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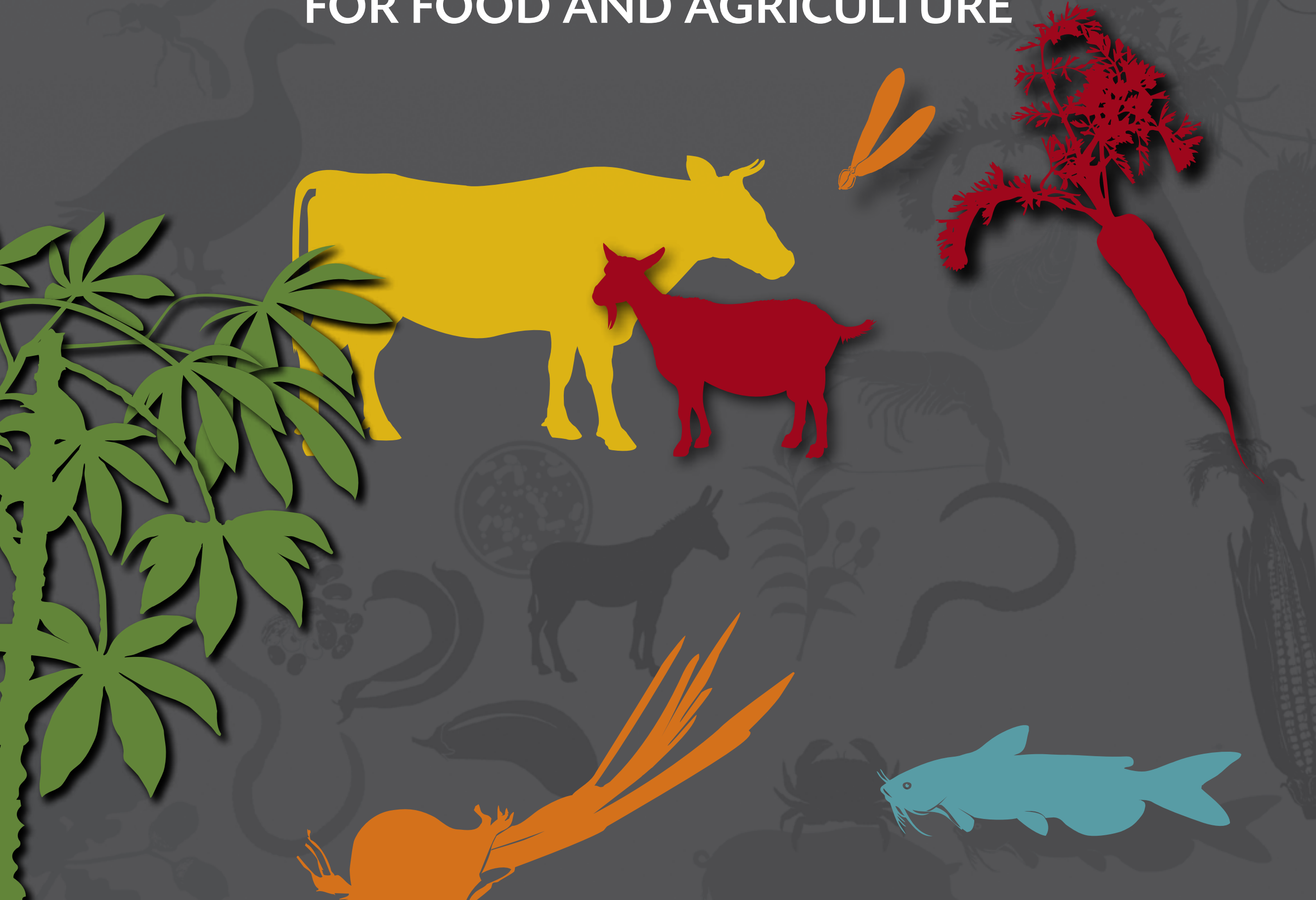
COPING WITH
CLIMATE CHANGE

THE ROLES OF GENETIC RESOURCES FOR FOOD AND AGRICULTURE



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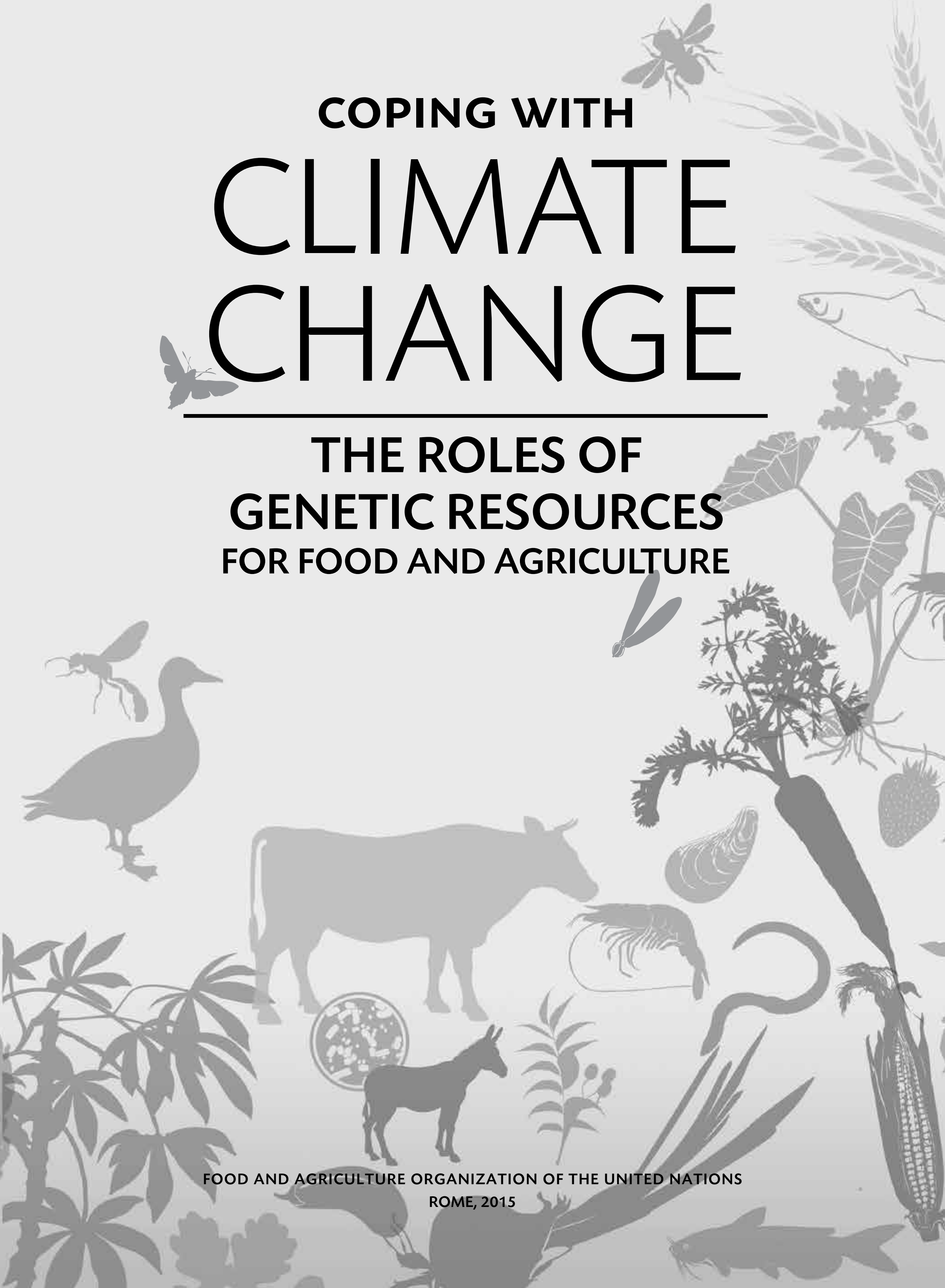

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Foreword

Tackling climate change is central to achieving a sustainable future for the world's growing population and food security must lie at the heart of these efforts. Climate change is one of the key drivers of biodiversity loss. The stressors and risks posed by climate change to the various sectors of genetic resources for food and agriculture (plants, animals, forests, aquatic resources, invertebrates and micro-organisms) are manifold. However, genetic resources for food and agriculture are also expected to play a significant role in mitigation of and adaptation to the consequences of climate change in support of efforts to achieve food security and nutrition objectives.

Genetic resources could contribute greatly to our efforts to cope with climate change, but in many cases the magnitude and speed of climate change will surpass our ability to identify, select, reproduce and – eventually – use these resources in the field. Climate change is already affecting natural ecosystems and food production systems. In its Fifth Assessment Report, Climate change 2014, the Intergovernmental Panel on Climate Change (IPCC) considers, among other things, the vulnerability of human and natural systems, the observed impacts of climate change and the potential for adaptation. The IPCC Synthesis Report recognizes that agriculture offers unique synergies that can contribute to efforts to meet the climate change adaptation and mitigation needs of the coming decades, in support of food security goals. Decisions and actions related to the management of genetic resources for food and agriculture need to be taken in a timely manner if we want to adapt agriculture to the effects of a changing climate. Future use of genetic resources for food and agriculture in climate change adaptation and mitigation depends upon ensuring that the relevant resources remain available.

The Commission on Genetic Resources for Food and Agriculture of the Food and Agriculture Organization of the United Nations (FAO) provides an intergovernmental forum for the discussion and development of knowledge and policies relevant to biodiversity for food and agriculture. Its work on climate change is of tremendous importance in supporting food global security and sustainable development, for present and future generations.

Maria Helena Semedo

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Since its establishment, the Commission on Genetic Resources for Food and Agriculture has overseen global assessments of the state of the world's plant, animal and forest genetic resources for food and agriculture and negotiated major international instruments, including the International Treaty on Plant Genetic Resources for Food and Agriculture. To explore the interactions between climate change and genetic resources for food and agriculture, the Commission has incorporated work on climate change into its Multi-Year Programme of Work and, in April 2013, adopted a Programme of Work on Climate Change and Genetic Resources for Food and Agriculture.

To review the state of knowledge on the impact of climate change on genetic resources for food and agriculture and to discuss the potential roles of these resources in adaptation to and mitigation of climate change, the Commission requested FAO to conduct a scoping study on climate change and genetic resources for food and agriculture. Based on several thematic studies, this publication presents an overview of the complex interactions between climate change and plant, animal, forest, aquatic, invertebrate and micro-organism genetic resources.

A scene-setting introductory section, providing a brief overview of the main international processes relevant to climate change, is followed by six sections dealing with the various sectors of genetic resources. Each section addresses two key questions: 1) What are the possible effects of climate change on genetic resources for food and agriculture and how does it influence their management? 2) What are the specific roles of genetic resources for food and agriculture in coping with climate change? The book ends with a discussion of the main conclusions and opportunities identified.

This publication aims to raise awareness of the important roles of genetic resources for food and agriculture in coping with climate change and to contribute to the mainstreaming of genetic resources for food and agriculture into climate change adaptation and mitigation planning at national and international levels.

Linda Collette

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Secretary of the FAO Commission on Genetic Resources for Food and Agriculture

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The sections in this book on plant, animal, forest, aquatic, invertebrate and micro-organism genetic resources were adapted by Dafydd Pilling from thematic studies produced for the FAO Commission on Genetic Resources for Food and Agriculture. He is thanked for his work.

Overall leadership was provided by Linda Collette. FAO staff and expert individuals – including Devin Bartley, Ehsan Dulloo, Kakoli Ghosh, Mathias Halwart, Kathrin Hett, Alexandre Meybeck, Albert Nikiema, Hope Shand, Oudara Souvannavong and Kim-Anh Tempelman – who provided comments and inputs during the preparation of this book are gratefully acknowledged.

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Summary

Genetic resources for food and agriculture play a crucial role in food security, nutrition and livelihoods and in the provision of environmental services. They are key components of sustainability, resilience and adaptability in production systems. They underpin the ability of crops, livestock, aquatic organisms and forest trees to withstand a range of harsh conditions. Thanks to their genetic diversity plants, animals and micro-organisms adapt and survive when their environments change. Climate change poses new challenges to the management of the world's genetic resources for food and agriculture, but it also underlines their importance.

At the request of the Commission on Genetic Resources for Food and Agriculture, FAO prepared thematic studies on the interactions between climate change and plant, animal, forest, aquatic, invertebrate and micro-organism genetic resources. This publication summarizes the results of these studies.

Agriculture, fisheries, aquaculture and forestry face the challenge of ensuring the food security of an additional 3 billion people by 2050. It has been estimated that this will require a 60 percent increase in global food production. Climate change is expected to make the task of achieving food security even more challenging, especially in the most vulnerable parts of the developing world. In these areas in particular, adapting agriculture, fisheries, aquaculture and forestry to the effects of climate change will be imperative for survival.

While the United Nations Framework Convention on Climate Change (UNFCCC) recognizes the important role of forests and other terrestrial and marine ecosystems in tackling climate change, the roles of genetic resources for food and agriculture have not been recognized explicitly. At first, most of the UNFCCC's work focused on climate change mitigation. In 2001, it began addressing the urgent and immediate adaptation needs of least developed countries. In 2010, Parties to the UNFCCC affirmed that adaptation should be addressed at the same level of priority as mitigation. The Parties established the Adaptation Committee and initiated the national adaptation plan process to address medium- and long-term adaptation needs.

The general lack of attention given to genetic resources in the international climate change arena results largely from a lack of awareness. While in the agricultural sector there is a clear understanding of the need to maintain and sustainably use

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genetic diversity in order to respond to ever-changing production conditions, there is an urgent need for greater awareness of the roles and values of genetic resources for food and agriculture among those engaged in climate change discussions.

Impacts of climate change on agriculture, forestry, aquaculture and fisheries

Climate change will cause shifts in the distribution of land areas suitable for the cultivation of a wide range of crops. Studies indicate a general trend towards the loss of cropping areas in sub-Saharan Africa, the Caribbean, India and northern Australia, and gain in the northern United States of America, Canada and most of Europe. Although farmers have always adapted their cropping systems to adverse environmental conditions, the speed and complexity of climate change pose problems on an unprecedented scale. Without adaptation and mitigation, climate change is predicted to negatively affect the production of the world's major crops in both tropical and temperate regions. There is evidence that climate change has already negatively affected wheat and maize yields in many regions.

Climate change will also create problems for the livestock sector. Heat stress, for example, reduces animals' appetites, production and fertility, and increases mortality rates. Feed supplies may be affected both locally (e.g. loss of grazing land because of drought) and globally (e.g. rising grain prices). Animals' water requirements increase with temperature, but in many places climate change is likely to mean that water becomes scarcer and supplies become more unpredictable.

Climate change affects ecosystem dynamics in various ways. Potential consequences include asynchrony between crop flowering and the presence of pollinators, and the spread of favourable conditions for invasive alien species, pests and parasites. As ecosystems change, the distribution and abundance of disease vectors are likely to be affected, with consequences for the epidemiology of many crop and livestock diseases.

Unfortunately, climate change also threatens the survival of the strategic reservoir of crop and livestock genetic resources needed to adapt production systems to future challenges. As conditions change, varieties and breeds may be abandoned by farmers and livestock keepers, and may be lost forever if steps are not taken to ensure their conservation. Catastrophic extreme weather events such as floods and droughts, which in many parts of the world are expected to become more frequent because of climate change, can pose an immediate threat to the survival of breeds and varieties that are raised only in specific small geographical areas.

Forest tree populations are unlikely to be able to migrate sufficiently quickly to keep pace with the changing climate. They will therefore have to adapt *in situ*, relying on their phenotypic plasticity and genetic diversity. Some scientists think that many tree populations will be able to cope relatively well with the effects of climate change. Others foresee significant problems. Predictions for tropical tree species tend to be more pessimistic than those for temperate and boreal species.

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The impact of climate change on forests is generally expected to be more severe in hot dry regions, where trees are at their adaptive limits, and in confined areas of moist forest surrounded by drier land. Potential problems associated with climate change include more frequent fires, break-downs in the synchrony between trees' flowering periods and the presence of pollinators, alien species invasions and more severe pest outbreaks.

Climate also affects many aspects of aquatic environments, including the temperature, oxygenation, acidity, salinity and turbidity of seas, lakes and rivers, the depth and flow of inland waters, the circulation of ocean currents, and the prevalence of aquatic diseases, parasites and toxic algal blooms. Climate change poses significant challenges both to capture fisheries and to aquaculture. Problems may arise because of direct physiological effects on aquatic organisms themselves or because the habitats upon which they depend are disrupted. Aquatic organisms living in restricted environments from which they cannot migrate to find more suitable conditions (e.g. those living in shallow rivers and lakes or kept in aquaculture cages) are particularly vulnerable. Aquatic ecosystems and their biota account for the largest carbon and nitrogen fluxes on the planet and act as its largest carbon sinks. Calcifying micro-organisms fall constantly to the ocean floor, and the calcium carbonate in the skeletal structures of marine invertebrates and the carbonates precipitated in the intestines of marine fish also make huge contributions to global carbon storage. Disturbances caused by climate change could adversely affect this essential ecosystem service.

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The vital contributions that micro-organism and invertebrate genetic resources make to agriculture and food production (creation and maintenance of soils, pollination, biological control of pests, etc.) are often overlooked. These organisms also play key roles in the carbon cycle and are therefore vitally important to climate change mitigation efforts. Changes to temperature and moisture regimes and to atmospheric carbon dioxide levels affect these organisms and their capacities to provide ecosystem services. However, little is known about precisely how they will be affected by climate change.

The interaction between genetic resources for food and agriculture and climate change – the effects of climate change on genetic resources on one hand and the potential key role of genetic resources in mitigation and adaptation on the other – has not yet been thoroughly studied and assessed. The effects of climate change on our ecosystems are already severe and widespread, and ensuring food security in the face of climate change is among the most daunting challenges facing humankind.

Responding to climate change – genetic resources as a basis for adaptation

Climate change creates the need for a much broader vision of risk management, especially given its potentially catastrophic effects on food production in many developing countries. While some of the problems associated with climate change may emerge relatively gradually, action is urgently needed now in order to allow enough time to build resilience into agricultural production systems.

Crops, livestock, forest trees and aquatic organisms that can survive and produce in future climates will be essential in future production systems. This will require revising the goals of breeding programmes, and in some places it is likely to require the introduction of varieties and breeds, even species, that have not previously been

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raised in the local area. Breeding programmes take time to reach their goals and therefore need to start many years in advance. Genetic resources for food and agriculture are among the keys to efficiency, adaptability and resilience in production systems. They underpin the efforts of local communities and researchers to improve the quality and output of food production.

It is vital that the genetic diversity needed to adapt agriculture and food production to future changes is not lost because of neglect in the present. Improvements to *in situ* and *ex situ* conservation programmes for domesticated species, their wild relatives and other wild genetic resources important for food and agriculture, along with policies that promote their sustainable use, are therefore urgently required.

A further prerequisite for the use of adapted genetic resources in increasing the resilience of future production systems is improved knowledge of these resources – where they are found, what characteristics they have (e.g. resistance to drought or disease) and how they can best be managed. Unfortunately, many locally adapted varieties and breeds of crops and livestock are poorly documented and may be lost before their potential roles in climate change adaptation are recognized. The roles of invertebrates and micro-organisms in food and agriculture are even less well studied. The same is true of many forest trees and aquatic organisms. Characterization studies for genetic resources are therefore a priority.

In crop production, maintaining genetic diversity has long been an essential element of strategies to reduce the effects of crop diseases and abiotic stresses such as drought. While it is difficult to predict the precise effects that climate change will have on the distribution and severity of diseases and unfavourable climatic conditions, the availability of greater genetic diversity is likely to increase the resilience of crop production systems in the face of new climatic and disease challenges. Improving collections of crop wild relatives is important, as they are likely to have genetic traits that can be used in the development of well-adapted crops for use in climate change-affected production systems.

Genetic diversity is also a vital resource for the livestock sector. Most livestock diversity is maintained *in situ* by farmers and pastoralists. Breeds developed in harsh production environments (e.g. hot, drought-prone or disease-infested areas) are often well-adapted to conditions that may become more widespread as a result of climate change. However, rapid changes to the livestock sector are threatening many locally adapted breeds and the production systems in which they are raised. Measures to promote the sustainable use and development of these breeds, and where necessary *in situ* and *ex situ* conservation measures to prevent their loss, are urgently needed.

Species diversity tends to increase the resilience of natural forests and tree plantations in the face of climate change, because it increases the likelihood that some of the species present will be able to thrive as conditions change. Genetic diversity within individual species similarly increases the likelihood that the species will be able to survive in a range of different environments. In plantation forestry, tree species and populations can be moved into new areas as climatic conditions change. Assisted migration of trees is recognized as a potentially important response to climate change, but has rarely been put into practice. The role that natural forests and tree planting can play in mitigating climate change through carbon sequestration is widely recognized. However, the significance of genetic diversity within species is less well appreciated. Trees can only provide mitigation services if they are well adapted to their surroundings and have the potential to adapt to future changes.


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Among wild and farmed aquatic organisms, most adaptation to the stressors associated with climate change is occurring through natural selection as their environments change. The most important traits in this respect include fecundity, tolerance of lower water quality (lack of available oxygen, acidification, increased or reduced salinity, increased turbidity and siltation,

and increased levels of pollutants) and resistance to diseases, parasites and toxic blooms. Climate change means that aquaculture and fisheries will have to rely on species, stocks and genetic strains that can live and perform adequately in a wide range of environments. For ecological and economic reasons, this will favour the use of fish that feed at lower trophic levels and that have relatively short production cycles. In warmer waters of variable quality, air-breathing species will have increased potential, especially in aquaculture. Aquatic ecosystems will also better contribute to mitigation services through their roles as carbon sinks if they are able to adapt successfully to climate change.

