Plant breeding and climate change

S. Ceccarelli
*International Center for Agricultural Research in the Dry Areas (ICARDA), PO Box 5466 Aleppo, Syria.*

**Abstract**

The paper discusses the contribution of plant breeding to the adaptation of crops to future climate.

Climate change is now unequivocal, particularly in terms of increasing temperature, increasing CO₂ concentration, widespread melting of snow and ice, and rising global average sea level, while the increase in the frequency of drought is very likely but not as certain.

Yet, climate changes are not new and some of them have had a dramatic impact, such as the appearance of leaves about 400 million years ago as a response to a drastic decrease of CO₂ concentration, the birth of agriculture due to the end of the last ice age about 11 000 years ago, and the collapse of civilizations due to the late Holocene droughts between 5000 and 1000 years ago.

The climate change occurring now will have—and is already having—an adverse effect on food production and food quality, with the poorest farmers and the poorest countries most at risk. The adverse effect is a consequence of the expected or likely increased frequency of some abiotic stresses such as heat and drought, and of the increased frequency of biotic stresses (pests and diseases). In addition, climate change is also expected to cause losses of biodiversity, mainly in more marginal environments.

Plant breeding has always addressed both abiotic and biotic stresses, and strategies of adaptation to climate changes may include a more accurate matching of phenology to moisture availability using photoperiod-temperature response; increased access to a suite of varieties with different duration to escape or avoid predictable occurrences of stress at critical periods in crop life cycles; improved water use efficiency; and re-emphasis on population breeding to provide a buffer against increased unpredictability. These measures must go hand in hand with breeding for resistance to biotic stresses, and with an efficient system of variety delivery to farmers.

As a crop that has been always considered as the most resilient amongst the winter cereals and that has a range of possible uses still largely unexplored, barley is an ideal crop that farmers in a number of countries are already using as a response to climate changes.

**Climatic changes today**

Today nobody questions whether climate changes are occurring or not, and the discussion has shifted from whether they are happening to what to do about them.

The most recent evidence from the Fourth Assessment Report on Climate Change of the Intergovernmental Panel on Climate Change (IPCC, 2007) indicates that the warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.
Quoting from the report:

- “Eleven of the last twelve years (1995-2006) rank among the twelve warmest years in the instrumental record of global surface temperature (since 1850)”
- “The temperature increase is widespread over the globe, and is greater at higher northern latitudes. Land regions have warmed faster than the oceans”.
- Rising sea level is consistent with warming. Global average sea level has risen since 1961 at an average rate of 1.8 mm/yr and since 1993 at 3.1 mm/yr, with contributions from thermal expansion, melting glaciers and ice caps, and the polar ice sheets.
- Observed decreases in snow and ice extent are also consistent with warming. Satellite data since 1978 show that annual average Arctic sea ice extent has shrunk by 2.7% per decade, with larger decreases in summer of 7.4% per decade. Mountain glaciers and snow cover on average have declined in both hemispheres.
  It is also very likely that over the past 50 years cold days, cold nights and frosts have become less frequent over most land areas, and hot days and hot nights have become more frequent, and it is likely that heat waves have become more frequent over most land areas, the frequency of heavy precipitation events has increased over most areas, and since 1975 the incidence of extreme high sea level has increased worldwide. There is also observational evidence of an increase in intense tropical cyclone activity in the North Atlantic since about 1970, with limited evidence of increases elsewhere. There is no clear trend in the annual numbers of tropical cyclones, but there is evidence of increased intensity.
  Changes in snow, ice and frozen ground have with high confidence increased the number and size of glacial lakes, increased ground instability in mountain and other permafrost regions, and led to changes in some Arctic and Antarctic ecosystems (Walker, 2007).
  The projections to year 2100 for concentration indicate that CO₂ emission is expected to increase by 400% and CO₂ atmospheric concentration is expected to increase by 100% (Figure 1).
  Some studies have predicted increasingly severe future impacts, with potentially high extinction rates in natural systems around the world (Williams et al., 2003; Thomas et al., 2004).

