

## Maize migration: key crop expands to higher altitudes under climate change in the Andes

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### Abstract

Climate change is expected to profoundly alter the growing conditions of agricultural crops, potentially causing decline in food production in several parts of the world. A switch from crops and crop varieties currently grown to others that are better adapted to new environmental conditions has been suggested as one possible adaptation strategy. While research has documented the upward migration of wild species linked to recent warming in mountain environments, there has been little empirical research on corresponding shifts in the ranges of cultivated species. This study examines changes in the elevation of maize cultivation on the slopes of Mt. Cotacachi, a volcano located in the Northern Ecuadorian highlands. The results show that during the past two decades, farmers in four communities have expanded maize cultivation an estimated 200–300 m in elevation, linked to their observations of climatic and environmental change. This suggests that in tropical mountain regions like the Andes that exhibit closely stacked agroecological zones, the upward movement of local crops and crop varieties constitutes one feasible locally based adaptive response to changes in growing conditions induced by global warming.

Keywords: climate change; global warming; maize; adaptation; crop shift; landraces; Andes

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### 1. Introduction

#### 1.1. *Adapting agriculture to climate change: the potential role of crop shifts*

Climate change influences the growing conditions for the earth's biological diversity, including cultivated crops. Computer modelling predicts that future changes in climatic conditions will cause progressive yield declines in key crops in many parts of the world (Cline, 2007; Parry, Rosenzweig, Iglesias, Livermore, & Fisher, 2004; Schenkler & Lobell, 2010). Significant declines could threaten both local livelihoods and the food supplies of major parts of the world's population, highlighting the need for effective adaptation measures that will keep farmers employed and fields productive (Adger et al., 2007; Nelson et al., 2009). The adoption of crops and crop varieties more suited to new climatic conditions has been suggested as one possible adaptation strategy (Easterling et al., 2007; Ortiz, 2011). During recent years, considerable research and breeding efforts have been devoted to the development of new crop varieties with traits adapted to expected climatic conditions (Chapman, Chakraborty, Dreccer, & Howden, 2012). While it is certainly important to continue breeding efforts, another potential but less explored strategy is the movement of already existent crop varieties into adjacent geographic areas.

A substantial body of research shows that global warming has already induced latitudinal and altitudinal changes in the ranges of many wild species during the last decades (Parmesan, 2006; Parmesan & Yohe, 2003); yet research on corresponding shifts for agricultural species and varieties remains more scarce. A limited number of studies have calculated geographical shifts in the suitability of growing conditions for different crops under future climate scenarios. These suggest that the latitudinal growing ranges of crops are likely to change in decades to come. In Europe, the growing range for maize is expected to expand

northwards, while at the same time the cultivated areas for many crops, including wheat, are expected to increase in the north and decrease in the southern parts of the continent (Elsgaard et al., 2012; Tuck, Glendining, Smith, House, & Wattenback, 2006). Another simulation shows that in northeast Iran, pearl millet performs better than maize under current climatic conditions, while rising future temperatures are likely to decrease this comparative advantage (Eyshi Rezaei, Gaiser, Siebert, & Ewert, 2013). A study based on farm survey and climate data from seven South American countries also indicates future changes in the expansion of major crops, concluding that “[p]redictions of the impact of climate change on net revenue must reflect not only changes in yields per crop but also crop switching” (Seo & Mendelsohn, 2008, p. 109).

Common to these simulation and model-based studies is that they omit consideration of how climatic and non-climatic factors shape farmers’ crop choice. In contrast to wild species, which possess some ability for autonomous movement, the growing range of agricultural crops depends upon farmers – their access to seed and the decisions they make about what to plant and where. Do present seed systems have the capacity to provide farmers with better adapted planting material from other geographical areas? Are farmers likely to experiment with alternative crops and crop varieties in response to climatic change without external intervention? Answering these questions requires further empirically based research on spatiotemporal changes in crop choice in relation to changes in climatic gradients. An exception to the general paucity of research on these issues is a recent case study documenting the northward expansion of maize cultivation in Denmark between 1999 and 2008 associated with a combination of climatic (higher temperatures) and non-climatic (cattle density) drivers (Odgaard, Bøcher, Dalgaard, & Svenning, 2011). The present study explores altitudinal shifts in crops and crop varieties through a case study of maize cultivation in the Northern Ecuadorian Andes.

