (FAO, 2019g). As climate change can be a driver of land degradation, such initiatives can be an important tool in climate change adaptation.

4.2.2 The use of forest genetic resources for climate change adaptation in the nationally determined contributions

The majority of countries (about 88 percent) that submitted NDCs mention forestry as a sector of importance to climate change adaptation. Countries refer to sustainable forest management practices such as the reduction of deforestation and the preservation of forests as carbon sinks, the restoration of degraded forest ecosystems and the establishment of protected areas (FAO, 2016).

A significant number of countries prioritize afforestation and reforestation measures for climate change adaptation, with a particular focus on the use of drought-tolerant or native species for planting. Malawi, Mexico and Somalia, for instance, all promote afforestation using indigenous or native species for adaptation.

A number of countries mention the use of mixed-species systems, such as agroforestry**,** as a risk-management practice that favours adaptation to climate change. In India, for instance, agroforestry will help to mitigate the risk of soil erosion in hilly areas, and protect mountain biodiversity, during extreme climatic events.

Some countries mention the protection of FGR as a priority for climate change adaptation. Nepal, for instance, plans *ex situ* conservation measures for threatened forest species. Burkina Faso refers to the creation of forest biodiversity conservation areas in cooperation with grassroots communities.

Some countries refer to the conservation or planting of mangroves for coastal protection and erosion control. Djibouti, for example, mentions that the rehabilitation of mangroves will enhance their role as a shield for coastal protection against the tides. Papau New Guinea, Samoa and Vanautu, similarly, all call for the establishment of mangrove forest buffer zones to protect climate-sensitive coastal ecosystems.

A few countries note the importance of selecting suitable provenances. Tonga, for example, mentions the promotion of reforestation and rehabilitation of cleared and degraded forests with climate change resilient, ecologically and socially appropriate tree species.

A number of countries make explicit reference to the potential for synergies between climate change adaptation and mitigation through forest conservation and management. Antigua and Barbuda, for example, promote the protection of wetland forests for carbon sequestration and for mitigation of floods and storm surges. El Salvador promotes landscape restoration efforts that both establish biological corridors and reduce the carbon footprint of agriculture through the adoption of agroforestry.

Several countries also reference the social, economic and environmental co-benefits of climate change adaptation and mitigation measures such as sustainable forest management. Cameroon, for instance, notes that sustainable forest management will create jobs and provide environmental and health benefits (FAO, 2016).

4.2.3 Tree breeding programmes

Like the breeding of aquatic species, tree breeding is relatively new compared to crop and livestock breeding. Tree breeding differs from crop breeding in that it aims to gradually improve breeding populations rather than to create new varieties (FAO, 2017d). Because of the long generation times of trees, traditional tree breeding is a lengthy process. In order to generate offspring with desirable traits and wide usage, tree breeding programmes typically use multiple breeding populations. Nowadays, most breeding programmes use molecular techniques, such as marker assisted selection, fragment analysis or microarray, which can identify offspring with traits important for commercial usage, such as straight trunk, large coppice surface and high biomass.

About 30 tree species have been studied intensively, tested and bred for increased wood production, improved quality and/or resistance to pests and diseases (Neale and Kremer, 2011; Yanchuk and Allard, 2009). Using a conventional breeding approach, *Picea sitchensis* genotypes with resistance to the white pine weevil were screened and deployed in reforestation programmes (Alfaro, King and VanAkker, 2013). In the United States of America, the resistance of *Pinus taeda* to fusiform rust has been increased considerably by breeding (McKeand, 2019).

4.3 Mitigation

Forests play a crucial role in sequestering carbon from the atmosphere and thus mitigating the effects of climate change. Increasing global forest cover has the potential to reduce the atmospheric carbon pool by 25 percent (Bastin *et al.*, 2019). There is limited evidence of enhanced tree growth due to CO_2 fertilization, and therefore it is unlikely that this effect will contribute to climate change mitigation (Gedalof and Berg, 2010).

Afforestation and reforestation are mentioned in the IPCC special report *Climate Change and Land* as an option for land-based CO_2 removal, as they result in long-term carbon storage in above- and below-ground plant biomass in previously unforested areas (IPCC, 2019a; Minx *et al.*, 2018; Smith *et al.*, 2016).

Successful reforestation efforts require not just testing of seed sources but also testing of the seeds' genetic diversity, as ideally the composition of planting stock should have high genetic diversity (Bessega *et al.*, 2019).

Forest dieback due to climate change negatively affects forests' potential to mitigate climate change (Mokria *et al.*, 2015). Because of the slow growth of trees, mitigation projects need to consider not just current climate change impacts but also those occurring over several decades. Seed or other reproductive material must be selected from seed sources where the present climate is similar to the climate that the area in question will face in 20 to 50 years time.

4.3.1 Reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries (REDD+)

Reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries (REDD+) is a voluntary mechanism of the UNFCCC that supports countries' efforts to enhance the forestry sector's role in climate change mitigation. It is intended as a means of reducing greenhouse-gas emissions by slowing, halting and reversing forest loss and degradation and increasing the removal of greenhouse gasses from the Earth's atmosphere through the conservation, management and expansion of forests. It involves work with various stakeholders to ensure that individual projects reflect the needs of forest-dependent communities while developing the forestry sector in a sustainable manner.

The key components of REDD+ are the preparation of a national REDD+ strategy and the establishment of reference levels of CO_2 emissions from forestry, monitoring (measurement, reporting and verification) of actions and results-based payments for enhanced carbon stocks (UNFCCC, 2014). Actions under REDD+ include the enhancement of forest carbon stocks by means such as sustainable forest management, the afforestation of land not previously forested and the reforestation of land previously converted from forest to other land uses (Global Forest Observations Initiative, 2013).

FAO provides technical support to countries in Africa, Asia and the Pacific and Latin America and the Caribbean in formulating REDD+ actions, implementing them and monitoring and reporting results (FAO, 2020f). Carbon stocks are generally estimated through a combination of remote sensing and ground-based observations on the basis of species-specific carbon estimates (Global Forest Observations Initiative, 2013; Pandey *et al.*, 2016).

Twenty countries (about one-third of the submitting countries) mention conserving or improving biodiversity as a thematic area in their national REDD+ strategies.[24] The strategies touch upon various aspects of biodiversity.

A few strategies mention the establishment of protected areas for biodiversity conservation. The strategy of Indonesia, for example, gives priority to forests and peatlands with high carbon stocks and high biodiversity for the establishment of protected areas. The strategy of Argentina has the objective of promoting the creation of new protected areas in biodiversity hotspots where there are currently no conservation measures.

Some strategies target the development of policies for improving the management of biodiversity. The strategy of Malaysia, for example, aims to create awareness among the general public about the value of biodiversity by 2025 and to formalize the role of indigenous communities as custodians of biodiversity through policy and legal provisions by 2021. The strategy of Peru emphasizes the creation

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[24] Argentina, Brazil, Cambodia, Chile, Colombia, Ecuador, Ethiopia, Ghana, India, Indonesia, Liberia, Malaysia, Myanmar, Papua New Guinea, Paraguay, Peru, Philippines, Sri Lanka, Viet Nam and Zambia. Viet Nam did not submit a strategy, but a safeguards report.

of multisectorial policies and programmes for landscape management with the aim of conserving biodiversity hotspots.

A few strategies note the economic value of biodiversity. For example, the safeguards report of Viet Nam mentions the importance of forest biodiversity conservation to tourism and notes the need to provide monetary and non-monetary incentives for the protection of forest ecosystem services. The strategy of Sri Lanka states that research areas to be considered include "recognition of biodiversity and ecosystem services and demonstration of their economic value".

Although these countries consider biodiversity in their REDD+ strategies, they do not specify the extent to which biodiversity and genetic diversity are considered in reforestation efforts.

4.3.2 The use of forest genetic resources for climate change mitigation in the nationally determined contributions

Over three-quarters of all countries describe the use of FGR as being key to the achievement of the national greenhouse-gas emission targets communicated in their NDCs. A large number of developing countries also reference forest-specific mitigation measures in their NDCs, probably because of the potential to generate climate change adaptation and sustainable development co-benefits for local ecosystems and communities.

Afforestation and reforestation are mentioned by many countries, particularly in sub-Saharan Africa. Malawi, for example, mentions natural and assisted natural forest regeneration. Côte d'Ivoire promotes incentive schemes, such as payment for ecosystem services, to encourage village reforestation and conservation of natural forests. In Timor-Leste, there are plans to promote natural regeneration and customary forestry practices such as "Tara Bandu".[25]

Reducing forest degradation and promoting sustainable forest management play central roles in national climate change mitigation efforts in a large number of NDCs, particularly in South Asia. For instance, Bhutan mentions the establishment of community and homestead forests of species with high forage and soil conservation value using participatory strategies with local peoples.

Many countries, particularly in Latin America and the Caribbean, also mention the reduction of deforestation and promotion of forest conservation. Uruguay, for instance, calls for the protection of native forests and avoidance of further losses.

A number of countries in Africa, Asia, Latin America and the Caribbean and the Pacific mention agroforestry as a mitigation action. Saint Lucia, for example, plans to implement an extension programme to enhance farmers' knowledge and skills related to agroforestry and undertake studies that will help to ensure the productivity and profitability of agroforestry projects.

Twenty-four countries refer to REDD+ strategies that reflect the use of FGR for mitigation actions in their NDCs.

4.3.3 Restoration and sustainable forest management

Conversion of forests to other land-uses, illegal logging and overharvesting of forests lead to greenhouse-gas emissions and can affect the regional climate (IPCC, 2019a). Sustainable forest management can therefore significantly contribute to a reduction in greenhouse-gas emissions. Improved forest management also has a large potential for climate change adaptation (Buckwell *et al.*, 2019; IPCC, 2019a).

In order to be successful, restoration efforts need not only to use suitable species but also to use suitable provenances that can be expected to thrive in current and future climates. Planting a variety of suitable provenances can help ensure that a forest will survive in spite of unpredictable changes in climate.

Selection of an appropriate sources of forest reproductive material for restoration measures should ideally be guided by growth performance studied using multilocation progeny or provenance trials and

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[25] "Tara Bandu" is a traditional Timorese custom that enforces peace and reconcilitation through the power of public agreement (Belun/The Asia Foundation, 2013).

climate modelling. Provenance tests can help identify tree populations that are adapted to a particular site and the range within which the reproductive material of a species can be transferred (Sgrò, Lowe and Hoffmann, 2011).

Various guidelines and tools have been developed to support restoration efforts. For example, the Society for Ecological Restoration's Standards for Ecological Restoration[26] specifically refer to the importance of considering genetic diversity in the context of restoration.

Vulnerability assessments and modelling studies can help guide the selection of suitable species and provenances and the identification of priority actions for sustainable forest management and restoration (Meybeck, Rose, and Gitz, 2019; Fremout *et al.*, 2020). Such models can be developed into applications that can be used by practitioners for decision-making: Bioversity International's Diversity for Restoration platform[27] is an online tool that assists decision-making on the use of appropriate tree species and seed sources for tree-based restoration or other tree-planting activities in specific areas (Bioversity International, 2020). The tool considers the local climate, and parameters such as the restoration objectives, the number of species to be planted and various climate change scenarios can be selected in order to determine ideal species and provenances. It currently allows selection of species for specific regions in Latin America, and will be further developed to make it useable on a global scale. Similar methods have been developed in other countries, for example Canada, Switzerland and the United Kingdom (Forest Research, 2020; Province of British Columbia, 2020; Tree App, 2020). Bioversity International, ETH Zürich and the CGIAR Research Program on Forests, Trees and Agroforestry (FTA) have developed SeedIT,[28] a mobile phone application for the tracking, management and diversification of seed collection (SeedIT, 2020).

4.3.4 Agroforestry

Agroforestry refers to production systems in which trees or shrubs are grown together with crops or livestock in the same land unit. Aside from providing economic stability through the diversification of species and products and contributing to food security and biodiversity conservation, agroforestry significantly contributes to climate change mitigation (IPCC, 2019a; Newaj, Chaturvedi and Handa, 2016). Agroforestry systems are estimated to contribute to mitigating 27 ± 14 t CO_2 equivalents per hectare per year (IPCC, 2013; Kim, Kirschbaum and Beedy, 2016).

Improved soil structure and increased plant cover in diversified farming systems further reduce CO_2 emissions because of lower rates of soil erosion (IPCC, 2019a). An analysis by Muchane *et al.* (2020) found that agroforestry can reduce soil erosion by 50 percent compared to crop monocultures, thanks to higher water infiltration rates, lower run-off and greater stability of the soil structure. Soil organic carbon increased by 21 percent, showing the large potential agroforestry has in carbon sequestration (ibid.). Combining trees with perennial crops such as coffee and cacao rather than with annual crops may result in higher carbon sequestration (IPCC, 2019a).

Agroforestry also has benefits for climate change adaptation (IPCC, 2019). The improvements in soil structure that agroforestry brings about also support adaptation to variable rainfall, as increased infiltration means that soil moisture can be retained and therefore provides a buffer in times of low precipitation (Mbow *et al.* 2014). Moreover, the shade provided by the tree canopy protects crops from high temperatures and thus contributes to yield stability (Sida *et al.*, 2018). Several studies are modelling potential impacts of climate change on species of interest in a determined area, for instance food tree species in Burkina Faso (Gaisberger *et al.,* 2017), agroforestry species in Yunnan Province, China (Ranjitkar *et al.,* 2016) and agroforestry species in Central America (de Souza *et al.,* 2017).

