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Changes in Climate, Crops, and Tradition: Cajete Maize and the Rainfed Farming Systems of Oaxaca, Mexico

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Abstract The traditional management systems of the Mixteca Alta Region of Oaxaca, Mexico offer historical lessons about resilience to changes and variability in climate. We interviewed small farmers to inquire about the dynamics of abandonment and persistence of a traditional management system known as cajete maize. The previous generation had sown cajete maize more extensively across the landscape, but farmers increasingly relegated it to high elevation, frost prone agricultural environments that were less suited for seasonal maize. We interpret farmers' narratives of changing cropping systems from a perspective of general agroecological resilience. The most recent years presented increasingly extreme climatic and socioeconomic hardships: increased temperatures, delayed rainy seasons, reduced capacity of soils to retain soil moisture, changing cultural norms, and reduced rural labor. Transformative change is required to develop novel cropping systems and complementary activities to agriculture that will allow for farming to be sustained in the face of these challenges.

Keywords Agroecological resilience · Climate change · Traditional management systems · Rainfed agriculture · Mexico

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Introduction

The landscape of the Mixteca Alta of Oaxaca, Mexico bears witness to a legacy of soil erosion and social marginalization that scholars address from different theoretical perspectives: cycles of social-ecological resilience (Perez Rodriguez and Anderson 2013), institutional failure (García-Barrios and García-Barrios 1990; García Barrios *et al.* 1991), as well as cultural norms and dominance (Edinger 1996). Less studied is the resilience of traditional management systems of the Mixteca Alta to climate change.

Climate change is expected to disproportionately impact tropical regions where the majority of small farmers and pastoralists reside (Easterling *et al.* 2007). Climate models predict shortened growing periods and decreased water availability among other trends that globally may result in a 10 % decrease in grain yields by 2080 (Parry *et al.* 2005). Dryland regions may experience a 25 % decrease of soil moisture due to the expected increase in frequency of warm years and reductions in rainfall (IPCC 2007; Bates *et al.* 2008; Maestre *et al.* 2012). It is expected that crop failures due to climatic variability will affect food security of the rural poor in many parts of the world (IPCC 2014).

However, it is also well recognized that small farmers already manage for climate (Wilken 1987: 224) through self-reliance, experiential knowledge, and the use of local resources (Altieri 2002; Tengo and Belfrage 2004). In dryland systems, farmers have developed numerous techniques to increase soil water holding capacity, thus reducing vulnerability to drought and abating processes of soil erosion (Barrow 1999). Examples include lithic mulching, tied-ridges, contour furrows, rainwater harvesting, and hand-dug pits (Boers and Ben-Asher 1982; Critchley 1989; Lightfoot 1994, 1996; Reij *et al.* 1996; Stigter *et al.* 2005). Such traditional management systems provide important insights for the resilience of small farms to climate (Altieri and Nicholls 2013).

The literature distinguishes between general resilience of any and all parts of a system to a variety of shocks and stresses (Folke *et al.* 2010) and specified resilience of a system to a particular shock or stress (Carpenter *et al.* 2001). General resilience may present challenges in terms of applicability while a narrow focus on specified resilience may lead to losses of other forms of resilience (Folke *et al.* 2010; Berkes and Ross 2013). Ecological systems and humans are viewed as coupled, but the social science component of resilience remains understudied (Tengo and Belfrage 2004; Davidson 2010; Berkes and Ross 2013). A broadened framework based on an inductive approach may provide important insights on the social diversity, flexibility and relationships at multiple scales that produce a resilience effect (Carlisle 2014).

Agroecological resilience has been measured as: yield stability during years of unfavorable climatic conditions (Gaudin *et al.* 2015); differences in the buffering effect of agroecosystems on microclimatic conditions (Lin 2009); the relative impact of extreme climatic events on farms (Holt-Giménez 2002; Philpott *et al.* 2008); and their subsequent rate of recovery (Rosset *et al.* 2011). These studies suggest that on-farm biodiversity contributes resilience and a faster rate of recovery from climatic disturbances.

In the field of agroecology the focus is primarily on specified resilience to abiotic and biotic factors. Few studies consider the farm, ecological, and social systems from a general resilience perspective. Here we use a general resilience perspective to explore changes in Mixteca Alta cropping systems. We were intrigued by the dynamics regarding abandonment and persistence of long duration cajete maize (*maíz de cajete*) over the last generation, specifically whether farmers are responding to perceived changes in climate and how these changes affect the resilience of farming systems. We also considered how these changes were adaptations to current cultural and socioeconomic realities.

Study region

The Mixteca Alta is for the most part classified as a subtropical dry winter climate (Cwb) according to the Köppen-Geiger system, receiving the majority of rainfall from June through September. Temperatures are lower at higher elevations, and frosts are common from October through March. Farmers in the communities where we conducted this study reported more prolonged drought, increased storm intensity, and later onset of the rainy season, (consistent with the regional climate record analyzed by Rogé *et al.* (2014): strong evidence that temperatures have risen over the last 50 years (ca. 0.16 °C per decade); some evidence of increasing trends in rainfall intensity over the same period; and a slight increase in late season relative to early season rainfall.

The Mixtec people (or people of the rain - *Ñuu savi*) have farmed the semi-arid highlands of southern Mexico since the very origins of agriculture. The Mixteca Alta is located midway between the Tehuacán Valley and Oaxaca Valley where the oldest evidence of maize domestication has been identified (Benz and Iltis 1990; Benz 2001). Agrarian communities flourished as early as 1400 BCE (Spores 1967, 1972, 1983, 2007; Blomster 1998: 287; Kowalewski *et al.* 2009). In pre-Conquest times, intensive hillside terracing gained prominence with the growth of hilltop urban centers between 300 and 100 BCE (Perez Rodriguez and Anderson 2013).

Mixtec strategies for growing rainfed crops in an unpredictable climate and in soils with high erosive potential included: diversity management to reduce the impact of crop failure and increase agroecosystem performance; the cajete maize cropping system, sown during the dry season to avoid flooding and frosts at the end of the rainy season; and landscape modification such as leveling, terracing, and land containers for enhancing agricultural productivity and sustainability (R. García-Barrios and García-Barrios 1990). However, Borejsza *et al.* (2008) note that while terrace agriculture increased productivity in the short term, eventual abandonment increased rates of erosion that left slopes barren in much of highland Mexico.

Disturbances in Mixtec society occurred in pre-Conquest periods: terrace construction, occupancy, and abandonment fluctuated with the movement of settlements and changes in populations from 200 to 1521 CE (Kowalewski *et al.* 2009: 297–303, 345–346). Trade, conflict, and elevated populations were characteristic of the period from 900 to 1521 CE (Perez Rodriguez and Anderson 2013). By Spanish contact, the majority of hillsides and drainages were terraced (Cook and Borah 1968: 144; Romero Frizzi 1996; Perez Rodriguez and Anderson 2013).

A key moment of social and environmental crisis occurred immediately following European contact. The Mixteca Alta population plummeted from 700,000 in 1520 CE to 20,000–25,000 in 1620 CE as a result of conquest, epidemics, and colonial living conditions (Cook and Borah 1968). Urban settlements were relocated from hilltops to valley floors following the European model of urbanization (Perez Rodriguez and Anderson 2013). Highland farmers who had maintained terrace systems resettled to the lowlands, leaving their terraces to erode (Pastor 1987). The post-Conquest periods introduced new products and production systems: silk and cochineal, animal husbandry, wheat, and the Egyptian plow (Romero Frizzi 1996:157–58). Terraces were widened or removed to accommodate animal traction (Perez Rodriguez and Anderson 2013). Some of these new systems reduced the need for agricultural labor and contributed to increased levels of soil erosion.