### 1.2. *Climatic change and temperature increase in the Andes*

Farmers in Northern Ecuador report observations of higher temperatures and changes in precipitation and seasonality during the last decades (Rhoades, Zapata Ríos, & Aragundy, 2006; Skarbø, VanderMolen, Ramos, & Rhoades, 2012). Local observations are compatible with scientific analyses of recent climatic trends in the Andean region, to the extent that these exist. Analyses of precipitation data often yield varied and insignificant results (Vuille, Bradley, Werner, & Keimig, 2003; Vuille et al., 2008); however, there is evidence for an increase in extreme weather, including El Niño events, since the 1980s (Seneviratne et al., 2012). There is also evidence of warming. A study based on data from 279 weather stations spanning the entire region shows an average warming of 0.1°C/decade over the last 70 years (Vuille et al., 2008), increasing to a rate of 0.32–0.34°C/decade during the last quarter of the twentieth century (Vuille & Bradley, 2000). Across the Andes and throughout much of South America, daily minimum and maximum temperatures have increased as well (Skansi et al., 2013; Vincent et al., 2005). In Ecuador, individual data series from 15 highland stations show increments in mean daily temperatures varying between 0.2°C and 2.4°C from 1960 to 2006 and an average total increase in temperature of 0.9°C, corresponding to a warming of 0.2°C/decade (Ontaneda, 2007). Trends of warming are expected to continue (Magrin et al., 2007; Urrutia & Vuille, 2009). Average temperature increases for Ecuador relative to 2000 are estimated to be +0.82 (±0.13)°C for the 2020s, +2.13 (±0.29)°C for the 2050s, and +3.36 (±0.45)°C for the 2080s (Jarvis, Ramirez, Bonilla-Findji, & Zapata, 2011). The Andean highlands are expected to experience more severe warming than the region’s lower elevations (Bradley, Vuille, Diaz, & Vergara, 2006). These observations and predictions highlight the need for research into adaptation to climate change and rising temperatures in the Andes mountains.

### 1.3. *Impacts on ecosystems and biodiversity*

Recent studies demonstrate that rising temperatures already affect ecosystems in the Andes – a region characterized by rich levels of both wild and cultivated biodiversity that has evolved in and adapted to the wide range of climatic and ecological niches in the mountain range (Brush, 1982; Troll, 1968; Young, Ulloa

Ulloa, Luteyn, & Knapp, 2002). While there is no indication of simultaneous movements of whole biotic communities, there are observations of migrations occurring for several singular species. For instance, research from Peru shows that three anuran species (*Pleurodema marmorata*, *Bufo spinulosus*, and *Telmatobius marmoratus*) have expanded their habitat ranges to more extreme altitudes, from a previous upper limit of 4500–5000 m to a new limit of 5244–5400 m (Seimon et al., 2007). Another study shows that rising temperature is one of the factors influencing the recent expansion of habitat ranges for potato tuber moths (*Phthorimaea operculella*, *Tecia solanivora*, and *Symmetrischema tangolias*) in the Ecuadorian highlands (Dangles, Carpio, Barargan, Zeddarn, & Silvain, 2008). Given these observations, it might be expected that the niches of some cultivated species have also expanded upwards.

#### 1.4. *Maize in the Andes*

Domesticated in Mexico perhaps as early as 8000–9000 BP (Before Present) (Piperno, Ranere, Holst, Iriarte, & Dickau, 2009), maize spread to the Andes several millennia ago. The earliest archaeological records for maize in Ecuador are from the coast where it may have been present already in 7500 BP (Pearsall, 2008). Over time, the crop has adapted to an array of different growing environments, and today it is cultivated from sea level up to all but the highest parts of the Andean agricultural landscape where its growth becomes limited by frost and low temperatures (Brandolini, Landi, Monfredini, & Tano, 2000; Timothy et al., 1963). Given that the rate at which temperature decreases with elevation varies at different latitudes (Lauer, 1993), the upper limit of maize cultivation varies throughout the Andes. For example, in Southern Peru maize has been reported to grow up to 3550 m (Zimmerer, 1996) whereas in Northern Ecuador it has been observed to grow up to only about 3000 m (Knapp, 1992; Timothy et al., 1963).

#### 1.5. *The present study*

The present study examines the expansion of maize cultivation in response to climate change on Mt. Cotacachi in the Northern Ecuadorian Andes. During previous fieldwork in Cotacachi in 2003–2004, farmers in the high-altitude community Ugshapungo (3200 m) reported that recently they had been able to cultivate maize due to rising temperatures (Skarbø, 2005). In 2010, the authors returned to research the nature of this upward expansion, guided by the following questions: (1) Do farmers in Ugshapungo continue to grow maize?; (2) Have farmers from neighbouring communities also begun planting maize in their upper fields?; (3) What are the spatiotemporal patterns of the expansion, and what kind of planting material has been used?; and (4) What are farmers' motivations behind and experiences from the expansion of maize into higher altitudes?

