

THE INTERNATIONAL
JOURNAL
Of Environmental, Cultural,
Economic & Social
SUSTAINABILITY

Volume 6, Number 5

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THE INTERNATIONAL JOURNAL OF ENVIRONMENTAL, CULTURAL, ECONOMIC
AND SOCIAL SUSTAINABILITY
<http://www.Sustainability-Journal.com>

First published in 2010 in Champaign, Illinois, USA by Common Ground Publishing LLC
www.CommonGroundPublishing.com.

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ISSN: 1832-2077
Publisher Site: <http://www.Sustainability-Journal.com>

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Typeset in Common Ground Markup Language using CGCreator multichannel typesetting system
<http://www.commongroundpublishing.com/software/>

Climate Change in the High Andes: Implications and Adaptation Strategies for Small-scale Farmers

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Abstract: Global climate change represents a major threat to sustainable farming in the Andes. Farmers have used local ecological knowledge and intricate production systems to cope, adapt and reorganize to meet climate uncertainty and risk, which have always been a fact of life. Those traditional systems are generally highly resilient, but the predicted effects, rates and variability of climate change may push them beyond their range of adaptability. This article examines the extent of actual and potential impacts of climate variability and change on small-scale farmers in the highland Andes of Bolivia, Ecuador and Peru. It describes how climate change impacts agriculture through deglaciation, changes in hydrology, soil and pest and disease populations. The article highlights some promising adaptive strategies currently in use by or possible for producers, rural communities and local institutions to mitigate climate change effects while preserving the livelihoods and environmental and social sustainability of the region.

Keywords: Andes, Sustainable Agriculture, Climate Change, Soil, IPM, Glaciers

SUSTAINABLE AGRICULTURE IN the Andes has always been predicated on the ability of individuals, families, communities and regions to respond to variability and build resilient systems in this highly variable eco-system. Climate change presents one of the current threats to sustainable farming in the Andes. Trends and forecasts (IPCC, 2007; Urrutia and Vuille, 2009) suggest that climate-related pressures will increase in the Andes due to climate change, demanding modifications in land use, production systems, indigenous knowledge systems, coping mechanisms, and livelihood strategies. Climate uncertainty and risk have always been a fact of life in the high Andes (defined here as being above 2,500 m.a.s.l.) and farmers have used local ecological knowledge and intricate production systems to cope, adapt and reorganize over time to meet this reality (Dillehay and Kolata, 2004; Halloy et al. 2005a). Nonetheless, climate change will represent substantially greater year-to-year climatic variation and unpredictability. It will likely increase the frequency of

extreme events (Hulme and Shead, 1999), be stronger at high altitudes than in lower areas (Foster 2001), and imply losses that could not be distributed equally among families, and therefore insured through cooperation (Crespeigne et al. 2010).

This article highlights the principal issues concerning the extent of actual and potential impacts of climate variability and change on small-scale farmers in the highland Andes of Bolivia, Ecuador and Peru. It also identifies some promising adaptive strategies currently in use by or possible for producers, rural communities and local institutions, as well as gaps in knowledge that require further analysis.¹ In this manner this article looks at the sustainability of social practices in the Andes vis-à-vis biophysical processes.

Glacier Recession

Glaciers are among the most visible and irrefutable indicators of climate change. Most of the world's tropical glaciers are located in the mountains of Peru (70% of world's tropical glaciers), Bolivia (20%) and Ecuador (4%) (Vuille et al. 2008). The glaciers' geographic positioning in the region makes them uniquely vulnerable to temperature increases and reduced cloud cover. Climate change is resulting in upward shifts in the freezing point isotherm and coincides with an overall warming of the Andean troposphere (Francou et al. 2003) and more pronounced warming at higher elevations than low elevations due to depletion of snowpack, which leads to a reduction in the albedo and greater absorption of solar radiation at the surface (Giorgi et al. 1997). Also, unlike mid-latitude mountain ranges, such as the Alps, ablation and accumulation seasons coincide in the Andes, which precludes the development of a long-lasting seasonal snow cover (Vuille et al. 2008).