Since the Revolution of 1910, livelihoods have increasingly been divided between subsistence farming and remunerated labor. Low market values for grains created by trade policies, such as the North American Free Trade Agreement (NAFTA), have undermined local economies and compromised the ability of communities to generate an income from agriculture (Edinger 1996; Perez Rodriguez and Anderson 2013; Schmook *et al.* 2013). A landed, yet highly mobile, labor pool has introduced dramatic changes in local farming systems: decreases in yield due to simplified farming practices; lower quality local farm labor; and the limited diffusion of modern technologies without increased productivity (Masera Cerutti 1990; García-Barrios and García-Barrios 1990).

The challenges of social marginalization have persisted despite decades of governmental and civil society initiatives. Oaxaca ranked in the lowest relative socioeconomic level in the nation along with Guerrero to the west and Chiapas to the east, while the municipalities we studied received the lowest socioeconomic rankings (Table 1, INEGI 2004). Similar to the international decline in small-scale farming (GRAIN 2014), populations in the municipalities we studied have steadily decreased in recent decades; notably, the population of children and adults of working age has decreased while the elderly have increased (Figs. 1 and 2; INEGI 2005, 2010).

Methods

In 2011, we conducted 29 in-depth interviews and 20 months of participant research with farmers from the communities of San José Zaragoza (Zaragoza) and San Miguel Huautla (Huautla). Farmers in both communities had substituted long duration cajete maize with relatively short duration seasonal maize (*maíz de temporal*) in the temperate, mid-elevation lands (*tierra templada*) between 20 and 60 years ago. Transects placed the temperate lands between approximately 1800–2000 masl (Ríos *et al.* 2012).

The communities differed in their experiences with drought and crop failure, as well as with their adoption of mechanized agriculture (Rogé *et al.* 2014). Zaragoza belongs to the much larger municipality of Santiago Tilantongo. The 25 households who farm there grow largely seasonal crops (Agency Authority, personal communication, August 28, 2011). We therefore included farmers from the neighboring community of San Isidro where cajete maize is more widely grown. Zaragoza has received comparatively more rainfall in the last decade than Huautla, and farmers have maintained their maize landraces for generations.

Table 1 Percent of the population ranked in terms of socioeconomic wellbeing from 1 (low) to 7 (high) in the two municipalities in the Mixteca Alta Region of Oaxaca, Mexico that participated in this study: Santiago Tilantongo (community of San José Zaragoza) and San Miguel Huautla. Data source: INEGI (2004)

Municipality	1	2	3	4	5	6	7
Santiago Tilantongo	19 %	81 %	0 %	0 %	0 %	0 %	0 %
San Miguel Huautla	100 %	0 %	0 %	0 %	0 %	0 %	0 %

Huautla encompasses a wide elevation gradient and different soil types that provide the environmental conditions for a diversity of agroecosystems. It is also a relatively small municipality, with approximately 300 households (Municipal Authorities, personal communication, March 15, 2011). Farmers experienced a series of drought years from 2005 to 2009 when many lost their landraces of maize. As a result, families replaced wheat for maize in their tortillas. Unlike Zaragoza where tractor cultivation has been partially adopted, farmers in Huautla largely use draft animals (*yunta*).

We conducted 29 semi-structured interviews, each lasting between 2 and 3 h. We prepared questions in advance about cropping systems, agricultural environments, climate, and family economy. However, our conversations evolved naturally. Following Eakin (2006), we selected interviewees who primarily grew seasonal crops and interviewees who additionally grew cajete maize (*cajeteros*, Fig. 3). All households grow seasonal crops, and most families raise small herds of sheep and goats. Forty-five percent of interviewees produce cajete maize (30 % in Zaragoza and 53 % in Huautla).

We interviewed those farmers who still resided in their communities. This introduced the potential selection bias for those families who practiced cyclical migration instead of the much larger community who were already well-established elsewhere (Moore and Vaughan 1994:147). The interviews represented approximately 10 % of households residing in Huautla and 30 % of households residing in Zaragoza. Interviewees described their households as related individuals living in proximity to one another and sharing common resources (land, animals, agricultural products, monetary income, etc.). Median household size in Zaragoza and in Huautla was five (Table 2). The median age of households interviewed was much younger in Zaragoza (19 years) due to a larger percentage of families with children living at home than in Huautla (35 years). We interviewed men and women either together or separately (Table 3).

Field notes were transcribed and sorted into pre-identified themes with a custom gawk script (Free Software Free Software Foundation 2008). Various R packages were used for data manipulation and analysis (Wickham 2007, 2009, 2011; Neuwirth 2011; R Core Team 2013; Dowle *et al.* 2014). We followed the protocol approved with exempt status by the Committee for Protection of Human Subjects at UC Berkeley (Protocol # 2010-02-880).

Results

Traditional Management Systems

Both cajete maize and seasonal maize systems were based on landraces highly valued for their productivity as well as culturally preferred for their storage and culinary qualities and for their sacred heritage. Mixteca Alta landraces are extremely

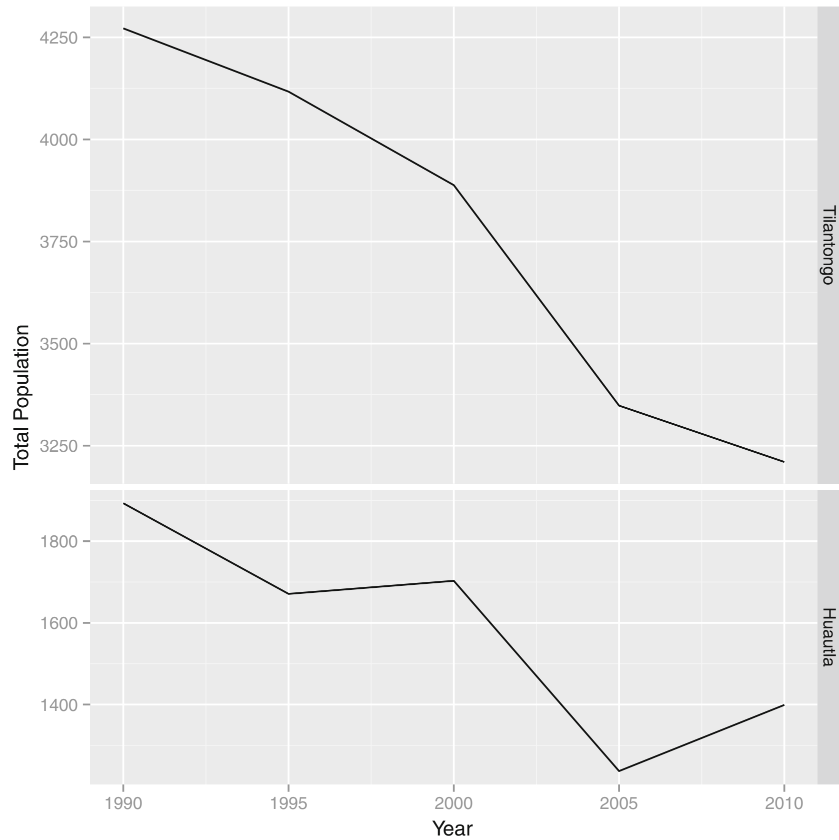

Fig. 1 Overall change in population of the two municipalities that participated in this study, Santiago Tilantongo (community of San José Zaragoza) and San Miguel Huautla, from 1990 to 2010. Data source: INEGI (2005) and INEGI (2010)