## 2. Study area and methods

### 2.1. *Study area: Cotacachi*

Cotacachi is a county located in Northern Ecuador's Imbabura province, approximately 80 km north of the capital, Quito. Of the county's 40,036 inhabitants (INEC, 2011), some 15,878 reside in 43 rural communities situated along the eastern slopes of the Cotacachi volcano (4939 m) (Unión de Organizaciones Campesinas e Indígenas de Cotacachi [UNORCAC], 2007). Agriculture has been a primary source of livelihood creation for millennia in this region. Although today members of approximately 70% of community households work off-farm (UNORCAC, 2007), agriculture continues to provide families with important food security and, in many cases, an additional source of income. Most households have individual landholdings between <1 and 10 ha in size (Skarbø, 2012). These lands are located along an altitudinal belt of approximately 1000 m, which can be divided into three zones: low (2300–2600 m), intermediate (2600–2800 m), and high (2800–3300 m). Most communities are located within only one zone, yet some stretch across two, in which case some households have parcels at different altitudes. As elsewhere in the Andes (Brush, 1982; Zimmerer, 1996), different crop

complexes predominate at different elevations (Skarbø, 2012). In the low zone, farmers typically intercrop maize with beans, squashes, lupines (*Lupinus mutabilis*), and quinoa (*Chenopodium quinoa*), along with some fruits (such as citrus, avocado, blackberry) and vegetables (including onions, cabbage, beets). In the intermediate zone, farmers produce a similar maize intercrop, alongside roots and tubers like arracacha (*Arracacia xanthorrhiza*) and oca (*Oxalis tuberosa*). Finally, the high zone is used primarily to cultivate cold tolerant cereals (wheat and barley), faba beans, potatoes, and other native roots and tubers (oca, melloco (*Ullucus tuberosus*) and mashwa (*Tropaeolum tuberosum*)), and to pasture livestock. Landraces make up approximately 90% of seed lots, and although local and regional markets and NGOs serve as sources of planting material, much seed is either saved on farm from the previous season or sourced within farmers' social networks (Skarbø, 2012). Among the diversity of crops in Cotacachi's agricultural system, maize is not only an important staple; it also plays a central culinary and cultural role as the main ingredient in a plethora of local dishes and as an important ritual object (Nazarea, Camacho, & Parra, 2006; Ramirez & Williams, 2003). While the county is ethnically mixed, the majority of rural community residents identify as indigenous (Kichwa) and speak both Spanish and Kichwa (UNORCAC, 2007).

## 2.2. Methods

Fieldwork was conducted in six communities, Ugshapungo, Morochos, Topo Grande, San Pedro, Iltaquí, and El Cercado, between May and July 2010. Of the area's 43 communities, these were selected because they cultivate land in the high zone near the original observation of upward maize expansion in Ugshapungo. Initial community visits and farmer interviews provided preliminary insight into the extent of maize cultivation in each community. In the communities where farmers reported to be planting maize at higher elevations, we conducted farmer-guided transect walks and, using a global positioning system (GPS; Garmin eTrex set to WGS 84), mapped the previous and present limits of maize cultivation. Points demarcating the previous limits are based on farmers' estimates of the location of their communities' highest maize fields 20 years earlier (1990). We chose a 20-year time frame because of initial reports from farmers in Ugshapungo that they first experimented with the cultivation of maize at higher elevations in the 1990s. Points that demarcate the present limits were taken at the top of the communities' current highest maize fields. The elevations measured with GPS are consistent with those registered in the mapping software (Google Earth), with a mean difference of +5.3 m. Semi-structured interviews ( $n=21$ ) with farmers conducted before, during, and after the walks revealed their motivations for and experiences from experimenting with maize at higher elevations. Key informants from each community were identified through recommendations of knowledgeable and experienced farmers from staff and leadership in Cotacachi's farmer union, UNORCAC (Unión de Organizaciones Campesinas e Indígenas de Cotacachi). Other key informants were recruited through chain referral as well as our own contacts from previous work in the area. We purposefully interviewed farmers mainly above 45 years of age in order to obtain informed assessments of agricultural changes over the past decades. All except four interviewees were male. In 2013, a return visit was made to each of the communities where transect walks had been conducted, and farmers were interviewed further about more recent high-altitude maize cultivation.

## 3. Results and discussion

### 3.1. A clear upward shift in maize cultivation

If you go up there now, you will see more maize than oca and melloco. It is almost as if what you used to see around here, you now see up there.<sup>1</sup>

Initial community visits revealed that in four of the six communities studied, maize cultivation had been expanded upwards.<sup>7</sup> Figure 1 and Table 1 show the previous (1990) and present (2010) limits of maize

cultivation along five transects in these four communities: Ugshapungo, Morocho, Topo Grande, and San Pedro. Two separate transects were conducted in Morocho because of the large expanse of agricultural lands belonging to this community. The previous upper limit indicated by farmers from the four communities ranged from 2870 to 2968 m.<sup>3</sup> In 2010, the highest fields were located between 3119 and 3267 m. This represents a clear upward shift of ~200–300 m in elevation, corresponding to a ground distance of 1.1–1.3 km during the last two decades.

