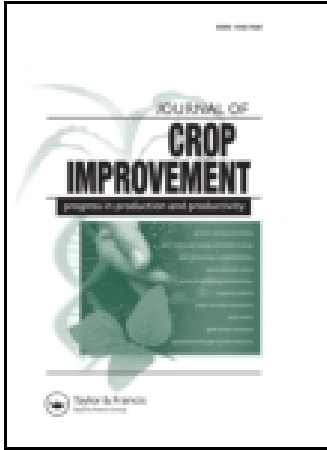


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Jon Hellin^a, Mauricio R. Bellon^b & Sarah J. Hearne^a

^a International Maize and Wheat Improvement Center (CIMMYT), Texcoco, Mexico

^b Bioversity International, Rome, Italy

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Maize Landraces and Adaptation to Climate Change in Mexico

JON HELLIN¹, MAURICIO R. BELLON², and SARAH J. HEARNE¹

¹*International Maize and Wheat Improvement Center (CIMMYT), Texcoco, Mexico*

²*Bioversity International, Rome, Italy*

*Mexico is the primary center of origin and diversity for maize (*Zea mays L.*). Farmers grow the crop largely under rain-fed conditions. Mexico is at considerable risk from climate change because of predicted rising temperatures, declining rainfall, and an increase in extreme weather events. Small-scale maize farmers are particularly vulnerable because of their geographical location as well as their limited adaptive capacity. Recommended climate change adaptation strategies include farmers' increased use of heat and drought stress-tolerant maize. Farmer adoption of improved germplasm has been disappointing because of inefficient seed input chains and farmers' preference for landraces for culinary, agronomic, and cultural reasons. Scientists have tended to overlook the fact that maize landraces have a critical role to play in climate change adaptation. Landraces may already exist that are appropriate for predicted climates. Furthermore, within the primary gene pool of maize and its wild relatives there exists unexploited genetic diversity for novel traits and alleles that can be used for breeding new high yielding and stress-tolerant cultivars. The breeding component of adaptation strategies should focus more on improving farmers' landraces. The desired result would be a segmented maize seed sector characterized by both (improved) landraces and improved maize varieties. The public and private sector could continue to provide farmers with improved maize varieties and different actors, including farmers themselves, would generate seed of improved landraces for sale and/or exchange.*

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© Jon Hellin, Mauricio R. Bellon, and Sarah J. Hearne

Address correspondence to Jon Hellin, International Maize and Wheat Improvement Center (CIMMYT), Apartado Postal 6-641, Texcoco 06600, Mexico. E-mail: j.hellin@cgiar.org

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IMPACT OF CLIMATE CHANGE ON AGRICULTURE

Climate change is likely to lead to increased water scarcity in the coming decades (Hendrix et al. 2007; Lobell et al. 2008) and changes in patterns of precipitation. Climate change is also likely to lead to an increase in temperature. Climate models show a high probability (>90%) that by the end of the 21st century, growing season temperatures will exceed the most extreme seasonal temperatures recorded in the past century (Battisti and Naylor 2009). While an increase in temperature of a few degrees is likely to increase crop yields in temperate areas, in many tropical areas, even minimal increases in temperature may be detrimental to food production (Lobell and Burke 2008). High temperatures reduce crop yields by affecting an array of physiological, biochemical, and molecular processes.

While it is true that farmers have a long record of adapting to the impacts of climate variability, predicted climate change represents an enormous challenge that will test farmers' ability to adapt and improve their livelihoods (Adger et al. 2007). Scientific research points to the negative impacts of climate change on small-scale farmers. This is especially the case in developing countries (Jones and Thornton 2003; Fischer et al. 2005; Morton 2007). A scenario of rising temperatures, declining rainfall, increase in extreme weather events, and shifting pest and disease patterns will lead to more short-term crop failures and long-term production declines (Lobell et al. 2011; Kang and Banga 2013; Chauhan et al. 2014). Until recently, the impacts of climate change had largely been regarded as a problem for the future; however, a key finding of The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) is that climate change impacts on food security are happening now (Vermeulen 2014).

The resulting decline in global per capita food production will threaten future food security (Brown and Funk 2008). There are also gloomy predictions of how environmental crises will affect global security (e.g., Raleigh and Urdal 2007). Through direct effects on livelihoods, climate change may under certain circumstances increase the risk of violent conflict. The environmental problems associated with climate change could also force a greater number of people to migrate to more favorable areas (Adger et al. 2003; Feng et al. 2010), leading in some cases to conflict in receiving areas; the arrival of "environmental migrants or refugees" can burden the economic and resource base of the receiving area, promoting native-migrant competition over limited resources, such as cropland and freshwater (Warner 2010).

Mexico is expected to be among the most negatively affected countries. Small-scale maize farmers are particularly vulnerable because of their

geographical location as well as their limited adaptive capacity. Climate change models suggest a drying and warming trend for many parts of Mexico during the main maize season (May–October), with this trend predicted to strengthen with time. Predicted trends include: i) a drying of lowland environments, ii) an expansion of lowland and mid-altitude environments up the elevation gradient, and iii) a substantial reduction of the highland environment (through displacement by warmer mid-altitude type environments and an expansion of areas too dry for optimal maize production). A large percentage of poor rural communities is located in the environments that may experience the trends described above (Bellon et al. 2005), highlighting the challenges that the rural poor—many of whom depend on maize for their livelihoods—face with climate change. Agricultural output in Mexico could decrease by 25.7% by 2080 as a result of climate change (Cline 2007) and one of the most affected crops will be the basic staple, maize.

