CROP AND FORAGE GENETIC RESOURCES

International interdependence in the face of climate change

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Introduction

Efficient use of agricultural diversity and genetic resources of both crops and forages will be needed to maintain current levels of food production in the face of future challenges under future conditions. The world’s population is expected to grow to 9.1 billion by 2050, with increasing consumption of dairy and meat products (United Nations, 2005). This increased demand means that production will need to be increased without the option of increasing the amount of arable land. The added expected impacts of climate change suggest that we face worsening multiple challenges and decreasing options to address these challenges. Plant genetic resources for food and agriculture (PGRFA) will play a crucial role in providing the genes to help confront these challenges.

Considerable interdependence exists among the different agro-ecosystems. Clear examples are livestock systems that depend on fodder species that originate elsewhere as well as sites where crops are grown often but which are not their centres of diversity. The conservation and flow of genetic diversity between and within countries is therefore critical for sustaining livelihoods, but it will also be necessary to intensify production. However, the intensification of cropping systems often leads to genetic erosion (Heal et al., 2004). Currently, only some 150 plant species are now being cultivated, and mankind primarily depends on no more than 12 of these (Esquinas-Alcazar, 2005). Despite this reality, there are calls for diversifying agricultural production to adapt to climate change, to enhance nutritional security, and to service an increasingly complex global market for agricultural goods (Cavatassi et al., 2006; Cleveland et al., 1994; Reidsma and Ewert, 2008). Trade-offs between intensification, conservation and diversification further complicate decision-making processes.

PGRFA have been widely exchanged over the past 10,000 years among farmers and, recently, by collection, ex situ conservation, and use by research organizations. The
globalization of plant genetic resources is evident in the expansion of crops outside their centres of origin, with near global coverage of many crops whose origins were once geographically restricted (Vavilov, 1926). The global interdependence on PGRFA has given rise to policies to facilitate the access and exchange of plant genetic resources across the planet (Palacios, 1998). However, no comprehensive knowledge on the current and future interdependence on PGRFA exists in order to determine the degree to which policies need to be improved or maintained during the coming years.

Studies using a variety of approaches have tried to quantify the interdependence on plant genetic resources (see, for example, Palacios, 1998). It is important in the face of climate change to re-appraise interdependence and identify the changes in demand for PGRFA to help create policies to address future challenges. This chapter focuses on the effect that climate change will have on the international interdependence on PGRFA. Rather than quantify current demand, we look for evidence of how climate change might enhance, reduce or shift patterns of demand in the future. Analysis is based on literature review and numerical analysis of climate data. We structure the chapter in the following way: (1) review of current patterns of interdependence for PGRFA (to set the baseline); (2) review of the expected impacts of climate change on agriculture; (3) quantitative analysis of the changes in ‘climatic interdependence’ among countries for a number of crops; (4) discussion of likely changes in interdependence based on evidence from previous chapters; and (5) discussion of policy implications to address future interdependence patterns.

Current international interdependence on PGRFA: establishing the baseline

Virtually all countries depend on PGRFA that were originally found in other countries. Today’s improved varieties have resulted from innumerable crosses between materials from different countries (Zeven and De Wet, 1982). The globally popular Veery wheat, for example, is the product of 3,170 crosses involving 51 parents from 26 countries. In addition, many countries rely on non-indigenous crops and thus need to import germplasm to grow them. Countries in southern and central Africa rely on crops that originated outside the region for 50–100 per cent of their food, with the majority of these countries exceeding 80 per cent dependence on ‘foreign’ germplasm (Palacios, 1998). Such dependence never falls below 80 per cent in the Andean countries. Crops such as cassava, maize, groundnut and beans originated in South America but have become extremely important staples in sub-Saharan Africa. Cassava is a major food source for 200 million Africans in 31 countries, with a farm-gate value of over US $7 billion (FAO, 1997). And Africa – with its indigenous millets and sorghums – makes a considerable contribution to other areas such as South Asia (13 per cent) and Latin America (8 per cent) (Kloppenburg and Kleinman, 1987). In many cases, problems with disease and/or pest susceptible varieties have only been resolved by breeding resistant varieties using genetic diversity from other countries (National Research Council, 1972).

The case of forages is similar. Over 90 per cent of the major cultivated forage grasses in the world are indigenous to sub-Saharan Africa (Boonman, 1993). These
grasses have been used to improve extensive cattle pastures in Latin America. Several examples of the use of pastures in non-native environments exist, and the following are just a few.