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[26] https://www.ser.org/page/SERStandards/International-Standards-for-the-Practice-of-Ecological-Restoration.htm

[27] https://www.diversityforrestoration.org/

[28] https://seedit.io/home

4.4. Conclusions and recommendations

The management of FGR can significantly contribute to both adaptation to and mitigation of climate change. FGR are severely impacted by changes in climate such as drought, storms, sea level rise and increased pest pressure. Most studies on the impact of climate change on FGR focus on the impacts on specific species within a specific region. Data from provenance trials can be used to assess the potential of different provenances to be established in different climates.

Raising awareness of the importance of FGR management in restoration efforts is essential to their success. It is also necessary to highlight the livelihood opportunities that sustainable FGR management offers via activities such as seed collection and distribution. Investment in capacity building for the collection, characterization, conservation and distribution of FGR is also needed.

The size of the population, the heritability of fitness-related traits, and the intensity, direction and duration of the selection pressure are elements influencing the speed of adaptive response within tree populations and they should be taken into account while designing sustainable forest management programmes worldwide. It is advisable to use the most diverse seed sources possible to ensure resilience to current and future changes in climate.

Efforts to incorporate climate change-related traits, including plasticity and adaptation to increased drought into tree breeding programmes need to be continued. It would be highly recommendable for future breeding programmes to focus more on increased pest and disease incidence using a combination of different approaches. Breeding programmes need to target several traits simultaneously while conserving a large genetic base for unpredictable adaptation needs.

Given the uncertainty of future climatic conditions and the complexity of adaptive traits in tree species, several measures have been suggested for building resilience to climate change into forest restoration initiatives: increasing population sizes; enhancing species and genetic diversity; ensuring the maintenance of tree cover in the landscape for genetic and geographic connectivity between tree populations; and identifying and protecting refugia populations (Sgrò, Lowe and Hoffmann, 2011).

Given the longevity of trees, considering climate change models is crucial when planning restoration projects. Several projects on vulnerability mapping have been implemented, and applications have been developed to support decision-making when selecting tree species and provenances. Such applications need to be scaled up and used in forest management in regions that are expected to be particularly affected by climate change.

Most of the research projects on the use of FGR in climate change adaptation and mitigation have originated in Europe. Many countries urgently require assistance in coping with the impacts of climate change on FGR and promoting their sustainable use in climate change adaptation and mitigation (FAO, 2014a).

While some countries have begun to consider the importance of biodiversity in restoration and mitigation actions, genetic diversity is not consistently considered in these efforts. Even in cases where there is political will to increase genetic diversity in restored or newly planted forests, implementation may be hindered by a lack of availability of adapted tree seeds and by insufficiently developed seed systems for supplying tree seeds or seedlings.

V. PLANT GENETIC RESOURCES FOR FOOD AND AGRICULTURE

5.1 Introduction

Plant genetic resources for food and agriculture (PGRFA) are genetic material of plant origin of actual or potential value for food and agriculture (FAO, 2010). They comprise modern cultivars, breeding lines, genetic stocks, obsolete cultivars, ecotypes, farmers' varieties/landraces, and weedy races, as well as crop wild relatives (CWRs) and wild species harvested for food (FAO, 2019f).

Climate change affects PGRFA in many ways, including via non-biotic factors, such as rising temperatures, changing precipitation patterns, increasing frequency of extreme weather events and rising concentration of CO_2 in the atmosphere, and biotic factors, such as emergence of new pests and diseases and changes in the virulence of existing ones. While impacts vary from crop to crop and with the location and the type of production system, there is scientific consensus that rising temperatures will be detrimental to crop production. Although PGRFA can adapt to changes in the climate via evolution, it is unclear whether this will happen quickly enough to keep up with the pace of climate change.

5.1.1 The impact of climate change on plant genetic resources for food and agriculture [29]

The effect of climate change on major crops has been the subject of many studies (e.g. Juroszek and von Tiedemann, 2013; Pautasso *et al.*, 2012; Vadez *et al.*, 2012). High temperature and prolongued drought affect the physiological responses of plants and this translates into negative effects on growth rates and therefore on yield. Substantial declines in the yields of important crops have already been reported and further declines are predicted, with particular negative consequences in those regions where food security is already a major concern (IPCC, 2014b, 2019a). In addition to higher temperatures and changing precipitation patterns, crop production will also be negatively affected by the projected rise in the frequency of extreme climatic events such as heat waves, droughts, storms and heavy rainfalls (IPCC, 2019a). Fruit and vegetable production is expected to be affected, as these crops are highly vulnerable to climate change during their reproductive stages, as well as to diseases (Tripathi *et al.*, 2016).

The impacts and severity of climate change vary by crop and by region, with the tropics and subtropics projected to be the most vulnerable to declines in crop yield (IPCC, 2019a). In East Africa, yields of staple crops such as maize, wheat and sorghum are projected to further decrease, while root crops such as sweet potato, potato and cassava are projected to be less affected (Adhikari, Nejadhashemi and Woznicki, 2015). Crops from which only the vegetative organ is harvested, such as sugar beet and some other root vegetables, are less prone to being affected by changes in climate than crops that complete an entire phenological cycle, as growth stages such as flowering are generally more susceptible to environmental impacts (Hoffmann *et al.*, 2009). In Australia, lack of rainfall and rising temperatures have led to stagnation of wheat yields (Hochman, Gobbett and Horan, 2017).

As rising temperatures entail longer growing periods in colder climates, a few isolated examples of positive impacts of climate change on the yield of certain crops have been found in colder regions of Europe, Asia and North America. However, the yields of other crops in the same areas may be negatively affected by higher temperatures. For example, it has been estimated that while changes in precipitation and temperature have contributed to a slowing in the growth of wheat and barley yields in Europe, they have had a slight positive impact on maize and sugar-beet yields (Moore and Lobell, 2015). Winter-wheat yields in the Russian Federation have increased by approximately 0.5 tonnes per hectare in the last decade, although increases in the occurrence of extreme heat events are projected to negatively affect the south of the country (Di Paola *et al.*, 2018). Tao *et al.* (2014) found that changes in temperature, precipitation and solar radiation over the last three decades increased wheat yields in northern China by 0.9 to 12.9 percent, but reduced wheat yields by 1.2 to 10.2 percent in the southern part of the country. At higher latitudes, early emergence of crops in spring due to warmer temperatures during winter could increase the risk of frost damage (NordGen, 2019).

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[29] This section draws on the IPCC special report on Climate Change and Land (IPCC, 2019a).

A review by Rötter *et al.* (2018) found that the majority of empirical studies on the effects of climate change on crops between 1995 and 2016 focused on the staple crops wheat, maize and rice, with the agroclimatic extremes of drought, heat and heavy rainfall the effects most commonly investigated. The impacts of climate change on PGRFA are usually investigated in terms of yield reduction and measured at production-system level. Irrigation and fertilizer management can make crop production systems more adaptable to climate change. However, such effects last only as long as the required inputs are available. Increasing evapotranspiration and decreasing rainfall mean that this may not be the case for water.

Aside from measurments of past and current impacts of climate change on specific crops, there is a wealth of research on modelling the impacts of future climate change scenarios on crop yields and on suitable ranges for crop production. Crops grown in the tropics are projected to be affected more negatively than those grown at higher latitudes (Levis *et al.*, 2018). If global warming can be limited to 1.5°C rather than 2°C, net reductions in yields of maize, rice and wheat are projected to be smaller, particularly in sub-Saharan Africa, Southeast Asia and Latin America (IPCC, 2018). Potato yields are projected to decline in most regions by the end of the century under high-emission scenarios (Raymundo *et al.*, 2018). A large number of studies focus on the future suitability of specific crops at country or regional level. Zhen *et al.* (2016), for instance, found that in Ethiopia the area suitable for growing wheat will shrink, as will the area suitable for teff, while the area suitable for maize will remain stable or may slightly increase. The suitable area for coffee will shift to higher elevations in many countries, including Brazil and Costa Rica, and in the United Republic of Tanzania production in highland areas is projected to decrease (Coto-Fonseca, Rojas and Molina-Murillo, 2017; Craparo *et al.*, 2015; Ovalle-Rivera *et al.*, 2015). Barley yields are projected to decline in the Mediterranean basin, with some areas more severely affected than others (Cammarano *et al.*, 2019).

Predictive models are increasing in resolution, with some studies including varieties with traits such as particular lengths of growing period, drought tolerance or heat tolerance, and are thus better at predicting which traits will be most relevant for adaptation to the climate of a particular area. For example, one study on pearl millet grown in several areas in the arid and semi-arid tropics found that some regions in India, Mali and Niger will need slightly longer duration cultivars with drought and heat tolerance traits to enhance yields in future climates, while other regions in India will need longer duration cultivars with only drought tolerance (Singh *et al.*, 2017); the study will help plant breeders to evaluate the potential of promising new traits of pearl millet for use in adapting to climate change at the selected locations and other similar environments.

Climate change will also affect the range and survival of CWRs, thus threatening an important resource for crop improvement (Jarvis *et al.*, 2010). For example, wild Arabica coffee is very sensitive to changes in temperature, and climate change models predict that the suitable area for this plant in Ethiopia will significantly decline, or even disappear (Davis *et al.*, 2012). The importance of CWRs as a reservoir for traits related to climate resilience is well documented, with the last few decades seeing a significant increase in the introgression of traits from CWRs into domesticated crop species and varieties (Dempewolf *et al.*, 2017; Nair, 2019; Ortiz, 2015).

Climate change alters the biology, physics and chemistry of plants and soils, and thus affects the availability of nutrients for plants, which can lead to changes in the taste and nutrient quality of foods (Brouder and Volenec, 2017). Protein and mineral nutrient concentrations may decrease, or lipid composition may change, with negative consequences for food quality (DaMatta *et al.*, 2010). In Japan, temperature increases over recent decades have caused apple trees to bloom earlier, which in turn has affected the acidity, firmness and water content of apples, thereby reducing their quality (Sugiura *et al.*, 2013). While in recent years wine quality in most growing regions has improved because of warmer temperatures and more frequent water deficits, yields have declined, and in some regions warming-induced changes in sugar composition negatively affect the colour and aroma of grapes (van Leeuwen and Darriet, 2016; Santillán *et al.*, 2019). One study found that greater unpredictability of rainfall altered the chemical composition of the forage legume *Onobrychis viciifolia*, leading to higher productivity and quality, at least in the absence of extreme climatic events (March-Salas and Fitze, 2019).

The IPCC Special Report on Climate Change and Land notes a trend towards increased photosynthetic activity in vegetation (referred to as greening), which is in part caused by CO_2 fertilization (IPCC, 2019a). However, it also notes that increased emissions from soils and vegetation due to climate change are expected to offset the sink effect of CO_2 fertilization, and that the extent to which it contributes to plant-level or ecosystem-level carbon sequestration is highly variable and dependent on a range of environmental factors. To increase their growth because of the effect of CO_2 fertilization, plants need to have an adequate supply of nitrogen and other nutrients (Asif *et al.*, 2019).

Recent rises in food insecurity can be attributed to a large extent to the increasing number of conflicts, often exacerbated by climate-related events (FAO, 2020f). FAO's *Quarterly Global Report of Crop Prospects and Food Situation* for December 2019 indicated that floods and earlier occurrence of dryness in East and Southern Africa had significantly reduced harvest expectation, and that unfavourable weather had reduced harvests in most countries in Central America and the Caribbean (FAO, 2019g.).

Climate change is expected to change the range and severity of pest and disease incidence, and there is strong evidence that this is already taking place (IPCC, 2019a; FAO, forthcoming). Models predict that while effects will vary from region to region, the mean probability of pest and disease incidence is expected to rise globally (Yan *et al.*, 2017). Warming in the Andean region has been linked to an increase in pest and disease occurrence in potatoes, which has driven farmers to shift their production to higher altitudes (Quiroz *et al.*, 2018).

Where insects are concerned, the population sizes of some species are expected to increase, whereas others are expected to decrease because of higher mortality rates (Phophi and Mafongoya, 2017). Different life-cycle stages can react differently to temperature increase. Global yield losses of wheat, rice and maize are predicted to increase by 10 to 25 percent per degree of global mean temperature rise because of the increase in the incidence of insect pests (Deutsch *et al.*, 2018). *Tuta absoluta*, *Ceratitis cosyra* and *Bactrocera invadens*, three important insect pests that have a strong impact on crop production in Africa, are projected to extend their ranges across the continent (Biber-Freudenberger *et al.*, 2016). The effects of rising temperatures on insect population dynamics will disrupt current host–parasite interactions and thus affect biological pest control (Meisner, Harmon and Ives, 2014).

Fungal pathogens are also affected by climate change. Studies in Europe and India have found that the incidence of fungal pathogens such as *Aspergillus flavus* and *Fusarium* spp. is highly likely to increase, which has implications for food safety as they produce mycotoxins such as aflatoxins that are harmful to human health (Moretti, Pascale and Logrieco, 2019; Shekhar *et al.*, 2018). In Latin America and the Caribbean, rising temperatures and increasing humidity of crop canopies due to climate change have been found to be responsible for a significant increase in the risk of infection with black Sigatoka, a banana disease caused by the fungus *Mycosphaerella fijiensis* (Bebber, 2019). Bananas are also projected to be affected by an increase in the area favourable to *Fusarium* wilt in the Philippines (Salvacion *et al.*, 2019).

