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Climate change and the transgenic adaptation strategy: Smallholder livelihoods, climate justice, and maize landraces in Mexico

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ABSTRACT

Climate change will affect agricultural production by subsistence farms in crop centers of origin, where landraces are conserved *in situ*. Various strategies for adaptation to climate change have been proposed. In this paper we examine the prospects of what we call the ‘transgenic adaptation strategy’, i.e. the appeal to use transgenic seeds to adapt to climate change, through the lens of smallholder maize farming in Mexico. Landraces are the bedrock of maize production in Mexico. We consider how maize farmers may respond to climate change and the effects of those responses on crop diversity. In this paper, we argue that the promotion of the transgenic adaptation strategy is problematic for biological and social reasons. Smallholder livelihoods in southern Mexico could suffer a disproportionate negative impact if transgenic technology is privileged as a response to climate change. Agroecological and evolutionary approaches to addressing the effects of climate change on smallholder agriculture provides an alternative adaptive strategy.

1. Introduction

Climate change is certain to bring challenges for global agricultural production (IPCC, 2007; IAASTD, 2008; Godfray et al., 2010; Vermeulen et al., in press). Though estimates for different geographic regions and crops vary and our understanding of climatic variation remains limited, agricultural production in many regions is expected to decline (Lobell and Field, 2007; Lobell et al., 2008). Indeed, some decline is already measurable. By one calculation (Lobell et al., 2011), the expected global maize yield fell ~3.8% due to climate change between 1980 and 2010. The mechanisms that threaten yield do not affect farmers evenly. Although subsistence farmers who grow local landraces (traditional varieties) contribute little carbon emissions to the Earth's atmosphere,[1] they tend to be especially vulnerable to climatic flux (Conde et al., 1997; Liverman, 1999; Eakin, 2000; Monterroso et al., 2011). Because small farmers who grow a wide variety of landraces serve as custodians of crop diversity, their vulnerabilities have implications for the *in situ* conservation of diverse crop landraces (Brush, 2004; Bellon and Hellin, 2011). As Ortiz (2011, p. 190) summarizes, “agrobiodiversity remains the main raw material for agroecosystems to cope with climate change because it can provide traits for plant breeders and farmers to select resilient, climate-ready crop germplasm.” In this way, climate change threatens not only the yields and livelihoods of traditional farmers, but also the ability of agriculturalists worldwide to cope with the effects of climate change through advances in crop breeding.

Several strategies for adaptation to climate change have been proposed to address crop productivity. One strategy emphasizes *changing cultural practices*. For instance, many farmers are changing the timing of planting or altering irrigation regimes (Conde et al., 1997; Cutforth et al., 2007). A second strategy involves adopting methods to *increase the resilience of agroecosystems* to environmental variability. The benefit here is that climate change brings uncertainty, so increasing a system's ability to weather that variability is essential (Vermeulen et al., in press). However, significant changes to an agroecosystem may be difficult for farmers to enact, particularly if their resources are stressed. A third strategy involves *improving seed varieties* to develop new traits, such as drought resistance (Grover et al., 2003; Edmeades, 2008; Pray et al., 2011). One variant of this third strategy has received considerable attention recently: employing transgenic methods to develop seeds that are well adapted to climate change.

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[1] On their relative contributions to atmospheric change, see IPCC (2007) and IFOAM (2009). An exception to our claim could perhaps be made for shifting (‘slash and burn’) agriculture, although as Tinker et al. (1996, p. 13) note, “the net CO_2 balance in shifting agriculture is near zero if the forest returns to its original biomass and soil organic carbon status.”

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In this paper we examine this position, which we will call the 'transgenic adaptation strategy' (TAS). The TAS seems to be gaining ground (as we show), although transgenic 'climate-adapted' varieties are still under development (Rivero et al., 2007; Edmeades, 2008; Ortiz, 2011).

Our paper examines the prospects for the TAS through the lens of smallholder maize farmers in Mexico who are known for their role in conserving traditional varieties of maize (Bellon and Brush, 1994; Louette et al., 1997; Soleri and Cleveland, 2001; Perales et al., 2003a,b), a key crop first domesticated in Mexico (Wellhausen et al., 1952; Doebley et al., 1985; Sanchez et al., 2000). Apart from the planting of commercial maize seed on less than one-fourth of Mexico's annual 8 million hectares (typically in irrigated and other high-quality fields), Mexican farmers plant saved seed from their own harvest or by acquaintances (Aquino et al., 2001; Brush and Perales, 2007; Beceril and Abdulai, 2010). This farmer-saved seed is comprised mainly of traditional landraces, but also includes advanced generations of commercial cultivars as well as "creolized" (or hyrbidized) commercial cultivars and landraces (Bellon, 1991; Van Heerwaarden et al., 2009). Most of these seeds are planted in rain-fed fields, which are typically smaller than 5 ha (De Janvry et al., 1995).