Long-term observations in the Andes show unequivocally rapid and accelerating retreat of the glaciers, with 30% of the total ice mass of glaciers retreating over the last 30 years (Urrutia and Vuille, 2009; Vuille et al. 2003, 2008). Deglaciation has affected most the lower-altitude small-sized glaciers (<0.5 km²), many of which might disappear in the next decades if the trends persist (Bradley et al. 2006; Coudrain et al. 2005; Francou et al. 2000; Halloy et al., 2005b; Kaser et al. 1990; Kaser and Georges 1997; Thompson, 2003; Vuille et al., 2003). These small glaciers are the most common in the Andes and make important contributions to the water resources of high elevation basins (Ramirez et al. 2001). Peru's most famous mountain, Mount Huascarán, has lost 1,280 hectares of ice, or 40% of the area it covered 30 years ago (Simms and Reid, 2006). Bolivia's Chacaltaya glacier, one of the sources of fresh water for 2 million people in the cities of La Paz and El Alto, has lost 82 % of its surface area since 1982 and is expected to completely melt within 15 years if present trends continue (Francou et al. 2003; Ramirez et al., 2001; Simms and Reid, 2006).

Glacial retreat will likely destabilize ice slopes, causing landslides and mudflows. Deglaciation water tends to pool in newly formed and often not stable lakes. In Peru's Cordillera Blanca, for instance, glacial melting resulted in a dramatic rise in the formation of glacial lakes from 223 in 1953 to 374 in 1997. Some of those lakes may be associated with cata-

¹ This document draws upon a consultation workshop on "Impacts of Climate Change in the Andes," organized by The McKnight Foundation's Collaborative Crop Research program and hosted by the International Potato Center in Lima, Peru (April 29-30, 2008). The authors gratefully acknowledge the intellectual input of participants at the workshop. We give special thanks to Rebecca Nelson, Pedro Oyarzun, Corinne Valdivia, Anji Seth, Vladimir Gil, Daniel Ruiz, Graham Thiele and Jere Gilles.

strophic outburst floods, such as those in Huaraz (1941), Los Cedros (1951) and Santa River valley (1970), which together claimed the lives of some 75,000 people (Carey 2005).

Climate change will affect glacier extent and runoff behavior differently depending on the catchment (Vuille et al. 2008). Nevertheless, over time glacier melting will contribute to the temporary increase, eventual reduction and ultimately likely disappearance of high altitude water bodies. It will influence the timing of the discharge of water from rivers in the mountains, decrease the volume of water available especially during the dry season (mountain glaciers act as a critical buffer against highly seasonal precipitation), and leave tens of millions of highland people without a continuous source of fresh water. For the time being, glacier recession and mass loss have increased water availability (Pouyaud et al. 2005) and some downstream users are adapting to this short-term enhanced water availability by planning crops accordingly (Mark 2008; Mark et al., 2005; Vuille et al. 2008). Over the medium term, however, glacial melt will decrease water supply aggravating present challenges for agriculture, food preparation and power generation in mountain communities (Buytaert et al., 2006; Ruiz et al., 2008; Young and Lipton 2006). It will also deny water supplies to major cities, many of which located above 2500 m.a.s.l. and entirely dependent on high altitude water sources for energy generation. Climate change will likely trigger social tension in “water-wars” and put urban populations and food supplies at risk.

The rapid retreat of glaciers requires the adoption of adaptive measures to prepare for future changes in runoff patterns. These measures should include the creation and strengthening of a system of stable, safe and well monitored water reservoirs of different sizes. Rather than relying exclusively on centralized infrastructure to capture, treat and deliver water supplies, the system should include decentralized management that responds to the needs and concerns of farmer groups and other local and community end users. A massive shift to less water-intensive agriculture is needed, including a systematic support to local innovations on drip irrigation, rainwater harvesting, cover crops and minimum tillage, enhanced soil organic matter content, and watershed restoration and management. Substantial water conservation measures are also needed for domestic and industrial purposes in rapidly expanding cities where much of the population growth in the Andes will occur over the next few decades.