Conservation of invertebrate and micro-organism genetic resources useful to agriculture and food production is necessarily based on maintaining whole organisms *in situ*. This requires both ensuring that management practices do not threaten the survival of these organisms in agricultural systems and avoiding the destruction of natural habitats that provide refuges for them or serve as potential sources of species that will be useful in the future (e.g. to provide biological control of emerging pest problems). Because of the important roles of invertebrates and micro-organisms in the cycling and retention of carbon in the soil, managing these organisms appropriately may serve as a means of increasing carbon sequestration and thereby reducing atmospheric carbon dioxide levels.

It is likely that climate change will necessitate more international exchanges of genetic resources as countries seek to obtain well-adapted crops, livestock, trees and aquatic organisms. The prospect of greater interdependence in the use of genetic resources in the future underscores the importance of international cooperation in their management today and of ensuring that mechanisms are in place to allow fair and equitable – and ecologically appropriate – transfer of these resources internationally.

An ecosystem approach to meet the challenges of climate change

An ecosystem approach to the management of agriculture, forestry and aquatic food production in the face of climate change will be essential. Adaptation and mitigation measures will require cooperation among the various stakeholders involved in managing production systems. It will also require paying attention to the various ways in which the overall dynamic of a system is affected by climatic change. Many factors interact to influence, for example, the activities of pollinators and useful soil invertebrates or the distribution and severity of pest and disease outbreaks. Greater efforts to understand these interactions and their effects on food and agricultural production are needed. However, uncertainty will always remain, and the capacity to adapt production systems to unexpected challenges must be maintained and strengthened. This will involve learning and adjustment over time, as knowledge is gained and as impacts are better understood.

Other key elements of an effective ecosystem approach in the context of climate change include identification of appropriate genetic resources for use in climate change-affected production systems, understanding these resources and how to manage them, and ensuring that they – and their associated knowledge – are available to those who need them. Also important will be to build greater resilience into production systems – improving their capacity to continue functioning and producing in the face of changes and shocks. Diverse genetic resources can play an important role in this. For example, the presence of several different pollinators or biological control agents tends to promote stability in the provision of these services, because some species may be able to cope with shocks or changes that severely affect others. Genetic diversity within species is important for similar reasons. It also provides the basis for adaptation to changing conditions through natural selection or human interventions.


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Introduction

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Genetic resources for food and agriculture play a crucial role in food security and nutrition, livelihoods and the provision of environmental services. They underpin the ability of crops, livestock, aquatic organisms and forest tree species to withstand a range of harsh conditions. It is thanks to their genetic diversity that plants, animals and micro-organisms adapt and survive when their environments change.

The effects of climate change are expected to reduce agricultural productivity, stability and incomes in many areas of the world, some of which already face high levels of food insecurity. As a result, it is likely to become increasingly difficult to meet the goal of increasing food and agricultural production to keep pace with the projected growth of the human population. Food-insecure people in the developing world – especially women and indigenous peoples – are among the most vulnerable to climate change and are likely to be hardest hit.

In the coming decades, millions of people whose livelihoods and food security depend on farming, aquaculture, fishing, forestry and livestock keeping are likely to face unprecedented climatic conditions. Meeting the challenges posed by these changes will require plants and animals that have the biological capacity to adapt – and to do so more quickly than ever before. To achieve sustainability and higher levels of productivity, production systems will have to rely increasingly on ecological processes and ecosystem services, on the diversity of varieties, breeds, strains and species, and on diversification of management strategies (Galluzzi et al., 2011).

Time is not on our side. FAO calculates that global food production will need to increase by approximately 60 percent by the middle of this century to ensure food security for an additional 3 billion people (FAO, 2012). Time is a key factor because adapting to climate change – developing suitable crops, trees, livestock and aquatic organisms, and identifying the practices needed to manage them sustainably – will take time.

Although the problem of climate change was identified as early as the nineteenth century, the issue did not appear on the international scientific and political agenda until the first World Climate Conference, held in 1979 (Gupta, 2010). Only in 1992, with the Rio Earth Summit, was an international instrument to address climate change adopted: the United Nations Framework Convention on Climate Change (UNFCCC).

Genetic resources for food and agriculture have received little explicit attention in the UNFCCC process. Forests have been discussed in the context of mitigation-related activities, but there is no specific reference to the important role of forest genetic resources in these activities. Similarly, crop and livestock genetic resources, aquatic genetic resources, micro-organisms and invertebrates have largely been absent from the UNFCCC policy debate.

In part, the lack of attention to genetic resources for food and agriculture is a consequence of the UNFCCC's emphasis on mitigation activities. Efforts to reduce greenhouse gas emissions have historically played a central role in the UNFCCC process (Burton, 2008). Recent years have seen a shift in decision-making at UNFCCC towards greater recognition of adaptation (i.e. activities that aim to reduce vulnerability and build resilience to climate change) and new funding mechanisms to support work in this field. This shift comes in response to growing awareness that:

- the effects of climate change transcend national boundaries;
- the effects of climate change are serious, widespread and advancing more quickly than anticipated; and
- minimal progress has been made in reducing greenhouse gas emissions and stabilizing their concentrations in the atmosphere.

Urgent and immediate adaptation needs of least developed countries began to be addressed in 2001. Under the 2007 Bali Action Plan, adaptation became one of the four pillars – together with mitigation, finance and technology – of efforts to combat climate change. The Cancún Agreements adopted by the Conference of the Parties to the UNFCCC at its sixteenth session in 2010 affirmed that adaptation must be addressed with the same level of priority as mitigation and established the Adaptation Committee. The Adaptation Committee provides technical support to climate change adaptation planning and implementation: National Adaptation Programmes of Action – addressing the urgent and short-term priorities of Least Developed Countries; and National Adaptation Plans – assisting countries to identify and meet their medium- and long-term adaptation needs.

The Durban outcomes in 2011 put new emphasis on adaptation and affirmed that further and wider action on the part of governments – from local to national levels – is needed to deal with existing climate change. At the Doha Climate Gateway in 2012, ways to further strengthen the adaptive capacities of the most vulnerable through better planning were identified.

In June 2014, the Subsidiary Body on Science and Technology (SBSTA) of the UNFCCC made some progress regarding work on agriculture when the SBSTA agreed to undertake scientific and technical work in the following areas (UNFCCC, 2014):

"(a) Development of early warning systems and contingency plans in relation to extreme weather events and its effects such as desertification, drought, floods, landslides, storm surge, soil erosion, and saline water intrusion;

(b) Assessment of risk and vulnerability of agricultural systems to different climate change scenarios at regional, national and local levels, including but not limited to pests and diseases;

(c) Identification of adaptation measures, taking into account the diversity of the agricultural systems, indigenous knowledge systems and the differences in scale, as well as possible co-benefits and sharing experiences in research and development and on the ground activities, including socioeconomic, environmental and gender aspects;

(d) Identification and assessment of agricultural practices and technologies to enhance productivity in a sustainable manner, food security and resilience, considering the differences in agro-ecological zones and farming systems, such as different grassland and cropland practices and systems."

The SBSTA also requested the United Nations Climate Change Secretariat to organize in-session workshops on these four elements, the two first to be held at SBSTA 42 (in June 2015) and the next two at SBSTA 44 (in June 2016).

The general lack of attention given to genetic resources in the climate change policy arena results largely from a lack of awareness. While in the agricultural sector there is a clear understanding of the need to maintain and sustainably use genetic diversity in order to respond to ever-changing production conditions, there is an urgent need for greater awareness of the roles and values of genetic resources for food and agriculture among those engaged in international climate change discussions. To this end, the Commission on Genetic Resources for Food and Agriculture (the Commission) submitted its thematic studies on genetic resources and climate change (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 the United Nations Climate Change Secretariat, as well as to the High Level Panel of Experts on Food Security and Nutrition (HLPE) of the Committee on World Food Security (CFS) as a contribution to the panel's report on climate change and food security (HLPE, 2012). The HLPE Report acknowledges the Commission's work on climate change. At its subsequent meeting, the CFS invited the Commission to continue and strengthen its work on climate change and genetic resources (CFS, 2012).


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In 2013, the Commission adopted a Programme of Work on Climate Change and Genetic Resources for Food and Agriculture (FAO CGRFA, 2014) with the following two objectives:

- to promote the understanding of the roles and importance of genetic resources for food and agriculture in food security and nutrition and in ecosystem function and system resilience in light of climate change; and
- to provide technical information to enable countries to understand the role of genetic resources for food and agriculture in climate change mitigation and adaptation, as appropriate.

FAO supports countries in their efforts to address challenges associated with climate change and food security through initiatives and programmes such as the Climate-Smart Agriculture (CSA) Initiative and the FAO-Adapt Framework Programme on Climate Change Adaptation. These programmes offer further opportunities for strengthening the role of genetic resources for food and agriculture in FAO's work on climate change. CSA recognizes that a more productive and resilient agriculture will need better management of natural resources such as land, water, soil and genetic resources through practices such as conservation agriculture, integrated pest management, agroforestry and sustainable diets (FAO, 2013).

The above description is by no means exhaustive. Other important players engaged in addressing climate change, include the Research Program on Climate Change, Agriculture and Food Security (CCAFS) of the CGIAR (Consultative Group on International Agricultural Research). Drawing on national and international contributions, including from FAO, as well as relevant information from international research programmes, the Intergovernmental Panel on Climate Change (IPCC) provides regular Assessment Reports on the state of scientific, technical and socio-economic knowledge of climate change, its causes, potential impacts and response strategies. The 2014 Working Group II contribution to the Assessment Report – impacts, adaptation and vulnerabilities (IPCC, 2014) – includes a thorough review and synthesis of the recent scientific literature regarding food security and food production systems in the context of climate change.

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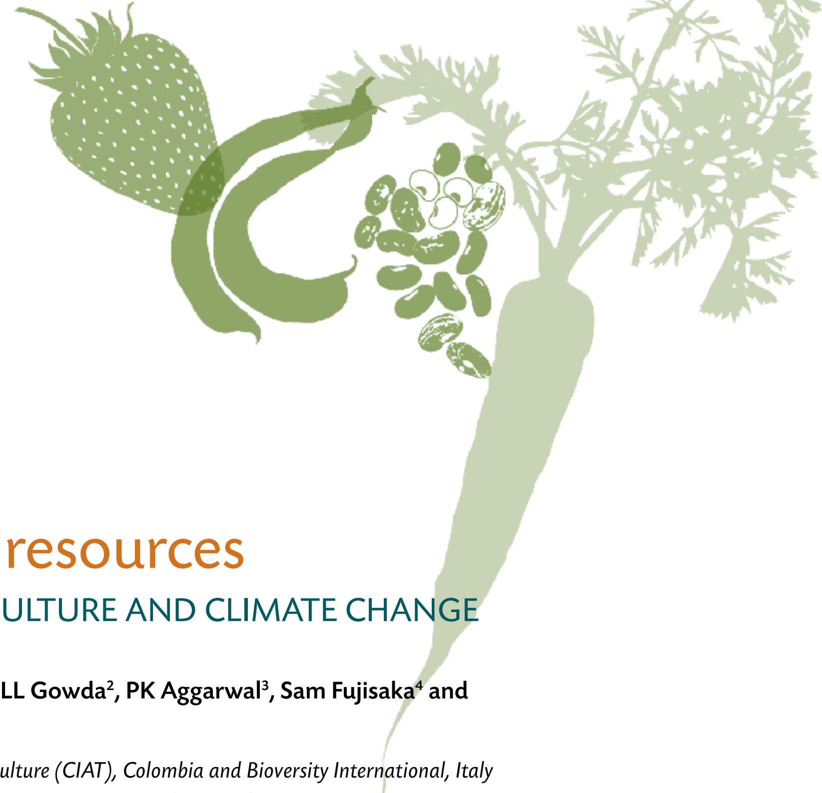

Plant genetic resources

FOR FOOD AND AGRICULTURE AND CLIMATE CHANGE

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Plant genetic resources for food and agriculture are the biological cornerstone of global food security. They are vital both in maintaining current food production and in confronting future challenges. Increasing the yields of major food crops in the face of climate change will depend on combining genetic traits from a wide range of origins, including wild species.

Effects of climate change on plant genetic resources and their management

According to the Intergovernmental Panel on Climate Change (IPCC, 2014) there is a medium level of confidence that if temperatures rise by 2 °C or more above late twentieth century levels, without adaptation, production of the world's major staple crops (wheat, rice and maize) will be negatively affected in both tropical and temperate regions, although some locations may benefit. There is evidence that climate change has already negatively affected wheat and maize yields in many regions (Lobell *et al*., 2011). Climate change will shift the distribution of land suitable for cultivating many crops. It is predicted that in sub-Saharan Africa, the Caribbean, India and northern Australia, the amount of land suitable for crop production will decline, while there will be gains in the northern United States of America, Canada and most of Europe. At the level of individual species, a study of

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NOTE: This section was adapted by Dafydd Pilling from Jarvis *et al*. (2010) and updated with material from the IPCC Fifth Assessment Report (IPCC, 2014) and the Second Global Plan of Action for Plant Genetic Resources for Food and Agriculture (FAO, 2012).

There is evidence that climate change has already negatively affected wheat and maize yields in many regions.

43 crops predicted that 23 would gain suitable area for cropping as a result of climate change, while 20 would lose (Lane and Jarvis, 2007).

It is predicted that there will be substantial falls in the yields of key crops in a number of food-insecure regions, with serious implications for food security (Lobell *et al.*, 2008). The areas in question include Southern Africa, where land suitable for growing maize – a major staple crop in the region – is predicted to disappear almost completely by 2050, and South Asia, where the productivity of groundnut, millet and rapeseed is predicted to decline.

For thousands of years, farmers have adapted their crops and their cropping systems as environmental conditions have changed. However, the speed and complexity of human-induced climate change are likely to present unprecedented challenges. New crop varieties will be needed, and in some cases farmers will have to shift to growing new crop species. The areas that are currently the most food-insecure will be worst affected and will have the greatest need for new crop varieties that are tolerant of drought, high temperatures, flooding, salinity and other environmental extremes.

In addition to its impacts on domesticated crops, climate change will affect the ability of many wild relatives of crop species to survive in their current locations. Species that are unable to migrate quickly will be particularly vulnerable to extinction. It has been estimated that between 16 and 22 percent of wild relatives of crop species may be in danger of extinction within the next 50 years – including 61 percent of peanut species, 12 percent of potato species and 8 percent of cowpea species (Jarvis *et al.*, 2008).

While it is clear that climate change will bring additional threats to the diversity of both domesticated crops and their wild relatives, few studies have specifically investigated genetic erosion in the context of climate change. Some of the centres of landrace diversity lie in regions that are among those most at risk from climate change. As conditions change, landraces are likely to be lost as farmers replace them with other landraces, or improved varieties, that are better adapted to the new conditions. The other side of the coin is that many landraces have characteristics that are potentially of wider value in adapting agriculture to the effects of climate change. It is possible that this could lead to greater demand for some landraces and thereby contribute to their survival.

Plant diseases and pests are heavily influenced by climate. The geographical ranges of many pathogens and disease vectors are limited by climatic factors such as low winter temperatures. For example, a study has shown that higher winter temperature (-6 °C versus -10 °C) increases the survival of rust fungi (*Puccinia graminis*) and that this leads to more serious disease impacts in various species of grass (Pfender and Vollmer, 1999). Higher temperatures shorten the generation interval in many pathogen species, enabling them to evolve more rapidly.

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Pathogens will not necessarily benefit from climate change. Like plants, they may be unable to migrate or adapt sufficiently rapidly as environmental conditions change. However, most pathogens will have an advantage over plants because of their shorter generation intervals and – in many cases – their ability to move rapidly over long distances via wind dispersal.

Many of the ecosystem services upon which crop production depends will also be affected by climate change, including pollination, biological control and nutrient cycling.

Many of the ecosystem services upon which crop production depends will also be affected by climate change, including pollination, biological control and nutrient cycling (see the section on invertebrate genetic resources). There have been few detailed studies of the effects of climate change on the provision of these services. Pollination is likely to present particular problems, as insects are highly sensitive to the climate. Climate change may disrupt the synchrony between the flowering seasons of crop species and the periods in which pollinators are active.

Roles of plant genetic resources in coping with climate change

Plant genetic resources will be vital in adapting crop production to the effects of climate change. Diverse species, varieties and cultivation practices allow crops to be grown across a wide range of environments. Over 10 000 years, diverse genetic resources have enabled farmers to adapt to gradual climatic changes and to other shifting demands and pressures. Traditional crop varieties are well adapted to


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current conditions in their local production environments. The challenge for the future is to maintain a good match between crops and production environments as the effects of climate change increase. Crop wild relatives will be a key resource in meeting this challenge, as their genes can promote resistance to many of the environmental stressors associated with climate change.

Crop production in all countries relies on genetic resources sourced from all over the world. This interdependency is likely to increase as a result of climate change. Novel climatic conditions will mean that landraces and varieties will no longer be well adapted to environmental conditions in the places where they have traditionally been grown. Better-adapted crops will need to be brought in from elsewhere. Climatic projections for Africa indicate that by 2050 many countries will experience novel climates that are not currently found within their borders (Burke *et al.*, 2009). International movement of germplasm will be essential in adapting agriculture to these novel climates.

National and international breeding programmes for a number of crops are already seeking to develop new varieties that will be well adapted to future climates. This is likely to increase demand for a range of plant genetic resources, including those of crop wild relatives. While this demand will be global, the natural distribution of wild relatives is restricted to the centres of origin of the respective crops, often specific subregions within continents.

On a more local scale, seed systems will be essential to the process of adaptation, providing farmers with the opportunity to exchange landraces that have a diverse range of characteristics and are developing under novel selection pressures associated with climate change. However, there are limits to the extent to which local seed systems can adapt. As changes accelerate, seed systems will need to stretch over wider and wider areas. There is a need for policies that support seed systems and seek ways of enabling long-distance seed exchange via seed fairs and other means. In addition to informal mechanisms, local seed systems could also include more formal community-based seed enterprises that facilitate smallholder farmers' access to improved and adapted cultivars and other inputs that may be required for adaptation to climate change.

Greater intravarietal diversity may be needed in order to cope with unpredictable extreme climate events.

Climate change is not only expected to bring directional changes (e.g. higher average temperatures at a given location in the future), but also to increase the variability of the climate. Farmers usually address directional changes either by drawing on adapted material from


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among the genetic resources already present locally or by seeking material from neighbouring areas. However, as the climate becomes more variable, and extreme events become more extreme, new strategies may be needed. Greater intravarietal diversity may be needed in order to cope with unpredictable extreme climate events. Traits that contribute to phenotypic plasticity (the capacity to cope with a wide range of environmental conditions) may become increasingly important.

Understanding the coping and risk-management strategies of farmers who are already facing extreme climatic stresses and variation will be useful in developing strategies that can be adopted by other farmers who will face similar challenges in the future. Research into the extent to which local landraces can cope with projected climatic changes without significant loss of productivity should be a priority. Insights drawn from studies of coping mechanisms and crop resilience could be used in developing policies for participatory plant breeding, exchange of genetic material and broader adaptation strategies for agriculture.

Climate change may increase the importance of plant species that have previously been underutilized or considered to be of minor importance. These may include, for example, species that are suitable for biofuel production and hardy species with specific characteristics that become more widely required as the harsh conditions to which they are adapted become more widespread.

Climate change may increase the importance of plant species that have previously been underutilized or considered to be of minor importance.

Breeding programmes will need to develop strategies for specific crops and regions, targeting the development of varieties that will be relevant to the challenges facing farmers 10 to 15 years into the future. Breeders will need to identify genetic resources with traits that can be used to develop varieties that will be able to thrive in extreme climatic conditions. There is a need to develop screening methods that can be used to identify the physiological basis of tolerance to such stresses. In recent years, research of this kind has progressed for tolerance of drought, salinity, submergence and heat stress in major food crops (see references cited in Jarvis *et al.,* 2010). The critical phases in plant development that are most affected by these stresses are becoming better understood.

Responding to climate change will present gene banks with a number of challenges. Many collections have major gaps. Threats to natural habitats and farming systems mean that urgent action is needed to collect, conserve and characterize traditional crop varieties, wild relatives and wild-harvested species that may be useful in climate change adaptation. In some cases, the relevant species will include fairly distant wild relatives. As wild species are generally more vulnerable than domesticated species to the threats associated with climate change, they should be priorities for collection. It is also important to ensure that collections cover the full geographic ranges of the targeted species, especially populations found at the extremes of the species' distributions, where novel traits may be found.

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However, extreme climates may pose an increasing threat to gene bank collections themselves. There have been a number of cases in which gene bank materials have been lost in climatic disasters. Hurricane Mitch severely damaged Central American banana germplasm collections, and extreme floods in Ecuador during the El Niño of 1997 destroyed the national cassava collection. This threat emphasizes the importance of establishing backup collections situated at separate locations.

On-farm conservation of plant genetic resources will become increasingly important in the context of climate change. Conserving genetic resources in complex, diverse, risk-prone environments builds on natural and farmer selection, and helps to maintain a variety of genetic options that farmers can use as climates change and become more variable. Traditionally, conservation of plant genetic resources has focused mainly on *ex situ* conservation. However, it is now being recognized that a complementary approach, involving both *in situ* an *ex situ* methods, has advantages.

On-farm conservation of plant genetic resources will become increasingly important in the context of climate change.

Successful conservation programmes that include both *in situ* and *ex situ* measures have been established in a number of countries. For example, Ethiopia has a fairly advanced programme of on-farm conservation that relies on cooperation between farmers and researchers to bring landraces such as those lost during the drought of the 1980s back into use. Landraces of the country's most important crops – including teff, barley, chickpea, sorghum and faba bean – are being taken from a gene bank, multiplied and distributed for on-farm conservation and improvement by farmers. The programme is based on a decentralized approach in which community seed gene banks provide farmers with a diverse range of crops.