The maize landraces conserved *in situ* by Mexican farmers are the product of long-standing patterns of natural and farmer-mediated selection. These landraces experience evolutionary forces – gene flow, selection, mutation, and drift – under diverse conditions in farmers' fields. Although the genetic differentiation of maize landraces have been examined (Pressoir and Berthaud, 2004b; Mercer et al., 2008), along with the possible patterns of gene flow (Pressoir and Berthaud, 2004a; Van Etten et al., 2008; Vigouroux et al., 2008), the details of *how* these landraces are evolving remain poorly understood. Thus, our capacity to predict how maize landraces will change as a consequence of climate change remains quite limited (Mercer and Perales, 2010; Bellon et al., 2011; Ureta et al., 2011). Perhaps the most reasonable expectation is that maize landraces themselves, and their productivity, will be increasingly threatened by climate change. Jones and Thornton (2003) estimate that Mexico's simulated maize yields will decline from 1555 to 1440 kg/ha between 2000 and 2055, resulting in an absolute decline in annual production of 883,200 t. Hertel et al. (2010) similarly predict a 5% decline in coarse grain production (including maize) in Mexico by 2030.[2]

The consequences of climate change for maize landraces will be mediated by farmers, particularly the smallholders of southern Mexico who grow them. Thus the successful maintenance of maize landraces will be somewhat dependent on the adaptation of these farmers to climate change. Maize landraces will also continue to evolve at the nexus of these strategies and smallholders' livelihoods, in the complex agroecosystems that comprise their maize milpas. Consequently, any attempt to grasp how the TAS may shape outcomes in a place like southern Mexico must begin by conceptualizing the likely ways that smallholders may respond to climate change. This explains the structure of our paper. We begin by examining the most likely responses of maize farmers to climate change, then turn to consider the TAS.

Our central contention is that small-scale maize farmers in Mexico could suffer negative effects if transgenic technology is privileged as a climate change adaptation strategy. Since the TAS does not yet exist fully-formed in Mexico, we cannot demonstrate our argument empirically. Thus, we advance our argument through an analytical review of the literatures on agriculture in Mexico, genetic conservation of maize, and climate adaptation, which suggest that farmers will be likely to respond to climate change in three ways. On this basis we consider the implications of a transgenic adaptation strategy for each of these paths. We conclude by crystallizing our analysis into three arguments that could be used to frame policy.

2. Literature review

2.1. Maize and smallholder agriculture in Mexico

Maize is planted throughout Mexico, from very warm and humid climates at sea level to temperate and dry in the central plateau. Distinct races of maize have been associated with particular environmental conditions since they were first classified (Wellhausen et al., 1952). Recently, Corral et al. (2008) formalized this pattern for a set of Mexican races, finding that 42 races could be classified based on rainfall, photoperiod, and, most significantly, temperature. Three groups were discerned based on their temperature ranges: temperate, semi-hot to hot, and very hot environments (with a fourth group named after three races with particular differences). The International Center for Maize and Wheat Breeding (CIMMYT) uses a similar classification system for their breeding programs based on three major temperature classes (annual average temperature of >24, 18–24, and <18 °C), with several subtypes related to rainfall (Hodson et al., 2002). A similar pattern was found on a smaller scale for landraces of Chiapas in which the three main races were each distributed within one of the three distinct altitudinal ranges (>2000 m, 2000–1200 m, and <1200 m; Brush and Perales, 2007). It has been experimentally demonstrated that landraces adapt to particular environments (Jiang et al., 1999) and that landraces from tropical temperate conditions do not tolerate warmer climates due to local adaptation (Eagles and Lothrop, 1994; Mercer et al., 2008). These studies have important implications for thinking about climate change adaptation. Although we cannot presently specify the precise importance of future temperature increases and precipitation changes for maize yields, changes in temperature should be expected to have strong effects on maize landrace productivity because of its tight relationship with evolved traits.

What changes are expected for Mexico's climate? Mexico has already seen a mean annual temperature increase of 0.6 °C since 1960 (SEMARNAT, 2009; McSweeney et al., 2008), with a greater increase in the dry season (December to May) than in the wet season (June to November). The frequency of hot days and hot nights has also increased since 1960, but precipitation does not show any consistent increase or decrease for the same period (McSweeney et al., 2008). It is expected that mean annual temperature will increase by 1.1 to 3.0 °C before 2060 in Mexico and by 1.3 to 4.8 °C before 2090, with more rapid warming in the north and central regions of the country. Projections indicate a substantial increase in frequency of hot days and nights, as well as a reduction in rainfall for Mexico overall of −3% to −15% by 2090, with regional changes of −60% to +8% (McSweeney et al., 2008). These changes are likely to negatively influence maize production, particularly in areas where precipitation events become more infrequent or intense. As the World Bank (2009, p. 2) notes in the most recent Mexico country report on climate change, "agriculture is highly vulnerable to weather extremes, in particular in the Northern parts of the country, where water scarcity is an issue, or the Southern parts of the country, where tropical storms cause extensive damage to crop[s]."

[2] Hertel et al. (2010) offer a "low" estimate of −12%, a "medium" estimate of −5%, and a "high" estimate of +2% for Mexico's coarse grains in 2000–2030. While it is unclear (a) how they produce this range, and (b) the degree to which maize dominates the "coarse grains" category, as a rough estimate we find these data plausible. Mexico is not alone in facing possible declines. Lobell et al. (2011) estimate that *global* maize yields lost ~5.5% of their expected gains due to climate change between 1980 and 2010. Naturally, any attempt to model climate-induced yield changes works with considerable uncertainties.