- By 1996, over 40 million hectares were sown to *Brachiaria* in Brazil (Miles et al., 1996).
- Ruzi grass (*Brachiaria ruziensis*) was introduced into Thailand and is increasing in demand (Phaikaew et al., 1993).
- *Cenchrus ciliaris* is now grown in 31 countries (Cox et al., 1988), with four million hectares planted in the United States, over six million hectares in Mexico, and 7.5 million hectares in Australia (Humphreys, 1967).
- Other African grasses (for example, *Panicum maximum*, *Chloris gayana* and *Pennisetum purpureum*) are now also widely distributed throughout the tropics.
- Alfalfa (*Medicago sativa*) is extensively cultivated in the warm temperate, cool subtropical regions and tropical highlands and is native to southwest Asia. Today, it is the major forage legume crop, covering 79 million hectares worldwide, including 13 million hectares in the United States, where it is the third most important crop in value (Putnam et al., 2007).
- Vetch originated in the Near East and is now grown on close to one million hectares worldwide (FAOSTAT, 2009).
- Red and white clover (*Trifolium pratense* and *Trifolium repens* respectively) originated in Europe and North Africa and are now widely cultivated in subtropical areas in North America, southern South America, Australia and New Zealand.
- *Stylosanthes*, from Latin America, is now used in India (Ramesh et al., 2005), Thailand (Phaikaew and Hare, 2005) and Australia for improving pastures and producing leaf meal for monogastric feed.

Crop wild relatives provide researchers with genes that are useful for developing biotic and abiotic resistance (Maxted et al., 2008; Gurney et al., 2002; Lane and Jarvis, 2007). The use of crop wild relatives has increased dramatically over the past decade and will continue to increase thanks to biotechnology tools (Hajjar and Hodgkin, 2007). A number of crops such as sugar cane, tomatoes and tobacco could not be grown on a substantial commercial scale in countries that are for the most part far from the native habitats of their wild relatives were it not for the contribution made by these wild relatives to disease resistance (FAO, 1997). Current interdependence is therefore highly related to the extent to which PGRFA contributes to crop improvement for sustaining agriculture and food security, but it is also very dependent on environmental compatibility. The actual flow of PGRFA between countries and regions is difficult to monitor and so is the actual knowledge of their usefulness and importance. Hence, an actual quantification of the current interdependence needs to be done in order to improve policies and decision-making processes.
Climate change impacts on agriculture and PGRFA

Climate change will likely bring increases in temperature of between 2–6 degrees Celsius, both increases and decreases in precipitation and increased frequency of droughts and floods (IPCC, 2007). These changes will especially affect rain-fed agriculture, making adaptation necessary. Climate change will also impact agricultural biodiversity by increasing the genetic erosion of landraces (Mercer and Perales, 2010) and shifting wild species niches, including crop wild relatives (Jarvis et al., 2008). Severe pest outbreaks may increase with climate change, profoundly affecting agro-ecosystems and global food availability, although this also may vary geographically (World Bank, 2008).

Modelling indicates that yields from rain-fed agriculture in some regions of Africa could be reduced by up to 50 per cent by 2020 (Challinor et al., 2007; Fischer et al., 2001; IPCC, 2007). Food production and access in many African countries will likely be severely compromised, exacerbating food insecurity and malnutrition (IPCC, 2007). The most problematic areas are southern Africa, where land that is suitable for maize, the major staple, will likely disappear by 2050, and South Asia, where productivity of groundnut, millet, sorghum, wheat and rapeseed will be heavily reduced (Lobell et al., 2008).

Even under the most conservative of scenarios, climate change will cause shifts in suitable areas for cultivation of a wide range of crops. Changes will include a general trend of loss in suitable areas in sub-Saharan Africa, the Caribbean, India and northern Australia as well as gains in the northern United States, Canada and most of Europe for a number of staple crops (Fischer et al., 2002; Fischer et al., 2005; Lane and Jarvis 2007). Developed nations will see an expansion of suitable arable land to higher latitudes and a potential increase in production if those lands are brought under cultivation (Fisher et al., 2001). By the 2080s, rain-fed cereal production in the developing world could decrease by 3 per cent in negatively impacted countries and increase by 6 per cent in positively impacted countries. Production losses from climate change could worsen hunger in developing countries beyond the current level of one billion going hungry (FAO, 2008; Fischer et al., 2002).

Although farmers have always had to adjust and adapt their cropping systems to changing climatic and environmental conditions, the speed and complexity of current climate change poses problems on a much bigger scale (Adger et al., 2007). Rising temperatures and changing rainfall regimes will not decrease the global suitability for crops per se, but they will cause geographic shifts in suitable cropping areas. For certain areas, there is high likelihood that currently adapted crops will become mal-adapted (IPCC, 2007). The use of plant genetic resources is thus critical for the improvement of the resilience of crop varieties and the sustainability of the production of agricultural goods. New within-crop diversity and/or different and better-adapted crops will be needed to respond to future conditions. The negative impacts of climate change can be mitigated if farmers can adapt by changing to more suitable varieties and, if necessary, crops (Lane and Jarvis, 2007). Barriers to such adaptation, however, are discussed in the following sections of this chapter.