The water pressure will be particularly hard on the high, cold and dry plateau of the lower Andes (the “puna” region) that covers from Cajamarca, in Peru, to Bolivia, Argentina and Chile, and is characterized by extensive *Stipa ichu* vegetative cover. North of Cajamarca, and all the way to Venezuela, the alpine grassland (“páramo”) occupies the same altitudinal niche as the puna (from 3,000 to 5,000 m.a.s.l.). The páramo is the major water source for the Andean highlands of Venezuela, Colombia, Ecuador and a vast area of arid and semi-arid lowlands in northern Peru. The páramo, however, is cold, wet and green, as it is continuously covered with fog and drizzle.

It is critical in this context to understand (and protect) the hydrological regulation services that the páramo provides through considerable water storing in lakes, peat bogs (“bofedales” or “ciénagas”) and wet grasslands mixed with shrublands and low-statured forest patches. Páramo soils absorb water easily and then release it slowly. Many of the largest tributaries of the Amazon basin have their headwaters in the páramo. Several urban centers in the northern Andes, including the cities of Bogotá and Quito, are almost completely dependent on páramo ecosystems for their water supply. The páramos provide environmental services to more than 100 million people (IUCN, 2002).

The páramo has an uneven topography, including rough and steep valleys and almost flat plains, with many concavities where water accumulates in bogs and lakes. It hosts 5,000 different plant species, the vast majority of which are endemic and highly adapted to specific physio-chemical and climatic conditions, such as low atmospheric pressure, intense ultraviolet radiation, and the drying effects of wind (Buytaert et al. 2006). The páramo's hydrological regulation processes are not well understood, yet the special composition and structure of the páramo Andosol soils make their structural degradation and decrease in water retention through agriculture and the other economic uses irreversible within human timescales (Buytaert et al. 2006; De Bièvre, 2008).

In order to protect the ecological services the páramo provides, large areas of páramo around major cities have been declared national parks (Chingaza near Bogotá, Cayambe-Coca near Quito, and Cajas near Cuenca). One possible additional adaptation strategy could be to create a system of credits to compensate local land users for the environmental services that páramos provide, as it has been developed for rainforests. In Costa Rica, for instance, funds from a special tax on the consumption of any crude oil derivative are used to pay smallholder owners of natural forests for the value of environmental services, including mitigation of greenhouse gases through C sequestration, protection of water sources, protection of biodiversity and preservation of natural scenic beauty for tourism (Rodríguez 2003). Páramo mitigation activities could also be supported with funds such as those of the Global Environmental Facility that encourages sustainable land management (GEF 2003). As it has been piloted in other parts of Latin America, in addition to direct payment to producers or producer associations, the forms of compensation could include technical assistance, training and marketing support; provision of social services and infrastructure; investment financing to improve property or farm management; product surcharges (certificates and special product seals); support to rural tourism and ecotourism community strategies; and expansion of access or use rights to natural resources (FAO 2004).

Temperatures and Rainfall

High elevation temperature changes are an early detection tool for global warming (Giorgi et al. 1997), and average temperatures in the tropical Andes have been increasing (Vuille et al. 2003). According to global circulation models, the anticipated temperature increases in the Andes will greatly exceed those in surrounding lowlands. The rate of increase is projected at two or more times those projected for average temperature increases (Bradley et al. 2006). In the Andes, as in other tropical high-altitude climates, diurnal temperature variations by far exceed seasonal ones and freezing temperatures are frequent (Troll 1968). With climate change, more diurnal temperature variation, important increases in maximum temperatures and significant variations in relative humidity, cloud and fog cover, and sunshine are expected in the area (Buytaert et al., 2006; Ruiz et al., 2008). A warmer climate will likely enhance the hydrological cycle, with higher rates of evaporation, greater proportion of liquid precipitation as opposed to solid precipitation, potential changes in precipitation amount and seasonality, likely reduction of soil moisture and groundwater reserves, and greater frequency of drought or flooding (Beniston 2005).