2.2. Climate adaptation and Mexican agriculture

It is widely recognized that coherent adaptation strategies are needed to reduce the negative effects of climate change on agricultural systems and biodiversity (IPCC, 2007; Hatfield et al., 2008; Mawdsley et al., 2009). The Government of Mexico's climate change program specifically identifies "the adoption and implementation of sustainable agriculture" (2010, n.p.) as a central component of the national adaptation strategy. Agricultural adaptation can take many forms, occur on a number of scales, and involve diverse actors. Smit and Skinner (2002, p. 95) identify four general categories of adaptation: "(1) technological development, (2) government programs and insurance, (3) farm production practices, and (4) farm finance management." For any given strategy, we can expect that the likelihood of successful implementation will vary under different social, cultural, and climatic conditions (Appendini and Liverman, 1994; Rosenzweig and Tubiello, 2007). Distinct social groups and regions will adopt different strategies. Given the complexity of decision-making at the farm scale, particular farmers may gravitate toward integrating a specific strategy even if it is not considered the most effective because of how it fits with other factors the farmer must consider, such as ease of management (Smit and Skinner, 2002; Rosenzweig and Tubiello, 2007). The diverse needs of farmers make it unwise to focus on adaptive strategies that are merely posited as "choices between products" (Smit and Skinner, 2002, p. 107). Moreover, the conflicting needs among social groups restrict the ways adaptation strategies will unfold (Smithers and Blay-Palmer, 2001).

Yet farming systems in centers of diversity are not static and may have the capacity to adapt to climate change through biological processes as well. The genetic diversity within and among landraces constantly responds to natural and farmer-mediated processes (Brush, 2000), such as novel pests or changes in seed sharing networks. Climate change promises to introduce novel biotic and abiotic conditions and will invariably result in continued modification to landraces conserved *in situ*.[3] The key benefit of landraces is the diversity of alleles they possess that express traits such as physiological tolerances (e.g., to temperature extremes; Hayano-Kanashiro et al., 2009) or phenology (e.g., flowering time that avoids the hottest periods) – traits which could facilitate evolutionary adaptation. The diversity found in landraces should allow them to adapt to novel conditions, express plastic responses (i.e., changes in phenotype that are not brought on by changes at the genetic level), share adaptive diversity among populations via gene flow, and/or maintain productivity under changing conditions. Due to the great genetic diversity within and among Mexican farmers' populations (Pressoir and Berthaud, 2004a,b; Rice et al., 2006) as well as their tendency to be produced across environmental gradients (Corral et al., 2008), maize landraces may maintain fitness under novel conditions better than improved varieties (Mercer and Perales, 2010). Yet if climate shifts faster than the pace that landraces can evolve, diversity could decline. We have no measures of the rate at which landraces change under farmers management.

Such potential loss of agrobiodiversity threatens not only sustainability, but also social justice. The ties between maize landraces and livelihoods in Mexico are particularly intense and freighted with cultural and political significance (CEC, 2004; Fitting, 2010). The decline of diverse landraces is often interpreted as a threat to Mexican identity, and as a symptom of threatened rural livelihoods (Esteva and Marielle, 2003). In effect, poor Mexican farmers are bearing a burden – greater climatic variability – caused by carbon emissions from relatively wealthy people elsewhere (Füssel, 2010; IAASTD, 2008; IPCC, 2007). To many small farmers, this is an injustice (e.g., *Via Campesina*, 2009).[4]

In this context, the complex issues surrounding farmers' climate adaptation strategies deserve special scrutiny. Eakin's research among Mexican maize farmers provides many insights here (Eakin, 2000, 2005, 2006; Eakin and Lemos, 2006, 2010; Eakin et al., 2010). For Mexico's maize farmers, climate adaptation is nothing new (Eakin, 2006). The distinctive coping strategies of agrarian households are shaped by a number of key variables, including social class, geography, gender, agroecological context, not to mention religion. Complicating matters further, different groups *perceive* climate adaptive capacity to different degrees and in ways that are shaped by social class and identity (Eakin et al., 2010). Thus, the factors that shape agrarian households' distinct capacities to adapt to the vagaries of climate are inherently complex. These household-scale factors combine with multi-scalar political and economic processes – over which households typically have little power. Two are especially significant for Mexican households: agricultural markets (liberalized in Mexico during the early 1990s) and the capacity of state institutions to support households. As Eakin et al. (2010, p. 21) observe, "the nature of coupled social–environmental problems ... require innovative institutional arrangements to address the complex biophysical processes occurring at local, regional and global scales, while fitting within the economic, socio-cultural and political constraints of decision-making." Consequently, successful "community *adaptation* to the complex regional problem of flooding requires a substantial cross-scale and cross-sector effort by multiple actors ..., an effort unlikely to arise from existing frameworks for governance" in Mexico. This implies a need to build state capacity for assisting households with climate adaptation, but there are structural barriers to doing so. Given persistent inequalities of wealth and power, any adaptive strategy "will have to take into account both structural reform that addresses the roots of socio-economic and political inequality and governance mechanisms to manage risk specific to vulnerable sectors such as agriculture" (Eakin and Lemos, 2010, p. 2). Yet structural reforms are unlikely soon: hence the difficulty of creating just strategies for climate change adaptation.