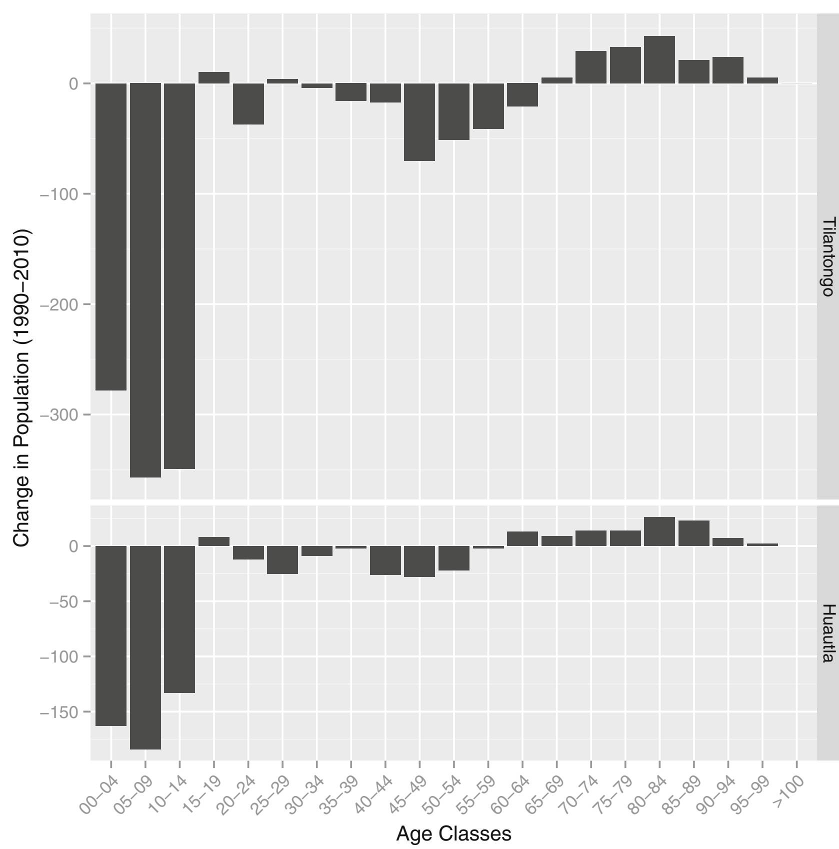

Fig. 2 Overall change in age classes of the two municipalities that participated in this study, Santiago Tilantongo (community of San José Zaragoza) and San Miguel Huautla, from 1990 to 2010. Data source: INEGI (1990) and INEGI (2010)

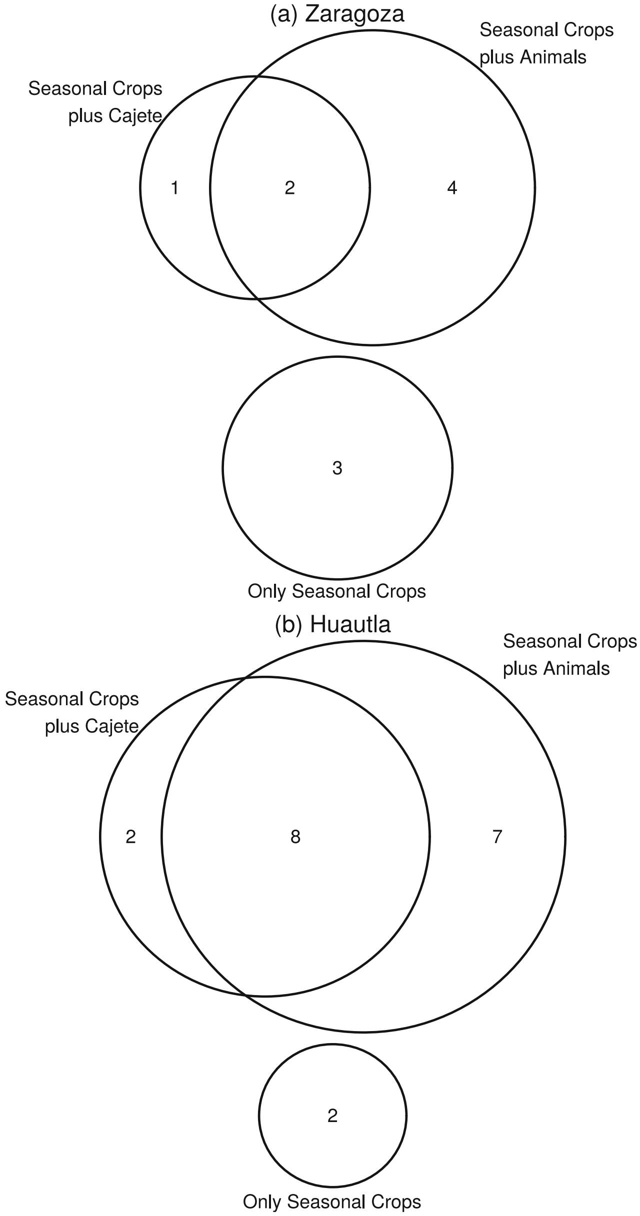

Fig. 3 The number of families interviewed in (**a**) Zaragoza and (**b**) Huautla who primarily grew seasonal crops, those who grew cajete maize in addition to seasonal crops, and those who raised goats and sheep in addition to seasonal crops (n=9). All families grew seasonal crops, a large number raised animals. *Circles* are drawn to scale

Table 2 Demographics of households interviewed in the communities of Zaragoza and Huautla, including median household size, median household age, percentage of households with children at home, and median number of children at home for those households with children

	Median size	Median age	% with children	Median # of children
Zaragoza	5	19	90 %	3
Huautla	4	35	36 %	3

Table 3 Number of male and female interviewees, as well as those that were conducted jointly with both men and women of the household, in the communities of Zaragoza and Huautla (n=29)

	Male interviewee	Female interviewee	Joint interview
Zaragoza	5	3	2
Huautla	13	3	3
Total	18	6	5

complex and often cross with one another. Ears of cajete maize sampled from Huautla resembled the *Chalqueño* landrace, while seasonal maize resembled *Bolita* and *Cónico* landraces (personal communication, Flavio Cuevas Aragón, INIFAP June 29, 2010). Aragón Cuevas *et al.* (2012) classify samples of cajete maize from Santiago Tilantongo as *Chalqueño* and *Mushito*, while Diego-Flores *et al.* (2010) cite literature that associates cajete maize production with the *Mixteco* landrace. Cajete maize is adapted to plantings in March due to its resistance to heat (*calor*) and its growing cycle of 7 months[1]; seasonal maize generally matures in 5 months.

