THEMATIC BACKGROUND STUDY

Climate Change and its Effect on Conservation and Use of Plant Genetic Resources for Food and Agriculture and Associated Biodiversity for Food Security

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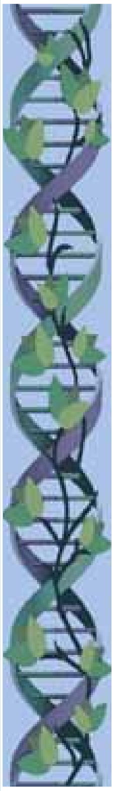
EXECUTIVE SUMMARY

We review the impacts and implications of climate change for the management and use of plant genetic resources for food and agriculture and associated biodiversity (PGRFA-AB). Climate change is predicted to bring about increased temperatures across the world in the range of 1.6°C to as much as 6°C by 2050. Although rainfall is predicted to increase globally, some areas will receive less annual rainfall, while others may receive much more. The timing of rains and crop-growing periods will also change. The frequency and duration of extreme weather events are also predicted to increase, although uncertainty exists about the expected degree of changes. These predicted changes in climate are expected to have fairly widespread impacts on agriculture, with poor countries in the south highlighted as being particularly vulnerable, having already weak economies and limited institutional capacities to adapt. More specifically to PGRFA-AB, evidence suggests important risks to wild biodiversity, including crop wild relatives. Changes in climate are also likely to place new pressures on conservation of landraces of crop species.

Although climate change does not always imply major changes in the way PGRFA-AB is managed, it may imply changes in priorities for action. The major issues flagged for attention are:

- Increased need for consolidating collections of wild species, including crop wild relatives, due to increased likelihood of extinction for narrowly adapted and endemic species
- Novel and increased demands on germplasm in genebanks for adapting agriculture to climate change, including the need to screening for different characters
- Review of breeding strategies and priorities, crop by crop and region by region, so as to make products of breeding programmes initiated today relevant to the challenges the world will be facing upon release of these improved materials
- The need to review and strengthen policies for promoting seed systems that encourage the maintenance of biodiversity (genetic diversity), including promoting longer-distance exchange of seed between farmers, and review the procedures in seed relief after disasters; and
- Increased demand on international policy to facilitate access to more genetic resource materials due to increases in interdependency brought about by shifts in climate zones globally.



1. BACKGROUND ON CLIMATE CHANGE

This report summarizes the likely implications of climate change for the conservation and use of plant genetic resources for food and agriculture and associated biodiversity (PGRFA-AB). PGRFA-AB refers to both species- and genetic-level diversity that is of use to food and agriculture (including wild species) and the direct ecosystem services that support agriculture, including services such as pollination and nutrient cycling. Climate change will have important direct impacts on PGRFA-AB, as will the very options and policies being adopted to adapt to climate change (e.g., current expansion of biofuels and associated policies).

This paper outlines the major issues surrounding climate change and its effects on PGRFA-AB. The objective is to identify ways in which climate change may alter the business of conservation and management of these resources, including implications for genebank managers, genetic resource users, *in situ* biodiversity management and the maintenance of some key biodiversity ecosystem services. The paper starts by providing a background to climate change, with an outline of the expected impacts in various regions of the world. The paper then summarizes some of the likely impacts on wild species of agricultural importance and discusses measures to react to the expected changes in climate. The impacts on agriculture are then summarized, followed by a discussion of how climate change may alter the approach to genetic resource conservation and use. The report then analyses the specific issue of *in situ* seed systems and on-farm diversity, and finishes by examining the international and national policy implications. The authors try to focus on how climate change changes the way PGRFA-AB users and stakeholders might go about their business, noting that the issue of climate change is one additional factor on top of a number of other important and very immediate concerns.

1.1 Climate change scenarios and review of IPCC findings

This section provides a brief summary of the far more complete analysis of expected impacts of climate change contained in the IPCC report (2007).

In mid- to high-latitude regions, models predict local increases in temperature of 1–3ºC to 2050, along with associated carbon dioxide (CO2) increase and rainfall changes, which may have small beneficial impacts on crop yields. In low-latitude regions, even moderate temperature increases (1–2°C) are likely to have negative impacts on yields of the major cereals. Further warming will have increasingly negative impacts in all regions (medium to low confidence). Projected changes in the frequency and severity of extreme climate events have important consequences for food and forestry production, and food insecurity, in addition to the impacts of projected mean climate (high confidence).

Simulations suggest greater relative benefits of adaptation with low to moderate warming (medium confidence), although adaptation will put stresses on water and environmental resources as warming increases (low confidence). In cereal cropping systems worldwide, adaptations such as changing varieties and planting times will on average enable avoidance of a 10–15% reduction in yield corresponding to 1–2°C local temperature increase. Adaptive capacity in low latitudes will be exceeded when local temperature increases by 3°C. Pressure to cultivate marginal land or to adopt unsustainable cultivation practices as yields drop may increase land degradation and resource use, and endanger biodiversity of both wild and cultivated species. Smallholder and subsistence farmers, pastoralists and artisanal fisherfolk will suffer complex, localized impacts of climate change (high confidence).

Food and forestry trade is projected to increase in response to climate change, with increased dependence on food imports for most developing countries (medium to low confidence).

1.2 Expected regional impacts

1.2.1 Asia

Results of crop yield projection using the HadCM2 model indicate that crop yields could increase by up to 20% in East and South-East Asia while they could decrease by up to 30% in Central and South Asia even if the direct positive physiological effects of increased atmospheric CO2 concentration are taken into account.

A northward shift of agricultural zones is likely. For example, the dry steppe zone in eastern Mongolia may push the forest-steppe to the north, resulting in a shrinking of the high mountainous and forest-steppe zones and expansion of the steppe and desert steppe (Tserendash *et al*., 2005). Suitable land and production potentials for cereals could marginally increase in the Russian Federation and in East Asia (Fischer *et al*., 2002). More than 28million ha in South and East Asia will require a substantial increase in irrigation for sustained productivity (FAO, 2003). Irrigation demand in arid and semi-arid regions of Asia is estimated to increase by at least 10% for an increase in temperature of 1°C (Fischer *et al*., 2002; Liu, 2002).

Climate change, as well as changing pest and disease patterns, is likely to affect how food production systems perform in the future. These factors will directly influence food security and poverty levels, particularly in countries with a high dependency on agriculture.

1.2.2 Africa

Africa is one of the most vulnerable continents to climate change and climate variability, a situation aggravated by the interaction of the multiple stresses that occur at various levels and the systems' low adaptive capacity (high confidence).