3. Farmers' likely responses to climatic change

As climate changes, how will Mexico's farmers respond? Previous research with small-scale farmers in southern Mexico suggests three expected responses.

3.1. New cultivars

The first response may be to introduce new cultivar types that may be better adapted to the new conditions. We expect the majority of new cultivars would be other landraces, not improved varieties, since the area devoted to cultivation of improved

[3] Presently agriculture only accounts for 7% of Mexico's total GHG emissions (World Bank, 2009).

[4] The rise of arguments for 'climate justice' can be explained by the fact that climate change has been brought on principally by the burning of fossil fuels in the global North (IPCC, 2007), yet many of the worst consequences of climate change will be experienced principally by the poor of the global South. Some in the climate justice movement interpret the TAS as an opportunity to create new financial opportunities in the North. For instance *La Via Campesina*, an international network of peasant organizations, prepared a response to an FAO-sponsored conference in Guadalajara, Mexico on "agricultural biotechnologies in developing countries," where they argue: "This conference has been prepared with no intention to hide the promotion of biotechnology as a solution for the food and climate crises, thus promoting the corporations' standpoint and agenda.... The crises are real but its solutions would not come from expensive, patented and controlled technologies set forward by a handful of transnationals. Indeed, these techno-fixes may pose further risks to hunger, health, environment and biodiversity" (*Via Campesina*, 2009, our translation). See also *Declaración* (2010).

commercial seed has remained relatively steady at 25% for more than two decades (CIMMYT, 1994; Aquino et al., 2001; Herrera et al., 2002). In Mexico, maize farmers may have already started to adapt to recent climate change by delaying planting when the rainy season starts late (Conde et al., 2006). Also, some farmers plant several cultivars with distinct drought tolerances and maturities in the same field, insuring at least some production in bad years and higher production in good years (Hernández, 1971). Although farmers are accustomed to choosing varieties with distinct traits (for instance, in response to market conditions: Perales et al., 2003a,b), it is not clear that they have experience switching varieties in response to the magnitude of anticipated climate change. The same may be true with seed acquisition.

Farmers planting landraces do not rely solely on their own genetic resources. Family members and acquaintances are by far the most common outside seed suppliers (Badstue et al., 2006; Brush and Perales, 2007). In one study of six communities from Oaxaca, a quarter of the farmers acquired or distributed landrace seed for the year under study and more than 88% of these transactions occurred between local family and acquaintances (Badstue et al., 2006). Seed from local origins is not only locally adapted; it comes with information from trusted sources (Perales et al., 2003a,b). A more recent study in five states in eastern Mexico concurred (Bellon et al., 2011). More than 90% of seed came from within a 10 km radius of the farmer's community (Bellon et al., 2011), although a small fraction (>1%) can also come from out of state (Brush and Perales, 2007). Long-standing seed exchange practices have proven to work well under unhurried demand for change, providing farmers with reliable seed. But are they equipped to confront rapid climate change?

In a period of rapid climate change, overreliance on local seeds may limit the success of farmers' responses. Seeds from neighboring communities with distinct agroecological conditions may be beneficial (Perales et al., 2005). Some argue that, given current variability across the landscape, the novel climate of the future exist within close range (Bellon et al., 2011). If so, maybe farmers may already be trading seeds that could benefit them in the future, but they may need to look farther afield. A farmer could be drawn to look outside the normal networks if aware of sufficiently different populations with desirable characteristics. Yet a lack of social networks may keep farmers from planting the seeds of others with whom they had never traded seed. New social networks to support this new seed sharing may be slow to emerge; the uneven geography of climate change further complicates such strategies. This conundrum could lead to the loss of seed diversity. How might farmers acquire informal seed with relative high success from unknown agents and places?

In some places there are traditions of such exchanges. In the Chalco region, on the outskirts of Mexico City, farmers seek out seed from relatively distant communities with similar environments every several years (Perales, 1998). Such networks may facilitate the spread of seed sharing that could allow landrace populations to effectively migrate with the changing environment. In this way, farmers might hope to find adaptive strategies within traditional practices. Badstue et al. (2006) found that the main reasons for acquiring seed were for experimentation and, to a lesser extent, to overcome lack of seed of their own. More research is needed to further examine the effectiveness of such mechanisms and the information that accompanies the seeds.

3.2. Adaptation by local maize varieties

The second likely response to declining yields is that farmers may, through selection, attempt to spur adaptation of existing local varieties (i.e., farmer breeding). Almost all maize farmers select their seeds as ears from their harvest pile (Herrera et al., 2002; Perales et al., 2003a,b). In Oaxaca, Mexico, farmers' selection criteria are complex, but the most important criteria appear to be related to seed viability (ears with evidence of pest or disease damage are usually discarded), large ears and large kernels, as well as traits that define variety type (Cleveland et al., 2000). It has been shown that farmers' selection solely on ears weakly affects plant characteristics through indirect selection (Louette and Smale, 2000). Yet some farmers select ears for seed in the field before harvest and thereby take into account plant attributes, which could include plant performance in stressful years. In a survey of 16 maize-farming communities in Mexico, Herrera et al. (2002) found that there are communities where selection of seed in the field is common and others where it is completely absent. The factors associated with greater selection in the field were unclear, but selection in the field was identified both in subsistence and commercial production. Mexican maize farmers seem to have an understanding of high and low heritability (h^2) traits, such as tassel color (high h^2) and ear length and seed size (low h^2; Soleri and Cleveland, 2001). Thus, natural selection may dominate changes in non-ear traits that will be important for adaptation to climatic change, but farmer selection could enhance or contradict that adaptation depending on the region.