A current increase in temperature has resulted in the snowline rising. The upper altitudinal limit of highland agriculture has also risen significantly in the past 50 years. It is expected that this trend will continue over the century, leading to an overall increase of at least 500

meters. With temperatures rising, the area for crop and animal species adapted to the coolest climatic zones at high elevations is shrinking. Both herding and agriculture have risen approximately 300 m in the last 50 years in southern Peru, with potato cultivation reaching a world record altitude of over 4,500 m.a.s.l. (Halloy et al., 2005b; Halloy et al., 2008; Seimon et al., 2007). In 1975, in the Huancavelica region of Peru, the upper limit for growing cultivars of bitter potatoes (*Solanum curtilobum*, *Solanum juzepczukii*) was 4,150 m.a.s.l. Currently they are grown between 4,150 and 4,300 m.a.s.l. These potatoes are increasingly occupying natural pasturelands and competing with high altitude livestock systems. The cultivation on these new areas implies high levels of production risk from frost, drought and hail (De Haan et al., 2009).

Frost ranks high among the most important limiting factors for agricultural production in the Andes, especially in Bolivia and the southern part of Peru. In general, there are two different classes of frost. Advectional frost (also known as “white” frost) is caused by large-scale cold air masses moving into an area under a cloudy sky, windy conditions and high relative humidity at a high dew point temperature (hovering above 0°C). It leaves the ground covered with a white layer of ice crystals (hoarfrost), usually does not harm crops and may even help in killing off diseases and pests. On the other hand, radiative frost is created on cloudless and calm nights (especially immediately before sunrise, at night’s minimum temperature) when the surface cools the dry air immediately above it. Denser cold air flows down from hills on to the plains, and ponds in lower laying areas of the landscape. Hence, radiative frost tends to be more frequent and severe at sites located on convex sites, valley floor or in the plains where it causes necrotic spots in foliage (hence its name of “black” frost). Hills and hillsides are warmer and have lower risk of frost. In the Andean highlands, the dry “black” frost is most common, and is also more harmful to crops than the humid “white” frost.

Frost occurs throughout the year and may occur within up to 200 days a year (Jacobsen et al. 2007). The critical frost risk period is between January and March (summertime) after efflorescence, i.e. not when frost is at its peak but when it can cause catastrophic damage to crop yields. Anecdotal evidence seems to show that frost episodes are increasing in frequency and severity in the high Andes. However, the greatest changes may in fact result in increasingly erratic frost events, even despite the lengthening of the frost-free period (0.49 days per year) due to the observed stronger increase in daily minimum rather than maximum temperatures.

Farmers seek to control soil moisture to reduce the impact of frost on their most sensitive crops. In general, they use a combination of irrigation, enclosures, terraces and trees to protect the fields from cold air deposits. In flatlands they use ponds (qochas), as well as furrows and small, rectangle-shaped shallow raised beds surrounded by irrigation canals (*sukaqollos*), and disperse fields to spread risk (Morlon 1992). Using drought-tolerant varieties is, however, the most effective approach. Most common potatoes (*Solanum tuberosum* subsp. *tuberosum*) cannot withstand temperatures lower than -3°C, whereas Andean species (notably *S. tuberosum* sub. *andigena*, *S. stenotomum*, *S. chaucha*, *S. goniocalyx*), as well as bitter potatoes (*Solanum juzepczukii*, *Solanum curtilobum*, *Solanum ajanhuiri*), quinoa (*Chenopodium quinoa*) and qañiwa (*Chenopodium pallidicaule*) can endure temperatures as low as -5°C (François et al. 1999). Some wild potato species have even higher levels of frost tolerance.