Inter-communal variation in the previous and present limits of maize cultivation indicates that site-specific variation in climate and topography also influences the elevation range for growing maize. The community of Ugshapungo, where we registered the highest elevation for current maize cultivation (3267 m), is located on a comparatively flat part of the mountain making it topographically better suited for agriculture. This is in comparison to Morocho, Topo Grande, and San Pedro, where beyond the uppermost maize fields land becomes increasingly steep and less accessible for cultivation.

In each community, the uppermost maize fields were surrounded by others sown with both maize and more traditional high-zone crops. This indicates that so far maize has not completely replaced the crops already grown in the high zone, but rather presents an important addition.

### 3.2. *Spatial shifts through time*

The upward movement of maize has taken place in a step-wise fashion. Farmers in each of the four communities reported to have begun to cultivate maize in the high zone between 1990 and 2006, with the uppermost fields registered in 2010 having been planted with maize for the first time between 2000 and 2008. The first shift occurred in the community of San Pedro. There, farmers reported to have introduced maize into the lower part of the high zone (2900–3000 m) around 1990, and today maize is one of the primary crops grown at this elevation. A further upward expansion took place in San Pedro between 2006 and 2007, and the highest maize field in 2010 reached 3119 m. In Ugshapungo, farmers reported that maize was first cultivated in 1997, and that since then it has only become more prolific. Lastly, in Topo Grande and Morocho, farmers started to cultivate maize in the high zone in 2006 and 2007, respectively. The current uppermost maize fields in Topo Grande (3192 m) were first planted with maize in 2007 and those in Morocho (3184 m) in 2008.

### 3.3. *Movement at the level of maize races*

On a more detailed level, we noted the upward expansion of several maize races. There are over 200 distinct maize landraces in Latin America that are adapted to different agroecological conditions (Goodman & Bird, 1977). Recently, landraces of Andean maize have been shown to contribute to social-ecological resilience involving changes in water resources and socio-economic livelihoods (Zimmerer, 2013). Given that temperature is a limiting factor in the growth of different maize races (Brandolini et al., 2000), elevation is an important regulator of their distribution in any given area (Eagles & Lothrop, 1994; Timothy et al., 1963). Based on extensive field work in the 1950s, Timothy et al. (1963) laid the foundation for the scientific classification of Ecuador's landraces, identifying 29 distinct races, 17 of which are specific to the highlands. During a survey of 89 farms in Cotacachi in 2010, 12 of these highland races were registered (Skarbø, 2012), showing evidence of a remarkably rich local diversity. Timothy et al. (1963) did not conduct transect walks like in the present study, and since their data collection was carried out mainly for taxonomic purposes they may not have included the entire altitudinal expanse of maize cultivation in their collections. Their surveys did well cover the Inter-Andean valley of Imbabura province of which Cotacachi forms a part, yet their reported elevational ranges are based on a larger data set encompassing 675 accessions from across the entire country (Timothy et al., 1963). Despite these methodological differences, their reports of the altitudinal ranges of different races are the best estimates available for the previous elevational expanses of maize races in the Ecuadorian highlands, including the Cotacachi area. They observed the races Mishca (local Kichwa name in Cotacachi: *raku sara*) up to 2800 m and Chillo (local Kichwa names: *tsapa sara*,