Crop varieties with increased tolerance to heat and drought stress and resistance to pests and diseases are critical for managing current climatic variability and for adaptation to progressive climate change. The challenge is that improved maize germplasm (and other climate-smart technologies) has not been readily adopted by Mexican smallholder farmers. In this paper, we argue that in the case of Mexico, researchers and development practitioners have tended to overlook the importance of farmers' maize landraces (local varieties) in climate change adaptation initiatives. We suggest that a more strategic approach would entail giving greater prominence to maize landraces. This has implications for policy makers, researchers, and development practitioners, as they engage in climate change adaptation, the purpose of which is to manage effectively potential climate risks during the coming decades as climate changes (Howden et al. 2007).

The rest of this paper is structured as follows. In the next section we present and discuss the theme of climate-smart agricultural technologies. This is followed by Section 3, which details how farmer adoption of these technologies is often less than anticipated. In Section 4, we argue for a broadening of the focus of climate-adaptation strategies by directing more resources at farmers' landraces. Using maize in Mexico as an example, we demonstrate the largely untapped potential that maize landraces have in helping maize adapt to climate change. We outline new crop breeding initiatives that are taking advantage of this potential. In Section 5, we emphasize that efforts also need to be directed at enhancing adaptive capacity rather than the promotion of specific adaptation options *per se*. In Section 6 we conclude.

CLIMATE-SMART AGRICULTURAL TECHNOLOGIES

Climate-smart agricultural technologies contribute to: i) an increase in global food security, ii) an enhancement of farmers' ability to adapt to a changing

climate, and iii) the mitigation of emissions of greenhouse gases. Key technologies and practices include climate-resilient germplasm and sustainable land-management practices.

Improved crop varieties are a key output of agricultural research and have contributed to significant increases in agricultural production and productivity (Pingali 2012). Scientific crop breeding will continue to play a critical role in meeting the challenge of increasing food production in the face of climate change. The development and dissemination of improved germplasm have the potential to offset some of the yield losses linked to climate change. Crop varieties with increased tolerance to abiotic stresses, including heat and drought stress, will play an important role in managing current climatic variability and adapting to progressive climate change (Cooper et al. 2008; Fedoroff et al. 2010). Research is required to identify traits associated with combined heat and drought tolerance, and the development of improved germplasm for high-temperature, water-limited environments. The development of climate-resilient germplasm is possible through a combination of conventional, molecular and, in some cases, transgenic breeding approaches (Cairns et al. 2013).

Climate change will be especially detrimental to crop production in cropping systems where soils have been degraded to an extent that they no longer provide adequate water-holding capacity to buffer crops against drought and heat stress. These effects will be most severe if irrigation is not available to compensate for decreased rainfall or to mitigate the effects of elevated temperatures. Improving genetic adaptation to heat or drought stress alone will not address these problems; there is also a need for complementary agronomic interventions (Hobbs and Govaerts 2010). Agronomic practices involving reduced or zero tillage, enhanced surface retention of crop residues (mulches), and economically viable crop rotations and diversification, e.g., conservation agriculture can contribute to cropping environments that maximize expression of crop genetic potential, buffer crops against erratic weather, and contribute to climate change mitigation. At the same time, trade-offs exist, for example because of the use of crop residues for feed or fuel (Hellin et al. 2013). These trade-offs need to be addressed and, if necessary, appropriate context-specific solutions must be developed to be not only environmentally but also socially and economically sustainable.

FARMER (NON)ADOPTION OF RECOMMENDED TECHNOLOGIES

Climate-smart agricultural technologies are just the latest in a long list of technologies that researchers and development practitioners have developed during the past decades and subsequently promoted in rural areas. The salutary truth is that the benefits from these technological innovations have

often not reached the majority of resource-poor farmers cultivating marginal lands because farmers have not readily adopted them. The reasons behind farmer (non) adoption of technologies are complex, but previous research on farmers' reluctance to adopt soil and water technologies in the 1980s (see Hudson 1991) and more recently conservation agriculture (Giller et al. 2009; Erenstein et al. 2012; Andersson and D'Souza 2014) sheds much light on this complexity.

An important factor in the non-adoption of climate-smart technologies has been rural labor shortages (Zimmerer 1993). Many farmers depend both upon production from their land and upon off-farm income-generating activities. This is very much the case in many parts of Mexico. This has far-reaching implications for the availability of labor at different times of year and can determine farmers' acceptance of practices such as conservation agricultural systems, especially if farmers are unable to purchase labor-saving technologies, such as herbicides to control weeds (Giller et al. 2009).

A major challenge to farmer acceptance of these technologies is that they are knowledge-intensive. While agricultural extension, education, and training can help many farmers maximize the potential of their productive assets through adoption of these technologies, their promotion has coincided with deep cuts to publicly funded extension services in the developing world (Ajieh et al. 2008). The breakdown of classical publicly funded agricultural research and extension services means that these services are now unable to address the needs of farmers living in marginal environments. In the majority of cases, the private sector has proven incapable of replacing previous state services because of high transaction costs, dispersed clientele, and low (or non-existent) profits (Muyanga and Jayne 2008). The absence of relevant and competent extension provision leads to low technology adoption rates.

As for crop breeding, efforts have tended to focus on producing high-yielding germplasm. Despite decades of maize breeding and the promotion of improved maize varieties, however, the majority of smallholder maize farmers in rain-fed areas of Mexico continue to use local maize varieties (Barkin 2002). It is widely accepted that farmers maintain crop diversity for social, economic, or cultural purposes, and/or when local varieties show an agronomic performance superior to that of improved varieties (Bellon 2004). Market-related issues in both input and output chains can influence farmers' propensity to adopt improved maize varieties. On the input side, bottlenecks exist in the value chains, which impede farmers' access to seed. On the output side, quality and scale-related barriers also exist, inhibiting the acceptance of farmers' maize in industrial maize markets (Keleman et al. 2013).