Agrobiodiversity, therefore, is critical for frost risk management, and farmers engage in careful cultivar selection and use. In a study in Palccoyo, Peru, of the 126 potato landraces evaluated, 26% exhibited signs of resistance to frost (Gutiérrez and Schafleitner, 2007).

Andean farmers' fields continue to have high levels of agrobiodiversity in many parts of the Andes. In one study in Quispillacta, Peru farmers were found to cultivate an average of 11 crops and 74 ecotypes on small plots of land (Machaca, 1993; Tapia, 1993). In Kuyupampa, Bolivia, farmers cultivate in the same fields 21 native potato varieties, 7 improved potato varieties, 7 oca (*Oxalis tuberosa*) varieties, 4 varieties of wheat, and 7 races of corn (Regalsky and Hosse 2009). Some of these varieties are adapted to specific microenvironments, altitude levels and climate conditions. Even when they are not fully adapted to microenvironments, their variety enhances the mixture's resilience (Morlon 1992). In a process of "Andeanization" of exotics, farmers have widely incorporated into their rotation schemes Old World crops such as faba beans, barley and even wheat--which were first introduced in the 16th century and now grow at 3,900 m.a.s.l.--in order to increase the resilience of the farming system and food security (Capparelli 2005; Mayer 2002).

Climate change is expected to pose a threat for on-farm conservation in the Andes, which is a major center of crop genetic diversity. Increasing crop genetic erosion is making farmers more vulnerable to frost risk. An in-situ potato conservation project in Sicuani, Cusco collected 256 native varieties in the 1998-2000 period, but in 2006 only 164 native varieties were found in the same area (Gutiérrez y Schafleitner, 2007). Native varieties, many of them frost-resistant, are rapidly being displaced by commercial varieties. This trend will be exacerbated by expected shifts in agricultural zonation and climatic limits to cultivation due to climate change, which will influence the productive capacity of at least some of those varieties and may result in rapid loss of habitat and genetic diversity.

Climate change will likely bring changes in rainfall amounts/intensities, and higher risk of drought in the Andes (Haylock et al., 2006; Liebmann et al., 2007). A number of studies predict more dramatic seasonal variation in precipitation in the high plateau (altiplano) with a possible decrease in September-November rains and an increase in the precipitation for the December-February period (Killeen et al., 2007; Liebman et al., 2007; Seth et al. 2006, Vergara et al., 2007). Breeders are developing varieties that can mature early as an important climate risk management strategy.

The El Niño-Southern Oscillation (ENSO) influences the amount of rainfall and its distribution. El Niño events tend to result in decreased rainfall in the highlands of Bolivia and Peru (about 3,500 m.a.s.l) but increased rainfall at lower elevations in the same countries and particularly in northwestern Ecuador and Peru. La Niña events show the opposite results (Ropelewski and Halpert 1987). El Niño events have been more frequent and intense in recent decades, while there were fewer La Niña events, but whether El Niño occurrence changes with climate change is still under research.

The risk for Andean communities in the short term is not so much related to reduction in water availability overall as it is linked to a change in the seasonal distribution and regularity of water supply, with increase in torrential rains during the wet season and a decrease of minimum flows during the dry season. This has important consequences for soil erosion as well as water quality, and availability for domestic consumption and agriculture.

Pests and Diseases

Adaptation to geographic and temporal variation in pest and disease pressure has always been a challenge for Andean farmers. Climate change -along with rapid market development, population pressures and globalization- has resulted in range expansion for important pests

such as moths that attack potatoes and quinoa, and the Andean potato weevil. Hence, the fast upward expansion of the Andean agricultural frontier into the páramos (Gondard and Mazurek 2001), as well as trading of seed contaminated with insect pests and virus diseases from the lowlands, have favored pest dispersal to higher elevation zones that typically were used by farmers as a source of pest-free seeds and tubers.