Climatic changes in history

Even though climate changes are one of the major current global concerns, they are not new. Several climate changes occurred before, with dramatic consequences. Among

Figure 1. Projected CO₂ emission in billion tonne carbon equivalent (left) and atmospheric CO₂ concentration in parts per million (right).
these is the decrease in CO₂ content which took place 350 million years ago and which is considered to be responsible for the appearance of leaves—the first plants were leafless and it took about 40–50 million years for the leaves to appear (Beerling et al., 2001).

A second climatic change was that induced by perhaps the most massive volcanic eruption in Earth’s history, which occurred in Siberia when up to 4 million cubic kilometres of lava erupted onto the Earth’s surface. The remnants of that eruption cover today an area of 5 million square kilometers. This massive eruption caused, directly or indirectly, though the formation of organohalogens, a worldwide depletion of the ozone layer. The consequent burst of ultraviolet radiation explains why the peak eruptions phase coincides with the timing of the mass extinction that wiped out 95% of all species.

The third major climate change was the end of the last Ice Age (between 13 000 and 11 500 BC), with the main consequence that much of the earth became subject to long dry seasons. This created favorable conditions

for annual plants, which can survive the dry seasons either as dormant seeds or as tubers, and eventually agriculture started, as we know today, in that area of the Near East known as the Fertile Crescent, around 9 000 BC, and soon spread to other areas.

The fourth climatic change was the so called Holocene flooding, which took place about 9 000 years ago and is now believed to be associated with the final collapse of the Ice Sheet, resulting in a global sea level rise of up to 1.4 m (Turney and Brown, 2007). Land lost from rising sea levels drove mass migration to the north west and this could explain how domesticated plants and animals, which by then had already reached modern Greece, started moving towards the Balkans and eventually into Europe.

During the last 5 000 years, drought, or more generally limited water availability, has historically been the main factor limiting crop production. Water availability has been associated with the rise of multiple civilizations, while drought has caused the collapse of empires and societies, such as the Akkadian Empire (Mesopotamia, ca. 4200 calendar yr B.P.), the Classic Maya (Yucatan Peninsula, ca. 1200 calendar yr B.P.), the Moche IV–V Transformation (coastal Peru, ca. 1500 calendar yr B.P.) (de Menocal, 2001) and the early bronze society in the southern part of the Fertile Crescent (Rosen, 1990).

How do people respond to climatic changes?

Although the debate about climate change is relatively recent, people, for example in Africa, have been adapting to climate changes for thousands of years. In general, people seem to have adapted best when working as a community rather than as individuals. The four main strategies of adaptation have been (a) changes in agricultural practices; (b) formation of social networks; (c) embarking on commercial projects, such as investing in livestock; and (d) seeking work in distant areas. The first three of these strategies rely on people working together to improve their community (Giles, 2007).

In continuous coping with extreme weather events and climatic variability, farmers living in harsh environments in Africa, Asia and Latin America have developed or inherited complex farming systems that have the potential to bring solutions to many uncertainties facing humanity in an era of climate change (Altieri and Koohafkan, 2003). These systems have been managed in ingenious ways, allowing small farming families to meet their subsistence needs in the midst of environmental variability without depending much on modern agricultural technologies (Denevan, 1995). They can still be found throughout the world, covering some 5 million hectares, are of global importance to food and agriculture, and are based on the cultivation of a diversity of crops
and varieties in time and space that have allowed traditional farmers to avert risks and maximize harvest security in uncertain and marginal environments, under low levels of technology and with limited environmental impact (Altieri and Koohafkan, 2003). One of the salient features of the traditional farming systems is their high degree of biodiversity, in particular the plant diversity in the form of polycultures and/or agroforestry patterns. This strategy of minimizing risk by planting several species and varieties of crops is more resilient to weather events, climate variability and change, and resistant to adverse effects of pests and diseases, and at the same time stabilizes yields over the long term, promotes dietary diversity and maximizes returns, even with low levels of technology and limited resources (Altieri and Koohafkan, 2003).