Farmers may prefer local maize varieties for culinary and cultural reasons (Brush and Perales 2007; Bellon and Hellin 2011). Perales et al. (2005) documented the importance of culture in determining maize diversity in Mexico. The authors found a significant association between linguistic

differentiation and morphological differentiation of maize varieties among Maya-speaking communities in the highlands of the southern Mexican state of Chiapas. There are also differences in preferences between women and men on account of their reproductive and productive roles; women set priorities toward food security and thus tend to favor varieties that are palatable, nutritious, and meet processing and storage requirements. Women can also generate income from the artisanal processing and sale of traditional maize products (Keleman and Hellin 2009).

Adoption studies related to smallholder production systems have shown risk to be an important component in farmers' decision making. From a farmer's perspective, it may well be too risky to purchase seed of an unknown variety if there is a chance that drought and/or frosts are going to have an adverse impact on crop yields. The result is that farmers often trust local varieties, considering farmer-saved seed to be a "known quantity" while fearing that unfamiliar seed would perform in unexpected ways (Arellano Hernández and Arraiga Jordán 2001; Badstue et al. 2007). This may well be a very rational decision; improved maize varieties, often developed on research stations, do not necessarily perform well under farmers' conditions. For example, in Mexico, a study that examined the relationship between maize research and rural poverty showed that maize production was largely coincident with areas of rural poverty; however, it also found a disparity in the locations of trials used for testing improved maize germplasm and where the poor lived, suggesting that the potential for spillovers from germplasm tested in those sites to poor farmers may be limited (Bellon et al. 2005). Improved varieties that crop breeders identify as superior to landraces under experimental conditions may actually yield substantially less under farmers' conditions because of genotype-by-environment interactions that remain undetected in the data from experimental plots (Keleman et al. 2013).

BROADENING THE FOCUS OF CLIMATE CHANGE-ADAPTATION STRATEGIES

Maize Landraces

Landraces have been defined as dynamic populations of a cultivated plant with a historical origin, distinct identity, often genetically diverse and locally adapted, and associated with a set of farmers' practices of seed selection and field management (Camacho Villa et al. 2005). The structure and dynamics of these landraces are the result of both natural and human selection (Bellon and van Etten 2013). Observers have posited that farmers' varieties will be lost in the face of technological change, with modern varieties eventually replacing landraces wholesale (c.f. Harlan 1975). Detailed, ground-level studies (Brush et al. 1992; Chambers et al. 2007; Bellon and Hellin 2011) have both highlighted the threats to farmers' local varieties and also their

resilience. In Mexico, 59 well-defined races (e.g., morphologically and genetically distinct sub-populations) of maize have been described (Sanchez et al. 2000; Ureta et al. 2012) and countless varieties exist at the farmer level.

Farmers' maintenance of local maize varieties may have a very important role to play in climate change adaptation in Mexico (Bellon et al. 2011). In many parts of Mexico, small-scale maize farmers recycle seed either by saving their seed from the previous harvest and/or obtaining it from fellow farmers (Badstue et al. 2007; Dyer and Taylor 2008). The vast majority of these farmers operate under rain-fed conditions, and climate is one of the most important risk factors in their agricultural systems. Maize landraces in Mexico show remarkable diversity and climatic adaptability, growing from arid to humid environments and from temperate to tropical environments. Ruiz Corral et al. (2008) found a very high level of variation among and within 41 Mexican maize races for climate adaptation and ecological descriptors. The general overall climatic ranges for maize included 0 to 2900 m altitude, 11.3° to 26.6°C annual mean temperature, 12.0° to 29.1°C growing season mean temperature, and 426 to 4245 mm annual rainfall (Ruiz Corral et al. 2008).

Bioclimatic modeling of the impact of climate change on the distribution of maize races in the future, while showing, on the aggregate, significant reductions in their potential distribution, also point to contrasting responses by race, showing no major shifts in areas with high race richness, highlighting the important role of race diversity in buffering the effects of climate change (Ureta et al. 2012). Providing farmers with access to more diversity of landraces can, hence, be an important strategy to mitigate the negative impacts of climate change on their livelihoods.

In some parts of Mexico, there may already exist crop germplasm in the form of farmers' local maize varieties that are appropriate for predicted climates (Bellon et al. 2011; Mercer et al. 2012). Farmers' local maize varieties should be part of the arsenal of climate-smart technologies and practices. In some cases traditional seed systems may be able to provide farmers with landraces suitable for agro-ecological conditions under predicted climate change, after all traditional seed systems are not closed or static but open and dynamic with seed coming in and out of the systems, with farmers experimenting and incorporating new seeds (Bellon and van Etten 2013). However, if suitable germplasm does exist, those farmers who are going to need it may not currently source it, suggesting that farmers are likely to need to source seed from outside their traditional geographical ranges. This may entail the development of new social networks (Bellon et al. 2011).

In practice, broadening the geographical reach of farmers' seed networks could be achieved through exchange visits; linking farmer groups in different locations; fostering the exchange of germplasm, knowledge, and practices among them; and encouraging cross-community experimentation with local and introduced crop varieties (Bellon and van Etten

2013). Landrace populations may also be able to ‘keep up’ with climate change because of farmer selection of climate-adapted traits among landraces (Mercer and Perales 2010; Mercer et al. 2012). Furthermore, maize’s wild relatives, *Tripsacum* species and *Teosinte* species and subspecies, are expected to respond differently to climate change because of different environments that they currently inhabit (Ureta et al. 2012).