Cajete Maize

While the production of cajete maize is in decline, it remains an important farming strategy for cold, high altitude regions above approximately 2000 masl that experience early frosts (*los altos* or *tierra fría*; Ríos *et al.* 2012). Cajete maize is dry-farmed; soils are cultivated during the dry season and farmers plant it several months before the rainy season begins. Cajete maize grows best in soils that retain residual moisture on flat ground or in terraced highland drainages (*jollas*). Soil fertility is maintained from surrounding oak woodlands and by the application of animal manure. *Cajeteros* carefully manage residual soil moisture in the dry season by tilling with the Egyptian plow in three directions from October – January: *barbechar*, *recruzar*, and *recortar*. The first tillage incorporates organic matter from the previous crop into the soil, whereas the latter two tillages dry mulch the soil surface to conserve residual soil moisture.

The majority of Huautla farmers had helped sow cajete maize or grew it themselves, whereas many Zaragoza farmers had no direct experience with cajete maize. Sowing of cajete maize is based on traditions of reciprocity between families. Fields are furrowed (*surquear* or *rayar*) from February – March and left to rest (*descansar* or *asentar la tierra*) for 8–15 days prior to sowing. Resting the soil prior to sowing enables farmers to locate pockets of residual moisture with their digging sticks (*pico y coa*). Groups of farmers are hosted by different families from February – April as they plant cajete maize in their fields. This combination of cultural practices

[1] Farmers used heat in reference to both temperature and dry periods during the year, which often overlap in monsoon regions of the world.

enables the young plants to grow for several months on residual soil moisture alone. The majority of households in Huautla exchange labor (*guetza*) for soil cultivation and planting cajete maize. Households also provide beverages and food to their helpers. In Zaragoza, food, drink, and 200 pesos per day are typically provided to workers (*mozos*).

Weeding (*desenhierbar*) is not an essential cultural practice, since cajete maize emerges during the dry season when weed pressure is low. However, some farmers weed with the Egyptian plow (*labrar*), and uncover maize plants by hand (*destapar*) at the start of the rainy season. Cajete maize is often harvested before seasonal maize. Those farmers who plant cajete maize in the same fields every year harvest the previous crop and cut its stover (*zacate* or *caña*) at the same time. Others who rotate their fields harvest cajete maize gradually through mid-December.

Farmers with temperate lands, approximately from 1800–2000 masl, reported abandoning cajete maize. A farmer from Zaragoza whose father had grown cajete maize 60 years ago claimed that it was no longer feasible because his soils had lost their ability to retain soil moisture. Additionally, the rains arrived too late in the season. Farmers in Huautla had similarly abandoned cajete maize some 20 years ago due to changing rainfall patterns. "Before, seasonal rains started earlier. In the generation of our parents, it rained on time and rains were predictable.[2] In November and December it rained enough to prepare soils for cajete."

The expansion of remunerated market economies reduced traditions of reciprocity, which in turn elevated production costs for *cajeteros*. A farmer from Huautla stopped growing cajete maize because upfront costs meant a greater loss if the crop failed. Moreover, as fields of cajete maize became more restricted in both communities, the damage caused by animals to those remaining increased. "We stopped sowing cajete maize 20 years ago, because ours was the first of the season and we suffered serious losses from animals, 70–80 cobs every night. Cajete is very certain, but the losses were high for us because we were the only ones planting it."

Despite these obstacles, farmers expressed an interest in reviving the practice. "We lost the cajete seed, but 2 years ago we started sowing our seasonal maize as cajete. We are taking the initiative to keep from losing of our customs and traditions."

Seasonal Maize

Seasonal maize is planted at the beginning of the rainy season in temperate lands that have less severe frost than higher elevations. Farmers value the precocity of seasonal maize: "Our children can eat within 5 months if the maize does well." Seasonal maize is part of a diversified system (*parcela diversificada*) that also produces beans, squash, fava, and peas. Farmers describe this combination of rainfed crops as well adapted, efficient, and diverse. Farmers also described seasonal crops as labor-efficient. Unlike cajete maize, households are able to sow seasonal crops independently.

Most Zaragoza farmers cultivate their soils for seasonal maize after May 20, although some till in the dry season from December 20 – January 15. In Huautla, soil cultivation starts as early as January and continues through June. Farmers sow seasonal maize after the first consistent rains of the season. Zaragoza farmers typically plant seasonal maize between May 15 and June 20, depending on rainfall patterns. Earlier sowing dates increase the chances of acceptable grain yields. In Huautla, July 16 is the last sowing date for seasonal maize. If farmers are unable to sow seasonal maize, they focus on bush beans and wheat.

Fields of seasonal maize (*milpa*) are intercropped with beans and squash, sown in some of the same holes as several grains of maize (*matas*). Farmers till furrows with animal traction while one or two family members follow sowing seed in the furrows and using their feet to cover the seeds with soil from the ridges (*tapa-pie*). Farmers weed from 20 days to 1 month after sowing. Zaragoza farmers often recruit workers to help with weeding. Farmers make a second pass with the Egyptian plow to mound the base of the young crop (*encajonar*) approximately 1.5 months from sowing, or 8–15 days after weeding. Huautla farmers mound seasonal maize 15–20 days after weeding only in good years when this is likely to increase crop yields. Harvest is from December 20 – January 15, with some farmers in Zaragoza hiring from 4 to 7 workers. Since seasonal maize is often intercropped, farmers harvest multiple times starting with beans, ears of maize, maize stover, and lastly chilacayota squash.

Agricultural Technology and Labor Considerations

The timing of agricultural work plays an important part in farmers' crop selection. Farming systems that include cajete maize are most labor intensive during the dry season months of October – April (Fig. 4). Cajeteros in Huautla cultivate their fields for seasonal maize earlier, from November – January, than those farmers that primarily grow seasonal crops. In Zaragoza, there is less time between soil cultivation for cajeteros and farmers of seasonal maize, possibly due to the earlier onset of the rainy season there; farmers in Zaragoza sow seasonal maize May – June compared to June – July in Huautla. The most labor intensive period for cajete maize is from February – March, compared to June for seasonal maize. Cajeteros in both communities practice soil cultivation year

[2] The farmer used the term "followed the *cabañuelas*," which we interpreted to mean "rains were predictable." The *cabañuelas* were atmospheric conditions in January that the elders used to predict rainfall patterns for the upcoming rainy season.