A number of countries in Africa already face semi-arid conditions that make agriculture challenging, and climate change is likely to reduce the length of growing season and force large regions of marginal agriculture out of production. Projected reductions in yield in some countries could be as much as 50% by 2020; crop net revenues could fall by as much as 90% by 2100, with small-scale farmers being the most affected (Kurukulasuriya *et al*., 2006; Benhin, 2008).

Climate change and variability are likely to impose additional pressures on water availability, accessibility and demand in Africa. Even without climate change, water demand in several countries in Africa, particularly in northern Africa, will exceed the limits of their economically usable land-based water resources before 2025. About 25% of Africa's population (about 200 million people) currently experience high water stress. The population at risk of increased water stress in Africa is projected to be 75–250 million people by the 2020s and 350–600 million people by the 2050s.

It is estimated that, by the 2080s, the proportion of arid and semi-arid lands in Africa will increase by 5–8%.

1.2.3 Australia and New Zealand

Agricultural production is projected to decline by 2030 over much of southern and eastern Australia, and over parts of eastern New Zealand, due to increased drought and fire. In New Zealand, however, initial benefits to agriculture and forestry are projected in western and southern areas and close to major rivers due to a longer growing season, less frost and increased rainfall (high confidence).

In Australia, the areas that will initially benefit include the Great Barrier Reef, eastern Queensland, the south-west of Western Australia, the Murray-Darling Basin, the Alps and the Kakadu wetlands. In New Zealand, areas that will benefit in the short term include the Bay of Plenty, Northland, eastern regions and the Southern Alps (medium confidence).

Climate change is likely to change land use in southern Australia, with cropping becoming non-viable at the dry margins if rainfall is reduced substantially, even though yield increases from elevated CO2 partly offset this effect (Sinclair *et al*., 2000; Luo *et al*., 2003). In contrast, cropping is likely to expand into the wet margins if rainfall declines. In northern Australia, climate change and CO2 increases are likely to enable cropping to persist (Howden *et al*., 2001). Observed warming trends are already reducing frost risk and increasing yields in southern Australia (Howden *et al*., 2003).

Australian temperate fruits and nuts are likely to be negatively affected by warmer conditions because they require winter chill or vernalization. Crops that rely on irrigation are likely to be threatened where irrigation water availability is reduced.

Climate change is likely to make a major horticultural pest, the Queensland fruit fly (*Bactrocera tryoni*), an important threat to southern Australia. Warming scenarios of 0.5, 1.0 and 2.0°C suggest expansion from its endemic range in the north and north-east to most of the non-arid areas of the continent, including the currently quarantined fruit fly-free zone (Sutherst *et al*., 2000).

1.2.4 Europe

Crop productivity (all other factors remaining unchanged) is likely to increase in northern Europe and decrease along the Mediterranean and in south-eastern Europe. Some crops that currently grow mostly in southern Europe (e.g., maize, sunflower and soybeans) will become viable farther north or at higher altitudes in the south (Audsley *et al*., 2006). By 2050, energy crops (e.g., oilseeds such as oilseed rape and sunflower), starch crops (e.g., potatoes), cereals (e.g., barley) and biofuel crops (such as sorghum and *Miscanthus*) show a northward expansion in potential cropping area, but a reduction in southern Europe (Tuck *et al*., 2006). Differences in water availability between regions are anticipated to increase.

Much of the European flora is likely to become vulnerable, endangered or committed to extinction by the end of this century. Options for adaptation are likely to be limited for many organisms and ecosystems. New sites for *in situ* conservation may be needed because climate change is very likely to alter conditions of suitability for many species in their current sites.

1.2.5 North America

Most studies project climate-related yield increases of 5 to 20% over the first decades of the century, with the overall positive effects of climate persisting through much or all of the twenty-first century. Increased climate sensitivity is anticipated in the south-eastern USA and in the USA cornbelt (Carbone *et al*., 2003), but not in the Great Plains (Mearns *et al*., 2003). Crops that are currently near climate thresholds (e.g., wine grapes in California) are likely to suffer through decreases in yields, quality or both with even modest warming (medium confidence) (Hayhoe *et al*., 2004; White *et al*., 2006). Yields of cotton, soybeans and barley are likely to change much more than those of corn, wheat and some vegetable crops (Antle, 2009).

1.2.6 Latin America

Under future climate change, there is a risk of important species extinctions in many areas of tropical Latin America (high confidence). By the 2050s, 50% of agricultural lands are very likely to be subjected to desertification and salinization in some areas (high confidence). Seven out of the 25 most critical places with high endemic species concentrations are in Latin America and these areas are undergoing habitat loss.

Generalized reductions in rice yields by the 2020s, as well as increases in soybean yields, are possible when CO2 effects are considered (medium confidence). For wheat and maize the projected response to climate change is more erratic, depending on the chosen scenario.

Other important expected impacts include reductions in land suitable for growing coffee in Brazil, and reductions in coffee production in Mexico. In drier areas of Latin America, climate change is likely to lead to salinization and desertification of agricultural lands.

The incidence of the coffee leaf miner (*Perileucoptera coffeella*) and the nematode *Meloidogyne incognita* are likely to increase in Brazil's coffee production area. According to Fernandes *et al*. (2004), the risk of *Fusarium* head blight in wheat crops is very likely to increase under climate change in southern Brazil and in Uruguay.

1.2.7 Small islands

It is very likely that subsistence and commercial agriculture on small islands will be adversely affected by climate change (high confidence). In some high-latitude islands, new opportunities may arise for increased agricultural production.

It is possible that in mid- and high-latitude islands, higher temperatures and the retreat and loss of snow cover could enhance conditions for the spread of invasive species and forest cover (Smith *et al*., 2003). For example, in species-poor sub-Antarctic island ecosystems, alien microbes, fungi, plants and animals have been extensively documented as causing substantial loss of local biodiversity and changes to ecosystem function (Frenot *et al*., 2005). With rapid climate change, even greater numbers of introductions and enhanced colonization by alien species are likely, with consequent increases in impacts on these island ecosystems.

1.2.8 Mitigation

A variety of options exist for mitigating greenhouse gas (GHG) emissions in agriculture, including improved crop and grazing land management, restoration of organic soils that are drained for crop production and restoration of degraded lands. Lesser order, but still important, mitigation is possible with improved water management (especially for rice), set-asides, land use change (e.g., conversion of cropland to grassland), agro-forestry and improved livestock and manure management.

Soil carbon sequestration has the greatest mitigation potential, with an estimated 89% contribution under adaptive management.

Deployment of new mitigation practices for livestock systems and fertilizer application will be essential to prevent an increase in emissions from agriculture after 2030.