In the Philippines, the South East Asian Research Institute for Community Education and the Community-based Native Seed Research Centre (CONSERVE) (two NGOs) are working with 140 farmers on the conservation of rice and maize varieties. CONSERVE maintains a backup collection of 585 rice varieties and 14 maize varieties on a farm within the local community, from which seeds are distributed to farmers. Another example from the Philippines is the Farmer-Scientist Partnership for Development Association, a joint initiative between NGOs and the University of the Philippines at Los Baños. This programme promotes on-farm conservation of rice and other crops and also maintains an *ex situ* collection. In Europe, conservation of crop biodiversity *in situ* and on-farm is being promoted in a number of countries in response to government and public interest in greening agriculture through the use of more traditional, organic and integrated farming systems.

Disaster management and seed-relief measures also need to adapt in response to climate change. Current approaches to seed relief do not take into account the significance of diversity or the need for seed that is well-adapted to the conditions at specific sites. Under normal circumstances, informal farmer seed systems maintain and promote local diversity. However, when major disasters occur, these seed systems can break down. They are often replaced by international seed distribution programmes that usually provide commercial varieties from outside the local area. Climate change is predicted to increase the occurrence of extreme


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As climate change proceeds, it is likely that a broader range of species will need to be exchanged between countries and regions. It will be important to ensure that these genetic resources can be accessed fairly and equitably by those who need them.

events such as floods, droughts and hurricanes, leading to greater reliance on seed relief. More-effective seed distribution networks that supply well-adapted seed need to be developed, both for post-disaster situations and to support longer-term adaptation of agricultural systems to climate change. Strategically located small enterprises dealing in local and improved adapted varieties could make it easier to obtain suitable material, particularly during emergencies.

In many countries, access to genetic resources is still limited by an overly complex policy environment. The International Treaty on Plant Genetic Resources for Food and Agriculture provides a multilateral legal framework that facilitates exchange of plant genetic resources. Its Multilateral System of Access and Benefit-sharing covers currently 35 of the approximately 150 food crops traded on the world market. Thousands of other crop or plant species are consumed and traded locally but do not enter the world trading system and much of the genetic diversity for these crops is not stored in genebanks. As climate change proceeds, it is likely that a broader range of species will need to be exchanged between countries and regions. It will be important to ensure that these genetic resources can be accessed fairly and equitably by those who need them.

Conclusions and recommendations

In many circumstances, responding to climate change does not imply drastic changes to existing strategies for promoting the sustainable management of plant genetic resources. However, to safeguard plant genetic resources and use them optimally to help cope with climate change, greater emphasis needs to be given to the following activities:

- enabling gene banks to respond to novel and increased demands for germplasm that can be used in climate change adaptation by including different characteristics in screening processes and ensuring that collections are comprehensive and include crops that are now considered to be “minor”;
- reviewing breeding strategies and priorities crop-by-crop and region-by-region so as to ensure that the products of crop-improvement programmes will be relevant to the challenges the world will be facing when the products are ready for release at the end of the crop-improvement cycle (five to ten years into the future);
- reviewing and strengthening policies to promote dynamic seed systems, including the establishment of community-based seed enterprises at strategic locations within countries, implementing measures that enable longer-distance exchange of seed between farmers, and reviewing priorities and procedures for post-disaster seed relief;

- consolidating collections of wild species, including crop wild relatives, because of the increased likelihood that narrowly adapted and endemic species will become extinct;
- ensuring that collections give sufficient emphasis to stress-adapted genetic material that can contribute to adaptation to climate change; and
- ensuring that policies facilitate international exchange of the genetic resources needed to adapt farming systems to shifts in the distribution of climatic zones.

The Second Global Plan of Action for Plant Genetic Resources for Food and Agriculture (FAO, 2012), negotiated by the Commission on Genetic Resources for Food and Agriculture and adopted by the FAO Council in 2011, contains a range of priority activities related to *in situ* conservation and management, *ex situ* conservation, sustainable use, and building sustainable institutional and human capacities that address challenges such as climate change and food insecurity, as well as novel opportunities such as the use of information and communication technologies and molecular methodologies. It highlights the following strategic elements needed to safeguard plant genetic resources for food and agriculture and use them optimally to help cope with climate change:

- greater emphasis on *in situ* conservation of genetically diverse populations, especially crop wild relative to allow evolution to continue and thus permit the continued generation of adaptive traits;
- a significantly expanded programme on *ex situ* conservation, especially of crop wild relatives, to ensure the maintenance of diversity of species, populations and varieties, including those adapted to extreme conditions and those from areas expected to be highly affected by climate change;
- increased research and improved availability of information on the characteristics of material held *ex situ* that will become useful under new climate conditions;
- increased support for access to and movement of plant genetic resources for food and agriculture to meet the greater interdependence of countries resulting from the new environmental conditions;
- more support for building capacity in plant breeding and seed-systems management that make effective and sustainable use of plant genetic resources for food and agriculture; and
- targeted and increased involvement of farmers and farming communities in national and local crop-improvement activities, including support for participatory research and plant breeding.

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Animal genetic resources

FOR FOOD AND AGRICULTURE AND CLIMATE CHANGE

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Domesticated mammals and birds contribute directly to the livelihoods of hundreds of millions of people, including an estimated 70 percent of the world's rural poor. They provide a wide range of products and services including food, transport, fibres, fuel and fertilizer. Over time, a variety of different breeds has been developed to provide these benefits in a wide range of environments. The significance of this diversity lies not only in its role in underpinning current livestock production, but also in the options it provides for adapting production systems to future changes.

Climate change presents a number of challenges both to the practical tasks of keeping animals alive, healthy and productive and to the task of ensuring that livestock diversity is maintained over the longer term. It threatens to make livestock-keeping livelihoods more precarious, transform production environments and disrupt established forms of livestock management.

Climate change comes as an additional driver of change in a global livestock sector that is already highly dynamic. Recent decades have seen rapid changes on an unprecedented scale – the so-called "livestock revolution" – driven mainly by rising demand for animal products, and facilitated by humans' increasing ability to control production environments (improvements to veterinary provisions, feed, housing, etc.) and to move genetic material around the world (improved transport infrastructure and biotechnologies such as artificial insemination).

While these developments have enabled large increases in the output of animal products, they also present challenges for the management of animal genetic resources. On the one hand, greater capacity to move genetic resources has created new potential for introducing animals that are not well matched to the production

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NOTE: This section was adapted by Dafydd Pilling from Pilling and Hoffmann (2011).

environment. On the other, the spread of homogenized, highly controlled, production environments has contributed to the increasing worldwide dominance of the small number of breeds that produce well in these conditions, with an associated decline in overall breed and genetic diversity.

While high external input, often large-scale, livestock production has expanded in many developing countries in recent decades, livestock keeping has continued to play an important role in the livelihoods of large numbers of small-scale farmers and pastoralists. The livelihoods and livestock-keeping practices of these smaller-scale producers have, to varying degrees and *inter alia*, been affected by rising and changing market demand, increased competition, changing lifestyles and employment opportunities, and growing pressures on natural resources. Animal genetic resource diversity has generally not fared well as a result of these changes and because of a widespread lack of adequate policies supporting the sustainable use, development and conservation of these resources (FAO, 2007a).

Climate change presents a number of challenges both to the practical tasks of keeping animals alive, healthy and productive and to the task of ensuring that livestock diversity is maintained over the longer term.

Different livestock production systems are affected in different ways by climate change. So-called land-based systems – in which livestock graze pastures and

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rangelands or are kept on mixed crop–livestock farms – rely largely on local resources and are relatively exposed to local-scale environmental changes. Large-scale "landless"[1] production systems, also referred to as "industrial" systems, are better able to isolate animals from changes in the local environment. However, they rely on heavy use of external inputs, the supply and affordability of which are potentially affected by climate change.

Effects of climate change on animal genetic resources and their management

The predicted effects of climate change include a trend toward higher temperatures over the coming decades. In the tropics and subtropics, in particular, rising temperatures will present significant problems for livestock production. Heat stress affects animals in a number of ways – production and fertility decline and death rates increase. High temperatures also increase animals' water requirements and reduce their appetites and feed intakes. Extreme heat waves already kill many feedlot animals in countries such as the United States of America (e.g. Hatfield *et al.*, 2008). The severity and frequency of these extreme events is predicted to increase as a result of climate change.

In general, high-output breeds from temperate regions are not well adapted to the effects of high temperatures. If they are introduced into areas where the climate is hot, particularly if humidity is also high and their diets are based on poor-quality forage, the animals suffer from heat stress and do not produce to their full potential. Higher temperatures associated with climate change are likely to exacerbate the problem of heat stress in such animals unless their management can be adapted to protect them from excessive heat. While in favourable circumstances this is technically feasible – for example by adjusting the animals' diets (easily digestible feed generates less heat) and introducing technologies such as ventilation fans, water sprays or misters – costs may be prohibitive.

Small-scale producers who have adopted high-output breeds but struggle to obtain the inputs needed to prevent the animals from becoming overheated, may find that their problems are exacerbated by climate change.

"Industrial" production systems – where advanced cooling technologies, water, power and a range of feedstuffs are readily accessible – may, to a large extent, be able to buffer their high-output animals against the direct effects of high temperatures. However, small-scale producers who have adopted high-output breeds but struggle to obtain the inputs needed to prevent the animals from becoming overheated, may find that their problems are exacerbated by climate change. In extensive grazing systems, the use of advanced cooling technologies is largely impractical, and it is difficult to do more than provide some shade for the animals and possibly places for them to wallow.

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[1] The term "landless" refers to the fact that the animals in these systems are not fed on feed produced within the holding and neither do they graze on local pastures. Livestock production in such systems takes up little land locally, but relies on land elsewhere for the production of feed.


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As well as affecting temperature levels, climate change is predicted to affect rainfall patterns. Many already semi-arid areas are expected to experience lower rainfall in the coming decades, with shorter growing periods for plants and more frequent droughts. This is likely to increase the risk that animals will suffer lengthy periods of nutritional stress. Climate change is also likely to affect feed quality, as high temperatures tend to increase the lignification of plant tissues and thereby make forage less digestible. While industrial producers may, again, be able to circumvent these problems by buying feed from outside the local area, producers in grazing and mixed-farming systems are likely to face increasing problems, particularly if their animals are not well adapted to coping with feed shortages and poor-quality feeds. In the industrial livestock sector, the main climate change-related threat to feeding strategies is likely to be economic rather than technical or biological, as climate change may affect the cost of grain and other feedstuffs.

The geographical and seasonal distributions of many infectious diseases, particularly those that are spread by vectors (animals such as insects and ticks) are affected by climate. Pathogens, vectors and host animals can all be affected directly by the climate (e.g. temperature and humidity) and by the effects of climate on other components of the ecosystem (e.g. vegetation and natural enemies). These interactions are complex and not well understood. Further complexity is added by the fact that the effects of climate change interact with changes in land use, trade, the movement of human and animal populations, the implementation of disease control measures, and a range of other management, sociocultural, economic and political factors. Outcomes in terms of disease epidemiology are difficult to predict, but if climate change brings hosts and pathogens together in new locations and ecological contexts, new threats to animal health are likely to emerge.

Outcomes in terms of disease epidemiology are difficult to predict, but if climate change brings hosts and pathogens together in new locations and ecological contexts, new threats to animal health are likely to emerge.

Extreme climatic events such as droughts, floods and hurricanes have the potential to kill large numbers of animals. If a breed population is concentrated within a limited geographical area, it may be devastated – even completely wiped out – by a climatic disaster. Climate change is predicted to increase the frequency and severity of climatic disasters and hence the risk to vulnerable breed populations. A major outbreak of a serious animal disease can pose a similar threat, particularly if large numbers of animals are slaughtered in order to prevent the further spread of the disease. The extent to which climate change will increase the threat that epidemics pose to livestock diversity is uncertain. However, some worrying recent developments, such as the spread of bluetongue virus in Europe, may be linked to climate change.

Locally adapted breeds developed in harsh production environments can be expected to cope with the effects of climate change more easily than their exotic counterparts. Many livestock-keeping communities are also highly experienced in managing their livestock in harsh and fluctuating environments. Nonetheless, rapid and substantial changes to local climates may outstrip the capacity of local animal populations to adapt through natural or human selection and also outstrip the capacity of their keepers to adapt husbandry practices. This may give rise to the need for breed or species substitution. Changes of this kind present a significant challenge, both in terms of ensuring that introduced genetic resources are well adapted to local conditions and in terms of ensuring that the original genetic resources do not become extinct.

The role of the livestock sector as a major contributor to climate change has been widely publicized (e.g. FAO, 2006). Greenhouse gas emissions occur throughout the livestock production cycle. Feed-crop production and the management of pastures give rise to emissions associated with the production and application of chemical fertilizer and pesticides and with the loss of soil organic matter. Further emissions occur because of the use of fossil fuels in the transport of animal feed. Forest clearance to create pastureland, or cropland for growing animal feed, also releases large amounts of carbon into the atmosphere. Further emissions occur directly from the animals as they grow and produce: most notably, ruminant animals emit methane as a by-product of the microbial fermentation through which they digest fibrous feeds. Emissions of methane and nitrous oxide occur during the storage and use of animal manure. Processing and transport of animal products give rise to further emissions, mostly related to the use of fossil fuels and infrastructure development.


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If mitigation policies were to promote the use of a narrow range of species and breeds within a narrow range of production systems, genetic diversity might be put at risk.

Mitigating the climatic impact of livestock production has potential implications for the diversity of animal genetic resources. Efforts to reduce greenhouse gas emissions from the animals themselves focus on improving feed conversion efficiency (less emission per unit of meat, milk, etc.) and reducing the amount of methane produced during digestion. Both are affected by the type of animal kept and the nature of the production system. Monogastric animals such as pigs and chickens have relatively good feed conversion ratios and their digestive processes produce less methane than those of ruminants. Within species, certain breeds and lines have been intensively bred for high output and good feed-conversion ratios in high external input production environments. If mitigation policies were to promote the use of a narrow range of species and breeds within a narrow range of production systems, genetic diversity might be put at risk.

In assessing livestock's contributions to climate change, it should be recalled that feed conversion ratios do not present the whole picture, either in terms of production efficiency or greenhouse gas output. Locally adapted breeds and low external input production systems normally have advantages in terms of fossil fuel consumption and the breeds often provide multiple products and services that are not accounted for in conventional assessments of livestock output and productivity. It is also necessary to consider the fact that the grazing systems of the developing world provide livelihoods to large numbers of livestock keepers, many of whom are poor and have few alternatives available. Moreover, many grazing systems make use of land that is unsuitable for crop production and therefore provide animal products without competing with the production of crops for direct human consumption.

Grasslands have great potential for carbon sequestration in the soil, but if managed badly can release large amounts of carbon into the atmosphere. It is difficult to generalize about the influence of livestock grazing on carbon sequestration in grasslands. Overgrazing increases the loss of soil carbon, but well-managed grazing can increase carbon deposition. In some circumstances, carbon sequestration under well-managed grazing can be greater than that occurring in ungrazed land, although this depends on the types of grazing, plant communities, soils and climate involved (Smith *et al*., 2008).

Some progress has been made in identifying development measures for dryland grazing systems that address both the need to improve local livelihoods and the need to improve the rate of carbon sequestration vs. carbon loss from the soil (FAO, 2009a). However, implementing such measures is challenging. Key barriers to success include:

> *"land tenure, common property and privatization issues; competition from cropping including biofuels and other land uses which limit grazing patterns and areas; lack of education and health services for mobile pastoralists; and policies that focus on reducing livestock numbers rather than grazing management"* (*ibid*.).

Roles of animal genetic resources in coping with climate change

Many generations of natural selection and human-controlled selective breeding, in a wide range of production environments, have produced great genetic diversity among the world's livestock. Breeds and populations that have been exposed to climatic extremes, heavy disease and parasite challenges, poor-quality feed, high elevations or difficult terrain have often developed adaptations that enable them to thrive where other animals struggle to survive. Although advances in feeding, housing and veterinary care have increasingly enabled the establishment of production systems that isolate animals from environmental stresses, locally adapted animals remain essential to many livestock-keeping livelihoods. As climate change progresses, and new environmental challenges emerge, some of the adaptive characteristics of these animals are likely to become more widely important.

Different species and breeds differ greatly in the extent to which they can tolerate climatic extremes. For instance, a number of studies (e.g. Lemerle and Godard, 1986; Burns *et al*., 1997) have revealed differences in heat tolerance among cattle breeds and cross-breeds. Tropical breeds tend to have better heat tolerance than breeds from temperate zones. A range of factors are involved, including properties of the skin and hair, sweating and respiration capacity, tissue insulation, surface area relative to body weight or lung size, endocrinological profiles and metabolic heat production. As milk yield in dairy cattle has risen, and growth rates and leanness in pigs and poultry have increased, the animals' metabolic heat production has increased and their capacity to tolerate high temperatures has declined (e.g. Zumbach *et al*., 2008). In chickens, several studies (e.g. Horst, 1988) have compared the heat tolerance of birds with different types of feathering. Both "naked-neck" and "frizzle-feathered" chickens have been found to cope better with high temperatures than their normally feathered counterparts. However, in recent years, few comparative studies of heat tolerance have been undertaken in other livestock species.

The fact that some breeds are more resistant or tolerant than others to particular diseases is well established (FAO, 2007a). However, the number of breeds and diseases that have been subject to scientific study is quite limited and the underlying physiological and genetic mechanisms are not well understood. Important examples of diseases and parasites for which resistant or tolerant breeds have been identified include African animal trypanosomosis, the stomach worm *Haemonchus contortus*, liver flukes, ticks and various tick-borne diseases including anaplasmosis. Within breeds, it is also possible to breed selectively for greater disease resistance.

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The different feeding habits of different types of animal are essential in enabling the livestock sector to utilize a wide range of feed resources, many of which are unsuitable for direct consumption by humans. For example different ruminant and camelid species have different feeding habits and tend to utilize different types of vegetation. Goats and camels make more use of browse (shrubs and trees) than sheep and cattle do. Within species, there are also differences in breeds' capacity to utilize particular kinds of feed. Documented examples include the Sokoto Gudali cattle breed of West Africa, which specializes in eating browse and will feed on woody material that other breeds find very unpalatable (Blench, 1999) and the Black Bedouin goat, which is well adapted to feeding on the high-fibre forages of its home production environment (Silanikove, 1997). Among cattle in general, zebu (*Bos indicus*) breeds tend to deal better with low-quality forage than taurine (*Bos taurus*) breeds, while the latter have better feed-conversion ratios when fed on high-quality feed.

> The different feeding habits of different types of animal are essential in enabling the livestock sector to utilize a wide range of feed resources, many of which are unsuitable for direct consumption by humans.

Grazing and browsing animals not only have to be able to thrive on the diet provided by the local vegetation, they also have to be able to cope with the other challenges that they encounter as they feed: heat, cold, rain, snow, ice, wind, steep or rough terrain, waterlogged ground, parasites, predators and so on. They may need to walk long distances and go for long periods without drinking in order to access forage over a wide area of rangeland. Several studies have shown the superior ability of dryland breeds such as the Black Bedouin goat, Black Moroccan goat and Black


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Grazing and browsing animals not only have to be able to thrive on the diet provided by the local vegetation, they also have to be able to cope with the other challenges that they encounter as they feed: heat, cold, rain, snow, ice, wind, steep or rough terrain, waterlogged ground, parasites, predators and so on.

Headed Persian sheep to cope with water shortages and hence graze over a wide area (e.g. Shkolnik *et al.*, 1980; Hossaini Hillaii and Benlamlih, 1995; Schoenman and Visser, 1995). Similarly, disease resistant or tolerant breeds are better able than other animals to utilize grazing lands that are infested with parasites or disease vectors. Camels are well known for having a range of morphological, physiological and behavioural characteristics that enable them to thrive in desert environments. For example, experiments have shown that dromedaries can maintain feed intake and digestion in the face of high temperatures and restricted access to water (Guerouali and Wardeh, 1998).

Diversity in feeding habits and capacities is an important asset as the livestock sector seeks to adapt to the effects of climate change on the availability of feed. As described above, not only are grazing and mixed-farming systems at risk from the effects of climate on the local vegetation, "industrial" livestock production may be affected by rising grain and fuel prices that undermine the economic sustainability of their current feeding strategies.

One option for adapting production systems to the effects of climate change is to introduce animal genetic resources that are well adapted to the changed conditions. These resources are likely to come from production environments where they have been exposed for many years to environmental conditions similar to those now prevailing in the areas into which they are being introduced. If climate change leads to major changes in local agro-ecosystems, at a rate that outstrips the capacity of livestock to adapt, such shifts in breed or species distribution may become increasingly necessary and frequent.

Species and breed substitution has already occurred in some production systems that have been badly affected by droughts in recent decades. Many livestock-keeping communities have traditionally been interested in experimenting with new breeds and introducing new blood to their herds or flocks and have adjusted the species composition of their holdings to adapt to changing circumstances. Mechanisms of this kind will probably have an important role to play in future climate change adaptation. However, if climate change leads to very substantial and rapid changes in local production environments, existing mechanisms may no longer be sufficient. If this happens, it may be necessary to take additional steps to facilitate livestock keepers' access to alternative animal genetic resources from more distant locations and provide them with information on the characteristics of these resources and their potential utility in climate change adaptation. This, however, is made difficult by the general lack of information available on the adaptive characteristics of specific breeds and their performance in diverse production environments.

It is possible that climate change will increase demand for international exchange of animal genetic resources that are well adapted to climatic extremes. At present, however, the dominant pattern of gene flow on a global scale remains focused largely on the movement of high-output breeds that need highly controlled production environments rather than on the movement of locally adapted breeds into equivalent agro-ecological zones. The majority of this gene flow is between the countries of the developed "North" and from the North to the developing "South". The main exception to this pattern during the last hundred years or so has been the movement of tropically adapted cattle from South Asia to Latin America. There have also been some introductions of grazing animals from the South into the hotter parts of developed countries such as Australia and the United States of America.