Furthermore, within the primary gene pool of maize and its wild relatives there exists unexploited genetic diversity for novel traits and alleles (Ortiz et al. 2009) that can be used for breeding new high-yielding and stress-tolerant cultivars (Jarvis et al. 2008; Ruiz Corral et al. 2008; Chauhan et al. 2014). Formal breeding efforts as part of climate change-adaptation strategies will likely depend heavily on the diverse crop genetic resources that farmers have helped develop across centuries (Burke et al. 2009).

Hence, along with farmers’ use of maize landraces, many farmers may be able to acquire improved germplasm with new adaptive traits. Thus, formal crop breeding still has a very important role to play in the development and diffusion of improved varieties with appropriate traits to cope with climate change. As Bellon (2009) notes, having a diversity of ‘winning’ (adaptive) combinations of genes and traits that are constantly being updated in response to changing situations and new knowledge should allow us to cope and adapt better to change. This is precisely the idea of the option value of the evolutionary services that on-farm conservation delivers (Bellon and van Etten 2013) and is likely to be critical to climate change-adaptation strategies.

Small-scale maize farmers’ adoption of improved germplasm has been minimal and, hence, public and private sector interventions are required to foster a well-functioning seed system that links formal and informal seed systems to enable farmers to access climate-adapted seed. The desired result would be a segmented maize seed sector characterized by both (improved) landraces and improved maize varieties. The public and private sector would provide the latter and different actors, including farmers themselves, would generate seed of landraces for sale and/or exchange.

Landraces as a Breeding Resource

In 1998, when the Food and Agriculture Organization (FAO) of the United Nations published the State of the World Plant Genetic Resources, there were 261,584 accessions of maize held in gene banks around the world. Of these, the number of unique landraces held in major collections worldwide ranged from 58,000 to 80,000 (Taba and Goodman 2007). The international gene bank at the International Maize and Wheat Improvement Center (CIMMYT) in Mexico holds in excess of 27,500 accessions of maize, covering primarily landraces (24,463; 97% of these from the Americas and Caribbean) but also breeding lines, teosintes, *Tripsacum* sp., and some pools and pre-breeding

populations. Within Mexico alone, approximately 18,000 further Mexican maize accessions are held by regional gene banks, universities, and at the new National Genetic Resource Centre within Mexico. These resources are often called an “ark” representing a broad swath of maize genetic diversity, which may offer a reserve of native alleles and genes of importance to crop production now and in the future.

Even under the more moderate climate change scenarios, predicted climate shifts within Mexico are significant; during the past 100 years Mexico has experienced between 0.5 to 0.9°C of warming (Verhulst et al. 2012), which represents 100 generations of maize or 0.009°C per generation. The moderate predicted changes in the next 50 years in Mexico equate to a 0.08°C warming per generation in some maize-growing regions; nine times that previously experienced.

Compared with hybrids, landrace populations have a wider plasticity in the range of environments a particular population can successfully grow in and still maintain yield. This is one of the reasons they are so valued by farmers. This adaptive feature is a reflection of the heterogeneous nature of the populations. However, the ability of landraces to adapt to the rapidly changing climate, as suggested by climate models, is a point of concern. The ex-situ landrace collections contain many materials that have evolved in environments that have a propensity for stress, such as drought, heat, or frost, during the growing season. For example, in the international maize collection at CIMMYT, there are in excess of 3,900 landrace accessions (more than half of which come from Mexico) that originate from locations where the monthly average daily maximum temperature during the flowering period (based on 1901–2009 data) exceeds 30°C. Such landraces offer a unique source of germplasm, genes, and alleles for “climate change tolerance,” which may be of benefit to crop improvement activities.

Existing breeding pools contain some genetic variation that can be and is being harnessed. The continuing genetic gain seen in relatively closed private-sector breeding programs is testament to this. However, many other useful genetic characters present in landraces will not have passed through the bottleneck of genetic selection. With increasing environmental variability, heterogeneity in traits deployed for adaptation is important to ensure durability in the long term. The use of non-elite germplasm in plant breeding is limited for very valid reasons, including issues such as linkage drag—desirable traits may be associated with undesirable ones in this type of germplasm; difficulty in making crosses; general adaptation difficulties—non-elite germplasm may be locally adapted and may not perform well outside very specific environmental niches; funding limitations—pre-breeding, the process of making non-elite germplasm suitable for use in breeding, can be costly and takes time; and the relatively short-term goals, from a breeding perspective, of many breeding projects. Indeed, many races of maize have been under-investigated as sources of beneficial genes with a focus

being placed on races more representative of an “ideal” plant type, e.g., the *Tuxpeño* race in the case of maize.

Concerted efforts are now focusing on the characterization of landraces at both genetic and phenotypic levels to better inform and enable selection and use of these important resources in plant breeding. Examples include the Seeds of Discovery Initiative funded by Mexico’s Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA) (<http://seedsofdiscovery.org/seed/about/>), and the French Government and industry-funded Amaizing Project (<http://www.amaizing.fr/index.php>).

While the most direct and simple approach to providing more climate-resilient materials to resource-poor farmers may appear to be simply a redistribution of those landraces that may be tolerant to changing climates, this may not be productive because of broad and local adaptation issues (Mercer et al. 2012) and local culinary preferences. Indeed, it is not only farmers cultivating landraces who face the challenge of increasing climate variability; improvement of all germplasm, including hybrids, open-pollinated varieties (OPVs), and landraces, for climate resilience is required as a tool in a suite of climate-adaptation strategies.