Desert-locust outbreaks are detrimental to crop production and thus food security, and climate change may be a factor that influences these outbreaks (Devi, 2020; Qiu, 2009). Higher temperatures and increased rainfall may have played a role in the outbreak of desert locust in the Horn of Africa in early 2020 (UNEP, 2020a).

In summary, the effects of climate change on major crops are well studied, particularly at species level, but less information is available for minor and neglected crops. The total land area climatically suitable for high productivity is projected to be similar in 2050 to today, as it will increase in higher latitudes and decrease in lower latitudes (IPCC, 2019a). The majority of studies focus mainly on the yield of a specific crop under climate change or on comparing different species under current and future conditions. There are also studies comparing the effects of climate change on different varieties of the same species or on the phenological cycles and the quality of specific crops. The available data suggest that adaptive measures implemented to date have not been sufficient to offset the negative effects of climate change on global crop yields (ibid.).

5.1.2 Conservation of plant genetic resources for food and agriculture

The conservation of PGRFA serves to maintain genetic diversity among and within plant species of actual or potential value for food and agriculture. Conservation strategies include safeguarding these resources in their natural habitats (*in situ* conservation of CWRs and wild food plants), managing them on farms (i.e. cultivating a diverse range of crop species and varieties, including farmers' varieties and landraces) and conserving accessions or samples in genebanks (*ex situ* conservation) (FAO, 2017e). Much of the diversity conserved is important for cultivating and breeding crop varieties that are adapted to climate change.

In situ conservation involves locating targeted wild plant populations, describing their conservation status, and actively managing and monitoring them in their natural habitats (FAO, 2017f). Many wild plant populations, including CWRs and wild food plants, are at risk of extinction caused by drivers such as habitat loss, habitat fragmentation, changes in land use and climate change (see Box 3). Species in some highly specialized and/or isolated habitats, such as montane environments and island or coastal areas, are especially vulnerable and are likely to be the first casualties of climate change (FAO, 2017d). Despite the increased public, political and scientific interest in conserving PGRFA, many countries lag behind in protecting CWR and wild food plants, especially in their natural environments (FAO, 2017f). A concerted effort to document and protect CWR and wild food plants *in situ*, and to collect them and ensure that they are safeguarded in *ex situ* storage, is required (FAO, 2010).

Box 3. Conservation of wild wheats in an Armenian nature reserve

Nature reserves provide a protected area for diverse species, including crop wild relatives (CWRs). The Erebuni Reserve in Armenia is home to diverse cereal species (*inter alia Triticum boeoticum*, *T. araraticum*, *Secale vavilovii* and *Aegilops squarrosa*). The reserve is located 8−10 km from Yerevan, covers 89 hectares and is 1 300−1 400 m above sea level (Khanjyan, 2004). Nikolai Vavilov, the famous Russian botanist, visited the area in 1934 and recommended the safeguarding of the CWRs *in situ*. The reserve was established in 1981.

The reserve is unusual in that its primary objective is the conservation of wild cereals. Studies have shown that these wild species show resistance to drought and heat stress as well as to fungal diseases (Goncharov *et al.*, 2014; Hovhannisyan *et al.*, 2011). Despite the protected status of the area, a study found that wild cereal diversity is declining due to adverse human impacts (Harutyunyan, Avagyan and Hovhannisyan, 2008). The study recommended also conserving endangered populations *ex situ* and restoring endangered/extinct populations using *ex situ* accessions (ibid.).

A significant amount of crop diversity, including farmers' varieties and landraces, is maintained mainly in farmers' fields, orchards or home gardens (FAO, 2019f). Many farmers continue to cultivate farmers' varieties and landraces due to agronomic, culinary or quality preferences or even locally important cultural values. The dynamic on-farm management of this diversity, including its exposure to different production regimes, environments, farmer selection and seed exchange systems, contributes to its continued evolution and adaptation. Many landraces are better suited to local ecosystems, climatic conditions and farming practices than other varieties, and have proven more resilient to unpredictable and difficult conditions (Alipour *et al.*, 2017; Coto *et al.*, 2019; Sani and Birniwa, 2020). However, this crop diversity is threatened by urban or infrastructure encroachment onto farmland, unsustainable use of natural resources, promotion and adoption of genetically uniform varieties, introduction of invasive alien species, changing patterns of human consumption, absence of (or inappropriate) policies and climate change (FAO, 2019f). Strengthening the improvement and management of PGRFA on-farm and enhancing their documentation and conservation *ex situ* is essential to their conservation (FAO, 2010).

Ex situ conservation includes the storage of orthodox seeds[30] in seed genebanks and safeguarding species that produce non-orthodox seeds or are propagated vegetatively as live plants in field genebanks or as plantlets through *in vitro* culture or cryopreservation (FAO, 2014b). Genebanks around the world hold collections of a broad range of PGRFA, with the overall aim of conserving germplasm for the long term and making it accessible to plant breeders, researchers and other users. This form of conservation

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[30] Orthodox seeds remain viable for a long period of time.

involves acquisition, storage, characterization, evaluation, regeneration, safety duplication and documentation (FAO, 2014b; Khoury, Laliberté and Guarino, 2010).

Germplasm of crop species and CWRs is conserved in more than 650 genebanks worldwide, with aproximatey 5.3 million accessions maintained under medium- and long-term conditions (FAO, 2020h). Major crops (wheat, maize, rice, potato, banana/plantain, etc.) are well represented in *ex situ* collections. CWRs and underutilized species (such as yams, Bambara groundnut and amaranth) are less well represented, and significant gaps remain in their collection and conservation.

Ex situ conservation of PGRFA is essential for global food security. There is therefore a need to secure adequate storage or maintenance conditions for the genetic materials already collected through the application of appropriate standards and procedures (FAO, 2014b). Many collections are still vulnerable to natural disasters, including those caused by climate change, and to human-made calamities such as civil unrest. PGRFA are also vulnerable to avoidable adversities resulting from a lack of funding and/or poor management. Because of ongoing issues of this kind, the Svalbard Global Seed Vault was created to provide backup storage for the global collections stored in seedbanks (Box 4).

Box 4. Svalbard Global Seed Vault

The Global Seed Vault[31] is a secure storage facility designed to safeguard the seeds of the world's food plants in the event of global crises, potentially including the effects of widespread natural disasters brought about by global warming. The vault is built into the side of a mountain on Spitsbergen, the largest of the Svalbard islands (a Norwegian archipelago in the Arctic Ocean), and was established and fully funded by the Government of Norway. Completed in early 2008, the vault stores seeds in a controlled environment and has the potential to house some 4.5 million seed samples. The Norwegian Ministry of Agriculture and Food is responsible for its overall operation and coordinates with the Nordic Gene Resource Centre[32] and the Global Crop Diversity Trust.[33]

Concerted efforts have been made to deposit duplicate samples of accessions from the CGIAR global collections and many national and regional collections. The vault currently contains more than 980 000 samples of the world's most important plant genetic resources for food and agriculture, originating from almost every country in the world.

In September 2015, the Syrian civil war prompted the first withdrawal of seeds from the vault when the International Center for Agricultural Research in Dry Areas (ICARDA)[34] requested seeds for drought- and heat-resistant strains of wheat and other crops that had been compromised in the conflict. These genetic resources are essential in the development of crop varieties resilient to the effects of climate change.

Maintaining the supply of seeds of high genetic quality requires complementarity between *in situ* and *ex situ* conversation. On-farm conservation in diverse, risk-prone environments builds on natural and farmer selection, and provides farmers with a diverse range of genetic resources that can be used in the context of climate change (FAO, 2015a). Efficient collaboration between genebank curators, breeders and policy-makers is essential to the success of PGRFA conservation efforts (FAO, 2017d). Policy-makers have pointed out the need to integrate *ex situ*, *in situ* and on-farm research data and knowledge in a more coherent and structured way (FAO, 2019h).

5.1.3 Characterization and evaluation of plant genetic resources for food and agriculture

Characterizing and evaluating the variation of plants is crucial to the estimation of their vulnerability to climate change (FAO, 2017d). Characterization of plant germplasm is the description of highly heritable characters, while evaluation is the study of environmental response traits and assesses the agronomic performance of the crop (FAO, 2014b). The process of characterization entails the description of a minimum set of standard physiological, morphological and seed-qualitative traits (ibid.). Evaluation requires analysis of agronomic data obtained through appropriately designed experimental trials.

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[31] https://www.croptrust.org/our-work/svalbard-global-seed-vault/

[32] https://www.nordgen.org/en/

[33] https://www.croptrust.org/

[34] https://www.icarda.org/

Sustainable use of PGRFA depends to a large extent on the amount and quality of the information available about these resources, including the environments to which they are adapted. Having access to characterization and evaluation information facilitates effective planning of how genetic resources can best be used and developed in order to address the impacts of climate change. Both characterization and evaluation use crop descriptor lists, such as those developed by Bioversity International in collaboration with FAO and specialized national, regional and international centres.[35] Descriptors have also been developed by the International Union for the Protection of New Varieties of Plants (UPOV)[36] and by the United States Department of Agriculture's National Plant Germplasm System.[37] FAO and Bioversity International have published passport descriptors widely used for the documentation and exchange of germplasm (Alercia, Diulgheroff and Mackay, 2015).

Accurate data on these descriptors allow a conserved accession to be linked to the ecogeographical location in which the population from which it comes has evolved. Descriptors associated with the location and date of collection are of particular relevance for CWRs, wild food plants and landraces. A number of tools, including CAPFITOGEN[38] and DIVA-GIS,[39] are freely available for eco-geographical analysis.

The FAO World Information and Early Warning System on PGRFA (WIEWS) provides access to passport data for materials held in genebanks worldwide (FAO, 2020h). Additionally, WIEWS is the portal through which the plant component of Target 2.5[40] of the Sustainable Development Goals (SDG) is monitored annually.[41] Global germplasm management systems, such as GRIN-Global[42] and GENESYS,[43] are increasingly being used for documenting not only passport data but also characterization and evaluation data from genebanks. GENESYS also includes information on the climate at the origin of accessions, and provides users with the option of searching for accessions originating from similar climates. A number of national and regional specialized web portals also currently publish information on *ex situ* collections, including the United States Department of Agriculture Germplasm Resources Information Network (GRIN),[44] the European Search Catalogue for Plant Genetic Resources (EURISCO),[45] the NARO Genebank system,[46] the Documentation & Information System database (web-SDIS) developed by the Plant Genetic Resources Network of the Southern African Development Community (SADC), and the International Rice Information System (IRIS).[47]

The need to connect all these information systems motivated the setting up of the Global Information System (GLIS)[48] of FAO's International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA). This system integrates and augments the others and creates a global entry point for information and knowledge relevant to strengthening capacity for PGRFA conservation, management and utilization. Not only does it connect crop accessions and material in plant breeding collections, it also links them to various datasets in disperse repositories. These include publications and phenotypic

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[35] https://www.bioversityinternational.org/e-library/publications/categories/descriptors/

[36] https://www.upov.int/tools/en/gsearch.html?cx=016458537594905406506%3Asa0ovkspdxw&cof=FORID%3A11&q=descriptors

[37] https://search.usa.gov/search?query=descriptors&affiliate=agriculturalresearchservicears

[38] http://www.capfitogen.net/en/

[39] https://www.diva-gis.org/

[40] SDG Target 2.5 "By 2020, maintain the genetic diversity of seeds, cultivated plants […] and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed."

[41] http://www.fao.org/wiews/data/ex-situ-sdg-251/overview/en/

[42] https://www.grin-global.org/

[43] https://www.genesys-pgr.org/

[44] https://www.ars-grin.gov/

[45] https://eurisco.ipk-gatersleben.de/apex/f?p=103:1

[46] https://www.gene.affrc.go.jp/about_en.php

[47] https://www.researchgate.net/publication/10667335_Linking_genotype_to_phenotype_the_International_Rice_Information_System_IRIS https://eurisco.ipk-gatersleben.de/apex/f?p=103:1:0:::::

[48] https://ssl.fao.org/glis/

and genomic data that are vital for plant breeding and adaptation. At the same time, GLIS facilitates access to PGRFA information for the benefit of other research communities.

The Joint FAO/IAEA Mutant Variety Database (MVD) collects information on plant mutant varieties released officially or commercially worldwide. It includes data on the mutagen and dose used and the improved traits. The database can be searched for varieties with early or late maturity or tolerance of biotic and abiotic stresses such as drought and pests, and can therefore be a useful tool for identifying candidates for cultivation or breeding to promote climate change adaptation.[49]

Characterizing and evaluating PGRFA and documenting them in databases is crucial to their availability for use and exchange. Exchange of germplasm within and across national borders already plays an important role in research and development in many countries, and this interdependence is expected to increase because of climate change (Vernooy and Clancy, 2017).