The term autonomous adaptation is used to define responses that will be implemented by individual farmers, rural communities or farmers’ organizations, or a combination, depending on perceived or real climate change in the coming decades, and without intervention or coordination by regional and national governments and international agreements. To this end, pressure to cultivate marginal land, or to adopt unsustainable cultivation practices as yields drop, may increase land degradation and endanger the biodiversity of both wild and domestic species, possibly jeopardizing future ability to respond to increasing climate risk later in the century.

One of the options for autonomous adaptation includes the adoption of varieties and species with increased resistance to heat shock and drought (Bates et al., 2008).

### Climatic changes, food and agriculture

Using the results from formal economic models, it is estimated (Stern, 2005) that in the absence of effective counteraction, the overall costs and risks of climate change will be equivalent to losing at least 5% of global gross domestic product (GDP) each year. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more, with a disproportionate burden on and increased risk of famine for the poorest countries (Altieri and Koohafkan, 2003).

The majority of the world’s rural poor, about 370 million of the poorest, live in areas that are resource poor, highly heterogeneous and risk prone. The worst poverty is often located in arid or semi-arid zones, and in mountains and hills that are ecologically vulnerable (Conway, 1997). In many countries, more people, particularly those at lower income levels, are now forced to live in marginal areas (i.e. floodplains, exposed hillsides, arid or semi-arid lands), putting them at risk from the negative impacts of climate variability and change.

Climatic changes are predicted to have adverse impacts on food production, food quality and food security. One of the most recent predictions (Tubiello and Fischer, 2007; Table 1) is that by the year 2080 the number of undernourished people will

<table>
<thead>
<tr>
<th>Region</th>
<th>1990</th>
<th>2020</th>
<th>2050</th>
<th>2080</th>
<th>2080/1990</th>
</tr>
</thead>
<tbody>
<tr>
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<td>885</td>
<td>772</td>
<td>579</td>
<td>554</td>
<td>0.6</td>
</tr>
<tr>
<td>Asia, Developing</td>
<td>659</td>
<td>390</td>
<td>123</td>
<td>73</td>
<td>0.1</td>
</tr>
<tr>
<td>Sub-Saharan Africa</td>
<td>138</td>
<td>273</td>
<td>359</td>
<td>410</td>
<td>3.0</td>
</tr>
<tr>
<td>Latin America</td>
<td>54</td>
<td>53</td>
<td>40</td>
<td>23</td>
<td>0.4</td>
</tr>
<tr>
<td>Near East and North Africa</td>
<td>33</td>
<td>55</td>
<td>56</td>
<td>48</td>
<td>1.5</td>
</tr>
</tbody>
</table>

**Table 1.** Expected number of undernourished in millions, incorporating the effect of climate.

**Source:** Tubiello and Fischer, 2007
increase by 1.5 times in the Near East and North Africa and by 3 times in sub-Saharan Africa compared with 1990.

Agriculture is extremely vulnerable to climate change. Higher temperatures eventually reduce crop yields while encouraging weed, disease and pest proliferation. Changes in precipitation patterns increase the likelihood of short-term crop failures and long-term production declines. Although there will be gains in some crops in some regions of the world, the overall impacts of climate change on agriculture are expected to be negative, threatening global food security (Nelson et al., 2009).

Food insecurity is likely to increase under climate change, unless early warning systems and development programs are used more effectively (Brown and Funk, 2008). Today, millions of hungry people subsist on what they produce. If climate change reduces production while populations increase, there is likely to be more hunger. Lobell et al. (2008) showed that increasing temperatures and declining precipitation over semi-arid regions are likely to reduce yields for maize, wheat, rice, and other primary crops in the next two decades. These changes could have a substantial negative impact on global food security.