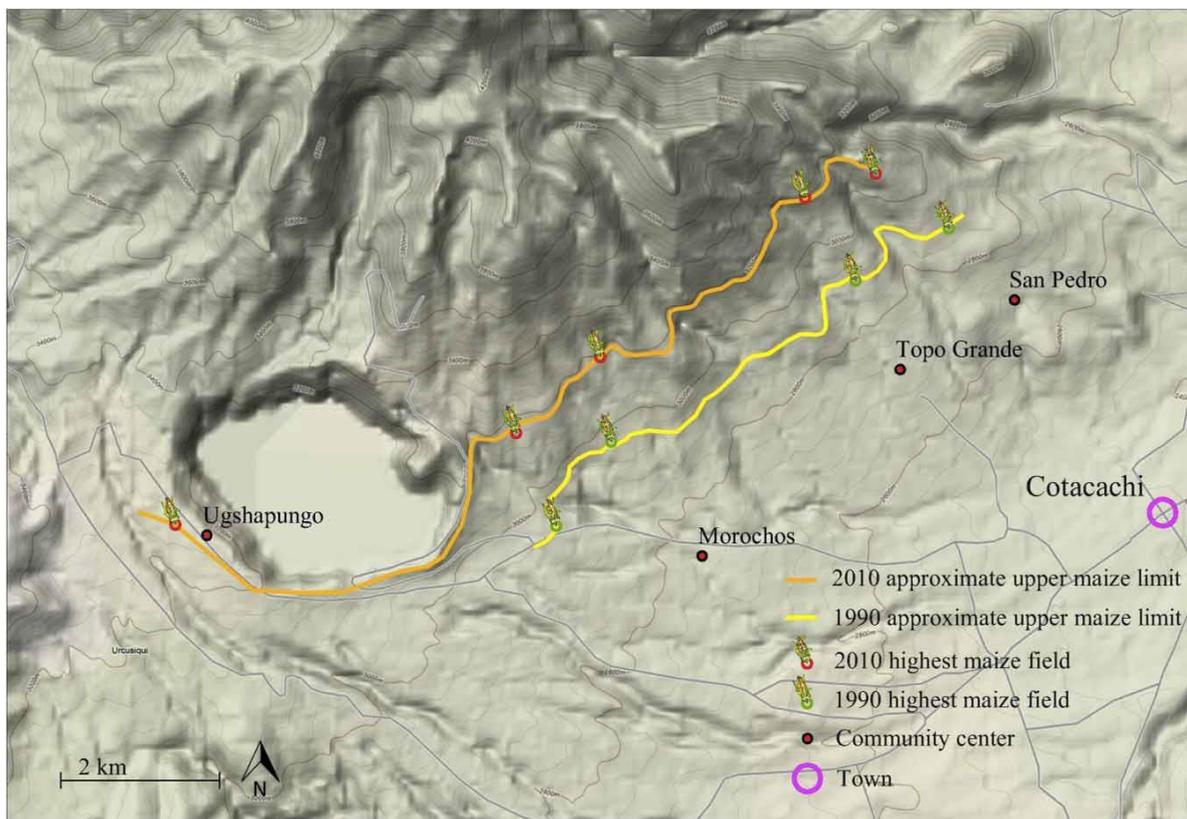


Figure 1. Map showing approximate previous (1990) and present (2010) upper limits of maize cultivation in Cotacachi. Elaborated by the authors. Map data: Google and authors.

*chivila sara*, *kaballu kiru sara*) as high as 3000 m. We observed both of these races above 3100 m, indicating an upward movement of multiple races.

We additionally noted that the race Tusilla, registered by Timothy et al. (1963) to grow between 90 and 1500 m, is now cultivated in Cotacachi's lower zone (2300–2600 m). There farmers explained that they only recently introduced Tusilla (local names: *muruchillu*, *maicena*) into their seed repertoire, confirming the previous lower expansion identified by Timothy et al. (1963). We also observed the race Chulpi Ecuatoriano (locally called *chullpi*) in the intermediate zone (2600–2800 m), past the upper limit of 2600 m reported by Timothy et al. (1963). It might only be a matter of time before farmers in Cotacachi introduce other races into new elevations, further breaking the previous delimitations of the area's agroecological zones.

#### 3.4. Seed sources and varietal adaptation

Farmers reported to have procured seeds locally for growing maize at high elevations, either from their own or neighbouring communities at intermediate elevation. Several farmers noted that it was necessary for the seed to get "accustomed" or "acclimatized" to growing in the high zone: "One selects the best cob from this very place, because if I sow the maize from down below – if I harvest down below and sow here – it will not yield. It has to be acclimatized to this place."<sup>4</sup> Thus, a farmer from Ugshapungo noted that when he began growing maize around the year 2000, he first used seed from a community in Cotacachi's low zone (San Bartolo), but with poor results. The year after, he obtained seed from San Nicolas, located just below Ugshapungo, and it produced well.<sup>5</sup> Most farmers emphasized that they now save the best producing seeds from their high-zone harvests to plant the following year. Those who grow maize in both the high and intermediate zones reported to use separate seed lots at the two locations, although some maintained that

Table 1. Elevations of previous (1990) and present (2010) upper limits of maize cultivation in four communities in Cotacachi.

Community	Limit 1990 (m)	Limit 2010 (m)	Difference in elevation (m)	Difference <sup>a</sup> between limits (km)
Ugshapungo	NA <sup>b</sup>	3267	NA	NA
Morochos West	2968	3180	212	1.3
Morochos East	2985	3184	199	1.2
Topo Grande	2893	3192	299	1.2
San Pedro	2870	3119	249	1.3

<sup>a</sup>Distance “as the crow flies”, measured on map.

<sup>b</sup>NA, not applicable. The entire community of Ugshapungo is located in the high zone where a previous limit to maize cultivation does not exist because maize was not cultivated there prior to the 1990s.

seed sourced from the intermediate zone could also be used higher up. In the case of the Tusilla now grown in Cotacachi’s lower zone, farmers reported to have used seed sold for animal feed purchased at local markets.