5.2 Adaptation

PGRFA provide an important resource for the adaptation of crop production to climate change. Yield stability in an unpredictable and variable climate can be maintained via phenotypic plasticity, diversity within the population (e.g. the presence of different flowering times buffers the threat posed by short-term droughts) and the presence of traits directly conferring resistance to biotic or abiotic stresses (Haussmann *et al.*, 2012). Stresses that climate-adapted plants need to withstand may include drought, heat, frost, salinity, submergence and elevated incidence of pests and diseases. The availability and adoption of such varieties can be facilitated by outreach policies and capacity building (IPCC, 2019a; FAO, forthcoming). The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) has implemented a number of projects that focus on the management of PGRFA for climate change adaptation (see Box 5).

Box 5. The use of plant genetic resources for food and agriculture in climate change adaptation – projects under the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) is a collaboration among all CGIAR research centres led by the International Center for Tropical Agriculture (CIAT). The programme aims to address the increasing challenges that global warming and declining food security pose to agricultural policies and practices through strategic, broad-based global partnerships. It implements projects in 20 countries across East and West Africa, Southeast and South Asia and Latin America, with funding support from governments and aid agencies. A number of these projects are focused on the use of plant genetic resources for food and agriculture (PGRFA) in climate change adaptation. Some examples are listed below.

Climate-smart food systems in Southeast Asia

Viet Nam and the Philippines are highly vulnerable to extreme events such as drought, flooding and typhoons, as well as to salinity intrusions and sea-level rise. The project Climate-Smart Food Systems in Southeast Asia aims to mitigate the effects of extreme weather events through crop diversification and the development of policy frameworks. The first component of the project focuses on generating and disseminating scientific evidence of the benefits of crop diversification in rice-based cropping systems and on breeding high-yielding potato varieties that are adapted to tropical climates. The second component focuses on strengthening seed systems through policy reforms and private-sector participation in order to accelerate adoption of climate-resilient crops.

Promoting climate-resilient maize varieties in Uganda

The uptake of quality-assured maize seed by smallholder farmers is persistently low, despite the fact that it has a much higher yield potential and is often more drought tolerant than the varieties traditionally grown by farmers. Just over 15 percent of Ugandan farmers buy quality-assured maize seed from the formal seed market, the rest rely mostly on home-saved seed and products from the local market that are not quality assured. This research project investigates the adoption of drought-tolerant maize varieties that have been developed for specific agro-ecological zones in Uganda by the International Maize and Wheat Improvement Center (CIMMYT) and partners. It also examines barriers to the uptake of advanced seed technology. The project is working closely with the Drought Tolerant Maize for Africa Seed Scaling (DTMASS) project.

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[49] https://mvd.iaea.org/

Crowdsourcing with ClimMob – farmers as citizen scientists

Gathering statistically relevant data on the performance of different varieties in various climates by imitating the conditions in farmers' fields can be expensive, and participatory approaches with farmers require training and time (Bioversity International, 2017). In order to gather a large amount of data directly from farmers' fields, Bioversity International has developed a new participatory research approach. Many farmers are enrolled in the process, and each of them receives a package with three different varieties. While growing the varieties the farmers note which of the three is best and which worst on a list of characteristics such as vigour, pest resistance, yield and quality. The varieties are drawn in different overlapping combinations from a pool of several varieties. For example, from a set of ten varieties, one farmer receives varieties 1, 2 and 3, while another receives varieties 2, 6 and 7. These citizen science experiments are referred to as "tricot" trials, which stands for "triadic comparison of technology options" (van Etten *et al.*, 2016).

A software named ClimMob was developed to turn the large number of individual replies into an overall ranking of the varieties. Because of the large number of participants, statistical models can be used to produce accurate results (Steinke, van Etten and Zelan, 2017). Additional variables, such as climate, soil, altitude and access to irrigation, can also be examined to see whether they affect the performance of the varieties. The results reliably indicate which varieties are best suited to specific climates, and can thus be translated into recommendations for climate change adaptation at farm level (van Etten *et al.*, 2019).

The approach has been tested in a number of countries, and the software is available online.[50] In Nicaragua, for example, a number of improved bean varieties from a national seedbank were tested. The number of households that participated in the crowdsourcing trials to propagate these beans increased from 62 households in December of 2015 to 818 households in March 2016 (Bioversity International, n.d).

Policy support for biologically rich, climate-resilient seed systems

This project has been working with partners in a number of countries to use the International Treaty on Plant Genetic Resources for Food and Agriculture to help farmers, plant breeders and researchers access crop genetic diversity for climate change adaptation. National multistakeholder teams conduct community-level vulnerability analyses with teams of farmers (and scientists/plant breeders from national agricultural research programmes) to document the impact of climate change on crops that are important for food security and identify traits that these crops need in order to perform better under changing climate stresses. The teams then consider three different "levels" of sources of crop genetic materials with the desired traits: first, local varieties maintained by local farmers; second, the national genebanks of the countries concerned; and third, other countries' genebanks and international genebanks. The project trains national multistakeholder teams on how to combine and use publicly available accession-level information, downscaled climate information (current climates and predicted future climates) and crop suitability models to identify materials with traits potentially adapted to the evolving climate conditions in the focus communities. It then supports the teams in requesting the identified materials from around the world through the Treaty's multilateral system (for free or at minimum cost) (Halewood *et al.*, 2017; Otieno *et al.*, 2018; Otieno, 2019).

Resilient Seed Systems Handbook

Access to and exchange of PGRFA play an important role in the capacity of farmers to adapt to climate change. The Resilient Seed Systems Handbook is a methodology based on Bioversity International's experience in PGRFA management that helps farmers adapt to the effects of climate change. It is intended for plant breeders, researchers, genebank managers, extension agents, policy-makers and other seed-sector actors involved in climate change adaptation research related to the use of PGRFA. It contains nine modules that represent the steps of the participatory research process for building more resilient seed systems: situational analysis and planning; software selection and preparation of data; climate change analysis and identification of germplasm; germplasm acquisition; field testing; seed production and distribution; germplasm conservation; participatory evaluation; and knowledge sharing and communication (Vernooy, Bessette and Otieno, 2019). The first edition of the handbook (*Resource box for resilient seed systems: handbook*) was published in 2016 and has supported scientists, breeders and extension agents in Africa, Asia and Latin America in collecting, evaluating and conserving PGRFA and making them available to farmers (Vernooy *et al.*, 2015).

For more information, visit https://ccafs.cgiar.org/climate-smart-food-systems-southeast-asia#.Xljxr6hKhpj
https://www.cimmyt.org/projects/drought-tolerant-maize-for-africa-seed-scaling-dtmass/
https://ccafs.cgiar.org/promoting-climate-resilient-maize-varieties-uganda-global-challenges-programme-project#.Xl0qH6hKhpg

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[50] https://climmob.net/blog/

Increasing species diversity within production systems, for example by adding cover crops, increases their resilience to climatic impacts (IPCC, 2019a). Adjusting sowing dates and choosing varieties that are better adapted to the climates in which they are to be grown can also contribute to sustaining yields (Eyshi Rezaei, Siebert and Ewert, 2017; Zimmermann *et al.*, 2017).

As different crops have different characteristics, some are better able to maintain yields under particular climate impacts than others. For example, cassava and mangoes were found to have higher yield potential than other crops with changing temperature and rainfall patterns in Kenya (Ketiem *et al.*, 2017). Quinoa (*Chenopodium quinoa*) is particularly tolerant of drought and salinity, with some genotypes being more tolerant than others (Ruiz *et al.*, 2016, 2014). In East Africa, crop yield response to climate change was found to have high spatial variation, which calls for community-based efforts to increase local adaptive capacity (Thornton *et al.*, 2009).

5.2.1 Management of plant genetic resources for food and agriculture in the nationally determined contributions

A number of countries mention the management of PGRFA as a priority adaptation measure in their NDCs,[51] for example through breeding, promotion of stress-tolerant crop varieties, or conservation and use of germplasm of landraces and wild relatives. Zambia, for instance, is promoting cassava, maize, sorghum, finger millet, bean and cowpea landraces and their wild relatives as a key strategy for improving and diversifying agricultural production.

Many countries report the development or use of drought-tolerant varieties as an adaptation measure. Rwanda, for instance, mentions sorghum breeding for increased yields and drought tolerance. Crop diversification is also mentioned by a number of countries. In Ethiopia, emphasis is placed on breeding and distributing varieties that are resistant to emerging diseases and pests and those suited for use in regions where the ones formerly grown have become unsuitable. Uganda prioritizes expanding research on climate-resilient crops and increasing diversification. Twenty-five percent of the countries with adaptation priorities in Southern Europe, Eastern Europe and Central Asia mention plant management[52] as an adaptation priority (FAO, 2019b). For instance, Uzbekistan lists improving climate resilience through crop diversification, conservation of indigenous plant species and agricultural crops resistant to droughts, pests and diseases, development of biotechnology, and breeding of new crop varieties adapted to changed climatic conditions associated with climate change.

Although some countries have recognized the importance of PGRFA in adaptation to climate change, their management is still not considered a major priority by most countries that have submitted an NDC.

5.2.2 Breeding

Agricultural crops have been bred successfully for millennia. This has led to considerable increases in the yield of major crops, but it has also increased their genetic homogeneity. Greater homogeneity may increase genetic vulnerability, because the lack of diversity renders crops more susceptible to adverse impacts such as those brought about by climate change. Crossing high-yielding varieties with CWRs or landraces can reduce genetic vulnerability, as these tend to have maintained a wider genetic base (FAO, 2017f).

Conventional breeding is still a lengthy and costly process. For example, breeding, delivery and adoption (BDA) of new maize varieties can take up to 30 years (Challinor *et al.*, 2016). Mean temperature changes may occur during this time and hence the crop cycles in farmers' fields at the time a variety is used may differ from those measured during the breeding process, leading to yield reductions (ibid.). Given the urgent need to adapt crops to climate change, analysing BDA data and reducing the time needed to complete the process, as well as prioritizing research programmes on breeding for climate resilience, are of utmost importance (Cairns *et al.*, 2013; Challinor *et al.*, 2016).

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[51] NDCs submitted by countries to the UNFCCC can be found here: https://www4.unfccc.int/sites/ndcstaging/Pages/Home.aspx

[52] The FAO NDC database uses the category *plant management,* defined by Smith *et al.* (2014) as practices such as the use of improved crop varieties, crop rotation, use of cover crops, perennial cropping systems and agricultural biotechnology.

Advances in plant genetics and biotechnology have substantially increased knowledge of genetic mechanisms involved in plant responses to climate change-related stresses and facilitated the identification of desirable traits for crop improvement (Wang *et al.*, 2018). Traits associated with climate resilience tend to be polygenic, in other words the expression of these traits involves several genes (Atlin, Cairns and Das, 2017). As the links between traits and genes come to be better understood, breeding can become more targeted. With DNA sequencing becoming faster, more precise and less expensive, the genomes of most staple crops and some minor crops have been sequenced and many traits have been mapped to specific genes. As a result, more analyses are being conducted over time, allowing for more specific mapping of traits.

Novel biotechnological applications and tools have the potiential to significantly facilitate characterization, as well as the generation of crop varieties with improved attributes (Mba and Dreyer, 2021). Zinc-finger nucleases (ZFNs) and transcription activator-like effector nucleases (TALENs) have been the most commonly used genome-editing technologies over the past two decades; the recent development of clustered regularly interspaced short palindromic repeats (CRISPR)/Cas systems has simplified targeted gene editing (Christian *et al.*, 2010; Jinek *et al.*, 2012; Kim, Cha and Chandrasegaran, 1996; Zhang *et al.*, 2018). Use of genome-editing technologies to characterize gene functions and improve agricultural traits has been reported in a wide variety of plant species. The targeted traits include some that are relevant to climate change adaptation, such as early flowering, resistance to various diseases (fungal, bacterial and viral) and insects, and tolerance of drought (Ali *et al.*, 2015; Andolfo *et al.*, 2016; Baltes *et al.*, 2015; Fang and Tyler, 2016; Gantz and Akbari, 2018; Ji *et al.*, 2015; Li *et al.*, 2012; Liu *et al.*, 2012; Shi *et al.*, 2017; Soyk *et al.*, 2017; Wang *et al.*, 2014, 2016b).

Breeding of commodity crops

The varieties currently available within commodity crops − wheat, rice and maize, for example − are the result of crop improvement via breeding. Breeders have always had to consider the climate in which crops are to be grown, and therefore breed for traits such as tolerance of droughts or flooding. Current trends in private breeding companies are summarized in Box 6.

Many breeding efforts, in particular at lower latitudes, target tolerance of drought, heat, salinity and flooding. Drought-tolerant hybrid maize varieties developed by CIMMYT (Box 7) were found to have higher yields than non-tolerant varieties in on-farm trials in Southern Africa, with the effect being more pronounced under conservation agriculture (Setimela *et al.*, 2018). At higher latitudes, breeding for the phenological adaptation of cereal and forage crops to frost and drought is common (Erath *et al.*, 2017; Mushtaq *et al.*, 2017; Zheng, Chenu and Chapman, 2016).