> It is possible that climate change will increase demand for international exchange of animal genetic resources that are well adapted to climatic extremes.

If demand for climate-adapted breeds does increase, it will be important to ensure that these breeds and knowledge associated with their management can be accessed fairly and equitably by those who need to use them. Even more fundamental – both for international exchange and for adaptation on a more local scale – will be ensuring that the breeds survive and that their characteristics are well documented. Conservation programmes, measures to support the sustainable use of animal genetic resources and comprehensive characterization studies will therefore be needed.

Conclusions and recommendations

The Global Plan of Action for Animal Genetic Resources (FAO, 2007b), adopted by the Interlaken International Technical Conference and endorsed by the FAO Conference in 2007, is the first internationally agreed framework specifically for the management of livestock biodiversity. It was adopted at a time when climate change had already been widely recognized as a major challenge for agriculture, food security and for humanity as a whole. The Global Plan of Action emphasizes the links between animal genetic resources, agro-ecosystem management and climate change adaptation. Effective implementation of the Global Plan of Action would be an important step towards improving the capacity of the livestock sector to respond to climate change – knowledge, availability (sustainable use, conservation and exchange) and strategies for use and development of animal genetic resources would all be strengthened.

While few aspects of improved animal genetic resources management are relevant only in the context of climate change, certain policy and management measures stand out as being particularly significant. The following recommendations are grouped according to their relevance to the four strategic priority areas of the Global Plan of Action.

Strategic Priority Area 1: Characterization, inventory and monitoring of trends and associated risks

- Methods need to be developed for characterizing adaptive traits relevant to climate change adaptation (heat tolerance, disease resistance, ability to thrive on poor-quality feed, etc.), for comprehensive evaluation animals' performance in specific production environments and for describing these production environments in a standard way.
- The use of these methods in surveys and phenotypic and molecular characterization studies of animal genetic resources should be promoted. There is a general need to improve characterization, inventory and monitoring of animal genetic resources, particularly in developing countries.
- Knowledge and awareness of, and respect for, local and indigenous knowledge relevant to climate change adaptation and mitigation need to be improved.
- Potential climate change-related threats to specific animal genetic resources should be identified and steps taken to ensure that long-term threats (e.g. gradual environmental changes) are monitored. Urgent action should be taken to address immediate threats (e.g. small populations at severe risk from climatic disasters).
- The possibility of modelling the future distribution and characteristics of livestock production environments should be explored in order to support the assessment of threats to animal genetic resources and the identification of areas that may be suitable for particular breeds in the future.
- Knowledge of breeds' current geographical distributions needs to be improved in order to support the above actions and facilitate the planning of climate change adaptation measures and conservation strategies for animal genetic resources.

- Knowledge related to animal genetic resources and their management should be made more widely available, including via information systems such as the Domestic Animal Diversity Information System (DAD-IS: http://www.fao.org/DAD-IS).

Strategic Priority Area 2: Sustainable use and development

Animal genetic resources management should be better integrated into the planning of climate change adaptation and mitigation measures at the level of the production system or agro-ecosystem and nationally.

- Options for increasing carbon sequestration in pastureland through better grazing management should be explored, along with the potential that such measures may offer for integrated approaches to climate change mitigation, livelihood development, conservation of wild biodiversity and sustainable use of animal genetic resources.
- Cooperation among the international forums and organizations involved in the management of animal genetic resources and other aspects of biodiversity, climate change adaptation and mitigation, and other environmental issues needs to be strengthened.
- Steps must be taken to ensure that livestock keepers and other relevant stakeholders are involved in planning climate change adaptation and mitigation measures in livestock production systems and in planning the role of animal genetic resources within these measures.
- Local knowledge of how to cope with harsh and fluctuating production environments should be built on or integrated into climate change adaptation strategies (where they are relevant to future objectives and projected environmental conditions).
- Plans to introduce breeds into new geographical areas should take account of climatic and other agro-ecological conditions and their predicted future trends.
- Breeding goals should be reviewed and, if necessary, adapted to account for the effects of climate change.
- Livestock keepers' access to inputs and livestock services relevant to climate change adaptation should be improved.
- The potential for introducing payments for environmental services as a means of promoting ecological and socio-economic sustainability in livestock production systems and hence the maintenance of the associated animal genetic resources should be explored.

Strategic Priority Area 3: Conservation

- Conservation strategies should account for the observed and projected effects of climate change, including agro-ecological changes, disaster risk and, if relevant, the effects of climate change mitigation policies.
- *In situ* conservation schemes should be reviewed, and if necessary adapted, to account for climate change-driven changes in the native production systems of the targeted breeds.

- *Ex situ* collections should be strengthened so as to ensure that they are sufficiently comprehensive, well managed, well documented and well located to provide insurance against climatic and other disasters.

Strategic Priority Area 4: Policies, institutions and capacity-building

- Awareness among policy-makers of the potential roles of animal genetic resources in climate change adaptation and mitigation should be promoted.
- National strategies and action plans for animal genetic resources (FAO, 2009b) should account for the effects of climate change and allow for future reviews and amendments, as necessary, to account for future climate-related developments.
- Exchange of information on climate change adaptation strategies for livestock systems and for the management of animal genetic resources should be promoted, along with the dissemination of information on specific climate-related breed adaptations and on breed performance in specified production environments.
- Transparent, fair and equitable access to the animal genetic resources needed for climate change adaptation, along with relevant associated knowledge and technologies, should be facilitated.

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Forest genetic resources

AND CLIMATE CHANGE

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Forests cover 30 percent of the world's land area. They provide habitats for countless species of plants, animals and micro-organisms, and are vital to the livelihoods of their human inhabitants and to broader economic and social development. Forests are usually managed for multiple purposes and supply a variety of products including timber, fruits, leafy vegetables, fodder, medicines and resins. They also provide environmental services, such as soil and water conservation and carbon storage, and contribute to meeting the recreational needs of increasingly urbanized populations. Forests contain more carbon than the atmosphere, and their roles as absorbers and producers of carbon dioxide make them particularly important in the context of climate change. About 1.4 billion people depend on forests directly for at least a part of their livelihoods.

Genetic diversity, the heritable diversity among individuals and populations within species, provides the basis for evolution. Over millions of years it has enabled forests and trees to adapt to changing conditions. Some tree species have been domesticated, but the management of forest genetic resources mainly involves tree populations that have undergone little selection by humans. The vast majority of forest genetic diversity remains undescribed, especially in the tropics. Estimates of the number of tree species vary from 80 000 to 100 000, but fewer than 500 have been studied in any depth. Until recently, studies of forest tree genetic resources have concentrated on the few species regarded as the most suitable for domestication for use in plantations and agroforestry systems to produce wood, fibre or

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NOTE: This section was adapted by Dafydd Pilling from Loo *et al.* (2011) and updated with information from the Global Plan of Action for the Conservation, Sustainable Use and Development of Forest Genetic Resources (FAO, 2014).


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fuel. The present and future potential of most tree species to adapt in response to novel climatic conditions or for genetic improvement for human use remains largely unknown.

Effects of climate change on forest genetic resources and their management

Predictions regarding the effects of climate change on forest genetic resources vary. Some scientists (e.g. Hamrick, 2004) consider that many tree populations have sufficient phenotypic plasticity[2] and genetic diversity to enable them to adapt reasonably well to the effects of climate change. Others foresee significant problems (e.g. Mátyás, 2007; Rehfeldt *et al*., 2001). Predictions for tropical tree species tend to be more pessimistic than those for temperate and boreal species. The impact of climate change is generally expected to be more severe in hot dry regions where trees are at their adaptive limits, and in confined areas of moist forest surrounded by drier land.

Many tree species have high levels of genetic variability in important traits such as drought tolerance, cold-hardiness and the timing of their flowering and fruiting. If environmental changes are directional and continuous, such species have the potential to evolve quite quickly. However, it is predicted that in many cases the magnitude and speed of climate change will surpass the capacity of tree populations to adapt, at least at the receding edge of their distributions. If the climate becomes increasingly variable on a local scale, this may further constrain the ability of tree populations to adapt, because the selective pressure on them will not be in one direction.

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[2] Phenotypic plasticity is the ability of an organism to change its phenotype in response to changes in the environment without genetic change (Price *et al*., 2003)

While the ranges of some tree species are expected to expand, others will diminish. In temperate regions, species' ranges are likely to shift towards the poles and towards higher elevations. However, retreat at the receding edge of species' distributions is likely to be more rapid than advance into new areas.

The data currently available suggest that climate change will affect forest genetic resources via many different demographic, physiological and genetic processes. Extreme climatic events that kill large numbers of trees may become more common. More gradual changes in temperature and precipitation may inhibit the capacity of forests to regenerate. In some places, pest and disease attack may become more severe because climatic conditions become more favourable for the attacking species or because climate-induced stress makes trees more susceptible to attack.

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Climate change may break the synchronism between trees' flowering periods and the active periods of pollinator species. A decline in the availability of pollinators limits gene flow and reduces the effective size of tree populations and therefore

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impedes their capacity to adapt to climate change. Climate change may also lead to more frequent fires. In areas that have not regularly experienced wild fires in the past, fire may become the main driver of change and lead to a rapid transition from fire-sensitive to fire-resistant tree species. Problematic species invasions may also become more common, with native trees being outcompeted by species that can migrate and reproduce rapidly.

For natural forests in temperate regions, it has been estimated that migration rates of more than 1 km per year may be needed if trees are to keep pace with climate change. This would mean that forests would have to move at least ten times faster than they did at the end of the ice ages. However, forest degradation and deforestation are likely to reduce the rate at which forests are able to migrate. In tropical regions, changes in rainfall regimes may be the most important climatic factors influencing tree distribution. Research has indicated that dry climate is a particular barrier to genetic exchange in tree species (e.g. Muchugi *et al*., 2006, 2008). As in temperate regions, natural migration rates in the tropics will not be sufficient to keep pace with the predicted rate of climate change, except in the case of some invasive species that can respond rapidly because their seeds are dispersed over very long distances or because they reach maturity very quickly.

The inability of most tree species to migrate naturally at a sufficient rate to keep pace with the rapidly changing climate will result in higher rates of mortality and a reduction in the size of the available gene pool, which may increase inbreeding among the surviving trees. The species composition of natural forests will shift. In some cases, high-value species will be threatened by competition from invasive species that move into their local areas.

Climate change is likely to have a significant effect on the distribution and severity of outbreaks of insect pests of trees. In Canada, for example, the mountain pine beetle (*Dendroctonus ponderosae*) has devastated forests throughout much of the interior of British Columbia (Konkin and Hopkins, 2009). The sustained outbreak is blamed on a long series of unusually warm winters. In addition to the loss of hundreds of thousands of hectares of plantation and natural forest, some genetic trials that constituted live gene banks have been destroyed.

Roles of forest genetic resources in coping with climate change

Species diversity can be expected to increase the resilience of natural forests and tree plantations in the face of climate change because it increases the likelihood that some of the species present will be able to thrive as conditions change. Genetic diversity within individual species similarly increases the likelihood that the species will be able to survive in a range of different environments. Within- and between-species diversity among trees can also contribute to ecosystem stability more broadly, particularly where trees are foundational species within the ecosystem. Diverse trees provide habitats for a diverse range of other species.

Species diversity can be expected to increase the resilience of natural forests and tree plantations in the face of climate change because it increases the likelihood that some of the species present will be able to thrive as conditions change.

Some tree species, and individual trees within populations, can be described as "phenotypically plastic". In other words, their morphology and physiology are flexible and they grow at least reasonably well under a range of different environmental stresses. Field trials at multiple locations can be used to identify species and populations that have this ability. Trees with high phenotypic plasticity are under less pressure to adapt genetically. At least in the short term, plasticity is likely to be more important than genetic adaptation in ensuring that tree populations are able to survive the effects of climate change. However, as plasticity itself has a genetic basis, it will tend to be selected for if the climate becomes more variable. The mechanisms underlying phenotypic plasticity are poorly understood, but epigenetic effects, which result from the modification of DNA expression but not sequence and can be inherited across several generations, may be important.

Some degree of phenotypic plasticity is found in most trees, but there is variation between and within species. Plasticity is likely to be particularly important in species that are not very diverse genetically and therefore have less potential to evolve in response to climate change. Identifying and utilizing species and populations with phenotypically plastic individuals may be an important element in climate change adaptation strategies, especially in regions where the climate is expected to become more variable. In the long run, however, relying on phenotypic plasticity could prove detrimental if environmental conditions change drastically and new, more adapted, phenotypes are needed.


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Natural forests are unlikely to be able to migrate sufficiently quickly to "follow" climates to which they are well adapted and will have to rely on genetic adaptation and/or plasticity, at least in the short term.

As described above, natural forests are unlikely to be able to migrate sufficiently quickly to "follow" climates to which they are well adapted and will have to rely on genetic adaptation and/or plasticity, at least in the short term. Trees that are grown in plantations can be moved by humans, either as seeds or seedlings, to sites where the future climate is expected to match their requirements. Although assisted migration of tree species and populations within species is recognized as a potentially important response to climate change, the approach has not yet been widely used; the example presented in Box 1 is an exception.

Predicting which locations will be suitable for particular tree species (or populations within species) under climate change is made more difficult by the long time scales involved. Trees can provide products and services over very long periods of time, in some cases for centuries. Long-term predictions for future climatic changes are very uncertain, in part because outcomes will depend on the effectiveness of current mitigation measures.

If assisted migration is to be widely used as a means of responding to climate change, it will require moving increased quantities of germplasm across national boundaries both for planting and for research. Unfortunately, international transfer of tree germplasm for research is reported to have become increasingly difficult and costly in recent years (Koskela *et al.*, 2010). New approaches that facilitate exchange are needed. However, it is also important to avoid indiscriminate movement of poorly adapted germplasm and to assess potential problems such as the risk that introduced species become invasive and reduce native biodiversity.

In managed forests, attempts can be made to increase resilience in the face of extreme climatic events. For example, the threat posed by increasing storm frequency in the Pacific has led to efforts to identify cyclone-resistance species for large-scale planting. In Vanuatu, for instance, there are plans to establish 20 000 hectares of whitewood (*Endospermum medullosum*) plantations over the next 20 years.

The role that natural forests and tree planting can play in mitigating climate change through carbon sequestration is widely recognized. However, the significance of genetic variation within species is less well appreciated. Trees can only provide mitigation services if they are well adapted to their surroundings and have the potential to adapt to future changes. Moreover, in the case of smallholder agroforestry systems, trees will only become established if they provide clear livelihood benefits. As current payment mechanisms to reward farmers for sequestrating carbon by growing trees are generally inefficient and provide only limited rewards, the main reason for farmers to plant trees will continue to be the desire to obtain

BOX 1

Changes in seed transfer guidelines in response to climate change – an example from Canada

During the 1980s, the Canadian province of British Columbia adopted the concept of seed zones. Provenance trials were established for commercially important tree species and the province's forest land was classified on the basis of geography, climate and vegetation. The boundaries of seed zones were identified by relating the adaptive characteristics of the tree populations to the ecological classification of the land.

Increasing concern about the effects of climate change led to a new approach in which the potential effects of climate change were assessed using an ecosystem-based climate envelope model. The results predicted that tree species whose northern range-limit lies in British Columbia could gain suitable new habitat at a rate of at least 100 km per decade.

On the basis of this and similar work, seed transfer policies in the province were re-examined and British Columbia now claims to be the first jurisdiction to have modified seed-transfer standards specifically in response to climate change. The modest modification allows seed of most species in most areas to be moved 100 to 200 metres upwards in elevation. The new policy is an implicit recognition of the need for assisted migration to ensure that plantations in the province will be adapted to future climatic changes.

SOURCES: Ying and Yanchuk, 2006; Hamann and Wang, 2006; Wang *et al.*, 2006; British Columbia Ministry of Forests, Lands and Natural Resource Operations, 2008.

the other products and services that the trees provide. The genetic attributes that enable the trees to provide these products and services are therefore crucial.

In many tropical countries there is a need to improve the capacity of stakeholders to identify trees that are suitable, in both environmental and livelihood terms, for use in mitigation schemes. For example, large-scale plantations of the gum arabic tree (*Acacia senegal*) are being promoted in Sahelian countries such as Burkina Faso, Mali, Niger and Senegal for climate change mitigation, reclamation of degraded land and income generation, even though knowledge as to whether the germplasm used can provide the required gum yield is limited.

Meeting demand for trees that can be used in climate change adaptation and mitigation will require adjusting the objectives of tree breeding programmes. Climate-related problems have so far received little attention in such programmes. However, many tree species have high genetic diversity for traits that are relevant to climatic adaptation, and this diversity provides a potential basis for selective breeding (as well as for natural selection). Box 2 lists a number of traits that are likely to be important in climate change adaptation and mitigation but have

BOX 2

Traits that will help trees adapt to climate change

DROUGHT RESISTANCE

For many tree species, changes in moisture regimes will present greater problems than temperature changes. Drought resistance is a complex trait that may include deep rooting systems, deciduous habit and efficient use of water.

PEST RESISTANCE

Climate change-related increases in pest and disease attacks are becoming a crucial issue in plantation forestry. In theory, pest and disease attacks caused by climate change could be addressed by breeding for resistance or tolerance. However, this approach might not produce results sufficiently quickly. Instead, it may be necessary to use tolerant genotypes already found in nature or bring in tolerant species from elsewhere.

FIRE RESISTANCE/TOLERANCE

Less rainfall and higher temperatures, combined with human activities such as forest clearance, can increase the frequency of fires. Many tree species growing in semi-arid regions have developed adaptations that confer a degree of resistance to periodic fires (e.g. thicker bark). However, species from more humid zones may be less well adapted.

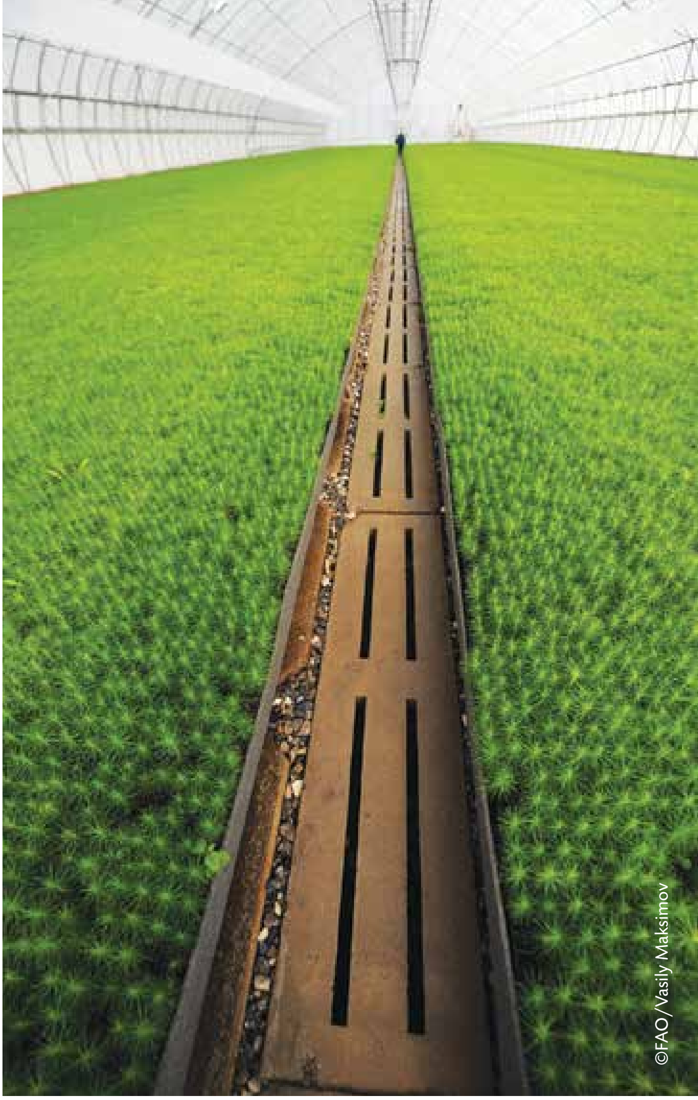
CYCLONE RESISTANCE AND SALT TOLERANCE

The combined effects of rising sea levels and more frequent storms pose a great threat to coastal forests. Low-lying islands are at particular risk. Differences in trees' ability to withstand storms and salinity may be more pronounced between species than within species. However, the possibility of selecting for resistant types within species needs to be explored.

PHENOTYPIC PLASTICITY

The capacity of trees to adapt their phenotypes to different conditions is not well understood. However, it is known that this capacity varies at intraspecific level.

SOURCE: Adapted from FAO thematic study Loo *et al*., 2011 seldom been considered in tree breeding programmes.



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Conclusions and recommendations

Research into adaptive traits that may be of use in climate change adaptation and mitigation needs to be strengthened. The adaptive and life-history traits of the majority of tree species, particularly in the tropics, have not been well documented. In the few species for which genetic evaluations have been undertaken, the focus has mainly been on traits directly related to production rather than on adaptive traits that could be important under climate change.

Provenance trials have shown that variation in adaptive traits is present in many tree species. However, many trials were established before the need to respond to anthropogenic climate change was recognized as an important research issue. There is a need for new trials that are specifically designed to assess responses to climate change. Information from old multilocational trials should also be used to gain insights into the effects of climate change and identify potential sources of well-adapted genetic resources. Old trials can also be used as sentinels to monitor the effects of climate change on tree species. A global database, or regional databases, of such trials should be established.