These observations have two important implications meriting further research attention. First, they indicate that present seed systems may be capable of providing farmers with seed adapted to changed climatic conditions. So far, farmers in Cotacachi have been able to access seed for their high-zone fields from neighbours or other communities in the area through their social networks. Farmers actively draw on their experiences and knowledge of regional agroclimatic conditions to plan their procurement of planting material, and local social relations allow such transactions to take place. Although this does not guarantee that the same opportunities will be available under the rapid climatic changes expected to occur throughout the present century, it is a strong indicator that the present seed system provides farmers with resilience to climate change. These results also concur with an analysis from eastern Mexico, concluding that for most communities, the geographical reach of the local maize seed system includes areas where the present climate is analogous to the climatic conditions predicted for the community in 2050, implying continued access to adapted planting material (Bellon, Hodson, & Hellin, 2011). Future research on local and regional patterns of seed provisioning as climate change proceeds will broaden our understanding of the capacity of existing seed systems to allow the movement of crops and crop varieties along altered agroclimatic gradients.

Second, farmers’ observations of changes in seed performance at different altitudes over time bring attention to responses within populations, suggesting that the maize populations in question have been able to rapidly respond to new environmental parameters after being moved uphill. There is still limited scientific understanding of maize landraces’ potential to adapt evolutionarily to climate change (Mercer & Perales, 2010). Yet, a growing body of research documents that plant populations across a number of other species have responded to climate change during recent years through phenotypic plasticity and/or evolution (Franks, Weber, Aitken, 2014). Farmers’ emphasis on the importance and effect of seed selection might suggest that at least some element of selection-driven adaptation is at work in our case. The overall high diversity of maize races present in Cotacachi indicates that the landrace populations that have been moved upward are genetically diverse, a factor associated with high adaptive capacity in general (Brown, 1999), and potentially under climate change as well (Mercer & Perales, 2010). Further examination of these migrated maize populations could yield interesting insights into possibly occurring plastic or evolutionary processes, advancing our understanding of the capacity and speed of adaptive change among maize landraces under climate change.



Figure 2. Maize fields at different elevations. A farmer from the community of Morochochos shows harvest loss in the intermediate zone (left, 2780 m) and good production in the high zone (right, 3184 m) (Photos by the authors).

### 3.5. *Motivation for and experiences from moving maize upward*

The key factors prompting farmers to move maize upward are: (1) decreasing productivity at lower elevations and (2) warmer and more favourable conditions at higher elevations (Figure 2). Reduced productivity is associated with the challenges posed to agriculture by climate change and intensified land-use. The disappearance of Mt. Cotacachi's glaciers at the end of the twentieth century (Rhoades et al., 2006) has affected stream flow in many of the area's waterways, reducing the availability of water for irrigation, livestock, and household use. At the same time, increased temperatures and irregular rainfall result in greater need for irrigation, more pest problems, and, consequently, higher incidences of crop damage and loss (Skarbø & VanderMolen, 2014; Skarbø et al., 2012). Both farmers and scientists link (Zehetner & Miller, 2006b) decreased productivity, in particular in Cotacachi's lower and inter-mediate zones, to poor soil fertility resulting from the shortening of fallow periods and overexploitation of soils as the population increases and land becomes more scarce.

While climatic change and irregularity also pose challenges to crop production in the high zone, the increase in temperature has allowed the entry of maize into these fields. A farmer from Ugshapungo notes: "Earlier it was cold, colder, and the maize did not ripen here at all, earlier it was only for potatoes, fava beans, mellocos, but now it ripens."<sup>6</sup> Farmers' observations in the other study communities are similar: "Earlier it [maize] did not produce up there, only melloco, potatoes, barley, quinoa, wheat, but now the weather has changed, now it is warm far up, not like before."<sup>7</sup> Farmer testimonies indicate that the changes in the upper limit of maize cultivation are linked to changes in environmental conditions, and do not simply reflect changes in preferences, or previous lack of knowledge of the possible growing range of maize. For instance, one farmer in Morochochos, now in his 60s, showed us the site where, as a young newlywed, he established his first homestead together with his wife. They had chosen this spot, at an altitude just below 3000 m, because his wife had inherited land here, and so they decided to plough and sow fields for their subsistence. "We sowed everything",<sup>8</sup> he explained. Some crops yielded well but, to their frustration, the maize plants would not develop. Due to the key importance of this crop in their diet, after years of failed maize harvests they

decided to leave the land fallow and move further down to his home community, Morochos: “For the maize I returned to my community”(see note 8).

When asked how it occurred to them to plant maize further up, some farmers responded that they had observed warmer temperatures at higher elevations and tested the conditions for maize by planting it in small plots. For others, experimentation happened almost by accident:

Little by little, sowing potatoes, quinoa, barley, sometimes there would be some maize in the barley, in the wheat, in the fava beans as well, and those [seed] would grow up on the hill. And so, there they grew well, like here, better than here they grew, and seeing that, we began to sow.<sup>9</sup>

As the first farmers in each community experienced success, their neighbours began to plant maize higher up as well.