Non-staple commodity crops receive less attention from breeders than staple commodity crops. Although cocoa is a high-value crop, there are no formal breeding programmes aiming to improve its climate resilience or its tolerance of abiotic stresses (Farrell *et al.*, 2018). There are some breeding efforts aiming to improve the adaptation of coffee to climate change, such as those undertaken by World Coffee Research,[53] a non-profit research organization funded by a number of industrial coffee companies,[54] and the Breeding Coffee for Agroforestry Systems (BREEDCAFS) project co-funded by the European Union.[55]

In addition to the direct effects of climate change, crops in coastal regions are also indirectly affected via rising sea levels and the resulting intrusion of saline water into fields and salinization of soil. This decreases the osmotic potential of the soil so that most plants become unable to retrieve water from it. Most adaptive measures focus on flood-proofing or raising seedbeds above sea level, for instance by planting crops on mounds of soil and building ridges and terraces to form barriers, as farmers do in the lower Niger delta (IPCC, 2019b; Musa, Popescu and Mynett, 2016). The adaptation of crops to saline water intrusion is not extensively documented, as salinity receives less attention than other climate change impacts (IPCC, 2019b; Renaud *et al.*, 2015). A review of rice-breeding programmes in Indonesia aimed at increasing tolerance to abiotic stresses found that new flooding- and salinity-tolerant

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[53] https://worldcoffeeresearch.org/

[54] https://worldcoffeeresearch.org/

[55] https://cordis.europa.eu/project/id/727934

varieties had a yield that was up to 125 percent higher than the varieties that are commonly used by farmers (Rumanti *et al.*, 2018).

Box 6. Trends in private breeding companies

Breeding programmes undertaken by private companies aim to utilize and incorporate genetic diversity into crops in the form of beneficial traits. The new varieties are bred to be adapted to growing in specific environments and regions. Increased resource-use efficiency is prioritized in many crops. The main traits targeted are general robustness or pest and disease resistance, but abiotic-stress responses such as tolerance of drought, flooding and salinity have been receiving increased attention for decades. Although adaptation to climate change is not commonly a major goal of commercial breeding, selection criteria go beyond yield and many breeders consider traits such as drought and salinity tolerance, for instance in breeding programmes for cereals, potato and sugar beet. In the breeding of forage crops, flooding tolerance is also considered. Heat tolerance is selected for in a few ornamental plants such as *Cyclamen*.

Even though resistance to stresses related to climate change is not always an explicit goal in breeding programmes, varieties are selected and tested under various environmental and regional conditions to ensure that they can be successfully grown in different parts of the world. Crop varieties developed in this way may be resilient to climate change impacts.

Where underutilized crops are concerned, some breeders note increasing interest, not necessarily linked to climate change, but related to protein crops (e.g. *Vicia* species and lupins), diversification of vegetable supply (e.g. underutilized vegetables such as black salsify and parsnip) and catch crops (e.g. mustard species) due to policies that support integrated crop protection/pest management (e.g. through crop diversification in crop rotation), notably in Europe. As breeding companies have to consider return on investment, the perceived lack of economic viability of certain crops means that companies are reluctant to invest in developing them. Lack of investment from the private sector may lead to a shortage of improved varieties in some crops. It is therefore important for the public sector to invest in them, and public−private partnerships need to be encouraged.

Note: Information in this box is compiled from personal communication with Annik Dollacker (Bayer), Anke van den Hurk (Plantum) and Szabolcs Ruthner (International Seed Federation).

Box 7. The Drought Tolerant Maize for Africa (DTMA) project

The Drought Tolerant Maize for Africa (DTMA) project was jointly implemented by the International Maize and Wheat Improvement Center (CIMMYT) and the International Institute of Tropical Agriculture (IITA) in 13 countries in sub-Saharan Africa and ended in 2015. The main goal of the project was to increase the food and income security of smallholder farmers through the development and dissemination of drought-tolerant, well-adapted maize varieties. Research institutions collaborated with farmers, extension specialists, seed producers, farmer community organizations and non-governmental organizations to improve maize production under drought and other constraints. Production was improved by at least one ton per hectare under moderate drought, a 20 to 30 percent increase over farmers' current yields (CIMMYT, 2020).

A total of 233 varieties, including about 200 distinct drought-tolerant maize varieties, had been released under DTMA across the target countries as of December 2015 and adapted to their various agro-ecologies. All of the varieties are resistant to major diseases with the exception of the recently introduced MLN (maize lethal necrosis). In addition, several varieties are tolerant to the parasitic weed *Striga hermonthica* and are efficient users of nitrogen. In the later years of the project (2013 and 2014), at least one DTMA variety was being grown in each of the 13 countries. In Nigeria and Zambia, DTMA varieties were already the dominant varieties. Countries with the largest adoption of DTMA varieties, as indicated by area occupied by DTMA varieties, included Nigeria (>23 percent), Benin (~22 percent), Malawi (~22 percent), Uganda (~20 percent) and Zambia (>10 percent). Estimates for the 2015 crop season indicated that 4 DTMA varieties occupied >100 000 ha each, 27 varieties occupied >10 000 ha each and 19 varieties occupied >5 000 ha each (CIMMYT and IITA, 2015).

A follow-up project, the Drought Tolerant Maize for Africa Seed Scaling (DTMASS) project, was launched in 2014 to enhance farmer uptake of climate-adapted maize germplasm in Ethiopia, Kenya, Mozambique, Uganda, the United Republic of Tanzania and Zambia.

Breeding of neglected and underutilized crops

Neglected and underutilized crops (also referred to as minor or orphan crops) are species or varieties that are not typically traded internationally and have commonly been overlooked by scientists, extension services and policy-makers. They are expected to become increasingly important under climate change, but are generally incompletely characterized and evaluated for agronomic traits when present in *ex situ* collections, which is a major constraint to their use in breeding programmes (Dawson *et al.*, 2019; FAO, 2019a). Many neglected and underutilized crops have traits that make them ideal for use in coping with climate change, for example grass pea (*Lathyrus sativus*) and many millet varieties are drought tolerant (Tadele, 2019; Umesh *et al.*, 2019).

While neglected and underutilized crops play an essential role in supporting food security in developing countries, they often provide low yields, as they have generally not been improved via breeding (Tadele, 2019). As they are not considered to provide a good return on investment, they receive little attention from commercial breeding companies. Most breeding is therefore done by public institutions.

Neglected and underutilized crops have received more attention in recent years, and genomic tools can significantly increase the pace of their improvement (Mabhaudhi *et al.*, 2017). For example, the African Orphan Crop Consortium is a partnership that aims to improve the nutritional value of 101 underutilized African crops by sequencing their genomes and developing breeding capacity.[56] Breeding of teff has led to the doubling of yields in Ethiopia over the past two decades (Chanyalew, Assefa and Tadele, 2019). The Teff Improvement Project, a research collaboration between the University of Bern, Switzerland, and the Ethiopian Institute of Agricultural Research (EIAR), has sequenced the teff genome and bred a drought-resistant teff (Cannarozzi *et al.*, 2018).

Although there are an increasing number of breeding initiatives for neglected and underutilized crops, there is still a lack of concerted efforts and policies to fully develop their potential in climate change adaptation (Mabhaudhi *et al.*, 2019). The project Policies and Practices to Facilitate the Implementation of Developed Strategic Action Plans for Plant Genetic Resources Conservation and Use for the Improvement of Food and Nutrition Security under Changing Climatic Conditions funded by the ITPGRFA's Benefit-sharing Fund invested in the participatory breeding of underutilized crops to support farmers in their efforts to adapt to climate change (see Box 8).

Box 8. The project Policies and Practices to Facilitate the Implementation of Developed Strategic Action Plans for Plant Genetic Resources Conservation and Use for the Improvement of Food and Nutrition Security under Changing Climatic Conditions

Declining soil fertility, erratic rainfall, increasing temperatures and frequent droughts are affecting the livelihoods of many smallholders in Malawi, Zambia and Zimbabwe. Small grains traditionally grown in these countries, such as sorghum and pearl millet, maintain their yield potential during droughts and thus contribute to food and nutrition security in a changing climate. However, these traditional crops were largely abandoned in favour of maize, which is more prone to yield reductions in drought conditions.

The project Policies and Practices to Facilitate the Implementation of Developed Strategic Action Plans for Plant Genetic Resources Conservation and Use for the Improvement of Food and Nutrition Security under Changing Climatic Conditions − funded by the International Treaty on Plant Genetic Resources for Food and Agriculture's (ITPGRFA's) Benefit-sharing Fund and currently being implemented by the Community Technology Development Organization, a regional non-governmental organiation (NGO) based in Zimbabwe, in collaboration with the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the Ministries of Agriculture of the three target countries − focuses on the development of climate change adaptation strategies through the management of plant genetic diversity. The project started in February 2016 and ended in March 2020. It aimed to improve small-grain varieties for adaptation to climate change through participatory testing, breeding and multiplication in more than 160 farmer field schools. By making available more than 300 varieties for research and development, including pre-breeding lines of small-grain crops from national, regional and international genebanks, using the ITPGRFA Standard Material Transfer Agreement, the project has increased the diversity available to farmers.

Processing, cooking and taste are the most important attributes affecting the adoption of small grains. In order to ensure that the varieties developed would meet the needs of farmers and consumers, female farmers were involved in the breeding process and identified traits that facilitate harvesting and processing and shorten cooking times. Four new pearl-millet and cowpea varieties were developed jointly by scientists and farmers. Two varieties of

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[56] http://africanorphancrops.org/about/

pearl millet (PMV4, PMV5) with high yields (large grain size, big panicle) and early maturity to increase drought tolerance have officially been released and certified for quality.

The project has also established community seed banks (CSBs) and supports the collection and conservation of traditional crop varieties. The majority of these CSBs are linked to the respective national genebanks, which not only supports the reintroduction of varieties that have been lost locally but also provides a backup for the community collections. The project promotes complementarity between *in situ* and *ex situ* conservation and facilitates farmer-to-farmer seed exchange through the organization of seed and food fairs.

Since the beginning of the project, the number of farmers growing small grains in the target regions has tripled, with the percentage of farmers increasing from around 10 to 30 percent.[57] A total of 4 800 people, 63 percent of whom are women, have directly benefited from the project by participating in farmer field schools, and it is expected that 23 000 people will benefit indirectly through seed and food fairs, field days and capacity building. The project worked through consortia of plant genetic resources institutions and strengthened collaboration between governments, meteorological services, NGOs, rural councils, farmers' organizations, extension services and national, regional and international genebanks and research institutions. The project's participatory approach, tailored to address local challenges and needs, helped to increase the resilience of farmers to climate change.

For more information, visit http://www.fao.org/plant-treaty/areas-of-work/benefit-sharing-fund/projects-funded/bsf-details/en/c/359522/?iso3=ZWE and http://www.ctdt.co.zw/

Breeding with crop wild relativess and landraces

CWRs are key sources of genetic diversity for crop improvement and have been used to introduce traits such as pest and disease resistance, abiotic-stress tolerance and increased yield into cultivated varieties (Dempewolf *et al.*, 2017; Dwivedi *et al.*, 2016; Hajjar, Jarvis and Gemmill-Herren, 2008; van Treuren, Hoekstra and van Hintum, 2017).

For example, crossing with CWRs can increase resistance to heat stress in chickpea (Von Wettberg *et al.*, 2018). Some banana cultivars have been found to have better water-use efficiency than others and to be able to continue growing under mild osmotic stress (van Wesemael *et al.*, 2019). Wild lentils have a range of different strategies for adapting to drought, including delayed flowering, reduced transpiration rates and deep rooting, all of which could be used in crop improvement (Gorim and Vandenberg, 2017). Wild barley (*Hordeum spontaneum*) exhibits a wide range of traits related to drought and salinity tolerance (Lopes *et al.*, 2015; Nevo and Chen, 2010).

Cultivated rice (*Oryza sativa*) is particularly sensitive to heat stress, with yields declining by 10 percent for every 1 °C increase in mean minimum temperature during the dry cropping season (Peng *et al.*, 2004). *Oryza officinalis*, a wild relative, has early-morning flowering traits and thereby escapes heat stress during the daytime and avoids heat-induced spikelet sterility at flowering; it could therefore be of use in breeding rice cultivars that are able to cope with hotter climates (Hirabayashi *et al*., 2015). Successful fine-mapping of a gene responsible for submergence tolerance in a rice landrace has facilitated its crossing with a high-yielding variety without any apparent negative effects on productivity (Bailey-Serres *et al.*, 2010). Box 9 showcases the development of rice that tolerates submergence. Wild barley (*Hordeum spontaneum*) and wild emmer wheat (*Triticum dicoccoides*) exhibit a wide range of traits related to drought and salinity tolerance (Nevo and Chen, 2010). Wheat landraces have various traits that render them tolerant to heat and drought (Lopes *et al.*, 2015).

Potential trade-offs between adaptive traits and yield can occur and need to be carefully evaluated. Pre-field phenotyping in greenhouses or growth chambers where plant properties such as leaf water potential, transpiration rate, root and shoot length and growth rate are measured can help identify plants with desired traits (Negin and Moshelion, 2017).

As with neglected and underutilized crops, most breeding programmes for the improvement of CWRs and landraces are conducted by public institutions (see Box 9 and Box 10).

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[57] The project is being implemented in the following districts: Mzimba, Chikwawa, Rumphi (Malawi); Chikankata, Rufunsa, Shibuyunji (Zambia); Murehwa, Mutoko, Chipinge (Zimbabwe).

Both *in situ* and *ex situ* conservation of CWRs are important in ensuring their continued availability. *In situ* conservation has the benefit of allowing continued evolution and the generation of adapted populations, while *ex situ* conservation in genebanks facilitates characterization and future use in crop improvement (Castañeda-Álvarez *et al.*, 2015; Hunter and Heywood, 2011).