Despite their significance in climate-related research, there has been a general decline in the establishment of provenance trials in recent years. A number of factors have contributed, including the costs of operating such trials, difficulties in international germplasm transfers, greater emphasis on social issues in the forestry sector and greater focus on new technologies such as molecular marker analysis of genetic variation. Even in commercially important species that have been subject to extensive provenance trials, populations from the edges of species' ranges and other atypical populations are rarely well represented. Future trials will need to cover a wider range of species and ensure that trees from all parts of the ecological ranges of these species are included. The most interesting adaptations are likely to be found in "marginal" populations. This was found to be the case, for example, in a multilocational provenance trial evaluation of the African locust bean tree (*Parkia biglobosa*) conducted in Burkina Faso (Ouedraogo *et al*., 2011).

Molecular studies can provide insights into the roles of specific genes in responding to climate change. They can also be used to identify patterns of genetic diversity within tree species and develop better understanding of how trees responded to climate change in the past. This kind of information is very useful in designing *in situ* conservation measures and prioritizing populations for *ex situ* conservation. However, molecular studies should be regarded as complementary to field trials rather than as an alternative.

In breeding programmes, more attention must be given to traits that increase resilience.

The potential role of assisted migration in climate change adaptation needs to be studied in greater depth, including evaluation of whether it is necessary to move associated species such as nitrogen-fixing bacteria and animal pollinators. Attention needs to be paid to successes and failures in current planting initiatives undertaken in response to climate change. In breeding programmes, more attention must be given to traits that increase resilience. In the case of natural forests, potential means of assisting adaptation to climate change include broadcasting seed or pollen in areas where current populations are expected to become maladapted under future climatic conditions. Other management actions, such as reducing harvesting intensity and planting trees in "corridors" to link fragmented forests, also need to be considered.

Assisted migration includes not only the managed movement of species to areas where they are not yet present, but also the introduction of better-suited populations within species. In many species in which genetic variability is large (as demonstrated by provenance trials and molecular studies), moving well-adapted populations is likely to be a better strategy than moving species because collateral environmental risks are lower. Assisted migration, whether at species level or at population level, will require the establishment of a well-designed regional- to global-scale traceability system for tree germplasm used in reforestation (forest reproductive material).

Gene banks for tree species need to be made more comprehensive. The majority of tropical tree species are not included in gene banks. In part this reflects the characteristics of the seeds of many tropical trees, which cannot be stored for any length of time in gene banks. Research is needed on how to include important species with recalcitrant seeds in seed banks or live gene banks. In the case of boreal and temperate trees, although species coverage in gene banks is relatively good, within-species genetic diversity is generally not well covered. Among all groups of trees, seed collections are not sufficiently comprehensive to meet the challenges that are likely to be posed by climate change.

Adapting to and mitigating climate change is likely to require increasingly frequent transfer of forest genetic resources across national borders. Given that international exchanges, especially for research purposes, have become increasingly difficult in recent years, there is a need to develop policy frameworks that facilitate access to resources while ensuring phytosanitary security and fair and equitable sharing of benefits. Within individual countries, policies defining the zones in which particular types of tree can be planted will also need to be reviewed. A further priority should be to improve linkages between international exchange and smallholders by revitalizing the role of national tree seed centres in developing countries.

There is a need to develop policy frameworks that facilitate access to resources while ensuring phytosanitary security and fair and equitable sharing of benefits.

Smallholder farmers are increasingly important as guardians of tree biodiversity in the tropics, and mechanisms need to be developed to reward them for their conservation activities and support them in adapting their livelihoods to the effects of climate change. Their capacity to identify species and varieties of trees that meet their livelihood needs and are suitable for environments affected by climate change needs to be strengthened.

Most of these conclusions are reflected in the Global Plan of Action for the Conservation, Sustainable Use and Development of Forest Genetic Resources (FAO, 2014) negotiated by the Commission on Genetic Resources for Food and Agriculture and adopted by the FAO Conference in 2013. One of the principles upon which the strategic priorities of the Global Plan of Action were developed is that genetic diversity is the mainstay of biological stability, enabling species to adapt to changing environments, including the effects of climate change and emerging diseases. Under its Priority Area 3: Sustainable Use, Development and Management of Forest Genetic Resources, the Global Plan of Action affirms that the challenge of achieving food security for all and environment sustainability in the context of the combined effects of climate change and increasing human pressure on forests is greater now than it has ever been. More efficient use and management of forest resources is therefore needed. Strategic Priority 14 focuses specifically on climate change:

> "***Support climate change adaptation and mitigation through proper management and use of forest genetic resources*** *– Genetic diversity is needed in order to ensure that species can adapt, as well as to allow for artificial selection and breeding to improve productivity. Thus, genetic diversity, including diversity among species, is the key to the resilience of forest ecosystems and the adaptation of forest species to climate change."*

The Global Plan of Action includes additional strategic priorities, under its four priority areas, that support efforts to mitigate and adapt to climate change.

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Aquatic genetic resources

FOR FOOD AND AGRICULTURE AND CLIMATE CHANGE

Roger Pullin and Patrick White

Aquatic genetic resources underpin all production of aquatic plants and animals, whether in aquaculture (farming aquatic organisms), capture fisheries (hunting aquatic wildlife) or so-called culture-based fisheries (akin to fish ranching). They provide the basis for future adaption of these systems to the effects of climate change and other challenges.

Aquatic ecosystems and their biota account for the largest carbon and nitrogen fluxes on the planet and serve as its largest carbon sinks. The bodies of some aquatic micro-organisms, such as foraminiferans and coccolithophores, incorporate carbon in the form of calcium carbonate. When they die and sink to the floor of the ocean, much of the carbon becomes buried in sediments, where it remains locked up indefinitely. Calcium carbonate in the skeletal structures of marine invertebrates – particularly echinoderms (starfish, sea urchins, etc.) – and the carbonate precipitates in the intestines of marine fish also make huge contributions to global carbon storage (Wilson *et al.*, 2009). Overall, the oceans absorb 2 gigatonnes more carbon per year than they release into the atmosphere.

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Climate affects many aspects of aquatic environments, including the

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NOTE: This section was adapted by Dafydd Pilling from Pullin and White (2011).

temperature, oxygenation, acidity, salinity and turbidity of seas, lakes and rivers, the depth and flow of inland waters, the circulation of ocean currents, and the prevalence of aquatic diseases, parasites and toxic algal blooms. Climate change is predicted not only to affect long-term averages, but also to influence patterns of short-term fluctuation. Projections for the twenty-first century include more frequent heat waves, less frequent cold spells, greater intensity of heavy rainfall events, more frequent summer droughts in mid-continental areas and greater intensity of tropical cyclones (USCCSP, 2008). In the tropical Pacific, El Niño-Southern Oscillation events are expected to become more intense.

Acidification of seawater, caused by increasing levels of carbon dioxide in the atmosphere, is a major threat to marine ecosystems.

Acidification of seawater, caused by increasing levels of carbon dioxide in the atmosphere, is a major threat to marine ecosystems (Nellemann *et al*., 2008). There is great concern that acidification may compromise the roles of calcifying organisms in sequestrating carbon. Moreover, if vulnerable planktonic organisms, such as crustacean zooplankton, are affected by acidification, marine food webs may change dramatically – with implications for the species composition of the whole ecosystem. Over the long term, climate change is also expected to cause changes in ocean currents, affecting the migration routes of some aquatic species and the dispersal of eggs and larvae.


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Estuaries, lagoons and other coastal brackish waters are likely to be affected in several ways by climate change (Bates *et al*., 2008; Andrews, 1973; Smock *et al*., 1994). These environments are particularly vulnerable to hurricanes and storms, which are predicted to become more frequent under climate change. Rising sea levels will also be a threat. Heavy rainfall over the land may increase the runoff of freshwater, nutrients, sediments and pollutants into coastal waters.

Among freshwater ecosystems, many rivers will be affected by changing precipitation and evaporation regimes (Ficke, 2007; MEA, 2005). Although the availability of water in 70 percent of the world's rivers is projected to increase under climate change, the remaining 30 percent will be adversely affected. More frequent droughts increase the risk that small lakes will dry out completely, leading to major disruptions of local fisheries and threats to biodiversity. Unusually heavy rains can also cause problems. For example, extreme flooding that temporarily merges previously separated water bodies can lead to the introduction of invasive species that threaten indigenous biodiversity.

Effects of climate change on aquatic genetic resources and their management

All the climate-related changes described above affect aquatic biodiversity and genetic resources. Although some aquatic species have the capacity to move in search of more favourable conditions, others are sessile or are only capable of limited movements. Populations that are unable to move must either adapt *in situ* or become increasingly stressed and eventually face the risk of extinction. Species kept in aquaculture systems are similarly immobile and vulnerable in the face of climate change. The same is true for isolated populations, such as those living in shallow lakes and mountain streams that have no passable connections to other bodies of water. Other species are unable to relocate because they are restricted to specific habitats such as coral reefs and sea grass beds.

Rising temperatures are already affecting the distribution and abundance of marine organisms. Some warm-water plankton, fish and other aquatic species are shifting towards the poles. Some zooplankton species have already moved up to 1 000 km to the north (Leemans and van Vliet, 2004). As new species become established in formerly cold waters, they will compete with the native cold-water species, some of which may be driven towards extinction. In most environments, higher temperatures will increase the productivity and growth rates of aquatic organisms. However, problems may arise because higher temperatures disrupt the timing of reproduction, negatively affect particular stages of animals' life cycles, limit the availability of food supplies or increase the prevalence of diseases, parasites and predators. Many aquatic organisms depend on having stable biological communities around them. They are therefore vulnerable not only to direct effects on their own physiology, but also to disruptions that may occur because other organisms are affected by climate change (Guinotte and Fabry, 2008). Some aquatic communities are reliant on particular species such as corals, kelp, mangroves and sea grass. If these species are unable to adapt, the whole community will be disrupted and may disappear completely. Extreme weather events may lead to escapes from fish farms, with adverse effects on the genetic diversity of wild populations.

Runoff increases turbidity and siltation. This can lead to the elimination of aquatic species that require very clear water (e.g. giant clams and corals feeding through symbiotic zooxanthellae[3]). Turbidity lowers light penetration and reduces the abundance and activity of the phytoplankton that form the basis of most aquatic food webs. It also hampers activities that require animals to have a clear vision of their surroundings – feeding, reproduction, avoiding predators, etc. Siltation can lead to the physical burial of sessile organisms such as corals and bivalves. Increased productivity following runoff events can have both positive and negative effects on fisheries. On the positive side, greater availability of nutrients (and possibly disruption of predator activity) can lead to rapid increases in the abundance of some invertebrates (Flint, 1985). However, runoff can generate harmful algal blooms or contaminate the water with pollutants (De Casablanca *et al*., 1997). Such effects are expected to lead to the loss of significant numbers of aquatic species, particularly where the direct effects of climate change are combined with increasing water abstraction and other pressures caused by human activities. Harmful algal blooms – which already pose a serious threat to coastal aquaculture and fisheries, particularly around the coasts of Asia – are likely to increase as waters become warmer. Climate change may also favour some microbial pathogens and promote the spread of diseases among aquatic populations.

The effects of climate change interact with those of other stressors of aquatic environments, such as overfishing, size-selective harvesting, dredging and dam construction. Broader threats include political and institutional frameworks that restrict the capacities of aquaculture-dependent communities to adapt, deficiencies in monitoring and early-warning systems and in emergency and risk planning, and more general problems such as poverty, inequality, food insecurity, conflict and disease.

The effects of climate change interact with those of other stressors of aquatic environments, such as overfishing, size-selective harvesting, dredging and dam construction.

Climate change will increase physiological stress in some farmed fish populations. Their productivity will be affected and they will become more vulnerable to diseases. Aquatic farmers will face lower returns and higher risks. Some aquatic hatcheries and farms will have to relocate or shift to keeping better-adapted populations or different species. Nevertheless, climate change is also likely to bring some opportunities. For example, higher temperatures will increase the ranges of some fisheries and will allow the farming of some aquatic species in new areas and with some increases in growth rates and productivity.

The safety of some aquatic produce for human consumption can be affected by short-term climate fluctuations and long-term climate change, particularly by

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[3] Zooanthellae are single-celled organisms that live within corals.


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higher temperatures in aquatic ecosystems and along post-harvest processing and marketing chains (Chamberlain, 2001).

Human use of aquatic genetic resources will have to adapt to the effects of climate change. In the case of capture fisheries, there is little that can be done to promote adaptation among the target species. Restocking with wild or hatchery-reared fish that have appropriate environmental adaptations is possible, but can have large and irreversible genetic effects on surviving wild populations. Conservation of wild aquatic populations in marine, brackish and freshwaters can be pursued by designating protected areas and managing them effectively, as well as by monitoring how exploited populations are coping with the changed conditions. If necessary, conservationists can resort to moving important aquatic genetic resources to other *in situ* sites or into *ex situ* collections and gene banks.

Roles of aquatic genetic resources in coping with climate change

Most adaptation by wild and farmed aquatic organisms to the effects of climate change is occurring via natural selection. In the case of aquaculture and culture-based fisheries, the effects of natural selection can be supplemented by selective breeding and by introducing species from other locations. In all cases, genetic adaptation depends upon the availability of a wide range of diversity in traits that influence the capacity of the aquatic organisms to survive and reproduce in the presence of environmental stressors (Pickering, 1981; Winfield and Craig, 2010). The high fecundity of fish in wild populations and in hatcheries means

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that natural selection can act very rapidly and produce adapted strains even within a few generations.

Both domestication of additional aquatic species and genetic improvement of already-farmed species provide opportunities for adapting aquaculture systems to the effects of climate change. For example, farming air-breathing fish or hypoxia-tolerant fish, such as anguillid eels, catfish and snakeheads, could become more important in some areas. Air-breathing fishes also tend to have wide thermal-tolerance ranges (FAO, 2008). Farming species that have short generation intervals and short production cycles is likely to have advantages. The longer that a crop of fish is held on a farm, the longer it is at risk from unfavourable climatic events.

There is abundant evidence for intraspecific variations in the thermal tolerance of aquatic organisms. Selective breeding for tolerance of high temperatures, and in some places low temperatures, is likely to become increasingly necessary under climate change. Wild and farmed populations of aquatic species also vary in terms


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of their resistance and susceptibility to pathogens and parasites. The resistance of some wild salmonids to microbial diseases and parasites is a good example of the importance of wild relatives of farmed fish as genetic resources for use in breeding programmes (Withler and Evelyn, 1990).

The use of genetics to develop disease-resistant, adverse environment-tolerant and specific pathogen-free strains for use in aquaculture has a relatively short history, but is likely to become increasingly important as ecosystems change because of climate change, invasive species and pollution. Little information is available on the genetics of tolerance to turbidity and siltation in aquatic species, apart from evidence that some species thrive better than others in turbid conditions.

A wide range of biotechnologies can be used to assist the selective breeding of farmed aquatic species for climate change adaptation. Cross-breeding (mating of individuals of two different varieties, stocks or strains within the same species) and hybridization (mating of individuals from two separate species) have long been used in aquaculture and culture-based fisheries. It is also possible to artificially produce polyploid[4] and monosex fish populations that might have applications in meeting climatic challenges. Rapid progress has also been made in analytical genetic technologies such as DNA markers, genome mapping, microarrays and sequencing. Gene discovery in aquatic organisms will increasingly target the improvement of traits related to tolerance of environmental stressors such as extreme temperatures, lack of dissolved oxygen, unfavourable salinity levels and disease challenge. In applying all the above-mentioned biotechnologies, it is important to consider the biosafety aspects of their use, including the effects of farmed organisms coming into contact with wild aquatic populations and ecosystems (Pullin *et al*., 1999).


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So-called euryoecious species – those that are able to thrive in variable and challenging environments – are likely to be less vulnerable than more-specialized species to the effects climate change and are likely to become more common and widespread. Euryoecious fish species may not be very attractive for commercial harvesting, but are nonetheless important for breeding programmes and related research. For example, the euryoecious tilapia *Oreochromis mossambicus* proved to be a bad choice as a farmed fish because of its poor growth and early maturation, but it has been a source of genetic material for breeding programmes, especially for the development of salt-tolerant hybrids.

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[4] Polyploid organisms have more than two paired sets of chromosomes.

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Aquatic ecosystems that adapt successfully to climate change also contribute to climate change mitigation, particularly through their ongoing roles as carbon sinks. The organisms involved are largely wild, but their roles are influenced by human activities. The FAO Code of Conduct for Responsible Fisheries (FAO, 1995) provides guidance on the sustainable use of aquatic systems for harvesting fish, but greater responsibility is also needed right along the production chain.

Aquaculture and fisheries have substantial scope for reducing their own greenhouse gas emissions, primarily by increasing the efficiency with which they use energy. In terms of the use of genetic resources, the key to success in mitigating climate change lies in an ecosystem approach that focuses on trophic relationships (Pullin, 2011). Shifts towards farming herbivorous or omnivorous fish and improving feed-conversion efficiency in aquaculture are particularly important.

Marine aquaculture still lacks domesticated herbivorous and omnivorous finfish species comparable to those used in freshwater aquaculture. Many marine fish browse and graze on coral reefs, on sea grass beds or in estuaries. The potential roles of such fish in aquaculture and culture-based fisheries need to be explored. It is also vital that efforts are made to conserve the ecosystems upon which these species depend – many of which will be threatened by climate change.

Watersheds and floodplains, and other freshwater wetlands, have immense importance as carbon sinks and in processing nitrogenous wastes. Aquatic genetic resources are essential to the provision of these ecosystems services. However, their roles depend on suitable and stable hydrological regimes. Many wetlands are under threat as they are drained for the development of intensive agriculture, forestry, human settlements and industry. By their very existence, responsible inland fisheries and aquaculture promote the maintenance of aquatic ecosystems and the associated climate-mitigation services (Molden, 2007).

Multipurpose use of scarce water resources will become increasingly important under climate change. For instance, in dryland ecosystems such as the African Sahel, seasonal aquaculture and fisheries can make important contributions to local livelihoods and the sustainable use of so-called wetlands within drylands. Small carps, catfishes, tilapias and various small indigenous species can be farmed in cycles as short as three months.

Integrated farming (e.g. crop–livestock–fish systems) could contribute significantly to climate change mitigation, and their potential for this needs to be explored thoroughly. Such systems can make efficient use of locally available nutrients and water. Fish such as Nile tilapia (*Oreochromis niloticus*) can improve the productivity of wetland farming systems and increase microbial biomass in the soil (Lightfoot *et al*., 1990). Integrated farming systems also require less fossil-fuel energy than intensive feedlot aquaculture and conventional agriculture (Haas *et al*., 1995).

Conclusions and recommendations

The roles of aquatic ecosystems and aquatic genetic resources in adaptation to and mitigation of climate change have been greatly underemphasized compared to the roles of terrestrial ecosystems and terrestrial genetic resources. Aquatic ecosystems contribute to the emission of greenhouse gases, but are also the most important current and potential mitigators of climate change. The key to maximizing the roles of aquatic genetic resources in adaptation and mitigation is to take care of aquatic ecosystems and conserve the genetic resources. This will not be successful without greatly increasing investment in research on aquatic biodiversity and backing this research up with more effective policy-making and stronger institutions and human capacities. It is also important to be aware that the effects of climate change interact with many other stressors of aquatic organisms and ecosystems. Fostering the adaptation of these ecosystems to the effects of climate change requires a holistic approach that includes collaboration with other food and agriculture sectors.

> The key to maximizing the roles of aquatic genetic resources in adaptation and mitigation is to take care of aquatic ecosystems and conserve the genetic resources.

Aquatic farmers and fishers should be encouraged, equipped and trained to pursue adaptation measures. Developments that are beyond their financial and technical capacities, such as provision of information and extension services, coastal defences, extreme-event forecasting and early warning systems, need to be undertaken by government institutions and science and technology organizations.

Unfortunately, partnerships for investigating, documenting, improving and sustaining the roles of aquatic genetic resources in adaptation to, and mitigation of, climate change are generally under-resourced and under-developed. In particular, partnerships among organizations dealing with specific food-producing sectors or subsectors, as well as those between the public and private sectors, need to be strengthened. Concerns about climate change can serve as catalysts for establishing new partnerships and strengthening existing ones.

Wild aquatic plants and animals are already adapting to climate change through natural selection and migration to new areas. There is also great scope for further domestication and breeding of aquatic organisms for use in adapting aquaculture to the effects of climate change. Various biotechnologies can be used to facilitate the process, but strict biosafety measures are essential whenever aquatic organisms are genetically altered, in order to avoid the risk of harming ecosystems and wild populations. Similar precautions should apply to the use of alien species (i.e. those introduced from other locations).

Further research is needed on the flows of carbon and nitrogen within the ecosystems that host and support aquaculture and fisheries. The development of responsible inland aquaculture and fisheries can play a role in the rehabilitation of degraded watersheds. In general, inland aquaculture and fisheries should become partners in the multipurpose use of scarce freshwaters – occupying parts of these waters, but not substantially consuming them. The rehabilitation of degraded coastal zones should be pursued: for example, through mangrove reforestation and ending overfishing and other destructive fishing practices.

Innovative aquaculture and fisheries operations, such as integrated farming systems and multi-trophic-level aquaculture, that can reduce the harmful effects of climate change and other stressors on aquatic ecosystems should be investigated and encouraged. Aquatic food production generally has many comparative advantages in terms of energy use and efficiency.

There is also an urgent need to expand *in situ* and complementary *ex situ* conservation of aquatic genetic resources, with particular attention to resources that have potential in climate change adaptation and mitigation.

There is also an urgent need to expand *in situ* and complementary *ex situ* conservation of aquatic genetic resources, with particular attention to resources that have potential in climate change adaptation and mitigation. More aquatic protected areas should be established and managed so as to promote the conservation of aquatic genetic resources, particularly in freshwater ecosystems.

Despite the crucial roles of aquatic genetic resources in global food security and sustainable livelihoods, information on these resources tends to be scattered and incomplete. Lack of standardization means that access to data and information is generally poor. The Commission on Genetic Resources for Food and Agriculture has initiated the preparation of the first report on *The State of the World's Aquatic Genetic Resources for Food and Agriculture*, focusing on farmed aquatic species and their wild relatives within national jurisdiction. Countries are being given the opportunity to report on the main drivers affecting their aquatic genetic resources, including climate change. The report should provide insights into the potential roles of aquatic genetic resources in climate change adaptation and mitigation.