The areas that are currently most food-insecure will be most affected by climate change. These areas have the greatest need for new crops and varieties that are...
tolerant to extreme conditions, such as drought, heat, flooding, submergence and salinity. The need for adapted germplasm will require the characterization, evaluation and availability of germplasm. Some of the more important traits to be found in varieties and genotypes for responding to climate change include: drought tolerance, extreme events tolerance, resistance to very hot and humid conditions and pest and disease resistance. Most of these traits are present in traditional cultivars or wild species. Unfortunately, with modern crop intensification, many such traditional varieties have become under-utilized and, in certain instances, lost completely (Shewayrga et al., 2008; van Heerwaarden et al., 2009; Chaudhary et al., 2004; Hammer et al., 1996; Parzies et al., 2000). The US Department of Agriculture indicates that out of the 7,098 apple varieties that were in use between 1804 and 1904, 86 per cent have been lost. Similarly, 95 per cent of cabbage, 91 per cent of maize, 94 per cent of pea and 81 per cent of tomato varieties no longer exist (Fowler, 1994). Agricultural expansion also accounts for wild habitat loss and for the genetic erosion of many wild gene pools that could provide both biotic and abiotic resistances for traditional and modern crop varieties (FAO, 1998). Most of the raw materials for adaptation are likely to be found only in gene banks, and while some gene banks lack appropriate characterization and distribution mechanisms, most of the genetic resources that are useful for adaptation remain inaccessible to the world.

Genetic erosion is likely to increase due to changes in the climate system. Recent changes in the climate system have already led to shifts in species distributions (Chen et al., 2009; Parmesan and Yohe, 2003; Root et al., 2003). The magnitude of these changes includes potential extinctions, and it is likely to increase with the growing levels of climate change (Carnaval and Moritz, 2008; IPCC, 2007; Nogués-Bravo et al., 2008; Thomas et al., 2004). Many ecosystems are projected to become more depauperate, and many communities are projected to start unravelling as the ecology of individual species is affected by the changing climate at different rates (IPCC, 2007). Many of these ecosystems hold several wild species, which in some cases are not properly conserved either in situ (Bass et al., 2010; Kim and Byrne, 2006) or ex situ (Ramirez et al., 2010).

The Food and Agriculture Organization (FAO) estimates that a large proportion of the gene pool of the major crops has been sampled and placed in ex situ collections. Much of the diversity found in farmers’ fields today, and a great amount of diversity that no longer exists on-farm, can now be accessed solely through gene banks (Fowler and Smale, 2000). However, improved mechanisms of in situ conservation are required in order to maintain evolutionary dynamics. In situ conservation has the advantage of maintaining interactions between species and is therefore also likely very important for maintaining evolutionary dynamics. However, its implementation typically involves traditional farming communities, indigenous territories and/or protected areas whose monitoring can be very difficult in some cases. One proposed approach is the preservation of a number of valuable crop species and varieties in selected areas of traditional agriculture (Brush, 2000). One example of this approach is the Globally Important Agricultural Heritage System Initiative (CGRFA, 2000). Conservation of forests and pristine sites valued for their wildlife or ecological value is
a means to achieve the in situ conservation of wild species and wild crop relatives. However, to date, no inventories exist on how many crop wild relatives might be preserved in situ, turning the issue of the in situ conservation of crop wild relatives into a more complicated issue.

Forages, however, are a different case, and they are more vulnerable to land use change than other crops. Forages in small-hold systems in the tropics are often intercropped and planted around fences or used in crop fallow periods or for vegetation on degraded lands, where competition for crop land, water and fertile soil are high and resources are limited. Climate change will require new management options and the use of alternative forage species or the increased use of existing forages in many areas. Use of specific forage species in small-hold livestock systems is limited by the length of the growing season and temperature (Cox et al., 1988; Thornton et al., 2006b). The predicted temperature increases of 2–6 degrees Celsius by the end of the century in Africa could cause the spread of tropical species from countries in other agro-ecological regions into new environments where water is not the limiting factor (Collier et al., 2008; Hoffman and Vogel, 2008; IPCC, 2007). Many of the important forage grasses, including Napier, Rhodes and Brachiaria, are not frost tolerant. As temperatures increase and the likelihood of frost decreases, these tropical species could be introduced into sub-tropical regions, including the tropical highlands.

Changes in climate in Africa are predicted to be more severe than in other regions (Collier et al., 2008; IPCC, 2007). Impacts will be substantial on the use of cultivated forages and on indigenous forage diversity in grasslands and natural pastures. Some areas of East Africa are predicted to receive 10–20 per cent more rainfall (Collier et al., 2008). Current grazing or marginal lands may be converted to crops, leading to the loss of forage diversity and to increasing degradation. Climate change could also allow (or suggest) the introduction of species from Latin America such as Centrosema and Stylosanthes guianensis, which are adapted to sub-humid areas. In areas that are predicted to get drier, continued cropping can result in more rapid degradation through the loss of land cover. The use of drought tolerant forages in these areas, such as buffel grass or Stylosanthes scabra, could, on the other hand, increase soil cover and reduce soil degradation (Batjes and Sombroek, 1997). Appropriate adaptation strategies need to be developed on a site-specific basis and transferred appropriately to analogous areas.