Using conventional crossing, coupled with modern techniques, such as genomics-assisted breeding and doubled-haploid technology, it is possible to incorporate some important novel traits more rapidly, and, in a more targeted manner (reducing linkage drag) from landraces into more breeder-friendly germplasm. This process, termed pre-breeding, does not seek to produce a finished product but rather a suite of easy-to-use donor materials with associated information that can be deployed in the improvement of all germplasm types from landraces to elite breeding lines. Multiple genetic sources for adaptation characteristics of interest should be explored to enable the development of landrace varieties (and panels of elite varieties) that have (within landraces and across elite varieties) high degrees of heterozygosity and heterogeneity for climate-resilience traits. Such materials better enable buffering capacity in times of stress as demonstrated in studies of the climate-durable crop pearl millet in Africa (Hausmann et al. 2012).

For those organizations involved in crop breeding, the challenge remains of ensuring that beneficial genes and alleles are incorporated into farmer-appropriate genetic backgrounds and that the resulting varieties are evaluated in field trials that best represent farmer conditions and management practices. Resource-poor maize farmers in Mexico tend to grow landraces for a number of reasons, including cultural and culinary preference, and limited access to improved materials. Bellon et al. (2005) documented that in Mexico where formal CIMMYT maize trials had been carried out, only 7 of the 158 sites used were actually in high probability rural poverty areas and only 16 of the 158 were within extremely poor municipalities. The disparity in the locations of the trials largely represents the focus on managed stress trials, the ease of travel to trial locations, and

most importantly the evaluation of lines, improved hybrids, and OPVs, which are the mainstay of international breeding efforts at CIMMYT. The importance of improving the genetic resilience of landraces has, however, been recognized and many national breeders in Mexico have components of their breeding programs that look at landraces. Given the range and diversity of landraces and farming niches, however, it is going to be a challenge to scale out improved landraces in a similar way to what has been achieved with OPVs and hybrids.

The development of suitable trait donor germplasm is an essential step towards facilitating the development of climate-resilient germplasm across the whole spectrum of variety types. Strategies, such as participatory plant breeding, need to be discussed and formulated to identify the most effective way to enhance the incorporation of useful genetic variation into the landraces currently used by farmers. These will involve trained plant breeders and active farmer participation. Farmers have been practicing selection for millennia and as long as they are provided suitable donor germplasm, they should be quite capable of making effective selections in their own fields for desired traits, including tolerance to climatic variability.

Considering more formal breeding approaches, while in many arenas the notion is unpopular, some prioritization of landraces will need to be considered to ensure that some landraces are genetically protected against future climatic variability. Irrespective of strategies developed for landrace improvement, it remains that, as a follow up to the development of donor germplasm and some improved varieties, breeders and extension agents should consider re-emphasis on the evaluation of farmer-appropriate technologies and technology packages in locations where target farmers live and work to capitalize on potential for spillovers from germplasm tested in those sites.

Adaptation Capacity

There also remains the challenge of enhancing adaptive capacity to climate change. Eakin and Lemos (2006) posit that the high uncertainties in climate-change scenarios meant that there was growing interest in improving adaptive capacity as an alternative focus of policy efforts, rather than the promotion of specific adaptation options *per se*. There is an expectation that nation-states will improve their capacity and that of their citizens to adapt to climate change (Eakin and Lemos 2006). Hence, while specific adaptation technologies (such as climate-adapted germplasm) and practices are critical, there is a need to direct more attention at the institutional changes that empower states to design and implement policy to increase adaptive capacity of different actors, including farmers. As Thornton et al. (2009) write, in place of defining large development domains for identifying and implementing adaptation options, what is needed are localized, community-based efforts to increase local adaptive capacity.

A systems approach is needed in which innovation is the result of a process of networking, interactive learning, and negotiation among a heterogeneous set of actors (Klerkx et al. 2009). This very much applies to climate-change adaptation because “the effectiveness of these adaptations for mitigating future sensitivity to climatic risk will be strongly influenced by the ways in which policy enables or inhibits households’ capacity to address climatic challenges” (Eakin 2005). This is largely because a households’ management of climatic risk is a function of numerous factors, including education, wealth, natural resources, social organization, and institutional relationships (Eakin 2005). This calls for increased farmer participation in stakeholder design of climate-adaptation strategies (Eakin et al. 2007) and an increase in various dimensions of social capital, including peer groups, networks, and collective action (Meinke et al. 2006). Strengthening the social relations of maize production and seed exchange among farmers are fundamental to a successful adaptation strategy (Mercer et al. 2012).

Public- and private-supported extension programs can play a key role in the design of more appropriate adaptation strategies by transferring technology, facilitating interaction, building capacity among farmers, and encouraging farmers to form their own networks. Extension services that specifically address climate-change adaptation include disseminating drought-resistant crop varieties; teaching improved management systems; and gathering information to facilitate national research work. The breeding and agronomic research work needs to be supported by other factors, including complementary investments in climate-responsive information and input-delivery systems; and strengthening of institutions to coordinate grain marketing with seed, fertilizer, and credit delivery. The development of reliable seasonal weather forecast, record of reliable weather, and strengthening of early warning system are also crucial for facilitating adaptation to climate change.