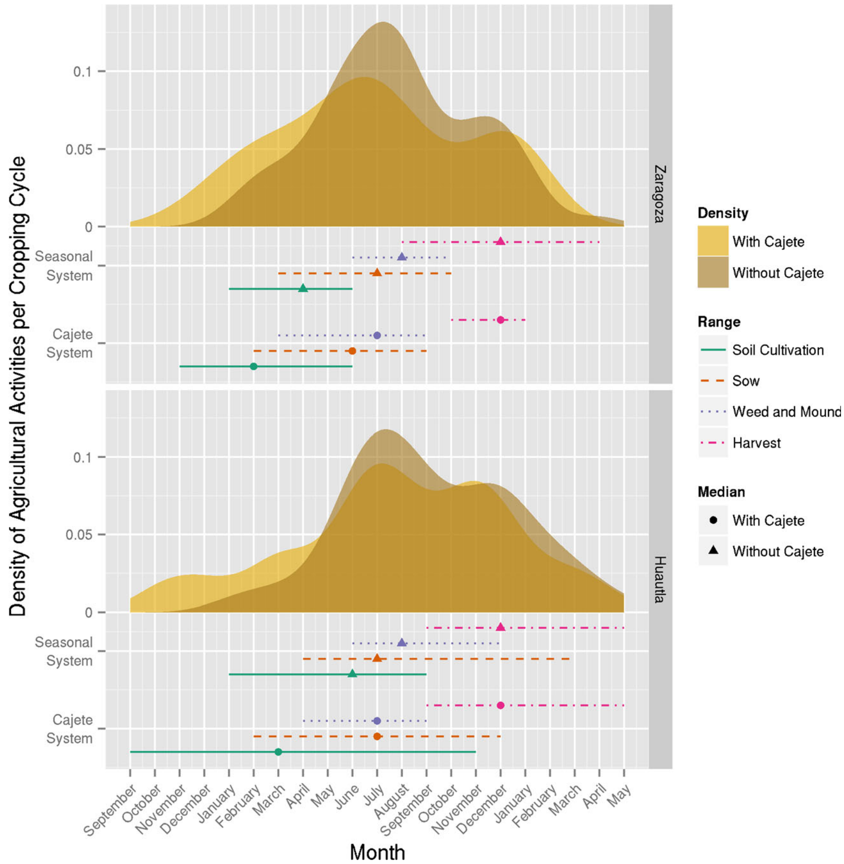

Fig. 4 Density plots of the months when agricultural activities were reported per cropping cycle (September of year 1 to May of year 2) for farming systems with cajete maize (*light shading*) and farming systems without cajete maize (*dark shading*) in the communities of Zaragoza and Huautla. The shaded curves represent the same area. All farming systems include seasonal maize, beans, peas, and wheat. The ranges of months that were reported for agricultural activities are represented by *solid lines* for soil cultivation, *dashed lines* for sowing, *dotted lines* for weeding and mounding, and *dot-dashed lines* for harvesting. The median month reported for the agricultural activities are represented by a *circle* for farming systems with cajete maize and by a *triangle* for farming systems without cajete maize

round, whereas seasonal maize farmers have a break in soil cultivation from at least October – December.

Modern agricultural technologies were introduced in the 1980s and 1990s. Tractors are not used for soil cultivation by farmers in either community for steep slopes or cajete maize systems because tilling fields with tractor-drawn disc harrows (discing) prevents them from locating pockets of residual soil moisture for cajete maize. In fact, cajeteros in Zaragoza prefer draft animals for all their crops. Likewise, farmers in Huautla have not widely adopted tractor technology in either seasonal or cajete maize systems.

Farmers in Zaragoza who grew seasonal crops had adopted tractors in 2000 through government assistance programs. A group of them subsequently purchased a tractor from the neighboring community of Tres Lagunas in 2004. Farmers use tractors for discing fields, but still prefer draft animals for all subsequent stages of soil cultivation. Even those in Zaragoza who use tractors recognize certain disadvantages of the technology: the discs affect soil aggregate structure and expose the least fertile soils (*cascajo*), which increases their dependency on synthetic fertilizers.

Synthetic fertilizers were adopted to different degrees in Zaragoza and Huautla, starting in the 1980s. Use is much lower in Huautla than Zaragoza, and those who do use fertilizers apply them judiciously due to their prohibitive cost. Farmers in both communities acquire synthetic fertilizers and pesticides through merchants, agricultural credit programs (*Banco Rural*), and subsidy programs (*Programa de Apoyos Directos al Campo*, PROCAMPO). However, the Banco Rural loan program only lasted for 3 years "because people could not pay back the interest."

Over the long term, farmers get greater yield stability from locally derived soil amendments, legume crops, and soil conservation practices than from synthetic fertilizers. These practices are based on farmers' traditional knowledge, as well as from introductions by civil associations like the Center for Integral Small Farmer Development (CEDICAM; Boege and Carranza 2009; León Santos 2007). Over 50 % of interviewees associated synthetic fertilizers with changing, ruining, and burning soils. In contrast, “beans give life to fields as if it were chemical fertilizer.” Farmers incorporate spontaneous plants, composts, soil from ant nests, tree leaves, and wood ash into their soils. Living barriers and contour ditches reduce erosion of the most fertile soils.

Sheep and goat corrals are moved every 3–6 months to improve soil quality. Farmers placed corrals in their least productive fields (*débiles* or *delgados*). However, households have reduced the size of their herds due to limitations in labor and pasture, especially in Zaragoza: “Twenty years ago we kept larger herds, but it was destructive. We are now reforesting.” Some of those who gave up animal husbandry described their fields as worn out (*acabados* and *estériles*). This was particularly the case when earnings from subsidy programs discouraged farmers from rotating out of maize production. Livestock provide manure inputs for farming as well as a source of cash when needed.

Biophysical and Climatic Considerations

Humid agricultural environments sown to cajete maize help farmers stabilize their crop yields across years. Farmers who grow cajete maize consider it highly resistant of heat in the dry season and of droughts in the rainy season (*caniculas*). “Even without rain, cajete maize survives.” In contrast, seasonal maize is sensitive to both droughts and excessive soil moisture. Soils where farmers plant seasonal maize experience greater fluctuations in soil moisture, and thus the crops are more vulnerable to inclement weather.

Those farmers who had never sown cajete maize primarily cited soil quality and soil moisture as biophysical constraints. In Zaragoza and Huautla, several farmers’ soils did not retain enough moisture, and changing rain patterns disfavor cajete maize. Dry season soil cultivation was impeded by a lack of residual soil moisture, which farmers attribute to greater heat and the late onset of the rainy season. Between the 1970s and 1990s, cajete maize was no longer sown in the temperate lands of Huautla due to reduced residual soil moisture. Farmers perceived that deforestation of oak woodlands in their territories had reduced the soil’s capacity to retain moisture.

In the last 6 years, both crops were affected by the lengthening of the dry season. Farmers perceived an increase in temperatures during both dry and rainy seasons, as well as problems with late season frost damage, which may have been the outcome of later sowing dates for seasonal crops. Zaragoza had experienced greater intensity of rainfall while Huautla experienced more drying. These were not contradictory narratives, but representative of the spatial heterogeneity of rainfall in the Mixteca Alta. Early season rainfall had decreased in both communities, with important implications for farming systems. “The climate has changed a lot. Before there was more water, more animals, and more trees. It is now more difficult to farm.” Elders recalled that previously rainfall started in April – May, while more recently rains began between June – July. Due to later onset of rainfall, cajete maize is now sown from March – April instead of February – March, and seasonal maize is sown May – July instead of April – May. Seasonal maize was reportedly affected by variable weather starting in the 1980s. Particularly in the 2000s, farmers were unable to sow their seasonal crops early due to the late onset of the rainy season.

Household Self-Sufficiency

Food Security and Grain Economies

Producing multiple crops increases the chances of obtaining year-round self-sufficiency. “If the maize does not do well, we have beans, and if not beans, wheat.” Nevertheless, households had recently suffered a series of bad years that were associated with inclement weather and low yields. More good years were experienced in Zaragoza (7 good years in the past 10) than in Huautla (5 good years in the past 10). The months of hunger (*meses de hambre*) in both communities ranged from 1 to 7 months, typically between January and November. The production of both cajete and seasonal maize reduced the months of hunger for some families. Additionally, families experienced different degrees of difficulty in reproducing their seed stock. Twenty percent of interviewees in Zaragoza had at some point lost their seed compared to 88 % in Huautla (Table 4).