Climate change increases child malnutrition and reduces food energy consumption dramatically. Thus, aggressive agricultural productivity investments are needed to raise food energy consumption enough to offset the negative impacts of climate-change on the health and well-being of children (Nelson et al., 2009).

How do crops respond to climatic changes?

Adapting crops to climatic changes has become an urgent challenge that requires some knowledge of how crops respond to those changes. In fact, plants have responded to increasing CO₂ concentration from pre-industrial to modern times by decreasing stomatal density—reversing the change described earlier which led to the appearance of leaves—as shown by the analysis of specimens collected from herbaria over the past 200 years (Woodward, 1987). In Arabidopsis thaliana the gene HIC (High Carbon Dioxide) prevents changes in the number of stomata in response to increasing CO₂ concentration (Gray et al., 2000); mutant hic plants exhibit up to 42% increase in stomatal density in response to a doubling of CO₂. The implication is that the response of the stomatal density to increasing CO₂ concentration in many plant species is now close to saturation (Serna and Fenoll, 2000). Stomatal density varies widely within species: for example, in barley, stomatal density varies from 39 to 98 stomata/mm² (Miskin and Rasmusson, 1970), suggesting that the crop has a fairly good possibility of adaptation.

Today it is fairly well known how plants respond to increased CO₂ concentration, which has both direct and indirect effects on crops. Direct effects (also known as CO₂-fertilization effects) are those affecting the crops by the presence of CO₂ in ambient air, which is currently sub-optimal for C₃ type plants like wheat and barley. In fact, in C₃ plants, mesophyll cells containing ribulose-1,5-bisphosphate carboxylase-oxygenase (RuBisCO) are in direct contact with the intercellular air space that is connected to the atmosphere via stomatal pores in the epidermis. Hence, in C₃ crops, rising CO₂ increases net photosynthetic CO₂ uptake because RuBisCO is not CO₂-saturated in today’s atmosphere and because CO₂ inhibits the competing oxygenation reaction, leading to photorespiration. CO₂-fertilization effects include increased photosynthetic rate, reduced transpiration rate through decreased stomatal conductance, higher water use efficiency (WUE), and lower probability of water stress occurrence. As a consequence, crop growth and biomass
production should increase by up to 30% for C₃ plants at doubled ambient CO₂; other experiments show 10–20% biomass increase under double CO₂ conditions. In theory, at 25°C, an increase in CO₂ from the current 380 ppm to that of 550 ppm, projected for the year 2050, would increase photosynthesis by 38% in C₃ plants. In C₄ plants, such as maize and sorghum, RuBisCO is localized in the bundle sheath cells in which CO₂ concentration is three to six times higher than atmospheric CO₂. This concentration is sufficient to saturate RuBisCO and in theory would prevent any increase in CO₂ uptake with rising CO₂. However, even in C₄ plants, an increase in water use efficiency via a reduction in stomatal conductance cause by increased CO₂ may still increase yield (Long et al., 2006).

However, the estimates of the CO₂-fertilization have been derived from enclosure studies conducted in the 1980s (Kimball, 1983; Cure and Acock, 1986; Allen et al., 1987), and today they appear to be overestimated (Long et al., 2006).

In fact, free-air concentration enrichment (FACE) experiments, representing the best simulation of the future elevated CO₂ concentration, gives much lower (about 50% lower) estimates of increased yields due to CO₂-fertilization (Table 2).

Indirect effects (also known as weather effects) are the result of solar radiation, precipitation and air temperature, and, keeping management the same, above a certain temperature threshold, cereals yields typically decrease with increasing temperatures and increase with increased solar radiation. If water is limiting, yields eventually decrease because of higher evapotranspiration. Precipitation will obviously have a positive effect when it reduces water stress, but can also have a negative effect such as by causing waterlogging.