1.3 Key messages related to global climate change

Increase in temperature throughout the world is projected to be in the range of 1.5–6°C by 2050, depending on the climate-change model and scenario for greenhouse gas emissions used. It is projected that precipitation will increase by 15–20% globally, but some areas will receive less rainfall while others will receive substantially more. Southern Africa is highlighted as a potential hotspot of change, with substantial drying and increases in temperature, whereas the highland areas of East Africa are projected to have considerable increases in rainfall. Extreme events, including hurricanes and droughts, are predicted to increase, although there is considerable uncertainty in these predictions. Sea-level rise is predicted to cause salinity problems in many coastal regions, and to reduce the area of arable land in low-lying regions. Indirect impacts of climate change on water availability for irrigation are also important.

2. IMPACTS AND IMPLICATIONS OF CLIMATE CHANGE ON PGRFA AND ASSOCIATED BIODIVERSITY CHANGE

2.1 Wild PGRFA-AB

Plant genetic resources for food and agriculture (PGRFA) are the biological cornerstone of global food security. The agricultural diversity and genetic resources that support food crops need to be used efficiently both to maintain current levels of food production and to confront future challenges (FAO, 2007). Increasing yields of major food crops – or even maintaining them – in the face of climate change will depend on combining genetic traits found in materials of a wide range of origins (Petit, 2001), including wild species. Unfortunately, wild species are especially vulnerable to climate change because they do not receive management interventions that help them adapt to changing conditions. Narrowly adapted species and endemics are especially vulnerable to the direct effects of climate change. Indirect effects may also have important impacts, through changes in biotic interactions, including changes in pest and disease pressure (Newton *et al*., 2008), competition and successional dynamics and changes in symbiotic compositional interactions. We currently understand much less about these biotic factors than we do about direct abiotic impacts.

Much effort over the past ten years has gone into the development of methods for predicting the future geographic distribution of species (Rotenberry *et al*., 2006). Typically, these methods use the conditions at points where the species has been found in order to construct a statistical model of its adaptation range, based on a set of user-defined environmental variables (Guisan and Zimmermann, 2000). The statistical model is then applied over a wider region to locate other areas where the environmental conditions are potentially suitable for the species in question. However, given that CO2 levels are nearly the same around the world, it is not possible to formulate spatial proxies for temporal trends, giving uncertainty to projecting global stocks (Ainsworth *et al*., 2008). Many species distribution models assume that climatic variables are the principal drivers of geographic distribution (Guisan and Zimmerman, 2000; Walker and Cocks, 1991), although other factors also have been used, including soils (Anderson *et al*., 2002), topography (Draper *et al*., 2003) and specific habitat conditions (Reutter *et al*., 2003). The extent to which climate affects the spatial distribution of wild species makes this an especially important theme when examining the impact of climate change on PGRFA-AB.

A number of studies have used climatic data for the present and the future (Thomas *et al*., 2004; Williams *et al*., 2003) and the past (Ruegg *et al*., 2006) in species-distribution models. There is an active body of research questioning the underlying principles of applying species distribution models to assessing extinction risk in the face of climate change (Lawler *et al*. 2006; Thuiller *et al*., 2004; Araújo *et al*., 2005a; Araújo and Rahbek, 2006). One of the principle problems with these approaches is that validation is difficult as the results are projections (Araújo and Rahbek, 2006). Some authors use 'hindcasting' to validate their results, whereby the past is used as a key to the future (Araújo *et al*., 2005b). Another less-used (and unfortunately costly and time-consuming) but potentially more powerful approach is to couple the modelling with field evaluations where species survival is measured under different climatic conditions (Zavaleta, 2006).

A central question in the application of species distribution models to understanding the impacts of climate change relates to the capacities of species to migrate (Pearson, 2006). Climate change does not necessarily bring about new climates, but does cause geographic shifts in climates, typically to higher altitudes and higher latitudes (Parmesan and Yohe, 2003). Species capable of migrating at unlimited rates are more likely to survive than those that migrate more slowly (Menendez *et al*., 2006). Most models assume that migration is either unlimited or non-existent, yet the reality is likely to be somewhere in between (Pearson, 2006). Thomas *et al*. (2004) estimate extinction rates of 1103 species in diverse parts of the world under these two migration scenarios, providing extinction rates of 21–23% with unlimited migration and 38–52% with no migration. Where the migration rate is known for the particular species, it is relatively easy to account for in the modelling.

One of the most complete analyses of projected changes in wild biodiversity is that of Thomas *et al*. (2004). They predict that 15–37% of wild plant biodiversity is threatened with extinction due to climate change by 2050. While not all these species may be of relevance to PGRFA-AB, over the next 40 years the wild relatives of many crop species fall into the category of threatened species. Jarvis *et al*. (2008) predicted that up to 61% of peanut species, 12% of potato species, and 8% of cowpea species could become extinct within 50 years.

Crop wild relatives (CWRs) are a key resource for climate change adaptation, providing researchers with genes and traits for biotic and abiotic resistance (Maxted *et al*. 2008; Lane and Jarvis, 2007). Crop wild relatives have saved agriculture millions of dollars, both directly and indirectly, by improving crop resilience to biotic and abiotic stresses (Dwivedi *et al*. 2008a). A number of crops, such as sugar cane, tomatoes and tobacco, could not be grown on substantial commercial scales were it not for the contribution to disease resistance made by wild relatives of those crops (FAO, 1997). However, CWR themselves are now under threat of extinction due to climate change. Under elevated CO2 levels, CWR produce relatively less fruit and seed than domesticated crops (Jablonski *et al*., 2002), increasing their risk of extinction. Moreover, CWRs remain a relatively low priority in germplasm collection due to financial and political impediments.

Increasing threats to natural habitats and farming systems make it imperative to collect, conserve and characterize traditional varieties (landraces) and wild relatives in order to have them available for use in mitigating the effects of biotic and abiotic stresses caused by climate change (Lane and Jarvis, 2007).

2.1.1 Key messages related to the impact of climate change on wild species

Climate change will impact the ability of wild species to survive. The threatened species include those with important genetic traits for agriculture and those upon which some societies depend directly through wild harvesting. Based on a cross section of about 1100 wild plant species, Thomas *et al*. (2004) predicted that 15–37% of them are in danger of extinction. Jarvis *et al*. (2008) predict that 16–22% of wild relatives of species with direct value to agriculture may be in danger of extinction.