Farmers also understand hybridization and the transfer and recombination of traits that result. Maize farmers recycle and 'creolize' commercial cultivars (Bellon et al., 2006), hybridizing (sometimes inadvertently) local landrace populations with commercial cultivars (Perales et al., 2003a,b). In the commercial producing region of Chiapas, one study found that 27% of the seed being used was originally acquired as a commercial variety that had since become creolized with local landraces from cross-pollination (Bellon et al., 2006). Similarly, in Morelos, Perales et al. (2003a,b) found that some farmers planted seed of commercial hybrids and local landraces mixed in the same field to force hybridization, or some planted one row of each type throughout the field. Farmers said they sought to introduce characters for reduced height and drought resistance from the commercial hybrids to their landrace populations without the need to repurchase seed.

Thus, at least some farmers are familiar with the practice of introducing new desirable genes into their landraces, which could be valuable for a more focused improvement program. For instance, narrowly adapted landraces from the highlands of Mexico (Eagles and Lothrop, 1994; Jiang et al., 1999; Mercer et al., 2008) could potentially be enhanced by judicious introgression of specific genomic regions from lowland germplasm. Such 'improved' landraces with genes of interest could be introduced for incorporation into the local gene pools. This has been done to provide breeders with attractive plant genetic resources that are easy to use, while being found within a farmer's genetic background (Haussman et al., 2004; Nass and Paterniani, 2000). Another approach is for researchers to offer farmers alternative varieties, based on local landrace populations, from which to experiment (Bellon et al., 2003). The aim of such participatory breeding would be to improve on farmers' adoption of varieties by their participation; the involvement of farmers in evaluating varieties in their own environments can improve the translation of findings into change in the *milpa* (Ceccarelli and Grando, 2007). A considerable amount of research has been conducted on this subject (e.g., Ceccarelli et al., 2000, 2003; Soleri et al., 2000; Morris and Bellon, 2004). Such experience may prove essential in designing adaptation strategies for landrace populations.

3.3. Declining maize production

Thirdly, if landrace populations cannot evolve as fast as climate changes, or if farmers are unable to find more appropriate landrace populations to plant, farmers may opt to grow less maize. In this event, they may either plant other crops or leave agriculture. It is unclear how great a decline in yield would force such change for maize in Mexico. A full discussion of these dynamics is beyond the scope of this paper, but a few comments are warranted.

Maize has been the main staple in Mexico for millennia (Smith, 1967) and its importance in food security for rural households cannot be overstated (CEC, 2004; Bellon et al., 2011). Even under harsh environmental conditions maize has a reliable yield. More than fifteen years after significant price declines brought on by NAFTA, the area planted under maize remains relatively unchanged and the number of small-scale households – about 85% of >2.5 million maize producers plant less than 5 ha – has not declined. One reason for this is that subsistence producers raise crops partly to produce their own food; hence their agricultural practices are not exclusively market-driven, but reflect the need to reproduce the household (De Janvry, 1981; Eakin, 2006; Isakson, 2009). Some have found that the area under maize production can even increase when maize prices decline, as maize farmers seek to compensate for declining prices by applying their labor more intensively (Dyer et al., 2006; Arslan and Taylor, 2009; Arslan, 2011).[5] Maize continues to be produced when opportunity costs are clearly unfavorable (Perales et al., 1998). Moreover, for most rural households, maize is no longer their main income source, as they have become highly diversified (Carton de Grammont, 2009). Given these complexities, we are presently unable to predict the amount of yield decline maize should have for Mexican farmers to abandon its cultivation – yet there must exist a theoretical breakpoint beyond which large numbers of maize farmers cease production.

4. The transgenic adaptation strategy

The transgenic adaptation strategy (TAS) is emerging against the backdrop of these complex and uncertain changes. Discussions around TAS center on the hope that insertion of individual genes (or 'stacks' of genes) could bolster a crop's ability to deal with the abiotic changes wrought by climate change. As a news feature in *Nature* describes, the world's largest seed companies, led by US-based Monsanto, are employing biotechnology intensively to find "commercial gains in crops that can withstand water- and nutrient-deficient soils" (Gilbert, 2010, p. 548; compare Ortiz, 2011).[6] Preliminary research suggests that there may be considerable gains from the suppression of drought-induced senescence, at least in transgenic tobacco (Rivero et al., 2007).[7] Since climatic change in many regions is expected to result in more erratic precipitation patterns, advances in drought resistance could bring important benefits.