Therefore, the most likely scenario for plant breeding is the following:

- higher temperatures, which will reduce crop productivity, are certain;
- increased CO₂ concentration is certain, with both direct and indirect effects;
- increased frequency of drought is highly probable;
- increases in the areas affected by salinity is highly probable; and
- increased frequency of biotic stress is also highly probable.

Table 2. Percentage increases in yield, biomass and photosynthesis of crops grown at elevated CO₂ (550 ppm) in enclosure studies versus FACE (Free-Air Concentration Enrichment) experiments (Long et al., 2006).

<table>
<thead>
<tr>
<th>Source</th>
<th>Rice</th>
<th>Wheat</th>
<th>Soybean</th>
<th>C₄ crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kimball (1983)</td>
<td>19</td>
<td>28</td>
<td>21</td>
<td>–</td>
</tr>
<tr>
<td>Cure and Acock (1986)</td>
<td>11</td>
<td>19</td>
<td>22</td>
<td>27</td>
</tr>
<tr>
<td>Allen et al. (1987)</td>
<td>–</td>
<td>–</td>
<td>26</td>
<td>–</td>
</tr>
<tr>
<td>Enclosure studies</td>
<td>–</td>
<td>31</td>
<td>32</td>
<td>18</td>
</tr>
<tr>
<td>FACE studies</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>0¹</td>
</tr>
<tr>
<td>Biomass</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cure and Acock (1986)</td>
<td>21</td>
<td>24</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td>Allen et al. (1987)</td>
<td>–</td>
<td>–</td>
<td>35</td>
<td>–</td>
</tr>
<tr>
<td>FACE studies</td>
<td>13</td>
<td>10</td>
<td>25</td>
<td>0¹</td>
</tr>
<tr>
<td>Photosynthesis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cure and Acock (1986)</td>
<td>35</td>
<td>21</td>
<td>32</td>
<td>4</td>
</tr>
<tr>
<td>FACE studies</td>
<td>9</td>
<td>13</td>
<td>19</td>
<td>6</td>
</tr>
</tbody>
</table>

¹ Data from only one year (Leakey et al., 2006)
Given this scenario, biotechnology and conventional breeding may help by developing new cultivars with enhanced traits better suited to adapt to climate change conditions. These include drought and temperature stress resistance; resistance to pests and disease; and tolerance of salinity and waterlogging. Breeding for drought resistance has historically been one of the most important and common objectives of several breeding programs for all the major food crops in most countries (Ceccarelli et al., 2007; Ceccarelli, 2010). Opportunities for new cultivars with increased drought tolerance include changes in phenology or enhanced responses to elevated CO₂. With respect to water, a number of studies have documented genetic modifications to major crop species (e.g. maize and soybean) that increased their water-deficit tolerance (Drennan et al., 1993; Kishor et al., 1995; Pilon-Smits et al., 1995; Cheikh et al., 2000), although this may not extend to a wide range of crops. In general, too little is currently known about how the desired traits achieved by genetic modification perform in real farming and forestry applications (Sinclair and Purcell, 2005).

Thermal tolerances of many organisms have been shown to be proportional to the magnitude of temperature variation they experience: lower thermal limits differ more among species than upper thermal limits (Addo-Bediako et al., 2000). Therefore a crop like barley, which has colonized a huge diversity of thermal climates, may harbor enough genetic diversity to breed successfully for enhanced thermal tolerance.

Soil moisture reduction due to precipitation changes could affect natural systems in several ways. There are projections of significant extinctions in both plant and animals species. Over 5 000 plant species could be affected by climate change, mainly due to the loss of suitable habitats. By 2050, the Fynbos Biome (Ericaceae-dominated ecosystem of South Africa, which is an International Union for the Conservation of Nature and Natural Resources (IUCN) ‘hotspot’) is projected to lose 51–61% of its extent due to decreased winter precipitation. The succulent Karoo Biome, which includes 2 800 plant species at increased risk of extinction, is projected to expand south-eastwards, and about 2% of the family Proteaceae is projected to become extinct. These plants are closely associated with birds that have specialized in feeding on them. Some mammal species, such as the zebra and nyala, which have been shown to be vulnerable to drought-induced changes in food availability, are widely projected to suffer losses. In some wildlife management areas, such as the Kruger and Hwange National Parks, wildlife populations are already dependant on water supplies supplemented by borehole water (Bates et al., 2008).