In Zaragoza, 2010 was the most often cited bad year due to the exceptionally high rainfall. “2010 was a very hard year. We had to buy wheat, beans, and maize. We spent a lot to purchase food.” Other bad years remembered in Zaragoza were 1999 and 2007. In Huautla, households depended largely on irrigated and dry-farmed wheat to withstand a multi-year drought from 2005 to 2009. Only 26 % of interviewees in Huautla had enough grain for tortillas in both good and bad years. Households were generally self-sufficient in grain during good years and dependent on grain purchases during bad years. However, almost a third of interviewees in Huautla never had enough grain, even in good years.

Cajete maize yielded more per cob from its larger kernels. However, seasonal maize was planted at a higher density than cajete maize: the distance between two cajete plants can accommodate three *matas* of seasonal maize. Grain yields at the field scale did not differ dramatically, although seasonal maize reportedly had a higher variability in grain yield.

For the four crops that yields were consistently reported – cajete maize, seasonal maize, beans, and wheat – the median good harvest in Zaragoza and Huautla were between 500 and 1000 kg per hectare, while the median bad harvest fell close to zero (Fig. 5). This corresponded with the reported median annual consumption of 911 kg of maize, 287 kg of beans, and 370 kg of wheat per year. Consumption of maize is greater

Table 4 Moments when seed stocks were lost by farmers in the communities of Huautla and Zaragoza

Community	Year	Description
Zaragoza	2010	Excessive rains; first time ever to lose their seed stock.
Zaragoza	1991	Post-harvest insect pest infestation.
Huautla	2011	Beans and maize failed and only wheat was harvested.
Huautla	2010	Four years of drought followed by a year of heavy rains, frost and rot (*chasluisa*) resulted in losses of maize, beans, and wheat. One farmer lost the seed his father had passed down to him.
Huautla	2007	No description provided.
Huautla	2004	Complete crop failure.
Huautla	2000	Complete crop failure.
Huautla	1987	Insect pests destroyed their crops.
Huautla	1986–89	Poor harvests due to a drought and the husband's poor health.
Huautla	1949	A farmer ate *nopales* and *quelites* for three years because of a drought. It was not possible to find beans, wheat or maize anywhere.
Huautla	1914	A bad year when people died from hunger.

in Zaragoza than in Huautla and vice versa for wheat. In Huautla, dry farmed wheat sustained households whose maize crops were challenged by unfavorable climatic conditions for several years. Overall yields were extremely variable for both cajeteros and farmers who primarily grew seasonal crops. Farmers' yields decreased in recent years, with almost complete crop failures for all major crops in 2010.

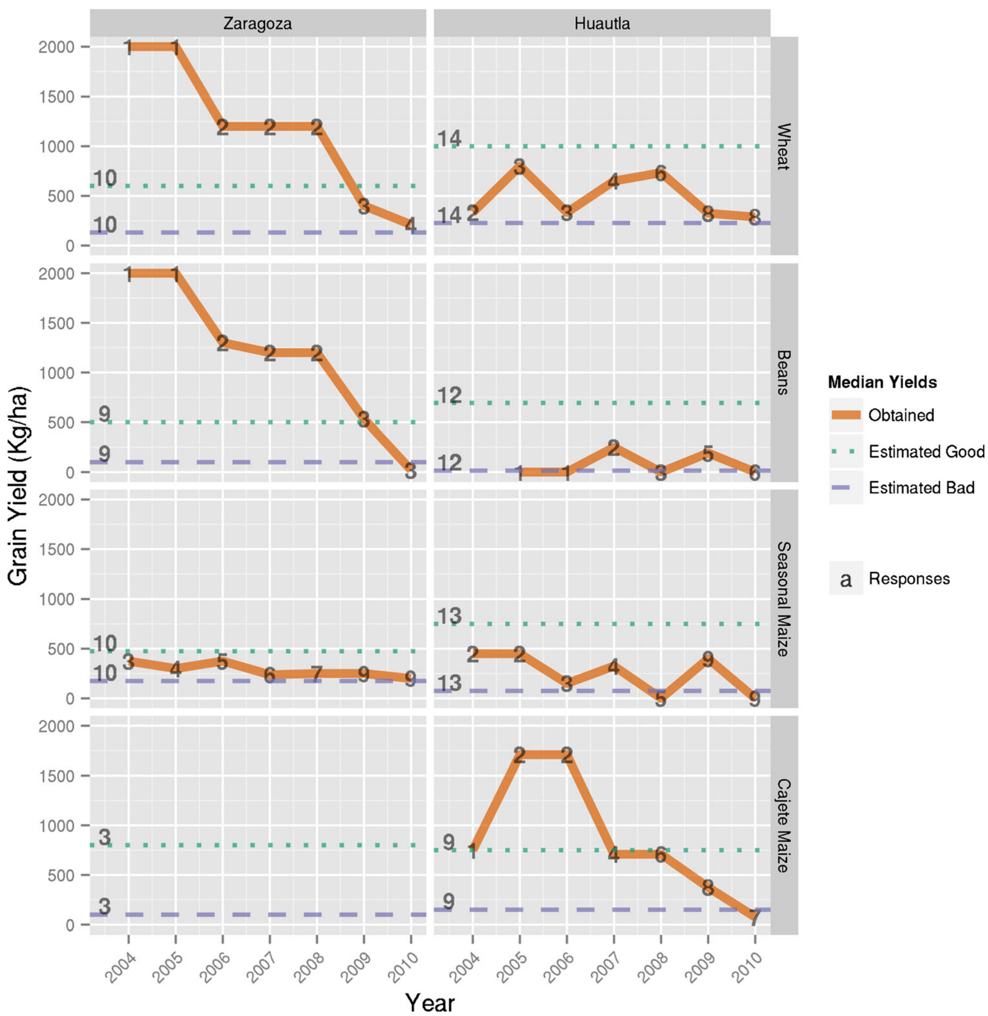

Fig. 5 Obtained and estimated median yields reported by Zaragoza and Huautla farmers from 2004 to 2010 for wheat, beans, seasonal maize, and cajete maize. The data are represented by the following symbols: median obtained yields as *solid lines*; median estimates by farmers of good and bad yields respectively as *dotted lines* and *dashed lines*; and the number of responses that informed each calculation are overlayed

Farmers prioritized the production of grains for the household (45 % of interviewees), though small quantities were sold and exchanged within their communities. Fifty percent of farmers interviewed in Zaragoza sold maize in 5 kg units (*maquilas*) to an estimated total of 200 kg in good years. Wheat was sold by the liter every 2–3 days to an estimated total of 100 kg per year. Beans and peas were also exchanged between families in Zaragoza.

Similarly, farming households in Huautla exchanged grain for labor, donated grain to community events, or sold grain locally. The exchange of grain for labor was described as indirect; families provide grain to each other in times of need and also help each other in the fields when needed. Less than a quarter of interviewees in Huautla sold or exchanged their grains outside the community. One Huautla farmer sold dry beans and vegetables occasionally in the Asunción Nochixtlán market, while another sold maize and beans to an intermediary from Puebla. Others in Huautla exchanged sacks of grain with absent landowners for use of their fields.