The above can best be achieved via a judicious mix of public and private service provision in the agricultural sector that also addresses multiple market and government failures in the delivery of technologies, inputs, and services (Cooper et al. 2008). This requires new institutional arrangements and policy instruments to enhance local capacity and stimulate the adoption of improved technologies for adaptation, managing risks, and protection of vulnerable livelihoods. This requires novel, flexible research and extension approaches that differ from those more commonly used by policy makers, donors, researchers, and extension agents (Ekboir et al. 2009). Enhancing the productivity and profitability in marginal areas will require approaches that promote the translation of innovations in plant science into concrete benefits for poor farmers and in ways that support the emergence of agricultural innovation systems as well as respecting and supporting farmers’ preferences for landraces; there is much emphasis on the importance of breeding crops

for future climatic conditions even though much of the world's farming population still relies on landrace populations rather than the products of formal breeding networks (Mercer and Perales 2010). Production is clearly important, but food distribution and exchange also determine food availability while access to food and food utilization are other important components of food security (Ingram et al. 2008).

CONCLUSIONS

Climate change threatens current agricultural output and, hence, there is a greater need to enhance agricultural yields and resilience of agro-ecosystems as well as to improve the livelihoods of farmers. Despite some uncertainties on the spatially differentiated impact of climate change on agricultural production, there is little doubt that germplasm, more suited to future climates, is critical along with improved agronomic and crop-management practices. Mesoamerica is the center of origin and diversity for maize, and landraces may already exist that possess traits that enable adaptation to predicted climates.

Formal crop breeding using landrace resources has a key role to play in climate change-adaptation strategies. Complementary adaptation strategies would include farmers' increased use of climate-adapted maize varieties (with improved tolerance to heat stress, and combined heat and drought stress), coupled with effective soil moisture-conservation techniques. The development and dissemination of climate-responsive germplasm may take several years because the process consists of several steps, including breeding, on-farm testing, release of varieties, and germplasm dissemination. Research efforts need to be directed at facilitating the development of pre-breeding germplasm, germplasm (landrace, OPV, and hybrid) enhancement and varietal release, training seed entrepreneurs, and increasing the provision of foundation seed. Furthermore, widespread farmer uptake of improved climate-adapted maize varieties relies on a functioning and efficient seed sector.

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REFERENCES

- Adger, W. N., S. Agrawala, M. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smit, and K. Takahashi. 2007. Assessment of adaptation practices, options, constraints, and capacity. In *Climate Change 2007: Impacts, Adaptation and Vulnerability (Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change)*, edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, 717–743. Cambridge, UK: Cambridge University Press.
- Adger, W. N., S. Huq, K. Brown, D. Conway, and M. Hulme. 2003. Adaptation to climate change in the developing world. *Prog. Develop. Stud.* 3(3): 179–195.
- Ajeh, P. C., A. E. Agwu, and A. C. Anyanwu. 2008. Constraints to privatization and commercialization of agricultural extension services as perceived by extension professionals and farmers. *Afr. J. Agric. Res.* 3(5): 343–347.
- Andersson, J. A., and S. D'Souza. 2014. From adoption claims to understanding farmers and contexts: A literature review of Conservation Agriculture (CA) adoption among smallholder farmers in southern Africa. *Agric. Ecosyst. Environ.* 187:116–132.
- Arellano Hernández, A., and C. Arriaga Jordán. 2001. Why improved maize (*Zea Mays*) varieties are utopias in the highlands of central Mexico. *Convergencia* 8(25): 255–276.
- Barkin, D. 2002. The reconstruction of a modern Mexican peasantry. *J. Peasant Stud.* 30(1): 73–90.
- Battisti, D. S., and R. L. Naylor. 2009. Historical warnings of future food insecurity with unprecedented seasonal heat. *Science* 323:240–244.
- Badstue, L. B., M. R. Bellon, J. Berthaud, A. Ramirez, D. Flores, and X. Juarez. 2007. The dynamics of seed flow among small-scale maize farmers in the Central Valleys of Oaxaca, Mexico. *World Develop.* 35(9): 1,579–1,593.
- Bellon, M. R., and J. Hellin. 2011. Planting hybrids, keeping landraces: agricultural modernization and tradition among small-scale maize farmers in Chiapas, Mexico. *World Develop.* 39(8): 1,434–1,443.
- Bellon, M. R., and J. van Etten. 2013. Climate change and on-farm conservation of crop landraces in centres of diversity. In *Plant genetic resources and climate change*, edited by M. Jackson, B. Ford-Lloyd, M. L. Parry. New York, NY: CABI Publishing.
- Bellon, M. R., D. Hodson, and J. Hellin. 2011. Assessing the vulnerability of traditional maize seed systems in Mexico to climate change. *Proc. Nat. Acad. Sci. USA.* 108(33): 13,432–13,437.