Box 9. Development and dissemination of "Scuba rice"

Extreme weather patterns caused by climate change mean that floods are becoming more likely (UNEP, 2020b). In recent years, severe cyclones have created extreme floods that have led to food insecurity for affected populations. "Scuba rice", a rice variety that tolerates submergence, was first bred by scientists at the International Rice Research Institute (IRRI) as a responce to regular flooding in India (Ismail *et al.*, 2012). The gene responsible for flooding tolerance was first discovered during a large-scale screening of the IRRI genebank collection (Ismail and Mackill, 2013). Using molecular markers, a QTL that conferred 70 percent of the phenotypic variation was mapped, and the corresponding gene (Sub1) later identified (Xu and Mackill, 1996). By means of marker-assisted backcrossing, the Sub1 gene was introgressed into different popular varieties, allowing them to withstand up to 17 days of submergence (Xu *et al*., 2006). In South and Southeast Asia, development of "Scuba rice" varieties targeted India, Bangladesh, Indonesia, Nepal, Mynamar, the Philippines, Cambodia, the Lao People's Democratic Republic, Thailand and Viet Nam in partnership with National Agricultural Research and Extension Systems (NARES) (IRRI and DFID, 2010).

IRRI scientists collaborated with national research systems, national and state governments, non-governmental organizations and public and private seed producers and breeders to multiply and disseminate seeds of Sub1 varieties (Emerick and Ronald, 2019). As a result, in 2017 alone, more than 6 million farmers in India, Bangladesh and Nepal grew Sub1 rice (ibid.). In addition, recent studies have been combining tolerance of several abiotic stresses, such as submergence, drought and salinity, in mega-varieties to improve resilience to climate change (Bharathkumar *et al.*, 2015; Ismail *et al.*, 2013).

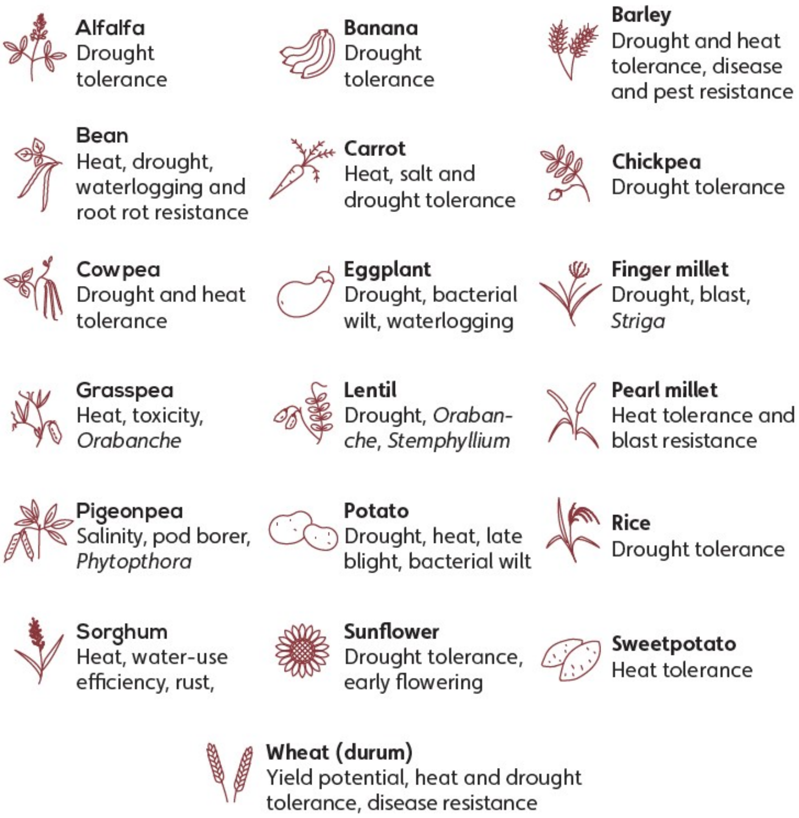
Box 10. The project Adapting Agriculture to Climate Change: Collecting, Protecting and Preparing Crop Wild Relatives

The project Adapting Agriculture to Climate Change: Collecting, Protecting and Preparing Crop Wild Relatives is a global, long-term effort to collect, conserve and use crop wild relatives (CWRs) to develop food and forage crops that thrive under climate change. The project is supported by the Government of Norway, managed by the Global Crop Diversity Trust and implemented in partnership with national and international genebanks and plant-breeding institutes around the world. It has four main components: prioritization of CWRs missing from genebanks based on global gap analysis; provision of support to collection missions for CWRs; conservation of CWRs in genebanks; and use of CWRs in pre-breeding efforts to prepare them for crop breeders and farmers.

Pre-breeding comprises the various activities undertaken to identify desirable characteristics or genes in non-domesticated and semi-domesticated varieties and introduce them into breeding lines that can be more easily crossed with modern varieties. The CWR pre-breeding initiative focuses on assessing germplasm derived from CWRs and evaluating them under field conditions in collaboration with breeders and farmers. The initiative includes more than 100 national and international partners from CGIAR centres, universities and non-governmental organizations in 48 countries. All projects include a strong emphasis on capacity building. Nineteen crops are currently being evaluated in pre-breeding programmes. The crops and the traits included in the project are listed in the figure below. The first CWR-derived new varieties developed by the project are expected to reach the market by 2022. All key germplasm material developed by the initiative will be made available through the Standard Material Transfer Agreement of the International Treaty on Plant Genetic Resources for Food and Agriculture.

The web database Germinate[1] was established in order to facilitate the sharing and use of data on the genetic materials studied in the initiative. It includes passport, phenotypic, field-trial, genetic, climatic and geographic-location data as well as user-submitted annotations.

Crops and traits investigated by the project



Sources: Global Crop Diversity Trust, (2019a, 2019b); The James Hutton Institut, (2020 (figure: Crop Diversity Trust 2019b, reproduced with permission).

5.2.3 Access to and adoption of plant genetic resources for food and agriculture

When the climate in a given location changes to such an extent that a variety normally grown there can no longer produce satisfactory yields, adopting a different variety, or in extreme cases a different species, may be the only way for farmers to sustain their livelihoods. These alternatives may be new improved varieties that have recently been put onto the market or established varieties that are commonly grown in climates that are similar to the one that is now emerging in the location in question. The suitability of a variety or species for a particular location depends both on the climatic conditions of the location and on the phenology and traits of the plants. In order to be used in adaptation to novel climates, germplasm needs to be accessible and available for exchange.

In northern China, maize production was adapted to a warming climate through the adoption of maize varieties with a longer growth period (Meng *et al.*, 2014). In South Australia, farmers switched to wheat varieties with a shorter cycle to adapt to increasing heat and drought (Robinson *et al.*, 2018). A study in Guatemala found that smallholder farmers' adaptation strategies included growing crops that they had previously not grown (Viguera *et al.*, 2019). Diversification of crops and adoption of new varieties were found to be the main adaptation strategies for farmers in southern Mali and in Italy (Nguyen, Seddaiu and Roggero, 2019; Sanogo *et al.*, 2017).

A study that modelled the effects of adaptation measures in the West Africa region found that adopting crops resistant to high-temperature stress during the flowering period resulted in higher yields than adopting rainwater harvesting, thus suggesting that adopting tolerant crops or varieties is a more effective option than adjusting watering practices (Parkes *et al.*, 2018).

Under the lead of the Standing Panel on Impact Assessment (SPIA), an external, impartial panel of experts in impact assessment, the CGIAR has implemented several projects that track the release and estimate the adoption of its improved varieties. The Tracking Improved Varieties in South Asia

(TRIVSA) project, implemented during the period 2010 to 2013, focused on the rainfed areas of South Asia (CGIAR, 2015a). It assessed the effectiveness of varietal improvement programmes focusing on the region's important food crops, including humid and subhumid varieties of rice and semi-arid varieties of sorghum, pigeon pea, pearl millet, groundnut and chickpea. The Diffusion and Impact of Improved Varieties in Africa (DIIVA) project collected data on improved crop varieties in Africa south of the Sahara (CGIAR, 2015b). The project focused on 20 crops and 30 countries – 152 crop–country combinations, together representing over 70 percent of the region's total agricultural production value.

Based on these two projects, the Strengthening Impact Assessment in the CGIAR (SIAC) project was implemented from 2013 to 2017. The project produced a database that includes varietal release and adoption estimates for 11 CGIAR mandated crops across 15 countries: 134 crop–country combinations in the South, Southeast and East Asia region (Maredia *et al*., 2016). Data were collected by the International Center for Tropical Agriculture (CIAT), CIMMYT, the Internaitonal Potato Centre (CIP), the International Rice Research Institute (IRRI), the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and their national partners and are based on expert estimates and a number of household surveys. The database is available on the Agricultural Science and Technology Indicators (ASTI) website of the International Food Policy Research Institute (IFPRI).[58]

The existence and availability of new adapted varieties does not necessarily guarantee their adoption by farmers. Farmers need to have access to them, which is not always possible, especially in the case of smallholder farmers in developing countries. Various factors can constrain access, including a lack of formal seed systems that link farmers to seed producers, inadequate infrastructure, limited mobility on the part of farmers (making it difficult for them to reach seed suppliers) and high prices that make improved varieties too expensive for farmers. Local seed markets are often the most important seed sources for smallholders; however, these markets have not been comprehensively considered in development projects (McGuire and Sperling, 2016).

Sociocultural factors may also play a role in varietal selection by small-scale farmers and therefore need to be taken into account in efforts to promote the adoption of new varieties (Mokuwa *et al.*, 2014). Even if farmers have access to improved varieties and sufficient funds to pay for them, they may still choose not to adopt them. For example, farmers may prefer certain morphological properties and dislike others – short stems, for instance, as they are considered to make threshing more difficult (Diallo *et al.*, 2018; Mokuwa *et al.*, 2014). A study in Mali found that new sorghum varieties were more likely to be adopted by farmers if they were developed through participatory plant breeding, thus allowing farmers to be directly involved in the process (Sissoko *et al.*, 2019). As women farmers usually handle the processing and cooking of crops, it is important to include them in participatory breeding efforts (see Box 8).

Seed systems

Atlin, Cairns and Das (2017) argue that successful adaptation to climate change will require active dissemination of new, resilient varieties developed within the last ten years and withdrawal of obsolete ones from the market. They further argue that while in developed countries this kind of shift is enabled by the presence of competitive seed markets, the lack of competitive seed systems in developing countries hinders the process (ibid.). A study in Ghana found that there is a need for increased collaboration between the government and research organizations in supplying the seeds of drought-tolerant varieties to producers (Azumah *et al.*, 2019). In Indonesia, strong government outreach and support for extension services led to widespread adoption of newly developed stress-tolerant rice varieties (Rumanti *et al.*, 2018).

Informal seed systems are important in the maintenance of neglected or underutilized crop species (FAO, 2010). However, the absence of formal seed systems for their distribution hinders their widespread adoption (Mabhaudhi *et al.*, 2019). In order to ensure adoption of improved varieties in developing countries, informal seed systems need to be taken into account and integrated with formal seed systems (Deu *et al.*, 2014; Westengen and Brysting, 2014). A study on potato seed networks in the Peru's central Andes found that seed networks continued to function after seasons of stress and thus

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[58] https://www.asti.cgiar.org/siac

worked as a safety net against crop failure (Arce *et al.*, 2018). Deu *et al.* (2014) argue that the complementarity of formal and informal seed systems leads to continuous availability of seeds and therefore increases food security.

Seed policies and their implementation significantly influence access to seeds, and thus the capability of farmers to adapt to climate change (Lopez-Noriega *et al.*, 2012). A study conducted in Rwanda, Uganda, Zambia and Zimbabwe found that national and regional seed laws prohibit the marketing of farmers' varieties within countries and across borders, thus hindering the adoption of potentially adapted varieties (Halewood *et al.*, 2017). In addition, most of these countries did not have online accession-level documentation, which makes it impossible to search for potentially adapted materials; insufficient implementation of the ITPGRFA and the Nagoya Protocol was further hindering the sharing of materials (ibid.)

A lack of sufficient quantities of basic commercial and registered seed has been found to be a more serious constraint to the availability of seed to farmers in developing countries than inadequate distribution systems (FAO, 2010). An analysis of the adoption of new maize varieties developed by CIMMYT's Drought Tolerant Maize for Africa[59] project (see Box 7) found that the unavailability of improved seed, inadequate information, lack of funds on the part of the farmers and high seed prices were hindering adoption in East and Southern Africa (Fisher *et al.*, 2015).

While the need to breed climate-resilient crops is mentioned by a number of countries in their NDCs, they generally do not refer to the dissemination and adoption of these new varieties. One exception is Cabo Verde, which seeks to strengthen capacity by promoting workshops on the introduction of crop varieties and species that are better adapted to prevailing climatic conditions.

5.2.4 Diversified cropping systems

At production-system level, interventions that increase diversity tend to increase resilience to the various effects of climate change (Gil *et al.*, 2017). Intercropping, for example, reduces the risk of complete crop failure, as the different crops grown will vary in their capacity to cope with particular climate change-related impacts, including diseases (IPCC, 2019a). Crop diversification can also improve the diversity of small-scale farmers' diets and contribute to their food security and nutrition, although depending on the crops grown this effect may not be consistent throughout the year (Brüssow, Faße and Grote, 2017; Mango *et al.*, 2018).