These crops are not only being promoted as potentially beneficial for large-scale, industrial production. They are also touted as a way for subsistence farmers to improve their lot and combat climate change (Pinstrup-Andersen and Schiøler, 2000). Proponents of transgenic agriculture have successfully tied climate adaptation to genetically modified (GM) seeds in popular discourse. For instance, an editorial in the *New York Times* (Ronald and McWilliams, 2010, p. A17), provocatively entitled "Genetically engineered distortions", argues that critics of transgenic technology have prevented it from helping "the poorest regions of the world – areas that will bear the brunt of climate change." The editorial posits that poor farmers who suffer from drought, for instance, would benefit from transgenic seeds (yet it cites no scientific papers or specific transgenic cultivars to support this claim). Similar illustrations, where transgenic agriculture is singled out as a crucial tool for climate change adaptation, abound in the popular media (compare, for instance, Aldhous, 2008; EC Newsdesk, 2008; Padma, 2008; Gray, 2009; Hall, 2010; Aslet, 2011). A lead editorial from the influential weekly, *The Economist* (2010), entitled "How to live with climate change," illustrates the narrative, celebrating transgenic agriculture's contribution to food security in an era of climate change: "Drought-resistant seeds are needed... [and s]ince genetic modification would help..., it would be handy if people abandoned their prejudice against it."[8]

Regardless of its scientific merits, this chorus seems to have contributed to enhanced support for transgenic agriculture. The head of the British Government's Environment Agency has said that his society "must be 'readier to explore' GM food as farmers' woes increase," in response to climate change (Hall, 2010); similarly, in Australia, newspapers report that farmers "need GM crops" to adapt to climate change (Anon., 2007). In Brazil concerns about climate change have triggered an expansion of research into transgenic seeds (ICTSD, 2009). Perhaps the most notable case concerns the Vatican, which was arguably the world's most important institution opposing the spread of transgenics in the 1980s and 1990s (Wainwright and Mercer, 2009). In a remarkable turnabout, a 2009 Vatican study calls for full support of transgenic agriculture partly to assuage the risks of climate change: "The predicted impact of climate change reinforces the need [for transgenic agriculture] ... so that traits such as drought resistance and flooding tolerance are incorporated into the major food crops of all regions as quickly as possible" (Potrykus et al., 2009, p. 4).

There have been numerous public criticisms of the transgenic adaptation strategy (cf. ETC Group, 2008, 2009; *Declaración*, 2010; Acevedo et al., 2011). Our aim is to weigh the arguments against the TAS specific to crop centers of origin, such as Mexico, where the introduction of novel genetic materials may be especially problematic. We first consider the limitations of adaptation strategies that focus on improving seed varieties in general and then consider drawbacks associated with transgenic methods in particular.

4.1. Limits to germplasm development for climate adaptation

The development of crop germplasm and varieties for climate change has been heralded as an essential mode of adaptation (e.g. Vermeulen et al., in press). Considerable emphasis has been put on development and use of varieties with appropriate stress tolerances (e.g., drought tolerance), changing of planting dates, or managing new pests with new chemicals (Cutforth et al., 2007). Some of these strategies are already applied in response to gradual climate change and extreme weather events. However, we may be hindered by a lack of experience with breeding for resilience to environmental variability, rather than simply for a new environmental mean. Breeders excel in generating varieties that allow a given crop to grow under new environmental conditions, but their work usually involves targeting an environmental mean – not more *variable* environmental conditions (Smithers and Blay-Palmer, 2001). While breeders do try to develop varieties that perform well across a region, the selection process sometimes can

[5] After a long period of declining prices received by maize farmers in Mexico, maize prices have increased since ~2008 (Dyer and Taylor, 2011).

[6] While the sums invested in these efforts are not publically available, Monsanto's research budget is almost as large as the total spent by the US public sector on agricultural research (Gilbert, 2010).

[7] There is some question as to whether genetic modification will be necessary to bring these gains, e.g., the first two 'drought-resistant' varieties of maize to be distributed for widespread planting – in sub-Saharan Africa – were developed through conventional plant breeding (CGIAR, 2009; Gilbert, 2010). See also Pray et al. (2011).

[8] The pattern of claims in the news media suggests that they may have resulted from corporate efforts to link transgenics with climate change adaptation as a marketing strategy, as suggested by Wallace (2010).

disregard data collected on germplasm from years with unusual conditions, reinforcing the aim of breeding for a region's norm.

Given that future climates will be in flux – both in terms of monotonically changing means and also increasing variability (IPCC, 2007) – an adaptation strategy should facilitate resilience to change by increasing the adaptive capacity of the whole agroecosystem. This raises two questions: what kinds of varieties can increase resilience to environmental change, and how do we breed for them? We know that farming practices that increase resilience and system stability include those that reduce soil erosion, increase water holding capacity of the soil, and increase biodiversity, which should all be helpful for continued productivity with climate change (Rosenzweig and Tubiello, 2007). What would be the equivalent for genetic materials? Genetic variation within and among varieties planted in a cropping system where evolutionary processes change the genetic make-up of crops as climate changes may be most useful (Mercer and Perales, 2010). This describes a landrace-based system better than one focused on improved varieties (IAASTD, 2008).