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Invertebrate genetic resources

FOR FOOD AND AGRICULTURE AND CLIMATE CHANGE

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Although the problems caused by invertebrate pests are well known – and considerable effort and resources are devoted to managing them – the vital contributions that invertebrates make to agriculture and food security are often overlooked.

Perhaps the most neglected group of all – in research, in farming practices, and in policies and strategies for agriculture and biodiversity – are the soil-dwelling invertebrates (the first of three major groups of invertebrate ecosystem-service providers discussed in this section). Small, out-of-sight and uncharismatic these animals may be, but their significance is enormous. Some larger soil-dwelling invertebrates, such as earthworms, ants and termites, have been described as "ecosystem engineers". They create the physical structures needed to maintain healthy soil communities and for basic soil processes such as water infiltration and storage, and sequestration and cycling of carbon. They help maintain the chemical fertility needed for plant growth. Also vitally important are the invertebrates that process the leaf litter that

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NOTE: This section was adapted by Dafydd Pilling from Cock *et al*. (2011).


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falls onto the surface of the soil. This subgroup includes a wide variety of species, ranging from tiny nematode worms and single-cell protista to larger animals such as woodlice, millipedes and centipedes. They are the main players in the transformation of freshly dead organic matter into humus and in the progressive release of nutrients. Finally, the smallest invertebrate predators – less than a tenth of a millimetre across and living in and around soil aggregates – stimulate the mineralization of organic matter by preying on micro-organisms.

None of these processes are isolated. Soil invertebrates are bound in complex webs of interaction with each other, with plants, with micro-organisms and with their physical surroundings. Some species are recognized as "keystones" within the soil community; their presence and roles have a disproportionate effect on other organisms. The loss of a keystone species within the soil can result in dramatic changes and impair the provision of ecosystem services on a vastly greater scale.

Soil invertebrates are bound in complex webs of interaction with each other, with plants, with micro-organisms and with their physical surroundings.

In most soil ecosystems, the resident invertebrate species have not been counted, let alone identified and described. The intricate ecological relationships within soil communities, and between them and above-ground biodiversity, remain very poorly understood. Nonetheless, it has become clear that in many agricultural systems, soil invertebrate communities are in decline. This has contributed to increased rates of land degradation, nutrient depletion, loss of fertility, water scarcity and declining crop productivity. Driving forces of the loss of soil biodiversity include the homogenization of agricultural systems, the spread of monoculture crop production, inappropriate use of agrochemicals and excessive soil disturbance caused by continuous tillage.

A second major group of invertebrate providers of ecosystem services are the pollinators. It has been estimated that at least 35 percent of world food production comes from crops that are dependent on insect pollination (Klein *et al*., 2007). Pollinating insects include wild species spilling over from natural or semi-natural habitats close to crop fields, and managed pollinators (usually honey bees) that can be brought in by farmers specifically to provide pollination. Both wild and managed pollinators are in decline – probably as a result of multiple interacting causes, including land-use change (e.g. the loss of flower-rich meadows), increased use of pesticides, socio-economic factors that make beekeeping less attractive, and the spread of the parasitic mite *Varroa destructor* and other pathogens of bees. The situation has caused such concern that it has been described as a "pollination crisis".

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Biological control agents – the natural enemies of pest species – are the third main group of invertebrate ecosystem-service providers. Biological control agents are commonly found in and around the agricultural ecosystems where their target species (i.e. particular pests) live. Almost all crop production systems benefit from the actions of naturally occurring local biological control agents. In addition, biological control agents can be introduced from outside as part of a deliberate strategy to reduce pest numbers. This can be done via permanent introduction of the agent into a new ecoregion (a strategy known as "classical biological control") or via introduction of the agent directly onto specific crops once or more during the cropping cycle (known as "augmentative biological control").

This section focuses on the three groups of invertebrates described above. However, it should also be recognized that some invertebrates are, in their own right, important sources of food and other products used by humans. The most economically significant products obtained from insects are honey and silk. In Western culture, terrestrial invertebrates themselves are not usually regarded as food for humans (apart from snails in some countries), but elsewhere in the world most large, easily gathered, non-poisonous invertebrates are eaten, including grasshoppers and locusts, crickets, cicadas, ants, termites, immature stages of beetles and moths, scorpions, spiders and worms. At present, these invertebrates are mostly gathered from the wild, rather than farmed. Wild invertebrates are a highly abundant and renewable resource and are a good source

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of protein, fats, vitamins and minerals. Collecting them for consumption or sale in local markets involves minimal inputs. For people who have little access to other sources of protein, invertebrates can be important components of the diet, and are often available when other foods are not.

The potential of cultivating invertebrates as an ecologically sound means of producing human or animal food is now beginning to attract some interest.

The potential of cultivating invertebrates as an ecologically sound means of producing human or animal food is now beginning to attract some interest. Compared to traditional vertebrate livestock, insects are generally more efficient at converting food into body mass, reproduce much more rapidly, occupy less space, use less water and produce less greenhouse gas. However, the mass production of invertebrates as food remains only a possibility. Research, testing, market development, supply chains, storage, preparation, promotion and human preferences would all need to be addressed before it could be realized on a large scale.

Effects of climate change on invertebrate genetic resources and their management

Climate change is expected to affect all three of the main groups of invertebrate ecosystem-service providers as well as invertebrate pests. Invertebrates have limited ability to control their body temperatures. Therefore, although some groups such as soil-dwelling organisms are to some degree buffered against the effects of temperature fluctuations in the wider environment, it is likely that rising temperatures will directly influence the distribution of invertebrate species. Many of the challenges associated with the management of invertebrate genetic resources in agriculture in the context of climate change will relate to climate-driven or human-assisted movement of invertebrate species.

Most invertebrates are expected to change their geographical distribution in response to climate change so as to remain in areas to which they are well adapted. This view is strongly supported by sub-fossil evidence of insect distribution during the glaciations and interglacial periods of the Quaternary Period. The sub-fossil record shows little evidence for the evolution of new species or for mass extinctions during the Quaternary. The sub-fossil remains can nearly all be matched to existing species, and the fact that species occur in similar associations implies that their physiological and ecological requirements have not changed significantly. There is evidence from the sub-fossil record that species disappeared at the beginning of the Quaternary, but little evidence for significant mass extinctions since then. This implies that the species that exist today have mostly existed unchanged since the beginning of the Quaternary, and that they have survived repeated glacial and interglacial periods. What the sub-fossil evidence does show, however, is that insect species have been highly mobile geographically. Broadly speaking, the species found in temperate regions during glacial periods are now restricted to cold areas of the subarctic and high


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mountains such as the Himalayas. The species found in temperate regions during the warmer periods of the Quaternary are those that we now associate with the subtropics. The implication is clear: species do not adapt to changing climate; they move to areas where they are well adapted.

The current world is very different from that of the early Quaternary Period. Human activities have created barriers to the migration of invertebrate species. These barriers are likely to affect species in natural ecosystems rather more severely than those associated with agro-ecosystems. The movement of the latter is likely to be facilitated rather than hindered by human-induced landscape changes. *In situ* adaptation of invertebrate species is expected to be most marked where movement is not an option (e.g. on low, isolated islands).

It is very difficult to predict how the combined effects of changing temperatures, changing rainfall patterns and elevated carbon dioxide levels will affect invertebrates and their capacities to provide ecosystem services or to act as pests. As yet, few studies have attempted to investigate interactions of this kind. Further complexity is added by the prospect that the other components of the ecosystem with which invertebrates interact – food plants, micro-organisms, etc. – will also be affected by climate change.

It is very difficult to predict how the combined effects of changing temperatures, changing rainfall patterns and elevated carbon dioxide levels will affect invertebrates and their capacities to provide ecosystem services or to act as pests.

Aided by human activities, the majority of invertebrate pollinators and pests, along with their natural enemies, can be expected to move with their host plants as crop and forage distributions change. However, as invertebrate species differ in their sensitivity to temperature and other climatic factors, the species composition of invertebrate communities will alter as they follow their associated crop or livestock production systems. Sensitivity to day length and other specific habitat requirements also affect the ability of some species to establish themselves at new latitudes.

It has been suggested that, in the future, parts of the world will have novel climates that have no current equivalent anywhere on the planet. This will inevitably lead to novel associations among invertebrate species and novel effects on agriculture. The consequences of such changes are difficult to predict. Some outcomes may be beneficial (e.g. the absence of some pests) and others harmful (e.g. the absence of some useful invertebrates). Human activities, both within agricultural systems and beyond (e.g. destruction and fragmentation of natural habitats), are likely to have a major influence on how invertebrates respond to climate change.

Extreme weather events such as heat waves, droughts and floods – which are predicted to increase in frequency due to climate change – are often followed by pest outbreaks. Among other contributing factors, these outbreaks can occur because the extreme event eliminates or weakens a pest's natural enemies. For example, field data indicate that parasitoids[5] are generally more sensitive than their hosts to climatic extremes and lag behind in population recovery (Thomson *et al.*, 2010). There is a danger that climate change will exacerbate such effects as long-standing relationships between pests and their enemies are broken by sequential extremes (e.g. droughts followed by periods of intense rainfall).

Warmer, shorter winters will mean that many invertebrates become active and start reproducing earlier in the year. Some species may be able to produce additional generations of offspring in a single year, which in the case of herbivores can have a major impact on host plants.

Warmer, shorter winters will mean that many invertebrates become active and start reproducing earlier in the year. Some species may be able to produce additional generations of offspring in a single year, which in the case of herbivores can have a major impact on host plants. Similarly, warmer winters may mean that pests are able to establish themselves in areas where they have not previously caused problems. The capacity of locally occurring natural enemies to respond and keep these pest populations under control may be in doubt.

Climate change is expected to have a profound effect on soil invertebrates and the services they provide. Temperature is a key factor regulating many of the biogeochemical processes in which invertebrates participate or by which they are affected, including soil respiration, litter decomposition, nitrogen mineralization and denitrification. Studies have shown that both elevated temperatures and elevated carbon dioxide levels affect the abundance of invertebrate species and the composition of

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[5] A parasitoid is an organism that spends a significant portion of its life history attached to or within a single host organism, which it ultimately kills (and often consumes).


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soil communities (e.g. Jones *et al*., 1998; Briones *et al*., 2009). Some species are better able to adapt than others. For some invertebrates, the ability to migrate down the soil profile to cooler and moister levels will offer an important survival strategy.

Warmer temperatures are likely to alter invertebrate behaviour, including the hunting behaviour of predators and the feeding habits of herbivores. Temperature can also affect the virulence of pathogens that attack invertebrates, and the capacity of host animals to survive the effects of parasitoids. Climate change is likely to involve shifts in rainfall patterns, which will interact with changes in temperature to influence wetting-drying cycles in the soil. In addition, the distribution, growth and physiology of plants are likely to be affected by climate change. Consequent changes in the nutritional composition of leaves will affect the diets of soil invertebrates.

Relationships between plants, herbivorous invertebrates and the natural enemies of these herbivores have developed over long periods of co-evolution. Species at higher trophic levels (predators and parasitoids) are more likely than herbivores to be affected by climate change, because their survival depends on the capacity of the lower trophic levels to adapt. Natural enemies with very specific host ranges – exactly the type of animal favoured for use in classical biological control programmes – may be particularly sensitive because they need to synchronize their life cycles with those of their hosts.

Climate change is expected to cause significant changes in the degree of synchrony between species' life cycles. In fact, even small changes can substantially influence the efficacy of biological control agents on a local scale. Recent studies have revealed that what had appeared to be generalist biological control agent species are often complexes of previously unrecognized specialist species. As specialists are generally more susceptible than generalists to disruption by climatic perturbations, the vulnerability of these biological control agents to the effects of climate change may be greater than previously anticipated.

Individual pollinator species may be affected by a breakdown in the synchrony between their life cycles and those of flowering plants. The diversity of pollinator communities should act as a buffer against reductions in crop yield. However, in the case of crops that are dependent on specialist pollinators, climate change-induced shifts in the location of production or loss of synchrony between pollinators' life cycles and the flowering seasons of plants are likely to cause problems.

Roles of invertebrate genetic resources in coping with climate change

Because of the many ecosystem services that they provide, invertebrates have a key role to play in adapting agriculture to the effects of climate change. The extent to which the individual services provided by invertebrates will be enhanced or impeded by climate change is difficult to predict. However, if invertebrate biodiversity is lost, the capacity of ecosystems to adapt is likely to diminish.

Healthy soils – and healthy, diverse soil invertebrate communities – will be vital to climate change adaptation. For example, earthworms help to maintain soil structure and the availability of water throughout the soil profile. Studies have shown that the presence of these animals can help to alleviate the effects of drought on crop production (e.g. Johnson *et al*., 2011). Studies have also revealed the remarkable ability of diverse soil invertebrate communities to restore the structure of degraded soils (e.g. Barros *et al*., 2004).

> Every effort should be made to avoid agricultural practices that disrupt resident soil invertebrate communities and the services they provide.

The potential for managing soil invertebrates to enhance their beneficial roles has been little explored. Few if any deliberate attempts have been made to introduce soil invertebrates into new countries or ecosystems. Given the potential for such species to become invasive, it is inadvisable to attempt any such introductions until soil ecology is much better understood than it is today. However, every effort should be made to avoid agricultural practices that disrupt resident soil invertebrate communities and the services they provide.

The presence of a diverse range of predators and parasitoids will tend to decrease the risk that pest populations will explode as their distributions and life cycles shift in response to climate change. The deliberate introduction of biological control


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agents is a well-established practice, and has a potential role to play in adapting crop production systems to new pest problems that arise because of climate change. Maintaining predator and parasitoid species with the potential to play this role is essential. Agricultural practices may need to be adapted to avoid damaging effects on invertebrate biodiversity in and around agricultural lands. In the case of organisms used in augmentative biological control, another potential strategy is to breed selectively for strains with desirable characteristics such as greater heat resistance, greater fecundity or a wider range of species hosts. To date, however, selective breeding of biological control agents has rarely been attempted.

In the case of classical biological control agents, the genetic diversity of introduced populations may be relatively low because the introduction was based on a small founder population. This lack of diversity may inhibit the ability of the population to respond to climate change. It may, therefore, be necessary to bring in additional genetic diversity in the form of new introductions from the original home range of the control agent. Another management option is to adapt the agro-ecosystem in such a way as to enhance the effectiveness of biological control agents that might otherwise struggle in changed climatic conditions. For instance, conservation habitats that provide food and refuges for biological control agents can be established next to crop fields. In the case of augmentative biological control, application strategies can also be adapted. For example, biological control agents that are adversely affected by drought can be applied in the evening when conditions are more humid.

It is likely that some pests, as they move into new areas in response to climate change, will at least temporarily "escape" from their natural enemies. This is likely to increase demand for classical biological control agents, especially in places


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where the newly established pest population is separated from its original home by a physical barrier such as the sea or a mountain range. For this reason, access to new classical biological control agents is likely to be particularly important for island countries. There is, however, a risk that the uncertainty and volatility that climate change is expected to cause in food supply and prices will reduce the attractiveness of using biological control agents. Because biological control methods operate with some time delay, uncertainty may lead farmers to opt for broad spectrum insecticides and their immediately obvious effects. This use of insecticides would, in turn, have a detrimental effect on biological control agents.

Conservation of both natural ecosystems and diversity-rich farming systems is essential to ensuring that sufficient biological control agents remain available for the future.

At present, and for the foreseeable future, there are no available means of conserving biological control agents *ex situ*. The lifecycles of these animals have no long-term dormant stages such as seeds or spores. The only option would be to maintain populations in culture. However, this would lead to the loss of diversity over time. Thus, biological control agents can only be maintained satisfactorily *in situ*. The most important reservoirs for biological control agent species are agro-ecosystems where management practices do not hinder their survival (e.g. those with little pesticide use). Most biological control agents are also likely to have reservoir populations in natural ecosystems (i.e. those not used for agriculture). Such habitats are likely to harbour additional genetic diversity within known biological control agent species. They may also be home to unknown species with future potential to act as biological control agents. Conservation of both natural ecosystems and diversity-rich farming systems is thus essential to ensuring that sufficient biological control agents remain available for the future. More research is needed before it will be possible to know which ecosystems are particularly important in maintaining which biological control agents.

As land use changes, it may be necessary to protect or develop corridors of suitable habitat that ensure food and nesting resources are available for pollinators.

Maintaining insect species that can provide pollination services for a wide range of crops is also vital to the future of agriculture in the face of climate change. Pollinator populations not only need to be able to cope with changing climatic conditions, they must also be able to provide the pollination services needed to meet increasing demands for food and retain the capacity to adapt to potential changes in the types of crops grown.

The natural habitats of wild pollinator species need to be identified and preserved. As land use changes, it may be necessary to protect or develop corridors of suitable habitat that ensure food and nesting resources are available for pollinators. The presence of areas of natural and semi-natural habitat next to crop fields has been shown to increase the diversity of pollinator populations and enhance the services they provide (e.g. Steffan-Dewenter and Tscharntke, 1999; Morandin and Winston, 2006; Ricketts *et al.*, 2008). Deliberate planting of climate-resilient plants that favour pollinators can serve as a means of maintaining the habitats and floral resources needed by wild pollinators and managed bees. An advantage of having a range of (non-crop) food resources available in the landscape is that the diverse vegetation is likely to support a diverse assemblage of pollinators. This is important, as crops with generalized flowers (i.e. flowers that can be pollinated by a range of species) may produce more reliably when a variety of different pollinator species are present (e.g. Hoehn *et al.*, 2008). The insurance provided by a diverse assemblage of pollinators may also facilitate adaptation, because different species will have different capacities to respond to climatic changes.

The world's most important managed pollinator species is the honey bee. This reflects the species' adaptability. It can flourish under many different conditions – from arctic to tropical and from rainforest to desert. Climate change may mean that, in any given area, new honey bee races or hybrids that suit local conditions will need to be introduced (e.g. those that are drought resistance or do not abscond).

Another option that may have to be considered in response to climate change is to explore the use of other bee species (or other insects) as managed pollinators. For example, some stingless bees (*Meliponinae*) and stem-nesting solitary bees (*Megachilidae*) can be domesticated and mass bred. Species could be chosen according to their ecological traits and environmental tolerances (e.g. generalist feeding and nesting habits) for use in adapting managed pollination strategies to the effects of climate change. As described above, crops that are dependent on specialist pollinator species may be particularly vulnerable to the effects of climate change. If problems occur, the only option may be to domesticate and manage the specialist pollinators.

It is important to bear in mind that there are some risks involved in using managed organisms in new environments, because they may interfere with native species. This can occur through competition for resources such as food and nest sites or through the introduction of pests or diseases. Alternatively, diseases can spread from native species to introduced managed pollinators. A notorious example was the transfer of the varroa mite from the Asian honey bee to the managed honey bee in Southeast Asia. Infection of honey bee hives with varroa mites is now a global concern. Given such risks, it is extremely important that transfer of managed organisms is based on established risk-assessment procedures.

> Many pollinators are able to move over long distances without assistance from humans. However, it is likely that climate change will increase demand for assisted movement of pollinators between countries.

Recent problems with managed honey bee populations have raised awareness of the vulnerability of pollination services. At present, crop pollination is probably limited by a range of factors, operating to different degrees in different locations, and including inappropriate crop management, lack of habitat for pollinators, pesticide use and unfavourable climate. There is a danger that climate change will intensify these problems. Strategies for dealing with them will need to be integrated into management systems at both farm and landscape levels. For example, shifting from monocultures to mixed cropping systems and agroforestry plantations might help reduce the impact of climatic changes by providing pollinators with favourable microclimates and alternative foraging and nesting resources.

Many pollinators are able to move over long distances without assistance from humans. However, it is likely that climate change will increase demand for assisted movement of pollinators between countries. Such transfers have major potential benefits, but can also generate significant problems. International trade in honey bees and their products is governed by relatively new international laws, which provide a framework for protecting the honey bee industry and for legitimate certified trade in honey bees. Sanitary issues are covered by the Terrestrial Animal Health Code of the World Organisation for Animal Health (OIE). No international regulations are yet in place for environmental risks such as displacement of indigenous pollinators.

Conclusions and recommendations

As yet, it is not possible to draw conclusions as to how climate change will affect specific invertebrate species and the services they provide. However, three general conclusions can be drawn. First, it is likely that climate change will disrupt the


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use of invertebrates in agriculture (although the exact nature of these disruptions cannot yet be predicted). Second, without interventions to counter them, these disruptions will result in production losses (although the extent of such losses is not yet known). Third, interventions to help invertebrates adapt and continue providing ecosystem services in the face of climate change are justified (although the methods with which to intervene and the policies needed to facilitate the interventions are not yet in place). Priority actions in the fields of scientific knowledge, conservation, use, access and policy are summarized below.

Scientific knowledge

- Knowledge of the services that the various groups of useful invertebrates provide to crop production needs to be improved, especially in the case of wild pollinators of major crops, soil invertebrates and natural biological control agents. Knowledge is particularly lacking in developing countries.
- The responses of invertebrate species, communities and food webs to climate change need to be quantified. It is only within the last two decades that scientists have begun to study the responses of invertebrate species to climate change. Many mechanisms have been identified. However, the combined effects of factors associated with climate change remain poorly understood.
- Further investigation is needed into past climate change in the tropics and its effects on invertebrates. While past climate change events are relatively

well documented in temperate zones (based on tree rings, glaciers and well-preserved sub-fossils), parallel data are largely lacking for tropical zones.