Farming and Remunerated Labor

Taking shelter in the shadow of commodified labor structures was not without consequence for rural places. "We are few that remain," and those who did stay generally were the elders. Farmers sacrificed their best management practices. "When fields are abandoned, they become eroded and unproductive. Yes, we can pasture them, but we can only grow food with permission, normally sharecropped. Infertile fields are abandoned while those that are still productive are rented. When fields are abandoned, the soil goes with the rains. Crops don't grow." Cultivated lands experience less erosion when cared for by farmers. Families also stopped raising animals when their children became established outside the community or regularly left to work.

Farmers typically earned monetary income through artisan crafts, construction, agricultural labor, and taxi driving. All interviewees in Huautla wove palm products, such as floor mats and sombreros. While farmers did not dramatically increase weaving in bad years, the industry provided a reliable, yet modest, income. Households wove a median of 19 sombreros per week, which would earn a total of 66 pesos through the intermediary who came to Huautla's weekly market. Farmers also generated income through the sale of livestock. For 20 % of interviewees in Zaragoza and a much larger 68 % in Huautla, animals were an income source in times of need. In Huautla, one head of sheep earned between 400 and 600 pesos and farmers sold up to 16 head of sheep and goats, depending on the year.

Traveling to find work was common across communities and genders. In Zaragoza and Huautla, 61 % of interviewees reported combining paid work in bad years, while 22 % reported families working in paid labor that conflicted with farming and 17 % did not work because of their dedication to farming. "I have preferred to only leave for short periods of time and continue my farming. We make do with the little that we have." Working closer to their communities while continuing to farm presented greater security than moving long distances. Farmers worked outside their communities for periods of 15 days – 3 months following the sowing of seasonal crops in July or the harvest in December.

The large majority of families are connected to economies further afield. Most had children who moved from their communities out of economic necessity or for new experiences. "The youth want to live a different lifestyle, and leave the community because of poverty. The salaries in Huautla are too low." Remunerated labor was a means to improve one's standing in the community, purchase land, and establish new families. In some cases, families had returned to their communities to retire. "It is for a naive idea that we must be buried in our community as *Huautecos*." Some also did not have the economic means to live elsewhere in their later years.

Discussion

There are several explanations for the abandonment of cajete maize in the temperate lands of both communities. Cultivation of cajete maize, though drought tolerant and highly adapted to fluctuations in soil moisture, diminished in prominence due to a series of interwoven and complex issues. Labor-efficient, short duration, and frost-resistant grains better accommodated the changing biophysical, cultural, and socioeconomic contexts. The contrasting experiences of farmers in Zaragoza and Huautla as well as between cajeteros and farmers who sowed seasonal crops offer insights into the general agroecological resilience of traditional management systems. We organize our discussion around three topics that emerged from our research: agroecological pathways, agrobiodiversity, and family economy.

Agroecological Pathways

Livelihoods chosen by farmers reflected distinct biophysical and socioeconomic conditions. Zaragoza had comparatively greater success with seasonal maize due to a more favorable climate. In 2010 most Zaragoza farmers had their first experience of losing their maize seeds due to exceptionally high rainfall. Additionally, Zaragoza's spatial proximity to markets might explain why remunerated labor had largely replaced traditional livelihoods based on animal husbandry and artisan crafts. They were also recipients of numerous government and non-governmental programs at the municipal level aimed at reforesting degraded areas (personal communication, Tilantongo's *Comisión de Bienes Comunales,* September 2011). Zaragoza's favorable rainfall conditions along with better socioeconomic circumstances encouraged relatively early adoption of tractors, pesticides, and fertilizers. Modern farming technologies were also accompanied by a reduction of traditional reciprocity in favor of monetary compensation for agricultural labor.

In contrast, Huautla farmers experienced more frequent hardships, from climate changes to insect pests, which severely challenged the reproduction of maize seed stocks. Huautla farmers depended on wheat for their tortillas during the extended drought period from 2005 to 2009. Huautla is a more isolated municipality and has less access to remunerated employment. While the youth and even entire households have relocated for opportunities to work, those who stayed (and in some cases returned) depend heavily on animal husbandry and artisan crafts for their livelihoods. Despite climatic and socioeconomic challenges, families sustained traditional management systems that approximated self-sufficiency in grains. These strategies include the recuperation of soils through the construction of land containers, the careful use of local resources such as animal manures, and specific knowledge about microclimates and soils. They also maintained farming technologies and cultural traditions such as reciprocity among households that reduce the need for monetary exchange.

These differences between Zaragoza and Huautla highlight the multiple strategies for approaching agroecological resilience in traditional management systems, which are poorly understood and more diverse than conventional models for agriculture. Smallholder agriculture in the global South is not solely aimed at production objectives, but rather multiple outcomes including livestock rearing and fodder production, cultural identity, and community standing (Rasmussen and Reenberg 2015). Rodriguez-Solorzano (2014) identifies two strategies of farmer adaptation to climatic variability that impact forest reserves in different ways: a saving strategy based on livestock leads to deforestation, while diversifying income through off-farm activities conserves forests (see also Quinn *et al.* 2011; Ruiz Meza 2015).

Agrobiodiversity

The study of cajete and seasonal maize provided several contributions to the understanding of the importance of on-farm biodiversity for agroecological resilience. Farmers in this study appreciated cajete maize for its resistance to drought during the dry and rainy seasons, as well as its early harvest that avoided late season frosts. Water stress tolerance of cajete maize is the combined outcome of gene expression (Hayano-Kanashiro *et al.* 2009) and farmer management (Rivas Guevara *et al.* 2006; Rivas Guevara 2008). Soils in the Mixteca planted to cajete maize retained more moisture than those planted to seasonal maize during a dry spell in the 2009 rainy season (Ríos *et al.* 2012), likely due to microclimate, soil characteristics, and water harvesting strategies (Rivas Guevara *et al.* 2006). However, the resistance of cajete maize was tested in 2010 when a late start to the rainy season severely affected yields in both Zaragoza and Huautla.

Climatic and soil conditions in temperate lands have changed to disfavor cajete maize production. In some instances, farmers chose not to cultivate cajete maize because their soils were too dry. Reasons for the abandonment of cajete maize included: warmer temperatures that increased the rates of drying; tractor cultivation that reduced the capacity of soils to retain moisture; erosion that exposed lesser quality soil horizons; and deforestation that affected hydrological cycles. Soil cultivation for cajete maize was impeded by the lengthened and warmer dry season. Decreased animal husbandry reduced inputs of organic matter, which consequently reduced the water holding capacity of soils. In landscapes with highly erosive soils like the Mixteca Alta, the recuperation of favorable soil conditions can greatly increase the yield potential of maize (Contreras-Hinojosa *et al.* 2005). However, in the study communities insufficient labor was available to recuperate soils for cajete maize.

In addition, cajeteros struggled to sow cajete maize due to reduced labor sharing, increased expenses, and perceived risk of crop failure in temperate lands. Cajete maize cultivation needs strong traditions of reciprocity among households and skilled farm labor (R. García Barrios *et al.* 1991; Rivas Guevara 2008; Edinger 1996). Farmers had reduced labor exchange between families and service to the community. Households may have become more interested in remuneration for agricultural labor after working outside their communities. Even without monetary compensation, farmers viewed cajete maize as a more expensive crop because it required more up-front investments before farmers could judge how the rains would come. Also, the few farmers who grew cajete maize in temperate lands experienced elevated animal damage due to its early-maturity.