Cereal and legume intercropping systems have been found to increase yield stability relative to single cropping in the tropics, and their use can thus support the adaptation of crop production to climate change (Raseduzzaman and Jensen, 2017). A study in the upper Blue-Nile basin in Ethiopia found that some farmers adopt crop rotation as an adaptation strategy, an option that can enhance soil fertility and water-use efficiency (Nigussie *et al.*, 2018). A study in Nigeria found that farmers are switching to mixed-cropping systems and crop rotation to adapt to climate change (Onyeneke *et al.*, 2018).

Mixing different varieties of the same crop within a field can also increase resilience to climate change impacts. For example, a study in Uganda found that farmers perceived that using varietal mixtures of common bean and banana provided higher yield than using only one variety (however, no empirical yield data were available to confirm this perception) (Nankya *et al.*, 2017). Mixtures of wheat cultivars can have higher yields than single varieties, but further research is needed to determine the mechanisms that control the performance of such mixtures in relation to biotic and abiotic stress tolerance (Borg *et al.*, 2018).

Both crop rotations and intercropping can help decrease pest and disease pressure on crops (Murrell, 2017). A climate-adapted "push–pull" system, in which maize is grown with greenleaf desmodium as an intercrop and *Brachiaria* cv mulato as a border crop to keep striga weed and stemborers out of the maize crop was found to provide yields that were 2.5 times higher than those from maize monocultures in dry areas of Kenya, Uganda and the United Republic of Tanzania (Midega *et al.*, 2015).

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[59] For more information, see http://dtma.cimmyt.org/index.php/about/background.

Integrated rice–aquaculture production can increase farmers' resilience to salinity intrusion, as it can be adapted to both freshwater and brackish water and allows for income diversification (Renaud *et al.*, 2015).

While diversification is mentioned by a few countries in their NDCs, there is no indication that it is consistently used as an adaptation strategy to deal with the effects of climate change.

5.3 Mitigation

PGRFA contribute to climate change adaptation to a greater extent than to climate change mitigation. However, the improvement of PGRFA for adaption to climate change also has mitigation benefits. Adapting to drought by increasing plants' water-use efficiency means that less water is needed for irrigation. A crop that is resistant to pests and diseases needs fewer pesticides. All these mechanisms reduce greenhouse-gas emissions from crop production.

Key mitigation actions in crop production are centred around reducing nitrous-oxide emissions from fertilizer applications and reducing methane emissions from rice paddy fields through improved water management rather than around PGRFA management (IPCC, 2019a). If PGRFA are considered in mitigation actions, it is usually at production-system or species level, for example intercropping to reduce soil respiration and increase carbon sequestration or using legume cover crops to reduce or avoid the use of nitrogen fertilizer, which due to nitrous-oxide emissions is one of the largest sources of greenhouse-gas emissions from conventional agriculture (ibid.).

Growing perennial grains instead of annual ones has the potential to sequester carbon and avoid nutrient leakage, and combining them with nitrogen-fixing legumes reduces the need for nitrogen fertilizer (ibid.). Legumes can also contribute directly to carbon sequestration, which has been found to be correlated with nitrogen fixation in soybean (Mapope and Dakora, 2016). Seeding legumes and integrating higher productivity varieties of grasses have been shown to increase carbon sequestration in grasslands (Ogle, Conant and Paustian, 2004).

The inclusion of cover crops in cropping systems has the potential to sequester an estimated 0.12 ± 0.03 Pg of carbon per year if applied at a global scale (Poeplau and Don, 2015). However, cover crops have been found to lead to reduced drainage and thus may lead to water-management issues in areas with shallow groundwater (Tribouillois, Constantin and Justes, 2018).

Only a small number of countries refer to the management of PGRFA as a mitigation action in their NDCs. Madagascar mentions the large-scale dissemination of improved rice-farming techniques, such as sustainable rice intensification. Malawi mentions that nitrogen-fixing plants are used to reduce fertilizer usage as a mitigation measure. In Uruguay, cover crops are used in soybean cultures, and good grassland-management practices are being adopted to reduce the loss of soil organic carbon and favour carbon sequestration. Bhutan mentions the establishment of hay meadows with high-yielding fodder legumes and grasses under conditions of high nutrient supply to reduce grazing pressure on forests.

Many countries mention mitigation actions involving PGRFA in their National Communications (NCs).[60] For example, Tonga mentions plant breeding aimed at developing and introducing varieties that perform well in soils with low fertility, thus reducing the use of nitrogen fertilizer and, in turn, nitrous-oxide emissions. Haiti refers to the genetic improvement of crops for better water-use and nutrient-use efficiency. Burundi mentions nitrogen-fixing plants. Myanmar mentions the selection of high-yielding rice cultivars with low methane emissions. Pakistan plans to introduce genetically modified crops that are more carbon responsive. Armenia mentions the introduction of grass species with higher productivity or carbon allocation to deeper roots.

To sum up, mitigation actions involving PGRFA are mainly production system-level interventions or focused on specific species. One exception is the selection of rice varieties that lower methane emissions.

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[60] National Communications are a type of report submitted by the countries that have ratified the United Nations Framework Convention on Climate Change (UNFCCC). They are prepared according to guidelines that have been agreed on by the Conference of the Parties to the UNFCCC and are more detailed than the NDCs.

5.4 Conclusions and recommendations

The effect of climate change on PGRFA has been extensively studied for all major crops around the world. A wealth of information is available at species level for staple crops, but there are also data for some commercial vegetable and fruit crops, and an increasing number of studies are looking at effects at variety or genetic levels. The effects of drought, heat and heavy rainfall are the most commonly investigated. The majority of studies focus on yield. Some consider the effect of climate change on phenology and nutrient content.

In most regions, the effects of climate change on PGRFA are negative, leading to reduced yields or in extreme cases to the unsuitability of currently grown species and varieties. The mean yields of staple crops such as maize, wheat and soybeans are projected to decline as the climate continues to change. The majority of regions around the world will be facing yield reductions, and therefore national climate change policies need to anticipate these impacts by supporting the adoption of adapted varieties and species.

Climate change is also expected to increase the range and incidence of some pests and diseases, which can have impacts both on yield and on food safety. This needs to be addressed by developing and selecting resistant varieties, by promoting the use of practices that reduce pest and disease pressure, such as cover cropping and intercropping, and by developing early-warning systems.

There is a lot of research looking at the genetic mechanisms responsible for controlling traits related to climate change adaptation and mitigation. The stresses most commonly analysed are drought and heat, and some research focuses on flooding tolerance.

Characterization, evaluation, conservation and exchange of PGRFA play key roles in successful adaptation to and mitigation of climate change. The sharing of characterization and evaluation information and the facilitation of access to other non-confidential research outputs through regional and global information systems are key to the improvement of collaborative research and plant breeding for adaptation. Efforts need to be made to identify traits that may be relevant to sustaining production in a changing climate. These traits should be included in existing collections and breeding pools and their associated information made available through regional and global information systems.

The Multilateral System of Acess and Benefit-sharing of the ITPGRFA makes available 2.2 million documented accessions, most of them coming from national collections. More emphasis needs to be placed both on sharing and on using material through this facilitated mechanism that provides access expeditiously and according to multilateral rules.

There are public breeding initiatives that specifically target traits related to climate change. Traits such as drought resistance are considered in commercial breeding programmes, as new varieties need to grow in various environments to be commercially successful. However, they do not represent a major breeding goal. Allocating funds to public breeding initiatives and public−private partnerships could further support the development of new climate-resilient varieties.

There is a need to continuously develop PGRFA through breeding to adapt them not just to current but also to future changes in climate. Adequate funding needs to be allocated to breeding programmes that specifically target traits that make crops more climate resilient. Breeding programmes should consider various climate change scenarios and aim to develop crops that can sustain yields under a range of possible future climates.

In recent years, there has been a growing interest in neglected and underutilized crops and their improvement in the context of climate change. This can be supported by policies and the allocation of funding for breeding programmes for underutilized crops.

Although many new varieties are released every year, not all are adopted by farmers. Barriers to adoption can include lack of availability of improved seeds, lack of information and high prices. While some studies are looking into the adoption of new varieties, there are significant knowledge gaps. Studies of successful adaptation should be used to develop best practices. Strategies that ensure that new varieties are integrated both into formal and into informal seed systems are needed.

Crop diversification has the potential to support farmers' adaptation to climate change. Extension services should promote the use of variety mixtures, intercropping and crop rotations. In order to enable farmers to better support their livelihoods, policies should aim to support diversified cropping systems.

Mitigation actions involving PGRFA are mainly production-system level interventions. The use of cover crops and legumes can significantly contribute to carbon sequestration, and their use should be promoted more systematically. Aside from that, efforts to increase resource-use efficiency in crop production also contribute to mitigation.

While some countries do consider the roles of PGRFA in climate change adaptation and mitigation in their NDCs, they are not consistently considered across the world. Given their immense potential to support efforts to maintain agricultural production in a changing climate, there is a need to further raise awareness of their importance and fully integrate their use into adaptation and mitigation planning.

VI. MICRO-ORGANISM AND INVERTEBRATE GENETIC RESOURCES FOR FOOD AND AGRICULTURE

Micro-organism and invertebrate genetic resources for food and agriculture (MIGR) contribute a range of invaluable ecosystem services to terrestrial and aquatic food production systems. Soil organisms cycle nutrients and make them available to crops, insect pollinators pollinate a wide range of crops, rumen micro-organisms allow ruminants to digest plant material that would otherwise be indigestible, and biological control organisms prey on pests. Around the world, invertebrates are used as food and feed, and micro-organisms are used to ferment foods. Many micro-organisms and invertebrates are not well characterized, although molecular tools are contributing to increased knowledge of their genetic diversity of MIGR (FAO, ITPS, GSBI, SCBD and EC, 2020).

6.1 The impact of climate change on micro-organism and invertebrate genetic resources for food and agriculture[61]

Micro-organisms and invertebrates occur in many different environments and are affected by climate change in many different ways. Micro-organisms that are kept in laboratories under controlled conditions are relatively protected from changes in climate, but only as long as electricity for cooling is available.

Soil-dwelling micro-organisms and invertebrates are components of highly complex ecosystems that are strongly influenced by the climate. Changes in precipitation and temperature lead to changes in vegetation type and soil community composition and diversity, which in turn affects processes such as organic matter accumulation and decomposition, and nutrient cycling (Maestre *et al.*, 2015; Coleman, Callaham and Crossley, 2018; Coyle *et al.*, 2017; Chen *et al.*, 2019;). Small changes can result in cascading effects across a wide range of soil organisms. Most studies of the impact of climate change on soil organisms focus on functional groups rather than on specific species (FAO, ITPS, GSBI, SCBD and EC, 2020).

Higher temperatures can lead to increased growth and activity among soil organisms, especially in formerly cold climates. Increased activity often means that organic matter is decomposed and stored carbon is released into the atmosphere, thus turning soil from a carbon sink into a carbon source (FAO, ITPS, GSBI, SCBD and EC, 2020). Warmer and dryer climates have been found to alter soil community composition in peatlands, one of the largest terrestrial carbon sinks, and thus are likely to negatively affect peat accumulation and carbon storage (Juan-Ovejero *et al.*, 2019). Mycorrhizal fungi seem to have narrower tolerance of climatic changes than pathogenic fungi (Větrovský *et al.*, 2019).

Increased levels of CO_2 in the atmosphere initially enhance photosynthesis and can lead to higher accumulation of carbon in soils in the short term. However, this effect does not persist in the long term, as increased atmospheric CO_2 also leads to increased decomposition of organic matter in soils (van Groenigen *et al.*, 2017). Earthworm activity and biomass increase with higher temperatures and sufficient soil moisture, but are negatively affected by drought and flooding, with notable differences in adaptability to these stresses between species (Singh *et al.*, 2019).

Aside from direct impacts of climate change, soil organisms are indirectly affected through changes in, or loss of, vegetation due to drought, increased precipitation, temperature changes or fire.
The responses of soil biodiversity to climate change are difficult to predict and will be strongly influenced by the starting condition of the soil in terms of biological activity and vegetation type (FAO, ITPS, GSBI, SCBD and EC, 2020).

Pollinators play a key role in global food security, as pollinator-dependent crops contribute up to 35 percent of global crop production volume (IPBES, 2017). The largest group of invertebrate pollinators are bees, but some species of flies, butterflies, moths, wasps and beetles also contribute to pollination (ibid.). The impact of climate change on pollinators, in particular on bees, has been the focus of many studies and assessments (e.g. FAO, 2011; IPBES, 2017). Pollinators are impacted by climate change in various ways. Climate change has resulted in range shifts, changes in abundance and shifts

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[61] This section draws from FAO, ITPS, GSBI, SCBD and EC (2020).

in seasonal activities in several pollinator species, and these changes are projected to increase (IPBES, 2017).

As pollination involves a mutualistic interaction between an animal species and a plant species, climate change can disrupt it by differently affecting the ranges of the species or the timing of their growth stages. If, for example, the timing of the life stages of a plant depends on day length, but the development of its pollinator depends on temperature, a change in the climate may mean that the flowering time of the plant is no longer synchronous with the emergence of the pollinator (IPCC, 2019a; Settele, Bishop and Potts, 2016). The fate of pollinators is closely linked to the fate of the plants they pollinate. When flowering plants are affected by dryness, wetness or flooding, food sources for pollinators decline (Walter, 2020). The predicted increase in climate variability due to climate change may also lead to higher pollinator mortality (Switanek *et al.*, 2017).