- Taxonomy and genetic characterization of invertebrates found in agro-ecosystems need to be improved, especially for biological control agents and soil invertebrates.
- More studies are needed on the capacity of key species to move in response to climate change, especially the rates of movement of soil invertebrates that do not have a motile stage in their lifecycles and the capacity of biological control agents to track changes in the distributions of their hosts.

Conservation, use and access

- Rearing technologies for use in the domestication of selected wild bee and other pollinator species need to be developed.
- Means of conserving and promoting generalist natural enemies of pests need to be developed. This will require improved knowledge of the movements of these organisms within landscapes and the ways in which their distributions are affected by the availability of resources such as food and refuges.
- The source habitats of pests and their associated biological control agents need to be identified and conserved. Adapting biological control strategies to the effects of climate change will probably require accessing genetic resources in their habitats of origin.
- Mass-production methods need to be developed for some important species of soil ecosystem engineers in order to facilitate experimental evaluation of their use in soil management.
- Further research is needed on the sustainable use and domestication of edible invertebrates. This potentially valuable food resource has been neglected. If it can be developed as a viable alternative to food from other animals, it could help mitigate climate change.

Policy environment

- An overarching strategy that integrates the management of invertebrates with the management of other ecosystem components is needed.
- Guidelines for facilitating and regulating the movement of invertebrate genetic resources between countries need to be developed. These guidelines should build on what is already available for biological control agents, and should include protocols for emergency responses and pest risk assessment.
- As climate change progresses, agricultural production systems are likely to be affected by new invasive pests. Coordinated development of standard protocols for pest risk assessment would facilitate detection efforts and allow timely responses to pest invasions.
- Responses to invasive pests will probably involve release of classical biological control agents. It may be appropriate to consider revising the relevant international phytosanitary standards to account for emergency responses to new invasive threats.

- Specific policies to address the needs of island states for biological control agents may be required, given that such countries are particularly vulnerable to pest invasions and that climate change is likely to increase the threat.
- In implementing the Nagoya Protocol on Access and Benefit-sharing, countries should consider the importance of access to invertebrate genetic resources for use in sustainable agriculture and the very significant role these resources play in efforts to achieve world food security.
- Countries should ensure that the management of invertebrate genetic resources for food and agriculture is well integrated into their national biodiversity programmes.

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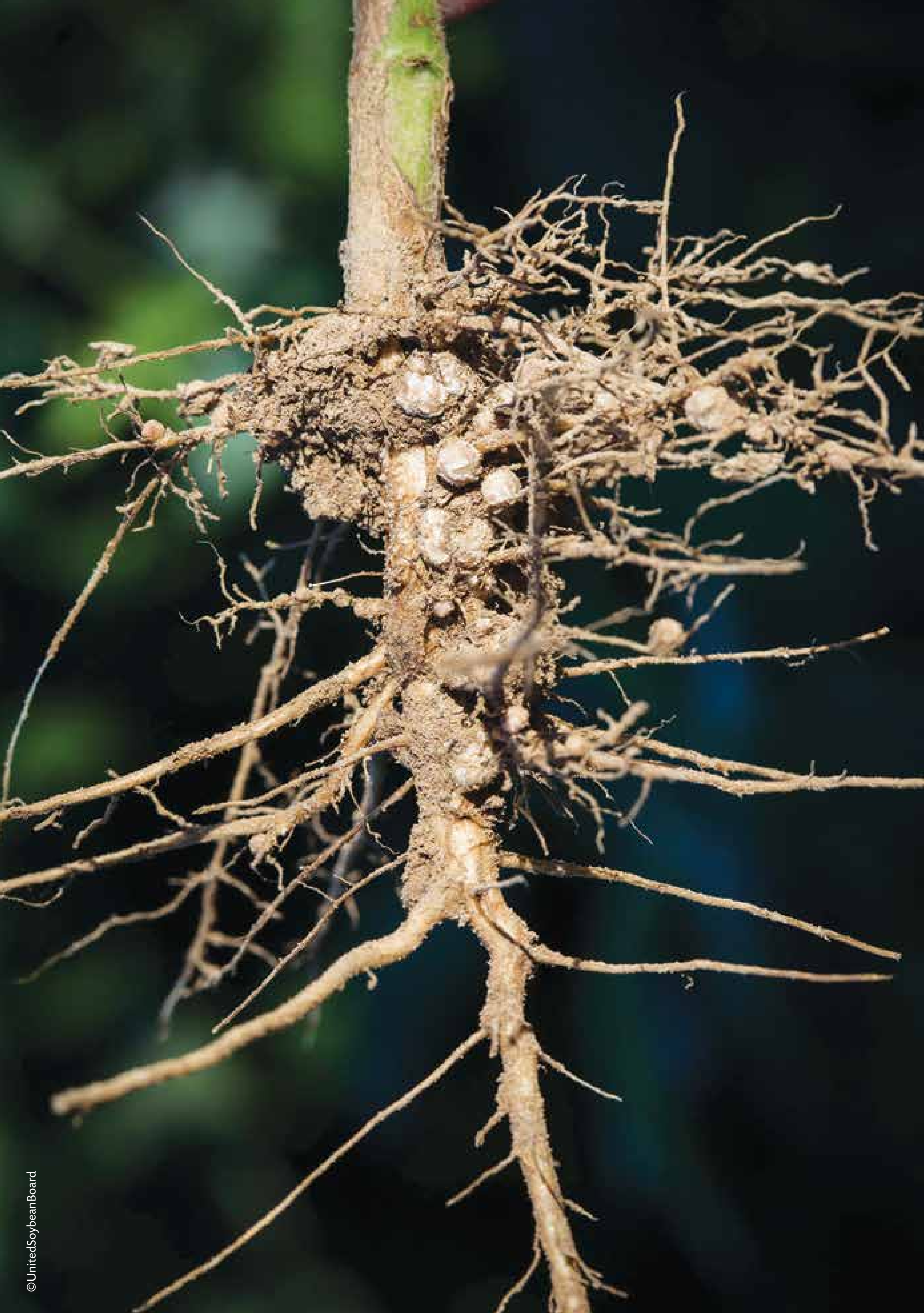

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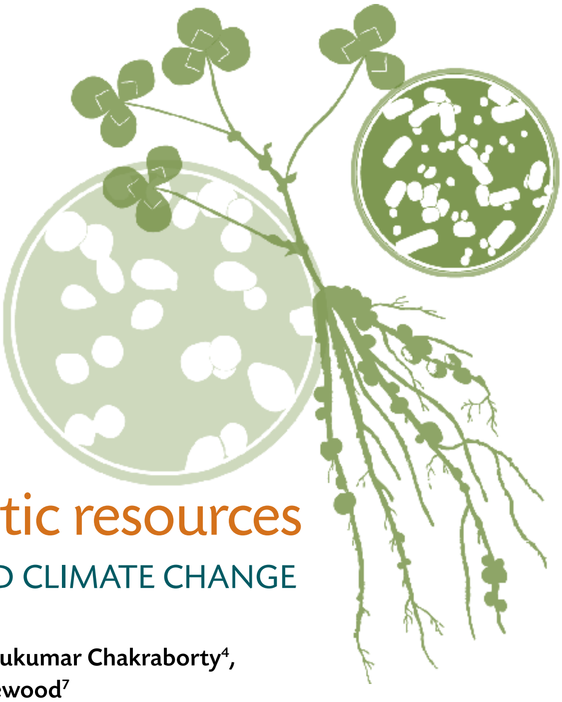

Micro-organism genetic resources

FOR FOOD AND AGRICULTURE AND CLIMATE CHANGE

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The diversity of micro-organism genetic resources is unrivalled. There are estimated to be between 5 million and 30 million micro-organism species in the world, only about 2 million of which have been formally described. They offer vast, as yet largely untapped, opportunities for improving the efficiency of agriculture and food production. However, they are largely ignored or regarded only as agents of disease in crops and livestock.

The roles of micro-organisms in agriculture and food production are diverse. In this section, micro-organisms are divided into five functional groups – soil inhabitants, plant and rhizosphere[6] inhabitants, plant pathogens, biological control agents and food production micro-organisms. These groups are in fact highly interlinked, with many micro-organism taxa fulfilling roles across all of them.

Micro-organisms are key players in the creation and maintenance of soil ecosystems. The process of soil formation begins when micro-organisms colonize the parent material of the soil (rocks, etc.). They create habitats for other organisms and help

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[6] The rhizosphere is the soil that is directly influenced by the roots of plants. It is the site of a range of complex interactions between living and dead soil components.

NOTE: This section was adapted by Dafydd Pilling from Beed *et al*. (2011).

to maintain and develop the soil over the longer term. Soil micro-organisms are vital to the global carbon cycle. They contribute to the sequestration of carbon in soil organic matter and the release carbon dioxide through decomposition.

Soil micro-organisms have been described as the "chemical engineers" of the ecosystem. They have enormous metabolic diversity and versatility, and can use all naturally produced compounds and most human-made compounds as substrates for their growth. They generate chemically complex compounds, such as humic material, that are important in maintaining the structure of the soil.

The main contributions of rhizosphere micro-organisms lie in extracting nutrients from soil materials and the atmosphere, producing substances that promote plant growth, and forming and maintaining soil structure.

Also essential to agriculture are the micro-organisms that live within plants and in the rhizosphere. The main contributions of rhizosphere micro-organisms lie in extracting nutrients from soil materials and the atmosphere, producing substances that promote plant growth, and forming and maintaining soil structure. Rhizobial bacteria live symbiotically within the root nodules of leguminous plants and fix atmospheric nitrogen in a form that can be used by plants (Brewin, 2004). Mycorrhizal fungi live symbiotically with plant roots, obtaining soluble carbon in exchange for improving plants' access to mineral and organic forms of soil nutrients such as phosphorus (Sylvia, 2005). The micro-organism communities of the rhizosphere can also change the soil environment to make it less favourable to pathogens and thereby improve crop health. Micro-organisms living within plants often provide their hosts with a number of services. For example, the fungus *Neotyphodium* produces substances that protect its host plants – various species of *Lolium* grass – from insect attack, drought, cold and fire (West *et al.*, 1988).


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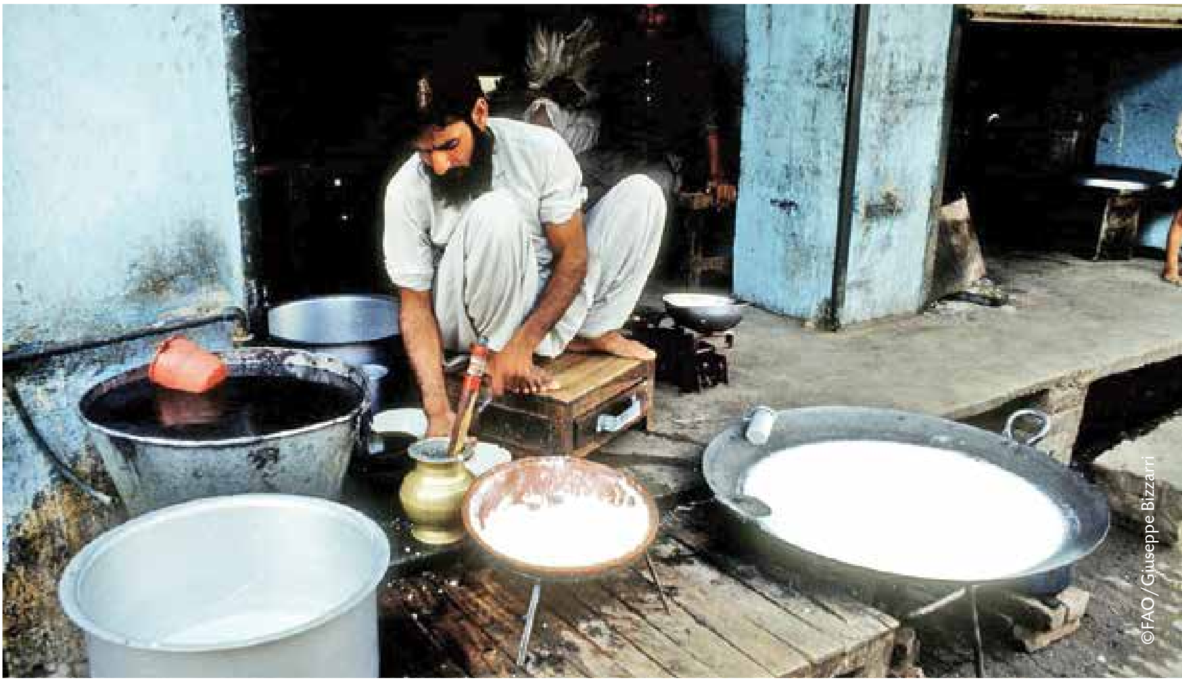
While plant pathogens may not normally be thought of as useful genetic resources, there are many reasons for ensuring that their biodiversity is maintained under controlled conditions. For example, certain pathogens are critically important to crop production. By switching on host defence mechanisms without



causing severe damage, a weakly pathogenic strain can make the host plant more resistant to subsequent invasion by a more virulent strain of the same species.

As well as their natural roles in suppressing pathogens within the soil, micro-organisms are deliberately used to control pests, weeds and pathogens. There are three main strategies for doing this: classical biological control (in which natural enemies are introduced into a new area to control an invasive pest); augmentative biological control (in which a mass-reared natural enemy is released onto a specific crop); and conservation biological control (in which the environment is manipulated to make it more favourable for natural enemies).

Micro-organisms also contribute in several ways to post-harvest food processing.

Micro-organisms also contribute in several ways to post-harvest food processing. Biological control using micro-organisms offers a means of protecting foodstuffs against post-harvest losses without using chemical pesticides that can leave harmful residues. Micro-organisms – including bacteria, and yeast and other fungi – are used to transform agricultural products into foods such as bread, cheese and beer. Micro-organisms themselves, especially the fruiting bodies of fungi (mushrooms, etc.) are consumed worldwide.

In addition to their huge genetic diversity and the diversity of their contributions to agriculture and food production, micro-organism genetic resources have several other characteristics that distinguish them from other genetic resources. First, they are so small that they are invisible to the naked eye, and this means that they are often overlooked. Second – and their most remarkable characteristic – is an unparalleled rate of reproduction, which they achieve thanks to their short generation intervals, which can be as little as 20 minutes. Another remarkable characteristic is their ability to colonize virtually every available niche on the planet, including places where conditions are too extreme for any other organisms. For example, they are able to live in deep-sea vents where temperatures exceed 100 °C and pressures are more than 400 times greater than atmospheric pressure at sea level.

Micro-organisms can adapt extremely rapidly to changes in their surroundings. This ability is linked to their genetic and reproductive mechanisms, which produce huge variability. Not only do micro-organisms have a very high rate of reproduction, they also benefit from "horizontal gene transfer". DNA is able to move from one micro-organism cell to another, from the environment into a micro-organism cell, or from one cell to another via a virus. This means that micro-organisms do not have to wait for the next generation in order to change their genetic characteristics.

Effects of climate change on micro-organism genetic resources and their management

The effects of climate on soil micro-organisms are to a large extent mediated via effects on plants. Vegetation supplies the majority of the energy needed by soil micro-organism communities and to drive the ecosystem services they provide. Changing temperatures, rainfall patterns and carbon dioxide levels can be expected to modify the yield and the quality of crops and other plants. This will affect the capacity of soil-organism communities to utilize plant litter, which in turn will affect the turnover of soil organic matter and the rate at which nutrients are released and made available to plants. It is not yet well understood how changes to the climate and to carbon dioxide levels affect the turnover of organic matter or how this influences plant growth. However, the key microbial processes affecting the retention and loss of soil nutrients are influenced by temperature and moisture.

Agricultural soils in intensive farming systems where a limited range of crops are grown may be less resilient and more vulnerable to such changes than soils in natural ecosystems where the diversity of the soil micro-organism community may allow more rapid adaptation.

In addition to affecting the availability of nutrients, elevated atmospheric carbon dioxide concentrations may affect the structure of the soil by altering the processes that control soil aggregation, for instance by affecting the concentration of the binding agents, secreted by micro-organisms, that hold soil particles together. Agricultural soils in intensive farming systems where a limited range of crops are grown may be less resilient and more vulnerable to such changes than soils in natural ecosystems where the diversity of the soil micro-organism community may allow more rapid adaptation (Mocali *et al.*, 2008).

The effects of climate change on the beneficial micro-organisms that live within plants and in the rhizosphere are difficult to predict (Pritchard, 2011). Interactions between plants and rhizobia and mycorrhizal fungi can be altered by small changes in the physiological processes that influence the allocation of carbohydrate resources to plant roots. The signalling mechanisms used by plants and micro-organism in establishing rhizobial endosymbiosis[7] may also be sensitive to climate.

Little is known about the likely effects of climate change on soil micro-organisms' capacities to enhance soil and plant health. The same is true for micro-organism communities found on leaf surfaces (the phyllosphere). Phyllosphere micro-organisms can directly influence plant health, both by producing plant hormones that affect plant development and by suppressing plant pathogens. Phyllosphere communities are likely to be affected by climate change. For instance, leaf-surface wetness – often difficult to predict based on common weather measures – has a significant influence on leaf-surface micro-organisms.

Another source of uncertainty is the influence of climate change on pathogen activity. Pathogenic micro-organisms are affected by complex interactions with their host plants or animals, their natural enemies, weather conditions and agricultural practices. Climate change is expected to affect the distribution of crop species and varieties, and as these shifts occur some pathogens will migrate with their hosts to new locations. Micro-organisms indigenous to the new locations may affect the crops for the first time. Outcomes in terms of crop productivity are likely to be affected also by other factors, such as whether climate change affects levels of disease resistance in the crops or brings about changes in plant growth that increase or decrease the availability of micro-climates that are favourable for the growth of the pathogens. Virulent pathogens may become more competitive compared to their less virulent counterparts, or vice versa. Human actions are also likely to play a role. For example, an increase in pathogen activity may lead to greater use of treatments such as fungicides. This, in turn, would increase the selective pressure on the pathogens to develop resistance to the treatments, with potential consequences for crop productivity over the longer term.

> Climate change is expected to affect the distribution of crop species and varieties, and as these shifts occur some pathogens will migrate with their hosts to new locations.

The vectors that transmit pathogenic micro-organisms are also likely to be affected by climate change. For instance, temperature influences insect behaviour, distribution, development, survival and reproduction – and hence the ability of the insects to act as disease vectors. With a 2 °C rise in temperature, it is estimated that many insects will be able to complete one to five extra life cycles per season (Yamamura and Kiritani, 1998). However, as the insects are themselves caught up in complex

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[7] Endosymbiosis is a symbiotic relationship in which one organism lives inside another.

ecological relationships that may be affected in numerous ways by climate change – with their own natural enemies, for example – predicting whether or not vector activity will increase is difficult.

An increase in the frequency of extreme weather events is another factor that may affect disease epidemiology. Water-logging of soils, for example, encourages root diseases. Changed weather patterns may affect the distribution of pathogens that are dispersed by the wind. The fact that disease epidemiology is affected by weather patterns has long been recognized (Box 3) and several examples have been documented over extended periods of time. However, the precise effects of climate change are difficult to predict and may involve major unexpected disease outbreaks.

The growth rates of biological control micro-organisms are highly dependent on temperature. Coupled with their short life cycles, high mobility and high reproductive potential, this means that even modest changes in the climate are likely to have a rapid effect on their distribution and abundance (Ayres and Lombardero, 2000). As insect pests are also greatly affected by temperature, their distribution and abundance is also likely to be influenced by climate change. However, given the many subtle ways in which interactions between pests and control agents can be affected by temperature and other climate-related factors, it is again difficult to predict outcomes in terms of pest impact or the effectiveness of control agents.

BOX 3

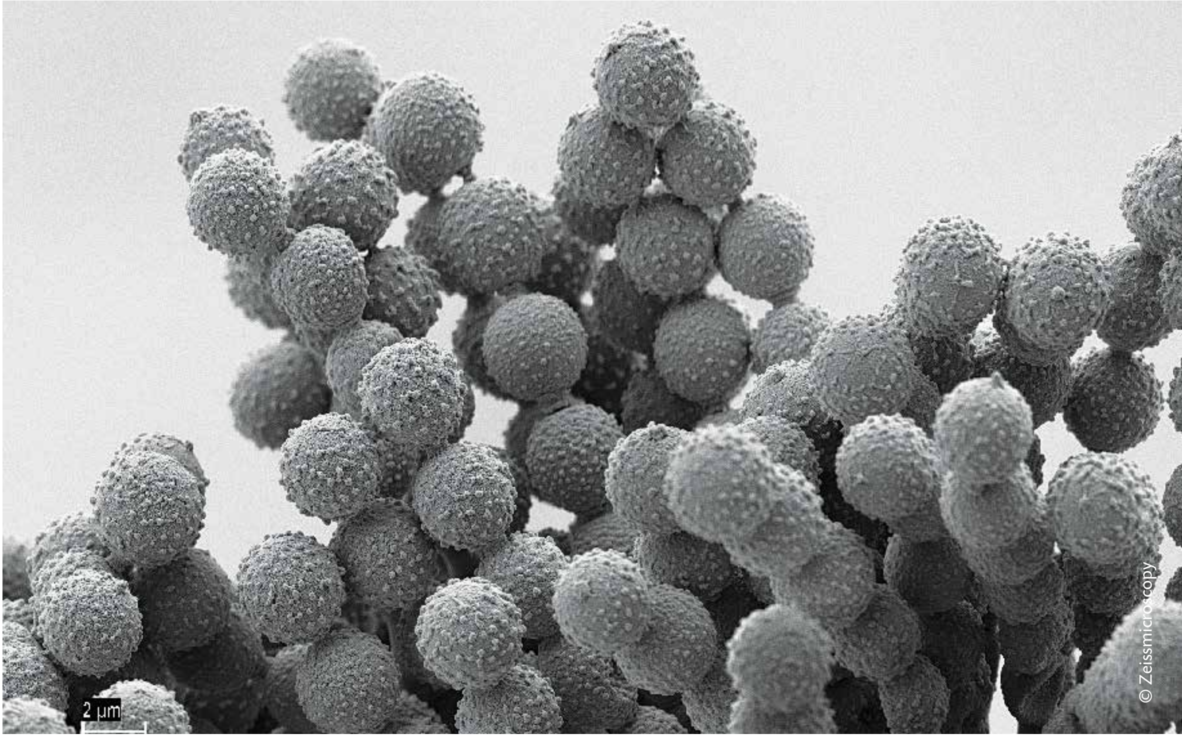
Effect of temperature on pathogen activity – an example

A study conducted in 1932 showed that when wheat was grown in sterilized soil and inoculated with the fungal pathogen (*Gaeumannomyces graminis*), the causal agent of take-all disease, the severity of the disease increased with temperature from 13 to 27 °C. However, in natural, unsterile soil the severity of the disease declined when the temperature exceeded 18 °C, because higher temperatures promote other micro-organisms that are antagonistic to the take-all fungus. This example demonstrates the need to study plant pathogens in association not only with their crop hosts, but also with their natural environments, where other organisms act to increase or reduce their abundance.