With the gradual reduction in rainfall during the growing season for grass, aridity in central and west Asia has increased in recent years, reducing the growth of grasslands and increasing the bareness of the ground surface (Bou-Zeid and El-Fadel, 2002). Increasing bareness has led to increased reflection of solar radiation, such that more soil moisture evaporates and the ground becomes increasingly drier in a feedback process, thus adding to the acceleration of grassland degradation (Zhang et al., 2003). Recently it has been reported that the Yangtze river basin has become hotter and it is expected that the temperature will increase by up to 2°C by 2050 relative to 1950 (Ming et al., 2009). This increase will reduce rice production by up to 41% by the end of the century and maize production by up to 50% by 2080.

The negative impact of climatic changes on agriculture and therefore on food production is aggravated by the greater uniformity that exists now, particularly in the crops of developed-country agriculture compared to 150–200 years ago. The decline in agricultural biodiversity can be quantified as follows: while it is estimated that there
are approximately 250,000 plant species, of which about 50,000 are edible, we actually use no more than 250—out of which 15 crops give 90% of the calories in the human diet, and 3 of them, namely wheat, rice, and maize, give 60%. In these three crops, modern plant breeding has been particularly successful, and the process towards genetic uniformity has been rapid: the most widely grown varieties of these three crops are closely related and genetically uniform (pure lines in wheat and rice and hybrids in maize). The major consequence is that our main sources of food are more genetically vulnerable than ever before, i.e. food security is potentially in danger. The danger has become real with the rapid spreading of diseases such as UG99, but applies equally well to climatic changes, as the predominant uniformity does not allow the crops to evolve and adapt to changing environmental conditions. The expected increase in biofuel monoculture production may lead to increased rates of biodiversity loss and genetic erosion. Another serious consequence of the loss of biodiversity has been the displacement of locally adapted varieties, which might hold the secret of adaptation to the future climate (Ceccarelli and Grando, 2000; Rodriguez et al., 2008; Abay and Bjørnstad, 2009).

**Combining participation and evolution: Participatory-Evolutionary plant breeding**

One of the fundamental breeding strategies to cope with the challenge posed by the climate changes is to improve adaptation to a likely shorter crop season length by matching phenology to moisture availability. This should not pose major problems as photoperiod-temperature response is highly heritable. Other strategies include increasing access to a suite of varieties with different duration to escape or avoid predictable occurrences of stress at critical periods in crop life cycles, shifting temperature optima for crop growth, and re-emphasizing population breeding.

In all cases, the emphasis will be on identifying and using sources of genetic variation for tolerance or resistance to a higher level of abiotic stresses, and the two most obvious sources of novel genetic variation are the genebanks (ICARDA has one of the largest genebanks, with more than 100,000 accessions of several species, including important food and feed crops such as barley, wheat, lentil, chickpea, and vetch) and farmers’ fields. Currently there are several international projects aiming at the identification of genes associated with superior adaptation to higher temperatures and drought; at ICARDA, but also elsewhere, it has been found that landraces, and when available wild relatives, harbor a large amount of genetic variation, some of which is of immediate use in breeding for drought and high-temperature tolerance.

The major difference between the two sources of genetic variation is that the first is static, in the sense that it represents the genetic variation available at the collection sites at the time the collection was made, while the second is dynamic, because landraces and wild relatives are heterogeneous populations and as such they evolve and can generate continuously novel genetic variation.