- Bellon, M. R., D. Hodson, D. Bergvinson, D. Beck, E. Martinez-Romero, and Y. Montoya. 2005. Targeting agricultural research to benefit poor farmers: Relating poverty mapping to maize environments in Mexico. *Food Policy* 30(5–6): 476–492.
- Bellon, M. R. 2009. Do we need crop landraces for the future? Realizing the global option value of in situ conservation. In *Agrobiodiversity and economic development*, edited by A. Kontoleon, U. Pascual, and M. Smale, 51–61. London, UK: Routledge.
- Bellon, M. R. 2004. Conceptualizing interventions to support on-farm genetic resource conservation. *World Develop.* 32(1): 159–172.
- Brown, M. E., and C. C. Funk. 2008. Food security under climate change. *Science* 319(5863): 580–581.
- Brush, S. B., and H. R. Perales. 2007. A maize landscape: Ethnicity and agrobiodiversity in Chiapas Mexico. *Agric. Ecosyst. Environ.* 121(3): 211–221.
- Brush, S. B., J. E. Taylor, and M. R. Bellon. 1992. Technology adoption and biological diversity in Andean potato agriculture. *J. Develop. Econ.* 39:365–387.
- Burke, M. B., D. B. Lobell, and L. Guarino. 2009. Shifts in African crop climates by 2050, and the implications for crop improvement and genetic resources conservation. *Global Environ. Change* 19(3): 317–325.
- Cairns, J. E., J. Hellin, K. Sonder, J. L. Araus, J. F. MacRobert, C. Thierfelder, and B. M. Prasanna. 2013. Adapting maize to climate change in sub-Saharan Africa. *Food Security* 5:345–360.
- Camacho Villa, T. C., N. Maxted, M. A. Scholten, and B. V. Ford-Lloyd. 2005. Defining and identifying crop landraces. *Plant Genet. Res.* 3:373–384.
- Chambers, K. J., S. B. Brush, M. N. Grote, and P. Gepts. 2007. Describing maize (*Zea mays* L.) landrace persistence in the Bajío of Mexico: A survey of 1940s and 1950s collection Locations. *Econ. Bot.* 61(1): 60–72.
- Chauhan, B. S., Prabhjyot-Kaur, G. Mahajan, R. K. Randhawa, H. Singh, and M. S. Kang. 2014. Global warming and its possible impact on agriculture in India. In *Advances in agronomy, vol. 123*, edited by D. L. Sparks, 65–121. Burlington, VT: Academic Press.
- Cline, W. R. 2007. *Global warming and agriculture: impact estimates by country*. Washington, D.C., USA: Center for Global Development and Peterson Institute for International Economics.
- Cooper, P. J. M., J. Dimes, K. P. C. Rao, B. Shapiro, B. Shiferaw, and S. Twomlow. 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? *Agric. Ecosyst. Environ.* 126(1–2): 24–35.
- Dyer, G. A., and J. E. Taylor. 2008. A crop population perspective on maize seed systems in Mexico. *Proc. Nat. Acad. Sci. USA.* 105(2): 470–475.
- Eakin, H. 2005. Institutional change, climate risk, and rural vulnerability: Cases from Central Mexico. *World Develop.* 33:1,923–1,938.
- Eakin, H., and M. C. Lemos. 2006. Adaptation and the state: Latin America and the challenge of capacity-building under globalization. *Global Environ. Change* 16(1): 7–18.
- Eakin, H., V. Magaña, J. Smith, J. L. Moreno, J. M. Martínez, and O. Landavazo. 2007. A stakeholder driven process to reduce vulnerability to climate change

- in Hermosillo, Sonora, Mexico. *Mitig. Adapt. Strategies Global Change* 12(5): 935–955.
- Ekboir, J. M., Dutrénit, G., Martínez, G., Torres Vargas, A., and A. Vera-Cruz, A. 2009. *Successful organizational learning in the management of agricultural research and innovation: The Mexican Produce Foundations. IFPRI Research Report No. 162*. Washington, DC: International Food Policy Research Institute.
- Erenstein, O., K. Sayre, P. Wall, J. Hellin, and J. Dixon. 2012. Conservation agriculture in maize and wheat based systems in the (sub) tropics: Lessons from adaptation initiatives in South Asia, Mexico and Southern Africa. *J. Sustainable Agric.* 36(2): 180–206.
- Fedoroff, N. V., D. S. Battisti, R. N. Beachy, P. J. M. Cooper, D. A. Fischhoff, C. N. Hodges, V. C. Knauf, et al. 2010. Radically rethinking agriculture for the 21st Century. *Science* 327:833–834.
- Feng, S., A. B. Krueger, and M. Oppenheimer. 2011. Linkages among climate change, crop yields, and Mexico–US cross-border migration. *Proc. Nat. Acad. Sci. USA*. 107(32): 14,257–14,262.
- Fischer, G., M. Shah, F. N. Tubiello, and H. van Velhuizen. 2005. Socio-economic and climate change impacts on agriculture: an integrated assessment 1990–2080. *Philos. Trans. R. Soc. London, Series B* 360(1463): 2067–2083.
- Giller, K. E., E. Witter, M. Corbeels, and P. Tittonell. 2009. Conservation agriculture and smallholder farming in Africa: The heretics' view. *Field Crops Res.* 114:23–34.
- Harlan J. 1975. Our vanishing genetic resources. *Science* 188:618–621.
- Hausmann, B. I. G., H. Fred Rattunde, E. Weltzien -Rattunde, P. S. C. Traoré, K. vom Brocke, H. K. Parzies. 2012. Breeding strategies for adaptation of pearl millet and sorghum to climate variability and change in West Africa. *J. Agron. Crop Sci.* 198:327–339.
- Hellin, J., O. Erenstein, T. Beuchelt, C. Camacho, and D. Flores. 2013. Maize stover use and sustainable crop production in mixed crop–livestock systems in Mexico. *Field Crops Res.* 153:12–21.
- Hendrix, C. S, and S. M. Glaser. 2007. Trends and triggers: Climate, climate change and civil conflict in Sub-Saharan Africa. *Pol. Geog.* 26:695–715.
- Hobbs, P. R., and B. Govaerts. 2010. How conservation agriculture can contribute to buffering climate change. In *Climate Change and Crop Production*, edited by M. P. Reynolds, 151–176. CABI Series in Climate Change. New York, NY: CABI International.
- Howden, S. M., Soussana, J.-F., Tubiello, F. N., Chhetri, N., Dunlop, M., Meinke, H. 2007). Adapting agriculture to climate change. *Proc. Nat. Acad. Sci. USA*. 104(50): 19691–6.
- Hudson, N.W. 1991. *A study of the reasons for success and failure of soil conservation projects. Soils Bulletin 64*. Rome, Italy: Food and Agriculture Organization of the United Nations.
- Ingram, J. S. I., P. J. Gregory, and A. M. Izac. 2008. The role of agronomic research in climate change and food security policy. *Agric. Ecosyst. Environ.* 126(1–2): 4–12.
- Jarvis, A., A. Lane, and R. J. Hijmans. 2008. The effect of climate change on crop wild relatives. *Agric. Ecosyst. Environ.* 126(1–2): 13–23.