2.2 Crop productivity

Climate change will cause shifts in areas suitable for cultivation of a wide range of crops. Using current and projected climate data for about 2055, the Ecocrop model and A2a scenario (business as usual), Lane and Jarvis (2007) predicted the impact of climate change on areas suitable for several staple and cash crops. Their study revealed a general trend of loss in suitable area in sub-Saharan Africa, the Caribbean, India and northern Australia, and gains in the northern USA, Canada and most of Europe. At the crop level, 23 crops are predicted to gain suitable area while 20 are predicted to lose. Fischer *et al*. (2002) predicted similar trends in sub-Saharan Africa, but predicted that developed nations will see considerable expansion of suitable arable land to higher altitudes and potential to increase production if those lands are brought under cultivation. Lobell *et al*. (2008) take these studies further to examine the likely impacts of climate change on food security. They find a number of hotspots where the yields of key crops are predicted fall markedly. These include southern Africa where land suitable for maize, a major staple, all but disappears by 2050, and south Asia where productivity of groundnut, millet and rapeseed markedly reduces. The greater inherent climatic sensitivity of some specialty horticulture crops may result in localized reductions in food security among populations that depend on them (Antle, 2009).

Although farmers have always adapted their cropping systems to adverse climatic and environmental conditions, the speed and complexity of climate change poses a new magnitude of problems. New within-crop diversity will be needed to adapt to future conditions, and under extreme conditions new crops will be required.

Areas that are currently most food-insecure will be most affected by climate change, and thus have the greatest need for new crop varieties tolerant of extreme climate conditions such as drought, heat, submergence and salinity. Adapting crop varieties to local ecological conditions can reduce risk due to climate change, but the need for adapted germplasm is urgent and requires characterization, evaluation, and the availability of materials now housed in genebanks. Comprehensive assessments are needed of both adaptation needs and suitable available genetic resources (Ainsworth *et al*., 2008). Crop wild relatives will play a crucial role in providing the genes and traits to help confront these challenges.

Diversity in species, varieties and cultivation practices has permitted agriculture to withstand moderate change in climate over the past 10 000 years. Traditional varieties are well adapted to current environmental conditions.

The challenge will be to accelerate their evolution as climate change makes the traditional varieties less suitable to the new climates.

2.2.1 Key messages related to the impact of climate change on agricultural productivity

According to IPCC and other studies, temperature increases of 1–2°C will result in an increase in production of some of the world's major staples, while temperature increases of more than 2°C will have increasingly negative impacts. Moreover, climate change will have important effects on the global distribution of major crops: some regions will gain suitability for crops currently considered marginal, while others will lose suitability for their staple crops. This has profound social and cultural implications, especially where staple crops will be heavily affected.

2.3 Impacts on crop diversity

The introduction of modern crop varieties has led to the erosion of genetic diversity (Fowler and Mooney, 1990). FAO (1997) estimates that since the beginning of the twentieth century about 75% of the genetic diversity of agricultural crops has been lost.

Climate change is likely to be an additional threat to agricultural biodiversity, increasing genetic erosion of landraces and threatening wild species, including crop wild relatives (Jarvis *et al*., 2008).

Current varieties will be lost as farmers replace them with other landraces or improved varieties that are better adapted to the new conditions. For example, an analysis of use of Guinea sorghum varieties in the Sudanian zone of southern Mali showed that the range of varieties grown by families and villages is heavily influenced by climate change, specifically as the rainy season has shortened over the last 20 years (Weltzien *et al*. 2006). Apart from this generality, there is no way of knowing exactly how climate change will affect landrace diversity, and there are few studies that specifically examine genetic erosion in the context of climate change. However, some of the centres of landrace diversity occur in regions most at risk from climate change.

PGRFA have been exchanged over the past 10 000 years through farmer exchange at markets, among neighbouring farms and, more recently, by collection, *ex situ* conservation and use by research organizations. Today, all countries rely on crop genetic diversity from all over the globe to provide potential adaptation to environmental and climatic changes, to maintain production systems' resilience and to meet the needs of an expanding human population.

Two clear issues may lead to greater interdependency as a result of climate change:

1. Novel climatic conditions will mean that currently adapted landraces and varieties become maladapted, requiring an influx of new materials with novel abiotic traits.
2. Climate change will bring about new and increased demand for PGRFA globally, requiring greater volume and variety of genetic materials.

Projected shifts in crop climates in Africa to 2050 indicate that many countries will experience novel climates not currently found within their borders in 2050 and that 75% of these will have analogues in at least five other countries. The international movement of germplasm will be essential to enable adaptation to these novel climates, hence there will be a need for facilitated exchange of exotic varieties and landraces from analogous sites elsewhere.

Thus, climate change will bring new and enhanced demand for genetic resources. National and international breeding programmes for a number of crops are already targeting new varieties with adaptations to future climatic stresses. The effort to breed for traits valued both today and for the future is likely to increase the general demand for PGRFA.

Demand will also likely increase for crop wild relative genetic resources. These genetic resources are being used in order to address both biotic and abiotic constraints (Lane and Jarvis, 2007), many of which are being exacerbated by climate change. While demand for such genetic resources is global, their natural distribution is restricted to the centres of origin of crops, often specific subregions within continents. For example, wild relatives of the cultivated peanut are found only in Brazil, Paraguay, Bolivia, Uruguay and Argentina. Crop wild relatives are poorly conserved in *ex situ* collections, hence policies must be implemented to facilitate collection of wild gene pools.

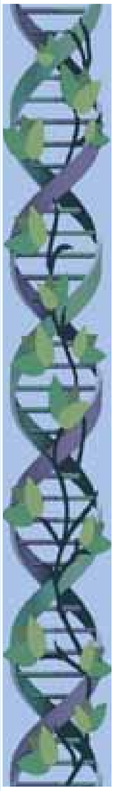
Biotechnology will also shift the demand patterns for PGRFA. On the one hand, molecular tools and high throughput methodologies mean that more accessions can be screened and potentially used. On the other hand, transgenics, marker-assisted selection and other biotechnology tools may reduce the amount of diversity required in breeding programmes, as individual genes rather than collections of traits become the target.

Climate change may also increase the importance of otherwise minor or underutilized crops and plant species. These include species suitable for biofuel production (biodiesel, ethanol and second and third generation biofuel technologies), and hardy crops and species that until now have had only local or regional significance but which may in the future provide valuable alternatives to confront climate change especially in marginal environments.

Evidence is inconclusive as to whether climate change will increase the threats to landrace diversity or, indeed, whether it may contribute to increased demand for landrace diversity. Landraces themselves contain the solution to many of the problems of climate change. They contain a wide range of traits for adaptation to abiotic and biotic stresses that may contribute to the adaptation of global agriculture to climate change. Further studies and strategic analysis should focus on better understanding the local-regional-global impacts of climate change on landrace diversity.