The importance of grasslands increases under the context of climate change, particularly for mitigation. Natural grasslands act as an important carbon sink (Morgan, 2005). However, increasing levels of carbon dioxide will increase overall biomass production and may result in reduced forage quality and digestibility due to lignification (Thornton et al., 2006a). Changes in the level of carbon dioxide could result in changes in species richness in natural pastures because some legumes are more responsive to increased levels of carbon dioxide as a result of biological nitrogen fixation (Aguiar, 2005). As a result, shifts in particular areas due to climate change will lead to changes in both the distribution of wild species and grasslands, producing a complex mixture of responses that could lead (in some cases, at best) to a substantial degradation of genetic resources.
Numerical analysis of the changes in climatic similarity between countries for selected crops (methods and results)

We performed a numerical analysis of the effect of climate change predictions on crop distributions to identify the extent to which climate change will impact climatic compatibility of genetic resources among countries. We analysed the climatic similarity between countries under current and future conditions and interpreted it as a proxy for genetic resource interdependence. We assumed that both crop distributional ranges and climatic compatibilities at the same time could provide an indication of whether similar PGRFA can be used in two sites, regardless of how much actual exchange has occurred between these two sites in the recent past. Mining current and future climates and detecting interdependencies between current and future climates, we identified the potentially useful links between countries today and in the future and determined whether interdependencies play (or could play) an important role in both the conservation and utilization of plant genetic resources now and in the future.

We selected 17 staple food and cash crops that account for 75 per cent of the global harvested area (FAOSTAT, 2009). There were a number of different climatic responses within these crops because they cover a range of different ecologies. Crops included cereals (that is, wheat, maize, millet, rice, sorghum and barley), legumes (that is, beans, groundnuts and soybeans), roots and tubers (such as potatoes, sugar beets, sweet potatoes and cassava), fruit (bananas and plantains), fibres (cotton), and high value industrial and cash crops (such as sugarcane and coffee). ‘Climatic similarity’ was described in terms of the following four dimensions:

1. current climatic similarities among countries (the baseline);
2. climatic similarity between countries in the future, which shows the likely changes in interdependence with respect to the baseline;
3. climatic similarity between each country’s current conditions and future conditions, which provides the extent to which the current climate upon which agriculture is built and for which genetic resources are adapted could be important for the future of other countries; and
4. climatic similarity between each country’s future conditions and current conditions, which provides the extent to which a country in the future could depend on other countries for genetic resources conserved presently.

A set of metrics (described later on) are used to assess each of these dimensions. Both dimensions (3) and (4) include the concept of self-dependence, which is useful to investigate the likelihood of a country being able to hold the necessary genetic resources for its own adaptation. The analysis looks at the similarity between countries for these four situations with respect to each of the 17 crops under study. Current harvested areas of each crop were used to define the production environments for each crop within each country (FAOSTAT, 2009). The extent of each crop within each country of the world was determined using a spatial allocation model (You and Wood, 2006; You et al., 2006). For each country and for cropped lands (per crop)
within each country, the current distribution of climates was derived from WorldClim (Hijmans et al., 2005). We downloaded monthly minimum, maximum and mean temperatures as well as monthly total rainfall gridded datasets at 30 arcs per second (approximately 1 kilometre in the Equator) and used them to derive 19 bioclimatic indices (Busby, 1991). The average of all cells within a country was taken as the country’s current climate.

Future climates were derived from the results of 18 global circulation models (GCMs) from the third and fourth IPCC assessment reports (IPCC, 2001, 2007) for the decade beginning 2050 and for the Special Report on Emission Scenarios (SRES) A2 emission scenario (business as usual). GCM minimum, maximum and mean monthly temperatures and total monthly precipitation outputs were downscaled using the delta method and were used to derive the same 19 bioclimatic indices as for current climate (Ramirez and Jarvis, 2008, 2010). The average of all cells within each country was again taken as an indicator of the country’s future climate.

For each crop’s distributional range, the 19 bioclimatic indices were standardized to have a mean of 0 and a standard deviation of 1. Three 19-dimensional Euclidean distance (ED) matrices of n-by-n (n varying on a crop basis) countries were computed:

1. ED between current climates to measure the current climatic compatibility between countries;
2. ED between future climates to measure the likely change in climatic similarity between countries and determine whether current compatibilities are to be preserved or lost in the future; and
3. ED between current and future (and vice versa) climates to determine opportunities for sharing genetic resources from one period to the other and from one country to the other.

Both matrices (1) and (2) provide a geographical perspective of the potential links between countries, and (3) provides both a geographical and temporal perspective of the potential links that can be established between countries. Since all of the variables were standardized, the ED is a non-dimensional and scale-independent measure. Therefore, direct comparisons between countries, crops and periods can be done with no bias.

With the aim of (1) investigating the likely changes in self-dependence; (2) comparing interdependencies of one country with the others; (3) investigating the relevance of current and future potential links; and (4) detecting key potential links in the future that are not suspected currently, we calculated a range of metrics aiming to provide a numerical basis for interpreting the results:

- average ED under current conditions (AEDC) – the ED assessed using current conditions for each pair of countries averaged on a country basis;
- average ED under future conditions (AEDF) – the ED assessed using future conditions for each pair of countries averaged on a country basis;
- average change in country self-dependence (ACCSD) – the average changes in ED for each country and its future;
• average change in country inter-dependence (ACCID) – the average changes in ED between each country and all of the others;
• average current-future (ACFI) and future-current (AFCI) interdependence – the average ED from one country’s current climates to future climates of all of the others and vice versa;
• number of gained (NGR) and lost (NLR) relationships – country rates of gained and lost climatic similarities; and
• new key climatic similarities (NNKS) – number of key climatic similarities that may arrive within the context of each crop when climatic conditions change.