An additional limitation would be the number of landraces that would require genetic transformation. If we consider that there are about 60 mayor races of maize (Sanchez et al., 2000) and each race may include several variants, in some cases with distinct adaptation to microenvironments (Eagles and Lothrop, 1994) and other only for color or quality differences, there are several hundred or more landraces. Engaging in the transformation of so many types of maize, while maintaining present genetic diversity, would be wanting on cost–benefit analysis.

4.2. Limits to transgenic germplasm development for climate adaptation

The use of transgenic varieties to combat climate change intensifies the problems inherent in using improved varieties. Yet it also introduces additional concerns. We contend that adaptation strategies envisioned for smallholders in Mexico should not assume the use of transgenic crops and we posit three reasons.

First, the diversity of environmental conditions found in many smallholder systems can make it risky to implement improved varieties, transgenic or not. Improved varieties of maize do not produce as well as landrace varieties in many parts of Mexico due to distinctive environmental conditions (Muñoz, 2005). This issue would not likely be resolved simply with the introduction of new transgenes. Thus, for instance, drought resistance inserted into an otherwise inappropriate genetic background is unlikely to improve production. Similarly, drought conditions vary (Wilhite and Glantz, 1985), so not all drought resistance transgenes should be alike. Drought can come in different intensities, at different points in a crop's life cycle. Given the great environmental heterogeneity in many (often mountainous) smallholder agricultural regions, this issue would likely be even more significant.[9]

In this respect, the first transgenic varieties do not appear to be promising. Indeed, a transgenic maize variety bred for greater drought resistance for the US (MON 87460) has not been demonstrated to significantly improve yield under stressful conditions (Reeves, 2010) and does not exceed the yield variation already found among the regionally adapted, conventionally bred, drought tolerant maize cultivars (APHIS, 2011). This cultivar is not expected to expand into areas where maize is not currently grown or otherwise alter maize production (APHIS, 2011). Drought resistance, however, may be easier to engineer than other more urgently needed traits associated with climate change (Ortiz, 2011). Consider, for instance, hurricane resistance,[10] which will increase in importance for southern Mexico (World Bank, 2009; Manuel-Navarette et al., 2011) and might be better achieved at the level of the farming system since a uniform improved variety might be less resilient than a diverse agroecosystem. In sum, transgenic crops could be less effective than hoped for climate change adaptation.

Second, there has been a notable lack of social and cultural acceptance for transgenic maize in Mexico since its inception. This was made clear after Quist and Chapela (2001) found transgenes in Oaxacan maize and set off an array of studies to clarify the degree to which transgenes could be found in Mexican landraces (Ortiz-García et al., 2005; Mercer and Wainwright, 2008; Piñeyro-Nelson et al., 2009).[11] Given that Mexican farmers have a strong culture of mixing or hybridizing varieties (Section 3.2), the introduction of transgenic maize could result in the spread of transgenes to other local landraces. There are a number of movements within Mexico (e.g., *Sin Maíz No Hay País*, *Red en Defensa del Maíz*) which are concerned about the multi-faceted threats to landrace maize and the farmers that grow it. Transgenic maize has been highlighted as a primary threat, and many have called for a complete ban on transgenic maize and special protection for landraces (*Declaración*, 2010; *Sin Maíz No Hay País* et al., 2011).[12] Similar concerns have been expressed in other centers of crop origin (e.g., farmers in India have protested *Bt* eggplant: Andow, 2010). Of course, if a technology increases productivity, farmers may pragmatically decide to use it, despite their disdain (Aerni and Bernauer, 2006). Nevertheless, we feel that it would be unwise to center a climate-adaptation strategy around an unpopular technology.[13]

The third reason that transgenics should not be central to any adaptation strategy is that such seeds may replace the existing landrace populations – which may possess the best capacity to survive climatic fluctuations in the long term. Landraces not only tend to have high levels of genetic variation, but that variation is already tightly coupled with the environmental variation present in a region (Mercer et al., 2008). Genetic variation within populations and/or the free flow of genes between populations through cross-pollination or mixing of seeds may allow landraces to evolve in response to climatic change (Döring et al., 2011; Davis et al., 2005; Mercer and Perales, 2010). In fact, studies of pearl millet in Niger have shown that reduced precipitation in the Sahel over the past three decades has selected on landrace populations such that they flower earlier, are shorter, and produce a shorter spike (Vigouroux et al., 2011). The plasticity landraces possess may also allow them to weather more variable conditions (Döring et al., 2011). By contrast, improved varieties (including transgenics) are typically bred for high productivity within a relatively narrow range of agronomic conditions and tend to be more sensitive to poor conditions than more genetically diverse open-pollinated

[9] As Ortiz (2011, p. 193) explains, ''engineering complex traits for adapting to climate change is likely to be much more challenging than the first generation of biotech crops such as herbicide tolerance or host-plant resistance to pests, which manipulated single transgenes. Transgenic . . . crops with enhanced environmental stress tolerance are also likely to require substantial advances in biosafety assessment and regulatory approval that are very different to first generation of commercial transgenic crops.''

[10] Hurricane resistance might have to include a complex of traits including possibly wind tolerance, flooding tolerance, and a strong root system for holding soil in place and surviving landslides.

[11] Recent events in Mexico – e.g., the passage of 'maize laws' in Michoacán and Tlaxcala including provisions against transgenic cultivars, protests against the field testing of transgenic maize varieties, and persistent actions of social organizations against transgenic maize – indicate that the transgenic maize issue remains intensely politicized (see RDMN, 2008).