2.3.1 Key messages related to the impact of climate change on landraces

Some of the centres of landrace diversity exist in areas under considerable climate risk, where diversity is valued for its resilience. It is however poorly understood how the increase of climate risk, and change in the climate baseline might impact the current diversity in landraces found *in situ*. Impacts are likely to be both positive and negative on landrace diversity depending on the region, but a priority for research and monitoring activities is to ensure that more diversity is not lost.



2.4 Effects of climate change on plant disease and insect epidemics

Plant diseases and insect epidemics are to a large degree controlled by climate and hence will be sensitive to climate change. Newton *et al*. (2008) posit that while breeding crops for pest and disease resistance has been relatively effective under stable climatic conditions, considerable advances will be necessary to maintain a semblance of balance under more and more turbulent abiotic stresses. While there is a natural tendency to assume that things will get worse, research on the effects of climate change on plant diseases continues to be limited, but some striking progress has been made.

2.4.1 Pathogen and vector responses to climate change

The range of many pathogens is limited by climate requirements for overwintering or oversummering of the pathogen or vector. For example, higher winter temperatures of -6°C versus -10°C increase survival of overwintering rust fungi (*Puccinia graminis*) and increase subsequent disease on *Festuca* and *Lolium* (Pfender and Vollmer, 1999). Increasing levels of atmospheric CO2 reduce the ability of soybean to defend itself against bean leaf beetle resulting in increased beetle populations (Zavala *et al*., 2008).

2.4.2 Virulence, aggressiveness or fecundity of pathogens

The number of generations of pathogen reproduction per time interval determines the rate at which pathogens evolve, and temperature governs the rate of reproduction for many pathogens: e.g., the root rot pathogen reproduces more quickly at higher temperatures (Waugh *et al*., 2003). Longer growing seasons (especially in higher latitudes) that will result from higher temperatures will allow more time for pathogen evolution. Increased overwintering rates at higher temperatures will also contribute to increased pathogen populations. Climate change may also influence whether pathogen populations reproduce sexually or asexually. In some cases altered temperatures may favour overwintering of sexual propagules, thus increasing the evolutionary potential of a population.

Pathogens, like plants, may be unable to migrate or adapt as rapidly as environmental conditions change. But most pathogens will have the advantage over plants because of their shorter generation times and, in many cases, the ability to move readily through wind dispersal.

2.4.3 Host–pathogen interaction responses to climate change

Chakraborty *et al*. (2000) reviewed the effects of increasing CO2 levels on plant disease. For biotrophic fungi, they found an increase in disease severity for six of ten biotrophic fungi studied, and a decrease for the other four. For 15 necrotrophic fungi studied, they reported that nine exhibited an increase in disease severity, four exhibited a decrease and two remain unchanged. This suggests that predicting effects of climate change on unstudied pathosystems will be challenging. Some mechanisms of the effects of elevated CO2 concentration on plants are fairly well understood and will have obvious effects on plant diseases. For example reduced stomatal opening and changes in leaf chemistry will reduce the incidence of disease caused by pathogens that infect through stomata, such as *Phyllosticta minima* (Mcelrone *et al*. 2005). But combining the direct effects of elevated CO2 on plants with the effects on disease will make predictions of plant productivity even more challenging. For example, von Tiedemann and Firsching (2000) found that benefits from elevated CO2 counterbalanced negative effects from ozone but did not compensate for the effects of fungal infection.

3. BIODIVERSITY ECOSYSTEM SERVICES FOR FOOD AND AGRICULTURE

There are a number of ecosystem services derived from biodiversity that will be affected by climate change. These include pollination services, soil biodiversity, organisms for biological control and nutrient cycling processes. Unfortunately few studies provide detailed analyses of the impacts of climate change on these services. Pollination is likely to be particularly problematic, as insect response to climate change is particularly sensitive. Climate change may have profound impacts on synchronicity between pollinators and crop flowering, resulting in reduced productivity. To our knowledge, however, no studies have explicitly analysed this. The projected impacts of climate change on wild plant species distribution (Thomas *et al*., 2004) will also affect composition of plant and animal communities, affecting biological control organisms.

4. RESPONSES TO CLIMATE CHANGE IMPACTS

4.1 Implications for genebanks

Climate change will threaten wild relatives of cultivated crops and potentially landraces themselves, but will also increase the need for diverse germplasm to bolster resistance to increasing abiotic and biotic stresses. These factors represent both a challenge for genebanks to ensure that important gene pools are adequately conserved and an opportunity for stimulating greater use of germplasm holdings. As climate change brings about novel demands on germplasm for adaptation, an emerging challenge to genebanks will be adequate characterization of their germplasm for traits and characteristics useful for crop improvement to respond to new challenges (see section 4.3 Characterization for useful traits in genebanks). Genebanks will need to implement pre-breeding as a standard procedure to stimulate greater use of diversity and to reduce the cost and increase the efficiency of breeding programmes. Different traits to those already screened for might become higher priorities, requiring genebanks to re-assess demands and potentially change their standard screening procedures.

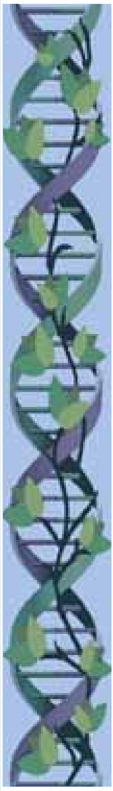
There are also a number of documented cases in which genebank materials themselves have been lost due to extreme climate events and these losses are likely to be an ever increasing problem. Hurricane Mitch severely damaged Central American banana germplasm and extreme floods in Ecuador during the El Niño of 1997 destroyed the national cassava collection. These events emphasize the need for back-up collections, especially for clonal crops. Cost increases for such conservation will have to be met.

Novel delivery mechanisms are also needed that matches abiotic adaptation traits of germplasm to sites. As the global geography of agriculture shifts with climate change, agricultural biodiversity must also move. This movement will require broad availability of landraces and varieties across regions and among regions. It will also result in an increase in demand for genebank holdings and a possible increase in long-distance and cross-continental requests for materials.

4.2 Collecting PGRFA

The goal of *ex situ* conservation as stated by Marshall and Brown (1975) is to conserve, "…95% of all the alleles at a random locus occurring in the target population with a frequency greater than 0.05". In these terms, many collections are incomplete and have important gaps.