Despite the above specifics, metrics are not reported given the number of countries and crops analysed here. Instead, we provide a summary of our findings. Our analysis shows that the current climatic similarity among countries for all crops was high. Regions were not only capable of providing genetic resources to other regions and importing/exporting food crops to supply the basic needs of their populations, but they also showed high climatic similarity. Indeed, they were probably able to provide genetic resources because of their climatic similarity. On average, a country’s croplands was significantly similar to more than 80 per cent of other countries’ croplands for all crops. Globally, 116 out of the 188 countries (62 per cent) analysed will likely decrease their ACCID, indicating an increased similarity among the global areas of these countries (see Table 4.1 and Figure 4.1). Of the remaining 38 per cent of countries, 94 per cent will likely increase their ACCID by only less than 5 per cent. For all crops, the similarities are likely to strengthen for more than 40 per cent of countries (with sugar beets showing the most similarity at 91 per cent and cassava showing the least at 41 per cent). Generally, moist environments are more likely to increase in climatic similarity, although no significant latitudinal trends were found as there were no separations among individual countries of different geographic areas (that is, Europe, sub-Saharan Africa, Latin America and Australia) (see Figure 4.1a).

Considering the entire area of the country and pooling results by region, climatic similarity is likely to increase with changing climates. On average, all regions showed reduced Euclidean distances in 2050s, with North America presenting the greatest decrease and Latin America presenting the least decrease. These values, however, may disguise a lot of variation within the country. Country self-distances (distance from a country’s current position to its future position) are the greatest for North Africa and North America, indicating a lower level of climatic similarity than in regions such as the Caribbean, where countries are relatively climatically similar (see Figure 4.1).

Although the ACCID ranged from between minus 24 per cent (Faroe Islands) and 54 per cent (Grenada), 97 per cent of the countries presented ACCID between 10 and minus 10 per cent. For 11 per cent of the countries (that is, Serbia and Montenegro, United Arab Emirates, Sweden, Romania, Macedonia, Lithuania, Iran, Iceland, Grenada, Georgia, France, Faroe Islands, Egypt, Canada, Bulgaria, Bosnia, Belgium and Azerbaijan), changing climate conditions were found to add at least one key link that was even closer than they would be themselves in the future.
## TABLE 4.1 Likely changes in interdependence for 17 crops globally for 2050

<table>
<thead>
<tr>
<th>Crop</th>
<th>A1</th>
<th>Decreases in ED (%)</th>
<th>Change in ED (%)</th>
<th>Maximum loss of interdependence</th>
<th>Maximum gain of interdependence</th>
<th>% Countries with key current actors to take PGR for future</th>
<th>% Analogues that may be more important</th>
<th>% Analogues that may appear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bananas*</td>
<td>Y</td>
<td>52.4</td>
<td>−0.12</td>
<td>Solomon Islands</td>
<td>Pakistan</td>
<td>2.9</td>
<td>53.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Barley</td>
<td>Y</td>
<td>70.4</td>
<td>−0.65</td>
<td>Finland</td>
<td>Yemen</td>
<td>16.8</td>
<td>69.6</td>
<td>5.6</td>
</tr>
<tr>
<td>Beans</td>
<td>Y</td>
<td>59.7</td>
<td>−0.31</td>
<td>Colombia</td>
<td>Saudi Arabia</td>
<td>14.2</td>
<td>67.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Cassava</td>
<td>Y</td>
<td>40.6</td>
<td>0.33</td>
<td>Solomon Islands</td>
<td>Guyana</td>
<td>0.0</td>
<td>40.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Coffee</td>
<td>N</td>
<td>55.3</td>
<td>−0.21</td>
<td>Kazakhstan</td>
<td>Yemen</td>
<td>1.2</td>
<td>49.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Cotton</td>
<td>N</td>
<td>45.4</td>
<td>0.08</td>
<td>Uganda</td>
<td>Saudi Arabia</td>
<td>8.3</td>
<td>65.7</td>
<td>2.8</td>
</tr>
<tr>
<td>Groundnut</td>
<td>N</td>
<td>90.2</td>
<td>−2.73</td>
<td>Iraq</td>
<td>Yemen</td>
<td>30.1</td>
<td>74.0</td>
<td>15.4</td>
</tr>
<tr>
<td>Maize</td>
<td>Y</td>
<td>57.4</td>
<td>−0.23</td>
<td>Solomon Islands</td>
<td>Yemen</td>
<td>9.7</td>
<td>60.6</td>
<td>1.3</td>
</tr>
<tr>
<td>Millet</td>
<td>Y**</td>
<td>86.4</td>
<td>−2.99</td>
<td>Germany</td>
<td>Albania</td>
<td>42.1</td>
<td>73.9</td>
<td>22.7</td>
</tr>
<tr>
<td>Potatoes</td>
<td>Y</td>
<td>68.8</td>
<td>−0.65</td>
<td>Finland</td>
<td>Oman</td>
<td>13.6</td>
<td>66.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Rice</td>
<td>Y</td>
<td>52.2</td>
<td>−0.16</td>
<td>Iraq</td>
<td>Somalia</td>
<td>8.8</td>
<td>59.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Sorghum</td>
<td>Y</td>
<td>63.3</td>
<td>−0.34</td>
<td>Peru</td>
<td>Oman</td>
<td>10.2</td>
<td>67.2</td>
<td>2.3</td>
</tr>
<tr>
<td>Soybeans</td>
<td>N</td>
<td>46.8</td>
<td>0.07</td>
<td>Colombia</td>
<td>Turkmenistan</td>
<td>12.1</td>
<td>66.9</td>
<td>2.4</td>
</tr>
<tr>
<td>Sugar beets</td>
<td>Y</td>
<td>61.1</td>
<td>0.27</td>
<td>Finland</td>
<td>Uzbekistan</td>
<td>31.5</td>
<td>90.7</td>
<td>27.8</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>N</td>
<td>43.6</td>
<td>0.04</td>
<td>Colombia</td>
<td>Turkmenistan</td>
<td>6.4</td>
<td>52.7</td>
<td>4.5</td>
</tr>
<tr>
<td>Sweet potatoes</td>
<td>Y</td>
<td>41.9</td>
<td>0.12</td>
<td>Bhutan</td>
<td>Saudi Arabia</td>
<td>1.7</td>
<td>51.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Wheat</td>
<td>Y</td>
<td>74.0</td>
<td>−1.15</td>
<td>Finland</td>
<td>Yemen</td>
<td>42.0</td>
<td>83.2</td>
<td>22.9</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>61.7</td>
<td>−0.25</td>
<td>Faroe Islands</td>
<td>Grenada</td>
<td>11.7</td>
<td>69.1</td>
<td>3.7</td>
</tr>
</tbody>
</table>