The persistence of such cropping systems as cajete maize are critical for the long-term resilience of regional farming and food systems because of their ability to withstand extreme weather conditions combined with their associated cultural knowledge and institutions (Singh *et al.* 2012; de Grenade and Nabhan 2013). The fact that cajete maize has persisted at all reflects the evolution of management systems described by Reyes-Garcia *et al.* (2014) as the bringing together of modern and traditional agricultural knowledge.

Existing crop genetic diversity that is adapted to low-input systems is all the more important for many resource-constrained farmers since most breeding aims to develop responsive crop varieties to high-input systems (Njeru 2013). Highland maize varieties in Mexico offer advantages to small- and medium-scale farmers who use a diversity of input strategies and may potentially sell their products in specialty markets (Keleman *et al.* 2013). Additionally, the genetic diversity of maize landraces and wild relatives in Mexico offer promising opportunities to adapt to climate change in a segmented seed sector that improves the landraces for smallholders while also developing improved varieties for commercial producers (Hellin *et al.* 2014). Such a response to climate change avoids the disproportionate negative impact on smallholder livelihoods in southern Mexico if transgenic technology becomes privileged (Mercer *et al.* 2012).

In contrast to cajete maize, seasonal maize is part of a diversified production system that is responsive and flexible to unpredictable climatic conditions. Farmers plant a sequence of crops in accordance with rainfall patterns. Farmers distinguished between the resilience of one crop that was capable of withstanding drought periods from the resilience of a cohort of crops that sustained acceptable yields even if some failed. This diversified system is also adaptable to climatic challenges and current social realities. Farmers largely met their food needs despite the climatic variability they experienced. While there was greater variability in yield for seasonal maize, the diversity of seasonal crops stabilized farmers' overall production. A diversity of crop varieties that are adapted to the heterogeneous landscapes of Mexico minimize risk from climate and pests (Altieri and Trujillo 1987; Liverman 1999). The milpa of intercropped seasonal maize also represents the reproduction traditional knowledge on how to effectively manage biodiversity for agroecological resilience (Carrera-Garcia *et al.* 2012).

In fact, this stabilizing effect was observed for cajeteros and for families who primarily grew seasonal crops. Their respective integrated farming systems produced similar overall yields despite the variability of the component parts: no obvious overall yield differences between cropping systems; no dramatic differences in the number of months of hunger; and no reported shifts in grain crops over the past 6 years despite cases of complete crop failure. Our findings qualified the argument made by García-Barrios and García-Barrios (1990) that households who grow both cajete and seasonal maize are the most food secure across years. Cajete maize harvests were well timed to stem the months of hunger, but farmers who cultivated temperate lands generally sustained sufficient production between seasonal maize in good years and wheat, which was reliably harvested during the dry season. Planting at the margins of rainfall cycles – whether cajete maize or wheat – provided farmers some insurance in cases of catastrophic failure. Similarly, Ayala-Ortiz and García-Barrios (2009) describe the multiple functions of rainfed agroecosystems in Mexico that make use of residual moisture to include among others environmental protection and food security.

Family Economy

Our findings suggest that households that grow primarily seasonal crops more easily integrate remunerated labor during the dry season than cajeteros. Labor allocation differed between farming systems. Cajeteros worked their farms more consistently throughout the year, while those who primarily grew seasonal crops concentrated their farm labor slightly more during the rainy season. While the seasonal crops can be cultivated with tractors and synthetic fertilizers, these are imperfect technologies for drylands with variable climate conditions because they are costly and negatively affect yields in dry years. Government subsidy programs also undermined the flexibility of seasonal cropping systems by discouraging rotations out of maize production. Although more research is needed, these observations concur with Lerner and Appendini (2011) that small farmers in Mexico produce maize for subsistence alone and/or engage in alternative on- and off-farm employment due to rapid urbanization and agrarian policies that have undermined markets for maize.

Clearly, alternative income-generating activities are necessary for small farmers, especially when markets are unfavorable for agricultural products. Drought tolerant and early maturing crop varieties, in combination with off-farm activities, have been found to enhance farmers' resilience in the uplands of Zambia (Mubanga and Umar 2014). Small landholders in Chiapas, Mexico grow more crops and also engage in more off-farm activities than large landholders who pursue more specialized and lucrative agricultural opportunities (Christman *et al.* 2015). Linkages to off-farm migration, resource access, landraces, and innovative knowledge enabled the socio-ecological resilience and the in situ conservation of maize agrobiodiversity by Bolivian smallholders (Zimmerer 2013). Similarly, pastoralists of the Hindu Kush Himalayan region would benefit from internally value-adding activities in the pastoral sector as well as external economic diversification (Ning *et al.* 2014).

However, the impacts of migration and remittances may also have equivocal or negative effects on agroecological resilience. Gray (2009) finds that migration and remittances have mixed and countervailing effects in the southern Ecuadorian Andes; both lost-labor effects that differed between men and women, as well as investment-promotion effects that resulted in increased maize production. Additionally, off-farm activities such as migration, employment, and trade seem to be related to the decline in sustainable farming practices in Bolivia due to their impact on farm labor availability and reduced opportunities for people to learn these practices (Gilles *et al.* 2013). Climate change and migration adversely affect coffee production in East Africa; however, biodiverse shaded coffee was more resilient and productive than monocultures (Jaramillo *et al.* 2013).

More research is needed to differentiate between patterns of labor migration for cajeteros and farmers growing primarily seasonal crops. Our research showed that labor migration exacerbates soil erosion in abandoned fields. Similarly, the spontaneous abandonment of agricultural production by small farmers was not found to reverse the net deforestation rate in

Mexico (García-Barrios *et al.* 2009). Some traditions, like sharecropping, had the potential to pass the management of fields into the hands of new caretakers. However, others potentially contributed to increased soil erosion, such as the usufruct of fallowed and abandoned fields for grazing animals with the exclusion of cultivating crops. Strategies for continued land stewardship have not fully addressed the level of displacement occurring in rural communities of the Mixteca Alta.

Conclusion

We found that the traditional management systems of the Mixteca Alta, based on cajete maize and seasonal crops, were agroecologically resilient in different ways. Cajete maize is climatically resilient yet poses challenges in its adaptability to changing conditions. Meanwhile, intercropping seasonal maize exhibits greater flexibility and adaptability. Seasonal crops combined with dry season wheat cultivation provided more options given changing cultural and socioeconomic conditions. From a systems perspective, the agropastoral components occupy different agricultural environments across the landscape. Also, traditional management practices like cajete maize actually improve agricultural soils by reducing erosion and increasing fertility and water holding capacity. These traditional systems provide useful lessons for similar regions of the world with highly variable rainfall patterns and drastically changing seasonality.

Nevertheless, recent years have presented increasingly extreme climatic and socioeconomic hardships. Farmers' management decisions are informed by climate and soil characteristics, culture and tradition, labor availability, income from non-agricultural work, household demographics, and compliance with government subsidy programs. Changes in cropping systems are often made based on socioeconomic considerations.

This suggests that transformative change is required to develop novel cropping systems and complementary activities to agriculture that will allow for farming to be sustained. Adaptability means drastic transformation and an ability to innovate when faced with unexpected situations. Addressing economic and political marginalization is critical to enhance the resilience of small farmers to climate change.

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