Adaptive capacity in its broadest sense includes both evolutionary changes and plastic ecological responses; in the climate change literature, it also refers to the capacity of humans to manage, adapt and minimize impacts (Williams et al., 2008). All organisms are expected to have some intrinsic capacity to adapt to changing conditions; this may be via ecological (i.e. physiological and/or behavioral plasticity) or evolutionary adaptation (i.e. through natural selection acting on quantitative traits). There is now evidence in the scientific literature that evolutionary adaptation has occurred in a variety of species in response to climate...
change, both in the long term, as seen earlier in the case of stomata (Woodward, 1987) or over a relatively short time, e.g. five to 30 years (Bradshaw and Holzapfel, 2006). However, this is unlikely to be the case for the majority of species and, additionally, the capacity for evolutionary adaptation is probably the most difficult trait to quantify across many species (Williams et al., 2008).

Recently Morran et al. (2009) have used experimental evolution to test the hypothesis that outcrossing populations are able to adapt more rapidly to environmental changes than self-fertilizing organisms, as suggested by Stebbins (1957), Maynard Smith (1978) and Crow (1992), explaining why the majority of plants and animals reproduce by outcrossing as opposed to selfing. The advantage of outcrossing is to provide a more effective means of recombination and thereby generating the genetic variation necessary to adapt to a novel environment (Crow, 1992). The experiment of Morran et al. (2009) suggest that even outcrossing rates lower than 5%, therefore comparable with those observed in self-pollinated crops such as barley, wheat and rice, allowed adaptation to a stress environments as indicated by a greater fitness accompanied by an increase in the outcrossing rates. This experiment, even though conducted on a nematode, is relevant for both self- and cross-pollinated crops and provides the expectations for evolutionary plant breeding, a breeding method introduced by Suneson more than 50 years ago working with barley (Suneson, 1956). Its ‘core features are a broadly diversified germplasm, and a prolonged subjection of the mass of the progeny to competitive natural selection in the area of contemplated use’. Its results showed that traits relating to reproductive capacity, such as higher seed yields, larger numbers of seeds per plant, and greater spike weight, increase in populations due to natural selection over time.

At ICARDA we are combining evolutionary plant breeding with participatory plant breeding (PPB), which is seen by several scientists as a way to overcome the limitations of conventional breeding, by offering farmers the possibility to choose, in their own environment, which varieties better suit their needs and conditions. PPB exploits the potential gains of breeding for specific adaptation through decentralized selection, defined as selection in the target environment (Ceccarelli and Grando, 2007).

The evolutionary breeding that ICARDA is combining with the participatory programs implemented in Syria, Jordan, Iran, Eritrea and Algeria aims at increasing the probability of recombination within a population that is deliberately constituted to harbor a very large amount of genetic variation. Such a population consists of a large mixture of nearly 1600 F1 lines of barley and is planted in 19 locations in the 5 countries where it is left evolving under the pressure of the changing climatic conditions. The breeder and the farmers will superimpose artificial selection with criteria that may change from location to location and with time. While the population is evolving, lines can be derived and tested as pure lines in the participatory breeding program, or a sub-sample of the population can be used for cultivation. The key aspect of the method is that the population is left evolving for an indefinite amount of time, thus becoming a unique source of continuously better adapted genetic material directly in the hands of the farmers. The latter guarantees that the improved material will be readily available to farmers without the bureaucratic and often inefficient systems of variety release and formal seed production.

**Conclusions**

The major danger when discussing the adaptation of crops to climate changes is that these discussions usually take place in comfortable offices isolated both from the outside climate and from the people who will be most affected by its changes.
By bringing back the analysis of the problems and the search for solutions to the thousands of small-scale and traditional family farming communities and indigenous peoples in the developing world that will be affected by climatic changes, by combining the indigenous agricultural knowledge systems with scientific knowledge, and by making use of the lessons from the past, we may be able to provide better adapted varieties that, together with appropriate agronomic techniques, could help millions of rural people to reduce their vulnerability to the impact of climate change.

References


maize are not affected by open-air elevation of CO₂ concentration in the absence of drought. *Plant Physiology*, 140: 779–790.