With the exception of one man from Ugshapungo, all other farmers interviewed expressed uncertainty when asked if they knew whether the upward expansion of maize cultivation had occurred in other communities. This man explains that it occurred to him and his neighbours to sow maize after having been served home grown *choclo* (green maize) during the *San Juan* festival in a neighbouring high-altitude community in the bordering county of Otavalo: “we talked amongst ourselves and then we began to sow it here as well, and it matured better than those sown in Cuicocha, Quiroga [in the lower zones], better it matured here and it continues to yield well.”<sup>10</sup> The variation in time between the upward movement of maize in each community and farmers’ uncertainty as to whether it had occurred in others suggests that the migrations are the result of several independent experiments. The most recent advances of maize production in these communities demonstrate that farmers continue to experiment. For example, a farmer in Morochos showed us a field at 3278 m, a small part of which had been planted with maize in 2009 but with poor results, the plants showing signs of stunting from cold. In Ugshapungo, several farmers reported to have tried growing maize in fields above 3300 m but without success: “further up it does not mature around here, further up I have sown, the maize grows to about 40 cm height, and there it stops, it does not produce cobs, nothing, it seems it is colder further up.”<sup>11</sup>

According to farmers, thus far, maize planted in the high zone has yielded more than maize planted in the inter- mediate zone; a point they relate to fewer pest problems and richer, less-eroded soils that better retain moisture. Farmers also refer to the high zone as “fresher” (*más fresquito*) because the near constant fog of the neighbouring *páramo* ecosystem<sup>12</sup> buffers it from the strong sunshine and prolonged dry periods that afflict the intermediate and low zones (see Zehetner & Miller, 2006a). One farmer explains:

Much better than down [in the community’s intermediate zone fields] it has ripened here. Down below it is all lost, all rotted. Because of much sun, and lack of water. Up here the humidity is better maintained, and the soil is very good, the soil is black, and there is natural fertilizer from the forest. Down below, on the other hand, it is sandy.<sup>13</sup>

In addition to higher yields, farmers also explain that the fresh maize from the high zone has a sweeter, better taste compared to that from lower zones. On the other hand, the dry maize has a harder consistency; smiling, one farmer explained that he had to use a nail to remove kernels from the cobs harvested in the high zone. Several also noted colour differences; the maize grown higher up does not yellow as much as the maize grown further down.

This is not to imply that the high elevation production of maize is without challenges. Since farmers first began to grow maize in Ugshapungo in the 1990s, occasionally, periodic frosts have caused severe damage; a reminder that it is near the current environmental limit. Additionally, the colder conditions slow plant growth from 8–9 months in the intermediate zone (consistent with Knapp, 1992) to 11–12 months in the high zone, meaning that the latter fields are occupied almost year round with a single crop. Still, the advantages seem to outweigh the costs for the increasing number of farmers opting to plant maize higher up.

Qualitative and quantitative differences in growth and yield characteristics between similar maize populations grown at different altitudes have been observed elsewhere as well (Eagles & Lothrop, 1994; Mercer, Martínez-Vázquez, & Perales, 2008). For instance, an experimental study in the tropical highlands of Kenya (Cooper, 1979) found that overall yield, cob dry matter content, and length of maturation period increased with altitude, in agreement with farmers' observations in Cotacachi. Research combining farmer participation, field and laboratory analyses could yield further insight into the extent of changes in morphological and organoleptic traits and expressions among migrated maize populations.

### 3.6. *Implications: potential future developments in high-zone agriculture*

Earlier, people from further down, like Chilcapamba, used to look up to us in Morochos and admire our fields – it [maize] produced really well up here in the community. Now, it does not grow well anymore, but up on the hill it does. It is as if the zones have shifted further upwards. Now maize grows well up there. Now we'll have to grow potatoes and mellocos even further up!<sup>14</sup>

As the above quote illustrates, Cotacachi's farmers are highly cognizant of the ongoing changes in local agroecological zonation. Farmers in Ugshapungo, the area's upper-most community, proudly announce "we can sow everything now!" This is a slight exaggeration as there is a notable absence of some heat-demanding crops, like fruits and the common bean (*Phaseolus vulgaris*), which are sown frequently in Cotacachi's lower elevations, the latter typically intercropped with maize. However, on our return in 2013, one farmer in the lower part of Ugshapungo had harvested a small quantity of common beans for the first time, and another reported that he had just ordered 10 plum trees in order to try them out. Also in 2013, farmers in Morochos reported to have harvested a few sacks of common beans from their higher fields during the last two years. At the same time, farmers from several communities explained that the conditions for more heat-dependent fruit crops, like lemons and avocados, had improved in the intermediate zone. If warming continues as predicted, these observations suggest that farmers will likely continue to experiment with more crops at higher elevations in the future.