**Notes:** * bananas and plantain  
** Pearl millet: Y, finger millet: Y, any other millet: N
On the other hand, 98 per cent of the countries have ACFI that is lower than their AEDC, meaning that they are closer to most other countries’ future conditions than they are to these countries’ current conditions. While 76 per cent of the climatically ‘far’ countries (that is, those presenting very high AEDC) will decrease their ED with some countries (thus, will become more similar to at least one country), 52 per cent presented the opposite pattern. However, significant within-country variability is still

FIGURE 4.1 Overview of changes in interdependence: (a) Changes in interdependence within country land areas. Self-distance (X axis) is the ED between each country’s current and its future conditions and average distance (Y axis) is the average ED between the country’s current climates and all of the others’ future climates. (b) Average changes in ED pooled by continental zone (Y axis) confidence interval versus the average distance between current and future climates of each country plus a 95 percent confidence interval, pooled by continental zone (X axis)
present within these figures due to the different orographic and landscape features of the various countries.

There are different observed trends in crop-based climatic interdependence. The proportion of countries increasing their ‘closeness’ (that is, ACCID < 0) is above 50 per cent for 12 of the 17 crops considered (see Figure 4.2), and the average ED decreases (that is, AEDF < AEDC) for 11 out of the 17 crops (such as bananas, barley, beans, coffee, groundnuts, maize, millets, potatoes, rice, sorghum and wheat). Cassava was the only crop for which no country showed a closer analogy than itself. Wheat, maize and millet showed 42, 30 and 42 per cent of their current country-level cropping environments under analysis being nearer to at least one other future cropping environment respectively. This outcome may indicate that environments included in these percentages may have at least one key country with which they should consider reviewing existing and past flows of plant genetic resources and that strengthening their current treaties with such countries could improve their current levels of PGRFA conservation and utilization.

Coffee had the least distance from current to future environments, probably due to strong climatic specialization. ACFI values for all crops, however, occurred within quite a small range (from 5.3 to 5.9). Most of the changes in the different environments of crops are near to the total area, suggesting that all of these crops hold relatively similar patterns of interdependencies and that their environments may be relatively similar now and in the future. Cassava, coffee, sugar beets and sweet potatoes from one side, and wheat, millet and groundnuts from the other are the only crops that showed significant differences in behaviour in comparison with the other crops.
Loss of similarity occurs when a cropping environment moves further away from all of the climates of other countries (that is, AEDF > AEDC). The environments of grain legumes (that is, beans and soybeans) are predicted to reduce their overall average climatic similarity (that is, ACCID > 0) in Latin American countries with croplands in the Andes, signifying that these countries tend to become more ‘climatically’ isolated and very likely to require very specific germplasm for adaptation to future conditions. Cold environments such as those in Finland are also likely to lose climatic similarity in their croplands. Finland is actually the most frequent ‘loser’ (of climatic similarity) in the whole world for the selected set of crops (that is, the country presenting an ACCID > 0 most frequently). On the other hand, Asian countries tend to increase their climatic similarity (that is, ACCID < 0) at greater rates than other countries (Table 4.1, Figure 4.1a), which may be due to their sub-tropical conditions and different within-region climate change patterns. The same thing happens in some sub-Saharan African countries such as Somalia and others nearby, especially in rice cropping. All of these results indicate that Asia and certain countries in sub-Saharan Africa could take more advantage of strengthened and globalized treaties for sharing PGRFA.