- Jones, P., and P. Thornton. 2003. The potential impacts of climate change on maize production in Africa and Latin America in 2055. *Global Environ. Change* 13(1): 51–59.
- Kang, M. S., and S. S. Banga. 2013. Global agriculture and climate change. *J. Crop Improv.* 27(6): 667–692. doi:10.1080/15427528.2013.845051.
- Keleman, A., and J. Hellin. 2009. Specialty Maize Varieties in Mexico: A Case Study in Market-Driven Agro-Biodiversity Conservation. *J. Latin Am. Geog.* 8(2):147–174.
- Keleman, A., J. Hellin, and D. Flores. 2013. Diverse varieties and diverse markets: scale-related maize “profitability crossover” in the central Mexican Highlands. *Human Ecol.* 41:683–705.
- Klerkx, L., A. Hall, and C. Leeuwis. 2009. Strengthening agricultural innovation capacity: are innovation brokers the answer? *Int. J. Agric. Res. Gov. Ecol.* 8(5/6): 409–438.
- Lobell, D. B., M. Bänziger, C. Magorokosho, and B. Vivek. 2011. Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Clim. Change* 1:42–45.
- Lobell, D. B., and M. B. Burke. 2008. Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. *Environ. Res. Lett.* 3(3): 1–8.
- Meinke, H., R. Nelson, P. Kocic, R. Stone, and R. Selvaraju. 2006. Actionable climate knowledge: from analysis to synthesis. *Climate Res.* 33:101–110.
- Mercer, K. L., and H. R. Perales. 2010. Evolutionary response of landraces to climate change in centers of crop diversity. *Evolut. Appl.* 3(5–6): 480–493.
- Mercer, K. L., H. R. Perales, and J. D. Wainwright. 2012. Climate change and the transgenic adaptation strategy: Smallholder livelihoods, climate justice, and maize landraces in Mexico. *Global Environ. Change* 22(2): 495–504.
- Morton, J. F. 2007. The impact of climate change on smallholder and subsistence agriculture. *Proc. Nat. Acad. Sci. USA.* 104:19,680–19,685.
- Muyanga, M., and T. S. Jayne. 2008. Private agricultural extension system in Kenya: Practice and policy lessons. *J. Agric. Edu. Exten.* 14(2): 111–124.
- Ortiz, R., S. Taba, V. H. C. Tovar, M. Mezzalama, Y. Xu, J. Yan, and J. H. Crouch. 2009. Conserving and enhancing maize genetic resources as global public goods: A perspective from CIMMYT. *Crop Sci.* 50:13–28.
- Perales, H. R., B. F. Benz, and S. B. Brush. 2005. Maize diversity and ethno-linguistic diversity in Chiapas, Mexico. *Proc. Nat. Acad. Sci. USA.* 102(3): 949–954.
- Pingali, P. L. 2012. Green Revolution: Impacts, limits, and the path ahead. *Proc. Nat. Acad. Sci. USA.* 109(31): 12,302–12,308.
- Raleigh, C., and H. Urdal. 2007. Climate change, environmental degradation and armed conflict. *Poly. Geogr.* 26(2007): 674–694
- Ruiz Corral, J. A., N. Durán Puga, J. D. J. Sánchez González, J. Ron Parra, D. R. González Eguiarte, J. B. Holland, and G. Medina García. 2008. Climatic adaptation and ecological descriptors of 42 Mexican maize races. *Crop Sci.* 48(4): 1502–1512.
- Sanchez, J. J. G., M. M. Goodman, and C. W. Stuber. 2000. Isoenzymatic and morphological diversity in the races of maize in Mexico. *Econ. Bot.* 54(1): 43–59.

- Taba, S., and M. Goodman. 2007. Background on the development of the “Global Strategy for the Ex Situ Conservation and Utilization of Maize Germplasm.” Available at <http://www.croptrust.org/documents/cropstrategies/maize.pdf>
- Thornton, P. K., P. G. Jones, G. Alagarswamy, and J. Andresen. 2009. Spatial variation of crop yield response to climate change in East Africa. *Global Environ. Change* 19(1): 54–65.
- Ureta, C., E. Martínez-Meyer, H. R. Perales, and E. R. Álvarez-Buylla. 2012. Projecting the effects of climate change on the distribution of maize races and their wild relatives in Mexico. *Global Change Biol.* 18(3): 1,073–1,082.
- Verhulst, N., B. Govaerts, K. D. Sayre, K. Sonder, R. Romero-Perezgrovas, M. Mezzalama, and L. Dendooven. 2012. Conservation agriculture as a means to mitigate and adapt to climate change, a case study from Mexico. In *Climate change mitigation and agriculture*, edited by E. Wollenberg, A. Nihart, M.-L. Tapio-Biström, and M. Grieg-Gran, 287–300. Oxford, UK: Earthscan.
- Vermeulen, S. J. 2014. *Climate change, food security and small-scale producers. CCAFS InfoBrief*. Copenhagen, Denmark: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).
- Warner, K. 2010. Global environmental change and migration: Governance challenges. *Global Environ. Change* 20(3): 402–413.
- Zimmerer, K. 1993. Soil erosion and labor shortages in the Andes with special reference to Bolivia 1953-91: Implications for ‘conservation-with-development.’ *World Develop.* 21(10): 1,659–1,675.