The successful cultivation of maize in the high zone presents an important opportunity to improve maize production and overall food security for those of Cotacachi's farmers with access to these lands. In several of the study communities, the high zone had, due to its distant location and marginal growing environment, combined with decreased farm labour capacity linked to increased migration and other off-farm activities, only played a minor role in supporting livelihoods during the past generation. The recent developments reported here, however, seem to be leading towards a renaissance for high-zone farming.

Nevertheless, this increased cultivation of the high zone also presents new problems. The further expansion of maize into the highest cropping zone might affect the cultivation of the cold-tolerant crops traditionally grown there. While thus far farmers have added maize to their highest fields without entirely supplanting other crops, it is possible that some of these will eventually be pushed to the margin of the agricultural system and abandoned by farmers, or cultivated even higher up in what is now brushland or forest. While the first possibility would have negative consequences for food security in terms of dietary diversity and the conservation of Andean plant genetic resources, the second would imply encroachment of unique ecosystems that are already considered to be endangered (Peñañiel Cevallos, Tipán, Nolivos, & Vásquez, 2006; Ruiz, Moreno, Gutiérrez, & Zapata, 2008). In 2013, farmers from one of the study communities reported an escalating conflict with environmental authorities concerning their recent increased use of upper croplands. The community had initiated the construction of a new road in order to facilitate cultivation in the high zone, but had been met with resistance by the Ministry of Environment and the project was put on hold. This suggests that if cropping zones continue to expand upward in response to a warming climate, there will be a need for new solutions that allow farmers to continue producing food and maintaining livelihoods in a sustainable manner. Relatedly, even if high-zone fields currently sustain good maize yields, future productivity will depend not only on climatic and environmental developments, but also on farmers' decision-making and management. Traditional practices supporting productivity in Cotacachi include crop rotation, intercropping,

and periodic fallowing. However, as noted, decreasing productivity in the lower zones during the recent past has been linked to over-exploitation of soils, concomitant with a partial shift away from these practices and towards reduced crop diversity and less fallowing. Therefore, the use of sound agroecological techniques in high-zone cultivation will be important for avoiding the overexploitation of these upper fields as well.

#### 4. Conclusion

This case study documents a completely farmer-led autonomous adaptation to climate change in Ecuador's Andean highlands. Prompted by poor maize harvests in the area's intermediate and low zones and observations of warmer temperatures, farmers in four of Cotacachi's communities have independently tested the growth of this key crop in some of their higher fields. Successful results have led neighbouring farmers to follow suit and the upper limit of maize cultivation has climbed an estimated 200–300 metres during the last two decades. These findings indicate that Cotacachi's crop zones are shifting upwards as plants and farmers respond to recent climate change. While the movement of crops and crop varieties into adjacent zones is unlikely to fully resolve the complex challenges posed by climate change, this study suggests that in the Andes, and potentially other tropical mountain areas where farmers' varieties are adapted to growing conditions along elevation gradients, local landrace seed may constitute a viable source of planting material for farmers seeking to adjust their crop and varietal composition to rising temperatures. Our findings highlight farmers' central role in guiding crop adaptation, and call for the inclusion of farmers' perspectives in further participatory and interdisciplinary research on crop populations' responses to geographical and climatic shifts. Finally, the results indicate that policies and interventions should pay careful attention to current efforts within local communities in order to support emerging adaptive responses, and further underline the importance of in situ maintenance of landrace diversity to support agricultural resilience to climate change (Mercer, Perales, & Wainwright, 2012).

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#### Notes

1. Farmer interview, San Pedro, 15 September 2009.
2. In two other communities, farmers were not cultivating anything in the high zone at the time of research. In Iltaqi, lands in the high zone are communally owned and had been rented to a hacienda, and in El Cercado, cultivation of the high zone had been abandoned altogether.
3. This upper limit largely corresponds to accession data on maize collected in Ecuador. Of the 1348 accessions in the Genesys database, only 12 are reported to be collected from sites above 3000 m, and none of these were from Imbabura province (Genesys, 2014).

4. Farmer interview, Ugshapungo, 1 December 2013.
5. Farmer interview, Ugshapungo, 1 July 2010.
6. Farmer interview, Ugshapungo, 3 December 2013.
7. Farmer interview, Morochos, 1 December 2013.
8. Farmer interview, Morochos, 16 June 2010.
9. Farmer interview, Morochos, 1 December 2013.
10. Farmer interview, Ugshapungo, 3 December 2013.
11. Farmer interview, Ugshapungo, 3 December 2013.
12. The páramo is a neotropical highland ecosystem stretching from the upper limit of continuous forest up to the area of perpetual snow (Mena Vásquez & Hofstede, 2006).
13. Farmer interview, Morochos, 16 June 2010.
14. Farmer interview, Morochos, 16 June 2010.

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