[12] Some farmers in Mexico have conducted citizen science on the presence of transgenes in local maize varieties and have developed local strategies to address contamination (Rosset, pers. comm., 2008).

[13] Farmers' opposition to transgenic seeds may be a key factor for the success of transgenic adaptation strategy. If farmers who maintain landraces come to perceive that some seeds are 'contaminated' by GM maize, *in situ* conservation practices will likely suffer (Bellon and Berthaud, 2006).

varieties or landraces. However, the rate at which landrace populations will evolve under climate change remains unclear (Mercer and Perales, 2010).[14] It is possible that plasticity and selection in landraces will more appropriately reorganize the genetic diversity on the agroecological landscape than could be achieved through a technological strategy, especially employing genetically uniform improved varieties (transgenic or not). Moreover, the adoption of transgenic seeds (or any large scale adoption of any improved variety) could reduce the genetic diversity conserved by farmers *in situ* (Bellon and Berthaud, 2006).

Thus, while transgenic crops are being offered as replacements for traditional varieties, and could ultimately supplant landraces, there may be inherent mismatch between the strengths of this technology and the conditions under which it would be applied.[15] As the IAASTD summarizes: ''No particular actor has all the answers or all the possible tools to achieve a global solution'' (2008, p. 45).

5. Conclusions

To conclude, we will crystallize three key points that could plausibly be used to guide policy.

The first concerns state capacity (see Section 2.2), which will be central to any coherent adaptation strategy for a country like Mexico. We have argued that maize landraces are likely better than transgenic crops for adapting to climate change. However, these landraces could be lost under rapid climate change if they cannot evolve quickly enough (by natural and farmer-mediated selection) or respond plastically to climate change. We do not presume that farmers' responses to climate change will automatically result in the maintenance of existing diversity. Thus there may well be appropriate interventions to facilitate the conservation of diversity in a way that improves farmers' ability to adapt. For instance, we could see the state playing a role in training farmers about the likely implications of climate change and helping them to prepare possible responses (for example, in extending their seed networks). Additionally, more research is necessary on the complex relations between climate change, agroecosystem dynamics, and agricultural practices. Even with a well-studied case such as maize in Mexico, there are important gaps in the kinds of knowledge that are crucial for adaptation (see Section 2.1 above). Investing in practical research on the likely effects of climate change for Mexico's diverse maize farms is essential. In the Mexican context, where the most important agricultural and environmental research institutions are all closely tied to (and largely funded by) the Government, state leadership is critical. In sum, our critique of the transgenic adaptation strategy is not to suggest that we should have no adaptation strategy at all. And any effective strategy will likely require state leadership and enhanced capacity in state agricultural agencies.

Our second point is to emphasize the potential for participatory maize research and breeding for climate adaptation (see Section 3.2). Strengthening the social relations of maize production and seed exchange are likewise fundamental to a successful adaptation strategy. Farmer involvement should be central to any successful agricultural adaptation strategy – not only because ethically farmers should be at the center of this research, but also because ultimately farmer adaptation is the only means of saving the landraces that are crucial for future generations. Strong adaptive strategies in poor regions are those that build upon existing strengths. In subsistence systems, this is often the plastic nature of diversified, low-risk, livelihood strategies. As the World Bank explains in their proposed framework on the role of local institutions in adapting to climate change, adaptive strategies that ''focus simply on improving total benefits to households without taking into account [how] households can address fluctuations in their livelihoods seem ill-suited to address the impacts of climate change'' for two reasons:

> On the one hand, they ignore the most important characteristics of climate-related stresses[:] increased riskiness of livelihoods. On the other hand, they ignore the very real concerns of the rural poor about preventing hunger and destitution. . . . To strengthen the adaptive capacity of the rural poor, therefore, governments and other external actors need to strengthen and take advantage of already existing strategies that many households and social groups use collectively or singly (2010, no page).

Among the ''already existing strategies'' that agrarian households in Mexico employ to reduce the risks associated with the vagaries of climate is the planting of diverse landrace varieties.

This brings us to our third and final point, which is to discourage an emphasis on the TAS for maize small-holders in Mexico (see Section 4.2). Rather than transgenic seeds, what is needed in our view is an intensive climate change research and adaptation program governed by an evolutionary agroecological perspective (Mercer and Perales, 2010). Such a program would center on participatory breeding within and evolutionary breeding framework (Döring et al., 2011) to adapt local landraces to climate change, while maintaining the very diversity that makes landraces resilient to environmental flux. It would also emphasize the sustainable management of water and soil resources, seed networks, and maintenance of a diversity of crops. Such a program should complement the strategies maize farmers already employ.

Those pushing for the TAS might not see these three points as leading toward the 'modernization' of Mexican agriculture. Yet they are, we feel, essential for successful adaptation.

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[14] Of course, there are no assurances that conventional breeding or genetic engineering will be able to keep up with climatic change.

[15] We recognize the internal heterogeneity of maize farming in Mexico. Where maize production is largely commercial and industrialized, as in areas of northern Mexico, farmers may favor the TAS.

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