A first requirement is that priority species and regions need to be identified. As wild species are the most exposed to climate change, consolidation of global germplasm collections of wild species, crop wild relatives, biological control species and underutilized and wild harvested species is a high priority. Collections of crop wild relatives are widely acknowledged to be deficient and in need of further work to complete the collections that do exist. Collections should cover all taxonomic species of relevance to crop improvement. In some cases fairly distant wild relatives will be needed. Collections also need to cover the full geographic distribution of the species, and especially populations on the extremes of the distribution where novel abiotic traits may be found.



4.3 Characterization for useful traits in genebanks

Climate change is expected to increase the frequency of drought, heat stress, submergence and increased soil salinity. There is, therefore, a need to find new sources of variation to cope with these stresses. Efficient and effective screening methods must be developed to identify and dissect the physiological basis of tolerance to abiotic stresses. Of late, research has progressed in this area for tolerance to drought, salinity, submergence and heat stress in major food crops (Table 1). We now have a better perception of the critical phases in plant development most affected by these stresses.

For example, early flowering provides an escape mechanism to drought and is a characteristic invariably used in breeding programmes. Substantial variation in root traits, water-use efficiency, amount of water transpired, transpiration efficiency, osmotic adjustment, stem water-soluble carbohydrates, stay-green and leaf abscisic acid have been reported in many cereal and legume crops. Reliable and easily measurable phenotypic screens are available for many of these traits. What is needed now is to apply this knowledge to identify new sources of variation to these stresses. In situations where genetic variation is not available either in cultivated or wild gene pools, applying the TILLING technology can help detect variation of these traits. A high throughput-based marker analysis is needed, however, to detect variation at the DNA level. Fortunately, the TILLING technology has been developed for wheat, rice, maize, barley, and soybean (Dwivedi *et al*. 2007a).

Discovery of novel traits is a high priority. There will be continued or increased demand for receiving germplasm with associated characterization data.

TABLE 1

Physiological traits associated with tolerance to drought, salinity, heat, and submergence tolerance in selected cereals and legume crops

Crop	Trait	Reference
	Drought	
Rice	Early flowering, deeper and thicker roots, root pulling resistance, root penetration, osmotic adjustment (OA), rapid stomatal closure, water-use efficiency (WUE), membrane stability, leaf rolling score, and leaf relative water content	Manneh *et al*. 2007; Dwivedi *et al*. 2008b
Wheat	Early flowering, stem water-soluble carbohydrate (SWSC), green flag-leaf persistence, WUE, transpiration efficiency (TE), and awns	Dwivedi *et al*. 2008b
Maize	Early flowering, anthesis silking interval (ASI), ears per plant, stay-green, chlorophyll content, OA, root traits, leaf abscisic acid (L-ABA)	Dwivedi *et al*. 2008b
Barley	Early flowering, plant stature, ear type, WUE, OA, high biomass combined with SWSC, water extraction, and TE	Dwivedi *et al*. 2008b
Sorghum	Early flowering, stay-green, SWSC, TE, rooting depth and patterns, epicuticular wax	Dwivedi *et al*. 2008b
Pearl millet	Early flowering, few tillers, low biomass and high harvest index including panicle harvest index, grain yield, individual grain mass Profuse rooting in the deeper layers of soil	
Chickpea	Early flowering, deep rooting and higher root length density	Kashiwagi *et al*. 2005, 2006
Groundnut	Early flowering, WUE, transpiration, TE, specific leaf area (SLA), and SPAD meter chlorophyll reading	Dwivedi *et al*. 2008b
	Heat	
Rice	Time of day when flowering (TDF) commences (early TDF protects fertility from high temperature), high temperature tolerance at grain filling (pollen shedding, pollen germination and pollen tube extension) Higher leaf transpiration rate to maintain lower leaf temperature combined with opening of flowers in morning (*O. glaberrima*)	Sheehy *et al*. 2005; Wassmann and Dobermann 2007; Matsui and Omasa 2002 Manneh *et al*. 2007
Pearl Millet		Howarth, 1991; Fussel *et al*., 1991

Crop	Trait	Reference
	Salinity	
Rice	Early vegetative stage: salt exclusion or low uptake, compartmenting of toxic ions in structural and older tissues, higher tissue tolerance by compartmenting salt into vacuoles, stomata that close faster upon exposure to salt stress Reproductive development stage: salt exclusion from flag leaves and developing panicles	Ismail *et al*. 2007
Wheat and barley	Na+ exclusion, K+/Na+ discrimination, sheath retention of ions, tissue tolerance, ion partitioning into different-aged leaves, OA, enhanced vigour, WUE, and early flowering	Colmer *et al*. 2005; Genc *et al*. 2007; Munns *et al*. 2006; El-Hendawy *et al*. 2007
Maize	OA and abscisic acid (ABA)	De Costa *et al*. 2007
Sorghum	Whole plant tolerance resulted from reduced shoot Na+ concentration, a major mechanism involved in salt tolerance	Krishnamurthy *et al*. 2007a
Pearl millet	Whole plant tolerance associated with reduced shoot N content, increased K+ and Na+ contents; with shoot Na^+ concentration a potential non-destructive selection criterion at vegetative-stage screening	Krishnamurthy *et al*. 2007b
Chickpea	Ability to maintain large number of filled pods; shoot Na^+ or K^+ not related to salinity	Vadez *et al*. 2007b
Pigeon pea	Reduced shoot Na^+ concentration	Srivastava *et al*. 2006
Groundnut	Pod numbers per plant	ICRISAT 2006
	Submergence	
Rice	Vigorous seedling growth, elongation ability, submergence tolerance, resistance to lodging or recovery from lodging after water level reduction	Manneh *et al*. 2007

4.4 Searching for new traits in crop germplasm

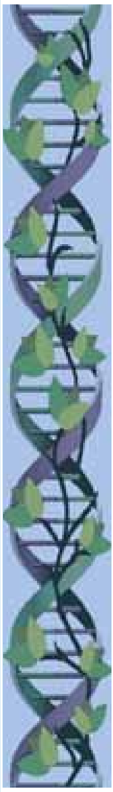
4.4.1 Re-synthesizing the progenitors of crop species to capture new variation

Many crops that were until recently considered typical diploids (e.g., rice and maize) are, in fact, ancient polyploids. These have undergone chromosome doubling during their evolution in spite of behaving cytologically as diploids. Re-synthesizing polyploids to generate additional diversity and as a mechanism for gene introgression has been suggested. For example, CIMMYT now has a major programme to develop synthetic wheats to broaden the genetic diversity of modern wheat. A few lines tested under dry conditions produced between 20 and 40% more grain than traditional wheat. A similar approach is being tested for the introgression of new genes into groundnut while minimizing the problems of sterility and suppression of recombination (Dwivedi *et al*. 2008a). This approach would be particularly important if the newly created variation is related to traits required as a consequence of climate change.