6.2 The role of micro-organism and invertebrate genetic resources for food and agriculture in climate change adaptation and mitigation

Many components of MIGR can be managed sustainably to contribute to climate change adaptation and mitigation. Soil micro-organisms and invertebrates in particular have many roles in increasing the resilience of soils to the impacts of climate change and mitigating its impacts through the storage of carbon, a process referred to as carbon sequestration.

The most efficient way to use soil micro-organisms and invertebrates in climate change mitigation is to avoid the loss of carbon already present in the soil (FAO, ITPS, GSBI, SCBD and EC, 2020). Agricultural land use is estimated to have led to the loss of 133 Pg of carbon from soils globally (Sanderman, Hengl and Fiske, 2017). Conventional tillage disrupts soil communities, decreases the abundance of earthworms and increases microbial respiration, thus reducing the amount of carbon in the soil (Briones and Schmidt, 2017; Lago, Gallego and Briones, 2019). Practices that improve carbon sequestration and reduce its loss by improving cropland and grassland management have great potential in climate change mitigation (IPCC, 2019a). Management practices such as conservation agriculture, organic agriculture and no-till, where soil disturbance is kept at a minimum, crop residues are retained and green manure or organic amendments such as mulch and compost are used, can reduce the net loss of carbon or even increase carbon stocks in agricultural soils (FAO, ITPS, GSBI, SCBD and EC., 2020; Garibaldi *et al.*, 2017; Powlson *et al.*, 2016; Skinner *et al.*, 2019). Biochar is a carbon-rich soil amendment produced through pyrolysis, a process in which organic material is exposed to high temperatures in the absence of oxygen. Biochar has considerable potential for use in carbon sequestration, because it does not degrade easily and remains in the soil for a long period of time (Wang, Xiong and Kuzyakov, 2016).Carbon-rich landscapes such as wetlands, peatlands, forests and permanent grasslands should be protected and restored (FAO, ITPS, GSBI, SCBD and EC, 2020; Kolka *et al.*, 2016).

Soils with a higher amount of soil organic carbon have a greater capacity to hold water than soils with depleted carbon stocks and therefore are more likely to maintain crop yields in the event of a drought (EASAC, 2018). Therefore, increasing soil organic carbon has benefits for both adaptation and mitigation. Some studies suggest that the presence of some macroinvertebrates in the soil may offer some protection from the negative effects of climate change (FAO, ITPS, GSBI, SCBD and EC, 2020). For example, the presence of termites is associated with greater soil moisture in dry conditions, and the presence of earthworms has been found to reduce the effects of warming on below-ground biodiversity (Ashton *et al.*, 2019; Siebert *et al.*, 2019). Conserving the diversity of groups of soil engineers, such as termites and earthworms, can have cascading positive effects on other soil organisms, and therefore increase the overall resilience of soils to climate change. The increasing knowledge of soil biodiversity at global scales will make it possible to link specific functional groups to terrestrial carbon stocks and devise strategies to better protect them (FAO, ITPS, GSBI, SCBD and EC, 2020).

Adopting different bee species that suit local conditions and have traits relevant to climate change adaptation, such as drought resistance, can potentially be a way of maintaining pollination services in the context of climate change. However, this approach bears the risk that the introduced species or subspecies may become invasive and place additional pressure on native species by competing for food resources. The bumblebee *Bombus terrestris*, for example, has been introduced into many countries for crop pollination and has outcompeted some local bumblebee species (Geslin and Morales, 2015; Rendoll-Carcamo *et al*., 2017).

One-third of the world's population, mostly in Africa, Asia and Latin America, traditionally eat insects (Raheem *et al.*, 2019). Edible insects are sources of proteins, amino acids and lipids, and play an important role in food security (Jantzen da Silva Lucas *et al.*, 2020; Raheem *et al.*, 2019). Owing to their fast reproduction, low resource use and low greenhouse-gas emissions compared to livestock, invertebrates are a sustainable food source (Alexander *et al.*, 2017). Their high food conversion efficiency makes them a viable alternative to livestock when feed resources are scarce and thus important resources for climate change adaptation (van Huis and Oonincx, 2017; Imathiu, 2020). Increasing the share of insect-derived protein in animal feed has the potential to reduce greenhouse-gas emissions from livestock production, but no study has quantified this potential to date (IPCC, 2019a).

While invertebrates have been approved for human consumption in Europe, consumption remains low, mainly due to low customer acceptance (Caparros Megido *et al.*, 2016). Food preferences are strongly influenced by social and cultural factors (Huis, Dicke and Van Loon, 2015; Looy, Dunkel and Wood, 2014). Transitional products in which the invertebrate is not recognizable (e.g powders) may help increase consumer acceptance (Caparros Megido *et al.*, 2016). A study found that exposure to the concept of eating insects was a determining factor in in the willingness of consumers to try them, thus highlighting the potential of information campaigns to increase consumption (Woolf *et al.*, 2019). Acceptance will probably also be influenced by pricing, perceived environmental benefits and the taste of the products (van Huis, 2013).

It is difficult to assess the number of existing breeding programmes for MIGR, as they may be conducted by private companies who sell MIGR for food processing, pollination or biological control. Information on the status and trends of bee breeding programmes can be found in *The State of the World's Biodiversity for Food and Agriculture* (FAO, 2019a). The genotype of a plant is known to affect its associated soil microbial community, and therefore understanding which genes play a role in attracting beneficial micro-organisms and selecting for them will improve crop productivity (Corbin, Bolt and Rodríguez López, 2020).

Improving understanding of the micro-organisms involved in digestion, particularly in ruminants, will provide a basis for interventions that improve the efficiency of feed utilization and reduce GHG emissions (McSweeney and Mackie, 2012; Haque, 2018). A range of rumen manipulation technologies, including genetic manipulation of rumen micro-organisms, are being explored (Galmessa *et al*., 2019).

Countries generally do not refer to the management of micro-organisms or invertebrates in their NDCs. One exception is Thailand, where micro-organisms are used as fertilizers. A number of countries, however, mention soil management practices as mitigation actions. For example, China mentions the adoption of management practices for natural grasslands that avoid the loss of soil organic carbon, and Mongolia mentions the improvement of pasture management in order to increase carbon sequestration.

6.3 Conclusions and recommendations

A growing number of studies have investigated the impact of climate change on MIGR, in particular on insect pollinators and soil micro-organisms and invertebrates. As there are so many of them, many invertebrate and micro-organism species are still undescribed or have not been studied thoroughly. For most, there are still major gaps in knowledge regarding their capacity to adapt to climate change and their potential uses in climate change mitigation. However, knowledge is constantly increasing. As MIGR provide many essential ecosystem services to agriculture and food systems, understanding how they are affected by climate change is essential.

Soil micro-organisms and invertebrates in particular have important roles in climate change adaptation and mitigation, and these depend on sustainable soil management. Adopting conservation agriculture, reducing the use of inorganic fertilizer and pesticides, cover cropping, mulching and retaining crop residues can both contribute to making soils more resilient to the effects of climate change and to mitigating climate change through increased carbon sequestration.

Management of MIGR needs to be adapted to the local environment. There are no “one size fits all” solutions. In very humid soils, for example, retaining crop residues may lead to rot and the outbreak of fungal diseases, and therefore this should only be done if the climate is sufficiently dry. While some pollinator species may be more adapted to climate change impacts than others, introducing alien species into a new territory may mean that they become invasive and lead to the loss of native species.

While there are many potential uses of MIGR in climate change adaptation and mitigation, they are usually not considered by countries in their climate change strategies. Research findings and sustainable management practices need to be brought to the attention of decision-makers in order to ensure that MIGR become part of the climate change agenda.

VII. MAIN CONCLUSIONS AND RECOMMENDATIONS

Genetic resources are contributing to climate change adaptation in various ways. Farmers, livestock keepers, fisherfolk and forest dwellers are using stress-tolerant animals and plants to adapt their production strategies to the effects of climate change. Increasing the resilience of food systems through diversification helps them to adapt to climate change.

Genetic resources can also support climate change mitigation. Tree-planting is used to sequester CO_2 from the atmosphere, and sustainable soil-management practices and the restoration of aquatic ecosystems such as seagrass beds has the potential to contribute greatly to carbon sequestration. Research is being conducted and management practices adapted with the aim of reducing greenhouse-gas emissions and increasing the efficiency of resource use.

There are many examples of locally adapted, diverse management systems that are resilient to climate change impacts, use resources efficiently, provide food and support livelihoods. Diverse systems with adaptation and mitigation co-benefits are particularly important in the context of climate change.

The impact of climate change on GRFA has been and continues to be studied, and there is scientific consensus that this impact is overwhelmingly negative. Suitable areas for certain types of crops, trees, livestock and aquatic species will shift or become smaller. Many pests and diseases are expected to become more widespread. Drought and heat will negatively affect many species and ecosystems relevant to food and agriculture. Knowledge is continuously increasing, and this helps to inform policy-making.

Production systems in all countries rely on genetic resources originating from other parts of the world, and this interdependency will increase in the future as novel climatic conditions render some breeds and varieties unsuitable for the regions in which they have traditionally been produced. Fair and equitable access to GRFA needs to be ensured.

A number of countries have recognized that GRFA play an important role in climate change adaptation and mitigation, and have included them in their NDCs. Some have included resilience to climate change in their national plant or livestock breeding plans. The latest IPCC reports refer to the role of GRFA, in particular to PGRFA, in climate change adaptation and mitigation.

Current breeding goals commonly include traits that are relevant to climate change adaptation and mitigation, such as robustness, resilience to particular stresses, and feed or nutrient efficiency. Advances in biotechnology and a decline in the cost of sequencing have significantly increased knowledge of genetic mechanisms of relevance to climate change adaptation and mitigation, especially in commercially important crop and tree species and livestock breeds. While these technological developments have been important in making breeding faster and more targeted, they should not be considered the only way to breed climate-resilient breeds and varieties. Participatory breeding approaches are also important, as they can guarantee that the improved varieties or breeds fit the needs of farmers and are therefore likely to be adopted.

There are still a number of knowledge gaps related to the use of GRFA in climate change adaptation and mitigation. While there are many breeding activities aimed at improving the climate resilience of major types of crops and livestock, there are hardly any quantitative data on their adoption and use. Such data could be collected via the country reports for the Commission’s global assessments (*State of the World* reports).

Furthermore, there is currently little information available on how, and to what extent, policies that support the integration of genetic resources into climate change adaptation and mitigation are implemented. For example, most countries do not specify whether they consider tree provenances or focus solely on species in their reforestation efforts under their REDD+ strategies. Such information may become available as the UNFCCC process advances.

In order to fully take advantage of genetic diversity in climate change adaptation and mitigation, characterization and conservation need to be improved. The wide variety of traditional, locally adapted crop varieties and livestock breeds can only be useful in climate change adaptation and mitigation if they exist in sufficient numbers to be sustainably used and if their specific characteristics are known and documented. Characterizing existing genebank collections and securing their funding is of utmost importance.

Most research related to GRFA and climate change is taking place in the developed regions of the world, while needs are greatest in developing regions. Improving technology transfer and promoting endogenous innovation are therefore essential.

Due to the urgency of the threat of climate change, action needs to be a priority. Existing policies need to be implemented, and should be allocated the necessary funds. The Voluntary Guidelines to Support the Integration of Genetic Diversity into National Climate Change Adaptation Planning should be used where GRFA has not yet been included in climate change adaptation and mitigation policies (FAO, 2015b).

Although awareness is increasing, the potential to use genetic resources in climate change adaptation and mitigation is largely untapped. There is no comprehensive adoption of diversified management practices or locally adapted breeds or varieties. Institutional measures that promote the scaling up of adaptation efforts at local, regional and global levels are needed (IPCC, 2019a).

Given that climate change adaptation and mitigation will require acton over the long term, long-term funding needs to be secured for projects and programmes in these fields. It is particularly important to continuously monitor carbon sequestration projects, as they can only make a difference in the fight against climate change if the carbon remains stored for a long period of time. If a planted forest is harvested or an aquatic ecosystem is degraded ten years after having been planted or restored, the stored carbon will return to the atmosphere and the mitigation effect will be reversed.

It is crucial for restoration and carbon sequestration projects to choose species or provenances that are adapted to the current or future climate of an area. Particular focus should also be laid on scaling up successful projects and diverse production systems that are resilient to climate change, use resources efficiently and contribute to climate change mitigation. Based on the work that has already been done, good practices can be developed and disseminated. It is important to ensure that practices and projects are adapted to the local context, as climate change impacts will vary strongly within regions. Participatory approaches that include traditional knowledge should be prioritized, so that the needs of local farmers, livestock keepers, fisherfolk, fish farmers and forest dwellers are addressed and that they have agency over the project, which should help ensure its long-term implementation.

The challenges that climate change poses are complex, and therefore the responses need to be equally complex. In order to scale up the use of GRFA in climate change adaptation and mitigation, continuous actions at all levels are necessary: research, breeding, characterization, conservation, sustainable management, policy development and awareness raising. Only with coordinated action at all levels can the use of GRFA in climate change adaptation and mitigation reach its full potential.

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