Novel climate conditions (that is, conditions not observed in any country under current conditions) appear in all of the current croplands except for cassava, coffee, rice and sweet potatoes. This outcome may be due either to a very high similarity in current conditions (that is, specialization of cropping environments) or because they are cropped in countries that become ‘climatically isolated’, or both. All cropping environments of all of the crops analysed show a significant number of areas (that is, > 30 per cent), with any other current-future and/or future-future ED being less than their self-future ED – meaning there is another place that is more compatible for them than their own place. The fact that the rates of lost interdependencies are far less significant than the rates of gained or strengthened dependencies should be also taken into account when analysing the patterns of exchange of future potential PGRFA. For all crops, at least 30 per cent of the cropping environments have lost climatic similarity with at least one other country. Due to the significant climatic and orographic variability within some countries, specific analyses within different cropping environments are required to further develop a collaborative and dynamic network that will allow fluxes of relevant genetic materials from one country to another.

**Expected changes in interdependence as a result of climate change**

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

1. Novel climatic conditions for countries will mean that currently adapted landraces and varieties may become maladapted, requiring the import of new materials with novel and more appropriate traits. The identification of environments from which these materials can be imported is therefore critical for adaptation.
2. Climate change will bring about new types of and increased demand for PGRFA globally, requiring greater volume and variety of genetic materials. Identifying the
appropriate channels through which these resources might flow from one country to the other will facilitate the utilization and conservation of PGRFA and will thus aid adaptation.

Almost 35 per cent of the global land area may experience ‘novel climates’ – essentially climatic conditions that are currently not experienced anywhere – and the geography of the world’s climate may shift significantly (Williams et al., 2007). In regard to agriculture, temperatures in the growing season in 2100 in the tropics and sub-tropics are likely to be hotter than experienced over the past century, particularly in the highlands, where cropping areas are more reduced and are subjected to other constraints. Current local planting materials are unlikely to withstand such conditions (Battisti and Naylor, 2009). In summary, our numerical analysis shows that, globally:

- regions are able to provide genetic resources because of their climatic similarity and/or compatibility with other regions;
- similarity among global areas will increase;
- some 30 per cent or more of the countries will benefit more from other countries’ PGRFA than from their own PGRFA;
- 98 per cent of the countries will increase their average climatic compatibility;
- 76 per cent of the currently climatically ‘isolated’ countries will become more similar to at least one other country;
- more than 50 per cent of the countries for 70 per cent of the crops analysed will become more interdependent; and
- at least 30 per cent of the cropping environments will lose at least one potential key link.

Between regions and countries:

- increased compatibility by 2050s was observed, with North America being the most benefited and Latin America the least benefited;
- large regions (e.g., North Africa and North America) tend to have lower climatic similarity compared to relatively small areas (e.g., the Caribbean);
- Serbia and Montenegro, United Arab Emirates, Sweden, Romania, Macedonia, Lithuania, Iran, Iceland, Grenada, Georgia, France, Faroe Islands, Egypt, Canada, Bulgaria, Bosnia, Belgium and Azerbaijan will have a key link with another country that is even closer than themselves in the future;
- Andean countries and high-latitude countries (that is, Finland) will become more ‘climatically isolated’; and
- climate and climate change geographical variability is high among regions and within them, and this factor will lead to the need for more site-specific analyses.
Crop level:

- similar ecologies often mean similar patterns of changes in interdependencies;
- adaption to climate change and flows of PGRFA between countries and regions might depend on both shifts of species distributions, land use changes and current and future conservation actions;
- sugar beet farmers would benefit the most from improved future PGRFA exchange mechanisms and cassava farmers the least;
- all areas cropped under cassava, coffee, rice and sweet potato will not present any ‘novel climate’ (a climate not existing currently). In fact, cassava was the only crop for which no country showed a closer analogy than the current;
- bananas, barley, beans, coffee, groundnuts, maize, millet, potatoes, rice, sorghum and wheat environments are more compatible in the future than they are currently;
- coffee was the most climatically specialized (and isolated) crop; and
- 42, 30 and 42 per cent of the environments where wheat, maize and millet are cropped (respectively) may need to review existing and past flows of plant genetic resources and strengthen their current treaties with at least one other country.

Developing countries have provided the biological basis for agriculture both in developed countries and for each other (Fowler and Smale, 2000). The dimension and direction of flow of PGRFA (for example, south to south and north to south) is notoriously difficult to track, monitor and quantify. The limited information available on flows seems to indicate that we are in a period of reverse flow in which material is no longer exported from its centres of origin. Rather, the opposite is occurring: farmers and research institutes in the developing world have become net recipients of both local varieties and of improved materials (Fowler and Smale, 2000; Visser et al., 2003). The quantification of PGRFA flows and utilization is needed in order to revise current projects and develop future actions.

M.B. Burke, D.B. Lobell and L. Guarino (2009) found that shifts in crop climates (that is, of maize, millet and sorghum) leading up to 2050 indicate that many countries will experience novel climates not currently found within their borders in 2050 and that 75 per cent of these will have analogues in at least five other countries. Our figures confirm that these crops are likely to present novel climates. The international movement of germplasm is essential to enable adaptation (ibid.). Overall, crops will become maladapted in the face of climate change (Lobell et al., 2008). Given the speed of climate change, farmers will most likely be unable to adapt rapidly enough through traditional selection practices (Burke et al., 2009). What will be needed is the facilitated exchange of exotic varieties and landraces from analogous sites elsewhere.