SOURCE: Henry, 1932.

According to some climate change models, the level of ultraviolet-B radiation (UV-B) is set to increase due to depletion of the ozone layer. This would have a big impact on micro-organisms used for biological control. Fungi and bacteria are generally more sensitive to damage by UV-B than weeds and insects. For example, the fungi currently used in augmentative biological control of insect pests have poor survival rates when exposed to UV-B. Even micro-organism communities deep under the ground can be adversely affected by UV-B radiation via its effect on the quality and quantity of plant root exudates.

Very little is known about the composition and dynamics of the micro-organism communities living on the surface of agricultural produce. Climate change can be expected to favour species or strains that are well adapted to newly prevailing conditions of temperature and humidity. Although it is clear that this will affect the composition of microbial communities and the



synergistic and competitive relationships among them, the magnitude and direction of these changes cannot be predicted.

Very little is known about the composition and dynamics of the micro-organism communities living on the surface of agricultural produce.

Increased temperature is likely to affect the ripening of fruits and vegetables, causing a shift in the life cycles of the micro-organisms naturally resident on the surfaces of these crops. These micro-organisms will also be influenced by any metabolic changes that climate change may cause in the crops (e.g. changes in pH or sugar content). Many surface micro-organisms can potentially provide protection against micro-organisms that are harmful to the quality of fruits and vegetables. Some are already used as post-harvest biological control agents; for example, fruits can be soaked in suspensions of yeast to reduce the effects of spoiling micro-organisms (Zhao *et al.*, 2010).

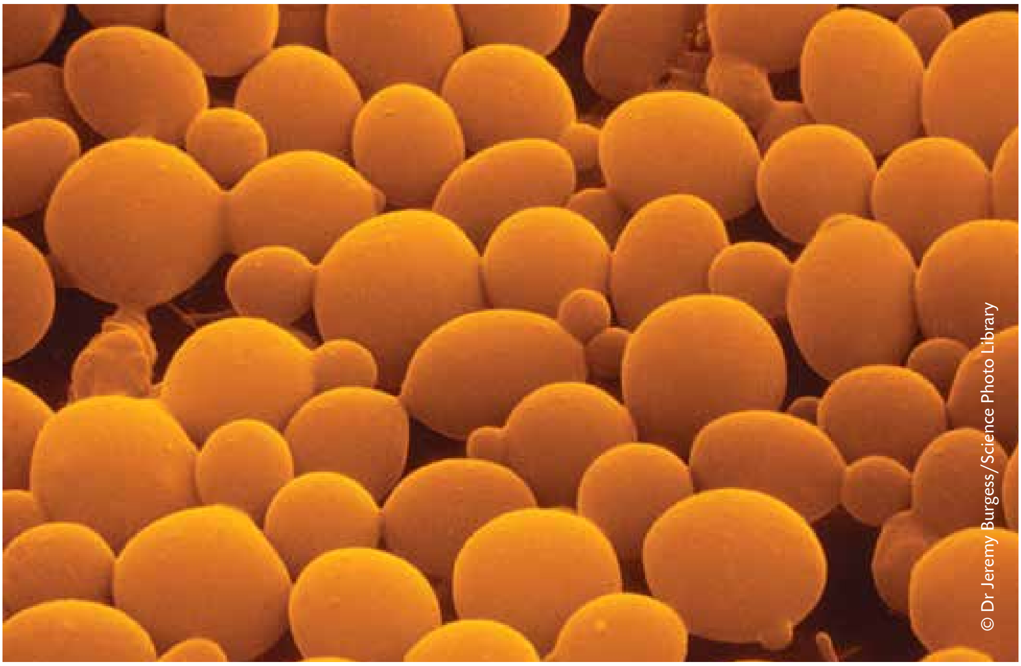
On a local scale, temperatures may increase much more severely than the predicted global average of a few degrees Celsius over a number of decades. Heat-induced stress in beneficial micro-organism populations may increase mutation rates and lead to selection of strains quite different from those currently present

Farming practices that increase soil micro-organism biodiversity – crop rotation and the use of green fertilizer, organic manure, biological control agents, etc. – have great potential in adapting agriculture to the effects of climate change.

(Foster, 2007). If the dynamic equilibrium between food-spoiling micro-organisms and the micro-organisms that control them is broken, intense pesticide treatments will be needed to prevent spoilage, and this may lead to higher costs and potential dangers to human health. An increase in overall humidity is expected to boost the growth of moulds on plants, especially if this is coupled with higher temperatures. More frequent heavy rain can lead to large increases in the amount of pesticide used, particularly the use of systemic pesticides that are not washed off by rain. Intensive use of systemic pesticides can have a significant effect on surface-borne micro-organisms, such as yeasts, and their roles in preventing spoilage.

Roles of micro-organism genetic resources in coping with climate change

Farming practices that increase soil micro-organism biodiversity – crop rotation and the use of green fertilizer, organic manure, biological control agents, etc. – have great potential in adapting agriculture to the effects of climate change. Micro-organisms can also be deliberately introduced to farming systems as bio-fertilizers. For example, root-nodulating bacteria (*Rhizobium* spp.) or free-living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bacteria (*Azospirillum* spp.) can be introduced to promote nitrogen fixing. The use of the mycorrhizal fungi (*Glomus* spp.) to promote nutrient acquisition by plants is another example. Soil micro-organisms can be used to manage plant pathogens. A large number of soil amendments containing micro-organisms are already commercially available as biopesticides. However, attempts to modify the soil ecosystem will only be successful if based on a clear understanding of the ecological niche and mode of action of the micro-organisms and their interactivity with resident soil communities.

Micro-organisms can also be used to improve post-harvest storage and in the processing of food crops. In some areas, climate change is likely to increase humidity and therefore exacerbate the problem of food spoilage, which already leads to massive post-harvest losses and serious threats to food safety. As much as half of all the grains produced in some countries are contaminated by mycotoxins, especially in wet years (Leslie *et al*., 2008). One circumstance in which the use of micro-organisms in the prevention of food spoilage could prove useful is in the delivery of emergency supplies following disasters such as droughts and floods, which are expected to become more frequent as a result of climate change.

Another potentially important contribution to agriculture lies in the role that micro-organisms can play in bioremediation. Climate change and the growing global human population will create demand for more land for use in agriculture. Some land is unusable at present because it is contaminated with pollutants of various kinds. Because micro-organisms are capable of breaking down a wide range of organic substances, they have great potential for use in removing contaminants and returning soil to a state in which it can be used safely for agriculture.

Given the enormous amount of carbon stored in the world's soils, micro-organisms are extremely significant to efforts to mitigate climate change.

Micro-organisms play an important role in the sequestration of carbon in soil organic matter and in the release of carbon in the form of carbon dioxide when soil organic matter decomposes. Given the enormous amount of carbon stored in the world's soils, micro-organisms are extremely significant to efforts to mitigate climate change. Their contribution to carbon sequestration can be promoted by practices such as amending soil with organic fertilizers, proper management of crop-residues, no-tillage agriculture, maintaining cover crops on the soil surface, avoiding flood irrigation and carefully managing the use of fertilizers.

Another positive feature of many beneficial micro-organisms is that they provide their services at relatively low cost in terms of greenhouse gas production. For example, naturally occurring biological control micro-organisms do not incur the carbon costs associated with the production, transport and application of synthetic pesticides. Likewise, micro-organisms such as mycorrhizal fungi and rhizobia that contribute to plant nutrition increase plant productivity without the greenhouse

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gas emissions associated with the production, transport and application of mineral fertilizers. The use of micro-organisms to increase shelf-life has the potential to reduce the amount of energy expended on freezing or refrigerating food (Di Cagno *et al*., 2009).

Conclusions and recommendations

Major efforts to improve knowledge of the roles of micro-organisms in agriculture and food production and how these roles will be affected by climate change are needed. It is currently impossible to predict how climate change will affect future interactions between crops, micro-organisms and other components of agricultural ecosystems.

The “invisible” nature of micro-organisms means that changes are difficult to observe even if they are already occurring. Systematic monitoring programmes that are able to identify trends in micro-organism genetic resources are needed. Some monitoring initiatives for soil micro-organisms and for pathogens have been established in technologically advanced countries, but similar programmes need to be set up in developing countries. Techniques for characterizing micro-organism species, communities and functions need to be improved, and studies conducted on the effects of climate on micro-organisms and the services they provide. This will have to involve a combination of field and laboratory-based work. Techniques need to be standardized in order to allow comparison of data from different locations.

Research efforts to improve practical applications such as the use of micro-organisms in biological control are also needed. A major problem in the use of microbial biological control agents is inconsistency in performance. The ability of micro-organisms to control plant diseases may vary because of variations in environmental conditions and may be sensitive to the timing of the agent's introduction onto the crop.

Techniques for characterizing micro-organism species, communities and functions need to be improved, and studies conducted on the effects of climate on micro-organisms and the services they provide.

Other priorities for improving the use of micro-organism genetic resources include better networking and coordination among scientists and policy-makers. Strategies for using micro-organisms in agriculture will require access to the relevant genetic resources and to knowledge of these resources. This will need to be facilitated through national, regional and international coordination in the use of technical capacity and human expertise.

The role of culture collections in international efforts to improve the management of micro-organism genetic resources needs to be improved. For example, many collections do not publish catalogues of their holdings and there is little consistency in policies and practices for accessing material from collections. There is clearly a need for much better coordination and harmonization at international level to support countries in pooling resources, information and know-how in ways that are accessible and that benefit all potential users. Urgent steps must be taken to promote the establishment of collections in developing countries, particularly in the tropics and subtropics. The issue of access and benefit-sharing needs to be addressed in order to facilitate international exchange of micro-organism genetic resources and cooperation in their use.

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Main conclusions and opportunities

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Climate change is affecting ecosystems and food production systems. Adaptation and mitigation can help reduce the negative effects of climate change (IPCC, 2014). This book presents a general overview of the expected impacts of climate change on genetic resources, as well as the roles of these resources in coping with climate change. Management at the level of the individual farm, livestock holding, forest or aquaculture farm will often need to adapt to changed conditions. However, if agriculture is to adapt to climate change, and achieve food security and nutrition goals in the coming decades, food production systems and the wider ecosystems on which they rely will have to become increasingly flexible, multifunctional and capable of providing multiple services (Galluzzi *et al.*, 2011). Responding to climate change will require focusing attention at the ecosystem level and ensuring coordinated policy responses both nationally and internationally.

Identify, conserve and learn how to use genetic resources for food and agriculture

Future use of genetic resources for food and agriculture in climate change adaptation and mitigation depends upon ensuring that the relevant resources remain available. Because many genetic resources are threatened with extinction, this necessitates effective conservation measures. While some genetic resources can be conserved *ex situ*, in other cases there is no option other than to conserve them *in situ* (on farm) in agricultural production systems or in natural or semi-natural habitats. Where possible, a combined approach involving complementary *in situ* and *ex situ* measures is generally recommended. *In situ* conservation clearly requires ensuring that the ecosystems upon which the targeted genetic resources depend are maintained in a healthy state. In the case of domesticated genetic resources, it also requires that the farmers, livestock keepers, aquaculture practi-


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tioners or foresters who conserve the targeted varieties, breeds and species benefit from this activity, either financially or through other improvements to their livelihoods.

Traditional crop varieties and livestock breeds are frequently overlooked in efforts to improve crop and livestock production. However, they have often been developed in harsh production environments and have characteristics that allow them to thrive in severe or variable conditions. Climate change underlines the importance of having crops and animals that are well adapted to the environments in which they are raised and of retaining the diversity necessary to adapt production systems to future changes (Jarvis *et al.*, 2010; Pilling and Hoffmann, 2011). The potential advantages of species, varieties and breeds that have previously been underutilized or discarded in favour of high-producing, but less environmentally adapted, equivalents should always be taken into consideration when planning interventions. Attention should be paid to the potential risks involved in attempting to raise non-adapted livestock or crops in harsh or variable environments, particularly if the production inputs needed to raise them successfully may be difficult for farmers or livestock keepers to obtain or afford. In breeding programmes for crops and livestock, more attention should be given to traits that increase resilience rather than focusing exclusively on maximizing yields.

Much more attention needs to be given to the roles of invertebrates and micro-organisms in agriculture and food production (Cock *et al.*, 2011; Beed *et al.*, 2011).

Research is needed at the level of taxonomy and characterization, as well as on the services provided by these organisms and how they are affected by climate change. Research into practical applications, such as the use of biological control agents against pests, also needs to be stepped up. Because of the "invisible" nature of micro-organisms and smaller invertebrates, greater attention needs to be paid to systematic monitoring of their distribution and abundance so that problems related to climate change can be detected in good time. Among pollinators, it may be necessary to domesticate and manage insect species other than the honey bee in order to provide pollination services in agro-ecosystems affected by climate change, particularly for crops that are reliant on specialist pollinators. In invertebrate species that are raised for use in the biological control of pests, breeding programmes to develop strains with desirable characteristics such as greater heat resistance, greater fecundity or a wider range of species hosts may need to be considered.

In aquaculture, the significant potential that exists for domesticating additional aquatic plants and animals that can be used in climate change adaptation should be fully explored, as should breeding strategies to develop climate-adapted stocks

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(Pullin and White, 2011). More research is required on the roles of aquatic ecosystems as carbon sinks and in processing nitrogenous wastes, along with the roles of aquatic genetic resources in the provision of these services.

In forestry, much needs to be done to strengthen knowledge of the adaptive characteristics of tree species, their life cycles, ecological relationships and potentials in climate change adaptation and mitigation. More attention also needs to be paid to genetic variation within tree species. Breeding programmes need to place greater emphasis on traits that will enhance trees' capacities to thrive in the climate change-affected environments of the future (Loo *et al*., 2011).

In the crop, livestock and forestry sectors, the Global Plans of Action negotiated by the Commission on Genetic Resources for Food and Agriculture represent important steps forward towards improving responses to climate change. They include activities aimed at improving *in situ* and *ex situ* conservation of genetic resources and their associated knowledge and at promoting their sustainable use. They promote new strategies for the use and development of these resources and for building institutional and human capacities that can address challenges such as climate change.

The forthcoming report on *The State of the World's Biodiversity for Food and Agriculture* will offer another opportunity to assess genetic resources for food and agriculture and their potential in the context of climate change. The report will focus on interactions between the different sectors of genetic resources (plant, animal, aquatic, forest, invertebrate and micro-organism) and on cross-sectoral matters, and will be based on an ecosystem approach. It will look at the contributions that biodiversity for food and agriculture as a whole makes to food security, livelihoods and environmental health, as well as to the sustainability, resilience and adaptability of production systems.

It is predicted that in most, or perhaps all, sectors of food and agriculture, climate change will increase the need for international exchange of genetic resources, both for production and for research. Policy frameworks will therefore need to facilitate access to genetic resources while ensuring phytosanitary and zoosanitary security and fair and equitable sharing of benefits. This should be complemented by putting in place appropriate procedures to address ecological risks such as the potential for introduced species to become invasive.

Promote an integrated and adaptive approach to the management of genetic resources for food and agriculture in ecosystems

Fostering the adaptation of production systems to the effects of climate change requires a holistic approach that involves collaboration among the various sectors of food and agriculture and with stakeholders involved in other aspects of environmental management and social and economic development. The application of the ecosystem approach – a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way – plays an important role. The ecosystems in which agriculture and food production are practised often have multiple roles or uses, whether in carbon sequestration, management of water resources, conservation of wild biodiversity, tourism or cultural activities. Some genetic resources for food and agriculture have the potential to contribute to several of these roles and uses at once and their potential to serve multiple purposes should be recognized and valued in planning and decision-making on their management.

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The effects of climate on the services provided by genetic resources for food and agriculture often involve subtle and complex interactions among the various components of the ecosystem. Pollination of a crop plant, for example, requires not only the presence of the appropriate pollinator species, but also synchrony between the life cycles of the pollinators and the flowering period of the plant, each of which may be affected differently

In the context of climate change, the resilience of agro-ecosystems is particularly important.

by climate change. Pollinators may, in turn, be affected by the influence of the climate on their habitats (e.g. places to nest) or on the distribution of diseases or parasites that affect them. Another, obvious, but important, example is that livestock production depends on the plants (wild or cultivated) upon which animals feed. Management responses aimed at preserving and promoting the services provided by genetic resources will therefore often need to focus not only on a single species, breed or variety, but also on its surrounding ecosystem. Examples include the maintenance of conservation habitats next to crop fields to serve as refuges for invertebrates that act as biological control agents.

Particular attention may need to be given to maintaining so-called keystone species within the ecosystem. Keystone roles can be played by small and apparently "insignificant" organisms, such as invertebrates that play an "engineering" role in the soil or naturally occurring biological control agents of pests. The loss of such species can have a disproportionally large effect on the rest of the ecosystem. Detailed knowledge of these kinds of ecological relationships improves our ability to promote resilience in production systems and in farming, livestock keeping, fishing and forestry-based livelihoods.


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It is likely that as part of climate change adaptation or mitigation measures, or efforts to conserve genetic resources, the introduction of domesticated or wild species into new geographical areas will need to be considered. In such circumstances, careful attention should be paid to potential impacts on the destination ecosystems, taking into account the potential for the introduced species to become invasive, the risk of introducing pathogens and, in the case of domesticated species, the capacity of local people to manage them.

Efforts should be made to avoid agricultural or other practices that destroy biodiversity or otherwise undermine the resilience of agricultural, forest and aquatic ecosystems.

The application of the ecosystem approach has the potential to contribute to the resilience of ecosystems – their capacity to continue functioning and producing in the face of changes and shocks. Resilience and adaptability will become even more important as the negative effects of climate change increase. Diverse genetic resources play a key role in resilience. For example, the presence of several different pollinators or biological control agents tends to promote stability in the provision of these services, because some species may be able to cope with shocks or changes that severely affect others. Genetic diversity within species is important for similar reasons, and as the basis for adaptation to changing conditions through natural selection or human interventions. The presence of (or potential access to) a range of species, breeds and varieties of plants and animals that can provide a range of different economic outputs (Asfaw and Lipper, 2011) can help to make the livelihoods of farmers, livestock keepers, foresters and fishers more resilient in the face of climatic and other changes.

Efforts should be made to avoid agricultural or other practices that destroy biodiversity or otherwise undermine the resilience of agricultural, forest and aquatic ecosystems. For instance, short-term solutions such as the use of broad-spectrum insecticides that have a detrimental effect on biological control agents or pollinators may affect ecosystem resilience in the longer term.

In the case of wild species such as forest trees, crop wild relatives and wild insect pollinators, it is likely to be necessary to protect or develop corridors of suitable habitat that will facilitate migration and prevent the species from becoming trapped in areas of unsuitable climate where they may become extinct. For species that lack the capacity to migrate independently with sufficient speed, assisted migrations may need to be contemplated.

> The ecosystem approach is *per se* an adaptive approach. It recognizes that change is inevitable and the need to monitor trends and to adapt.

The ecosystem approach is *per se* an adaptive approach. It recognizes that change is inevitable and the need to monitor trends and to adapt. The long-term consequences of climate change are difficult to predict. It may lead to greater variation and unpredictability – more frequent extreme weather events, for example. It may throw up new and unexpected ecological relationships that create new challenges for farmers, foresters, livestock keepers, fisherfolk, aquaculture practitioners and other managers and users of ecosystems. Unexpected threats to the survival of genetic resources or the stability of ecosystems may arise. An adaptive approach to the management of these systems in the face of climate change is therefore essential. The capacity to respond to rapidly emerging crises such as pest outbreaks and alien species invasions needs to be built into approaches to the management of genetic resources. Coping with climate change will require learning and adjustment over time, as knowledge is gained and as impacts are better understood.

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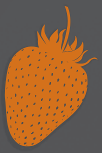
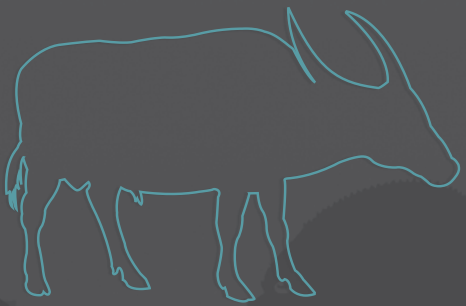
Genetic resources for food and agriculture play a crucial role in food security, nutrition and livelihoods and in the provision of environmental services. They are key components of sustainability, resilience and adaptability in production systems. They underpin the ability of crops, livestock, aquatic organisms and forest trees to withstand a range of harsh conditions. Climate change poses new challenges to the management of the world's genetic resources for food and agriculture, but it also underlines their importance.

At the request of the Commission on Genetic Resources for Food and Agriculture, FAO prepared thematic studies on the interactions between climate change and plant, animal, forest, aquatic, invertebrate and micro-organism genetic resources. This publication summarizes the results of these studies.





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