4.4.2 Exotic genetic libraries

Wild relatives have contributed resistance in crops to several pests and diseases. Development of exotic genetic libraries (Zamir, 2001) consisting of marker-defined genomic regions taken from wild species and introgressed on to the background of elite crop varieties will provide a resource for the discovery and characterization of genes that underlie traits of agricultural value. The benefits of such an approach have been demonstrated in tomato: introgressed lines carrying three independent yield-promoting genomic regions produced yields more than 50% greater than those of controls under both wet and dry conditions (Gur and Zamir, 2004). Thus, a goal of surpassing yield barriers provides a rationale for implementing similar strategies in other crops important for global food security. Introgression lines have been reported in rice, wheat, and barley (Dwivedi *et al*. 2008a).

4.4.3 Mining allelic variation associated with drought, heat, and salinity tolerance in genebank materials to support crop improvement



Key to successful crop improvement is the ability to identify and access genetic diversity including new or improved variability for target traits. The large size of some collections makes this process very difficult, and core collections have been proposed as a means of facilitating this process. Conventional core collections (10% of entire collection) based on passport and characterization data are available in barley, cassava, cowpea, finger millet, foxtail millet, maize, Musa, pearl millet, potato, rice, sorghum, sweet potato, wheat, and yam (Dwivedi *et al*. 2007a). In crops with large germplasm collections, mini core collections (10% of core or 1% of the entire collection;) have been suggested (Upadhyaya and Ortiz, 2001).

The Generation Challenge Program (GCP) (http://www.generationcp.org) initiated a programme to characterize the diversity of crop germplasm collections held by the centres of the Consultative Group on International Agricultural Research (CGIAR) in terms of the genetic structure and associated phenotypic variation. This led to the development of a composite collection of most of the cereals, legumes and clonal food crops. In many cases the composite collection has been profiled at the molecular level; and reference sets have been developed in chickpea, sorghum, groundnut, and pigeon pea. The development of such a composite collection and reference sets provide unique opportunities for researchers across the globe to assess PGRFA in terms of new traits and to assess associations among traits and genetic markers that can be used to support crop improvement.

5. IMPLICATIONS FOR *IN SITU* PGRFA CONSERVATION

5.1 Resilience from complex seed systems

There is an important research gap in understanding plants' genetic capacity to adapt to climate change. While a broad range of studies examine the generic impacts of climate change on crop productivity, few studies examine varietal-level changes in adaptation. To the knowledge of the authors, no study explicitly examines the capacity of local landraces to adapt to projected changes.

Seed systems are an essential component of local-level adaptation. Landraces with a variety of different traits and under novel selection pressures from climate change can be exchanged, giving farmers access to adapted materials and increased ability to adapt to changes as they occur. There are, of course, limits to the extent to which local seed systems can adapt to change. As changes accelerate, seed systems will need to stretch over longer and longer distances. Policies are needed that promote seed systems, seek further understanding of their role in adaptation to climate change and seek ways to enable long distance seed exchange via seed fairs and other mechanisms are needed.

Future research needs to separate two different effects of climate change in this context:

1. Directional change towards possible higher temperatures or reduced or increased rainfall. Farmers' seed management strategies usually address such changes by searching for new variation, either within existing, variable material or by accessing material from neighbouring regions. The role of such exchanges needs to be understood and strengthened.
2. With the predicted increase in climate variability and widening of the extremes, farmers may need to change their traditional seed-management strategies: How much intra-varietal diversity is necessary to cope with those unpredictable extreme climate events? Which traits can actually add phenotypic plasticity? This again is particularly important in areas on the environmental limits of cultivation at present.

Understanding the present coping and risk management strategies of farmers who are already facing such stresses and variation already today, could help to farmers who will face them in the new future.

Research to understand further the extent to which local landraces can absorb projected changes without important reductions in productivity is a priority. These insights could then direct policy in terms of development of participatory plant breeding, local, national and regional exchange of crop diversity and broader policies related to agricultural adaptation.

5.2 On-farm germplasm conservation

It is important that on-farm conservation (or *in situ* conservation) is implemented within the context of agricultural development strategies to promote both development and conservation. On-farm conservation is a dynamic form of plant genetic resources management that builds on natural and farmer selection. It is prevalent in complex, diverse, risk-prone environments where local subsistence farming is risk-laden (Bertacchini, 2008). It is therefore a valid strategy for addressing vulnerability to climate risk in regions, in that it provides a variety of germplasm options for farmers to use under shifting climate patterns.

Traditionally, *in situ* conservation has been used to conserve forest trees, wild species and valued ecosystems, while *ex situ* conservation was a predominant approach for conservation of PGRFA. This is changing, however, as scientists recognize that each approach has particular advantages and disadvantages. Effective conservation systems that incorporate elements of both are now referred to as integrated approaches to genetic resources conservation.

There are several examples of successful crop genetic conservation that have elements of both *in situ* and *ex situ* conservation. There is a reasonably advanced programme in Ethiopia of on-farm conservation. The project relies on cooperation between farmers and researchers to restore landraces such as those lost during the drought of the 1980s. Landraces of the most important crops, including teff, barley, chickpea, sorghum, and faba bean are being re-introduced from stocks stored in a genebank, multiplied, and then reintroduced for conservation and improvement on-farm by the farmers. A decentralized approach has been adopted in which community seed genebanks provide farmers with a diverse range of crops.

In the Philippines, NGOs, the South East Asian Research Institute for Community Education, and the Community-based Native Seed Research Centre (CONSERVE) are working with 140 farmer curators in Mindanao on the conservation of rice and maize varieties. There are links between *ex situ* and *in situ* conservation; and CONSERVE maintains a backup collection of 585 rice varieties and 14 maize varieties on a farm within the community from which seed are distributed to farmers. Another example from the Philippines is the joint initiative between NGOs and the University of the Philippines at Los Baños, called the Farmer-Scientist Partnership for Development Association. This programme promotes on-farm conservation of rice and other crops and maintains an *ex situ* collection.

In Europe, conservation of agricultural biodiversity *in situ* and on-farm is under consideration in a number of countries in response to government and public interest in the greening of agriculture through the use of more traditional, organic, and integrated farming systems. NGOs are active in this area in Austria, France, Germany, Ireland, Norway, Switzerland, and the United Kingdom.

Given the context of climate change, enhancing *in situ* conservation would be a valid means of building resilience at the community level, providing multiple options for planting to confront future hostile climates or enhanced climatic risk.