Thus, climate change will bring new and enhanced demand for genetic resources in order for farmers to adapt to the new climatic situation. National and international breeding programmes for a number of crops are already targeting new varieties with adaptations for future climatic stresses (see, for example, Ortiz et al., 2008), including heat, drought and waterlogging tolerance. In addition, 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 the genetic resources of crop wild relatives to address biotic and abiotic constraints, many of which are being exacerbated by climate change (Lane and Jarvis, 2007). While demand for such genetic resources is global, their natural distribution is generally restricted. For example, no wild relatives of the cultivated peanut exist outside Brazil, Paraguay, Bolivia, Uruguay or Argentina (Ferguson et al., 2005; Jarvis et al., 2003). The increased demand for these resources implies increased interdependence among countries, possibly encouraging a greater flow of germplasm from south to north since many centres of origin occur in the south (Fowler and Smale, 2000). The opposite can occur for beans or maize, for which the centres of diversity are in the northern hemisphere (that is, in Mexico and the United States). Since crop wild relatives are poorly conserved in *ex situ* collections (Ramirez et al., 2010), policies must facilitate the access to wild gene pools through targeted collection to fill specific gaps (Maxted et al., 2008; Maxted and Kell, 2009; Ramirez et al., 2010).

Biotechnology will also affect the demand for PGRFA. On the one hand, new tools and methods 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. Although increased demand for new varieties to confront climate change will rely heavily on biotechnology, it is difficult to foresee the outcome of these developments on interdependence (Hajjar and Hodgkin, 2007; Ortiz et al., 2008).

Climate change may also increase the importance of otherwise minor or under-utilized crops and plant species. These include species suitable for biofuel production (biodiesel, ethanol and second and third generation biofuel technologies) as well as 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.

**Conclusions**

This chapter has reviewed the interdependence of PGRFA and discussed how climate change might change interdependence patterns and levels. The numerical analysis of climatic similarity is presented as a proxy for potential genetic resource interdependence. The analysis shows that similarity between countries will be greater for 75 per cent of the global croplands. Regardless of the level of ecological specialization of a crop, there will be a significant shift in the climates of these crops, which may bring novel climates that are often nearer to the current climates of other countries (that is, 98 per cent of countries increase their climatic compatibility, and 76 per cent of the crops present novel climates). The exchange of PGRFA among countries will thus continue as a key issue in the face of climate change, although some changes in the mechanism may be required (that is, a clear definition of the key providers and key receivers). Although some special cropping environments will decrease their climatic similarity, the gaining and strengthening rates will markedly overcome climatic
interdependence loss rates in all regions and crops. There will, therefore, be sig-
nificant opportunities for setting collaborative networks to conserve, characterize, 
 improve and share PGRFA. There is high likelihood of a change in the types of 
demand for PGRFA in the future and a likely increase in overall demand.

Changes in the types of demand are expected in the following ways:

- an increased demand for PGRFA with characteristics that will help adapt agriculture 
to future climates (heat, drought and waterlogging-tolerant materials, among others);
- an increasing demand for crop wild relatives to address biotic and abiotic 
constraints; and
- an increased demand for ‘minor’ crops (including neglected and under-utilized 
crops) that might help communities adapt to climate change in marginal envir-

onments and/or contribute to climate change mitigation through biofuel or a 
similar combustible.

Increases in demand are expected for the following reasons:

- shifting geography of climate, leading to shifts in crop distribution among and 
within countries;
- the appearance of globally and regionally novel climates making locally adapted 
genetic resources less suitable or no longer suitable beyond the next 20–30 years; and
- increasing global population and expected negative impacts of climate change on 
agriculture, leading to more and more need for new seed technologies to produce 
more food in less area with greater water productivity.

Facilitated access to PGRFA will be needed. While facilitated access and benefit shar-
ing exists for Annex 1 crops from the International Treaty for Plant Genetic Resources 
for Food and Agriculture, there are few options for benefit sharing of non-Annex 1 
crops.1 Twelve of the crops we analysed are in Annex 1 (that is, bananas, barley, 
beans, cassava, maize, millet, potatoes, rice, sorghum, sugar beets, sweet potatoes and 
wheat). Exclusions include major staples (including some of those studied in this 
chapter’s climatic similarity analyses such as groundnut, soybeans and coffee), 
numerous forage species, crop wild relatives, and many minor and/or neglected and 
under-utilized crops. Thousands of farmers depend on these non-Annex 1 crops, and 
adaptation to climate change without a facilitated exchange of genetic resources will 
be difficult. A more facilitated germplasm exchange for these crops would enable 
ex situ conservation through new collecting (conservation status is incomplete for 
many of these crops and species) and would make the genetic resources themselves 
available for countries to adapt to the future challenges of climate change.

Note

1 International Treaty on Plant Genetic Resources for Food and Agriculture, 29 June 
References