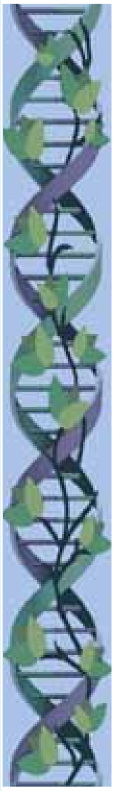
6. IMPLICATIONS FOR BREEDING

There are important new demands for crop improvement programmes to combat climate change, focused on the development of varieties with greater resistance to abiotic extremes. Breeding programmes must develop crop-specific and region-specific strategies today so that the products are relevant to problems and conditions in 10–15 years' time.

Breeders must therefore identify germplasm with traits that can be used to develop crop cultivars adapted to climatic extremes, thus helping to provide food security to the peoples/regions most affected by climate change. A summary of candidate traits of importance for inclusion in new varieties to combat climate change for major crops is shown in Table 1 (above).

7. IMPLICATIONS FOR DISASTER MANAGEMENT AND SEED RELIEF

The current approaches of seed relief do not take into account the need for diversity and adapted seed for specific site conditions (Sperling *et al*., 1991). Under normal conditions, informal farmer seed systems maintain and promote local diversity. When important disasters occur, however, such seed systems can break down and are then often replaced by international seed distribution programmes that usually distribute commercial varieties from the wider region or even from other regions. Climate change is predicted to increase the occurrence of extreme events such as floods, droughts and hurricanes, leading to increased reliance on seed relief. This future scenario brings with it the need for more effective seed distribution networks that distribute well-adapted seed to communities. This will help to reduce communities' dependence on seed relief after future disasters. Seed relief can also be used as a mechanism to deploy adapted seed to support long-term adaptation of agricultural systems to climate change.



8. IMPLICATIONS FOR INTERNATIONAL POLICY

Access to genetic resources is still limited in many countries due to a complex policy environment. There are about 150 different crops traded in the world market, only 35 of which are covered by the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) – a treaty that sets a multilateral legal framework that facilitates exchange of genetic resources. There are also thousands of crops or species that 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.

Moreover, many crops and forages of regional importance have been excluded from the ITPGRFA, including soybean, groundnuts, sugar cane and the wild relatives of cassava to name but a few. In terms of forage species, the majority of species covered by the Treaty are from temperate regions, and African forage grasses (including Napier, Rhodes grass and *Brachiaria*) and Latin American forage legumes are under-represented. As temperatures increase and hence the likelihood of frost decreases, these tropical species will be available for introduction into subtropical regions and their area of cultivation will probably expand into the tropical highlands. Furthermore, many underutilized and minor crops that are not covered by the Treaty are potentially important for climate change adaptation, and hence efforts to facilitate access and benefit-sharing for these species are important.

Finally, there are over one billion people living in families that are self-reliant for the seeds they plant each year, and who serve as the *in situ* conservers of abundant crop genetic diversity for both traded and non-traded crops. International policy must work to reduce the barriers to collection and wider use of genetic resources. Specifically, more collections are required for both wild and cultivated material and for species currently under-represented in genebanks.

Climate change adds greater pressure on the international system for germplasm exchange, as there is a considerable increase in interdependency and crop improvement programmes will face a range of new challenges. Moreover, the new challenges are not limited to those stemming from climate change. Increasing population combined with huge global increases in demand for staple food/feed crops will coincide with climate change. In addition, targets will be moving, literally. The geography of agriculture is predicted to shift considerably. Current maize growing regions in southern Africa, for example, may shift northwards into other countries in Eastern and Central Africa.

9. IMPLICATIONS FOR MANAGEMENT OF BIODIVERSITY-RELATED ECOSYSTEM SERVICES FOR FOOD AND AGRICULTURE

The impacts of climate change on biodiversity-related ecosystem services do not necessarily imply a need to change the way these services are currently managed. Rather, the better these services are managed today, the more chance they have of being maintained in the future and of being less negatively affected by climate change. On the other hand, however, a shift in emphasis is needed to the collection, characterization and use of the global diversity of landraces and wild relatives of major crop species and to the 'minor' crops on which people in more marginal and bypassed areas depend.

10. RECOMMENDATIONS AND IMPLICATIONS FOR INTERNATIONAL POLICY

In many cases, climate change does not imply drastic change of existing strategies for the management and use of PGRFA-AB. Rather, it requires modified priorities but requires only minor adjustments to the way in which business is undertaken. This review has highlighted the following issues as being worthy of further attention:

- There is an increased need for consolidating collections of wild species, including crop wild relatives, due to increased likelihood of extinction for narrowly adapted and endemic species. The collections need to emphasize the stress-adapted genetic material that can contribute to adaptation in the face of climate change.
- Genebanks must be better able to respond to novel and increased demands on germplasm for adapting agriculture to climate change. Genebanks need to include different characteristics in their screening processes and their collections need to be comprehensive, including what are now considered 'minor' crops.

- Breeding strategies and priorities need to be reviewed on a crop-by-crop and region-by-region basis so as to make products of crop improvement programmes initiated today relevant to the challenges the world will be facing when the bred materials are ready for release at the end of the crop-improvement cycle (5–10 years).
- There is a need to review and strengthen policies for promoting dynamic seed systems, including the promotion of means of longer-distance exchange of seed between farmers, and review of priorities and procedures in seed relief after disasters.
- There is an increased demand on international policy to facilitate access to more genetic resource materials through increased interdependency brought about by global shifts in climate zones.

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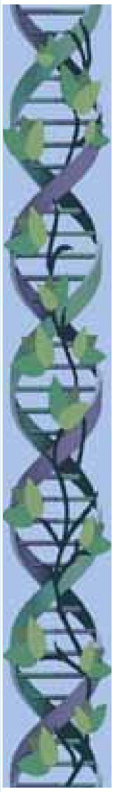

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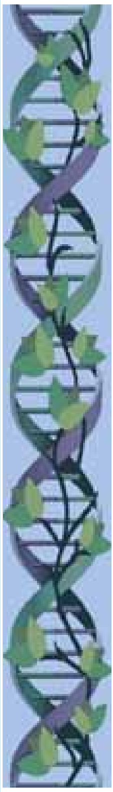

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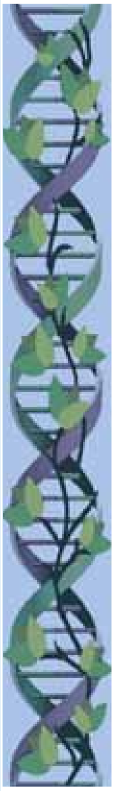

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