The wide range of thermal environments found along altitudinal gradients in the Andes may increase the risks presented by invasive pest species in the near future. More species can “be packed” into a long thermal axis than into a shorter one. Small differences in elevation or vegetative cover can also create strong microclimatic differentials over short distances and allow persistent microclimatic refuges for pests to develop (Dangles et al. 2008; Hagen et al. 2007). Typically, two species cannot share the same niche, because one of them will out-compete the other, but niches can be partly overlapping (McArthur 1970). Increasing temperature may allow ectothermic insect pests to tolerate higher levels of competition therefore influencing how closely species can be “packed” into a resource axis.

While the number of insect species per unit area tends to decrease with increasing altitude, rising temperatures will allow extension in their ranges of the insect species to higher altitudes, and increases in diversity of insect herbivores and intensity of herbivory. The effects of temperature increase on insect pests are expected to be greater in the mountainous regions than in lowlands, due to much larger percent temperature rises in these areas (Hodkinson, 2005). Nonetheless, insect responses to climate change will likely be specific to site (including altitude), species and host plant, and temperature changes may have conflicting effects (Bale et al. 2002).

Climate may influence directly on insect pests either by killing them through temperature and humidity change or by determining their rate of growth and development. For example, as temperatures increase, short life-cycle pest species such as aphids or moths may be able to complete more generations in a year (Bale et al., 2002, Dangles et al. 2008; Sporleder et al., 2004). Climate change will also affect indirectly insect pests by modifying the distribution limit of their host plants as seen through the expansion of cultivable areas (Ziska & Runion 2007). Last but not least, climate change may affect farmers’ ability to control pests because the effectiveness of some pesticides tends to reduce with high temperatures and humidity levels (the timing and amount of rain following their application). If pests are able to complete more generations in a season then this may lead to greater pesticide use, which in turn may lead to the more rapid development of pesticide resistance.

Climate variability and change may substantially increase the risk of plant disease (Coakley et al. 1999, Garrett et al. 2006). Precipitation creates environmental conditions favorable to many fungal and bacterial pathogens, while water stress from decreased precipitation may render plants less able to defend against pathogen attacks. The general trend towards warmer temperatures expands the potential geographic, altitudinal and seasonal range for many pathogens. Interactions, thresholds, and feedback loops may dramatically increase disease pressure in response to global climate change (Garrett 2008, Scherm and VanBruggen 1994). For example, the ‘compound interest’ buildup of pathogen pressure during periods of disease-conducive conditions can lead to large increases in pathogen populations. If season length increases, more conducive conditions may cause greater population increases than anticipated. Management practices that depend on reducing local pathogen reproduction (sanitation, intercropping or mixtures, some types of disease resistance) will become less effective if regional inoculum loads increase.

Climate change and globalization have contributed to the range expansion of potato late blight. Late blight (caused by *Phytophthora infestans*) is an especially serious disease that attacks potatoes in general but particularly native potatoes, and causes approximately \$5 billion of damage annually on a global level (Judelson and Blanco, 2005). Late blight is particularly difficult for highland tropical farmers to manage because in these areas potatoes are produced year round and disease is generally present at all times (Forbes and Landeo, 2006). Therefore, farmers must protect plants from emergence through harvest. Traditionally, farmers have used a number of approaches to fight late blight, including nutrient management, seed selection, raised seedbeds, planting a mix of crops and planting more susceptible cultivars at higher altitudes (Thurston, 1994). The latter strategy works because higher altitudes have traditionally marked a boundary zone, where low temperatures have limited the severity of the disease (Kromann et al, 2009). This phenomenon is perhaps most clearly represented by the high production areas in Peru that until recently have been virtually blight free. Unfortunately, because of rising temperatures, some high altitude communities have recently seen blight for the first time, with devastating results. The primary strategies for adaptation to late blight risk would appear to be greater use of resistant cultivars and increased disease management capacity among farmers, including participative selection of blight resistance. A number of potato genotypes that provide useful levels of resistance to late blight have been identified, including some improved from native varieties (Cañizares and Forbes, 1995).

Host diversity, as variety mixtures or intercropping, at the plot level has been studied for late blight control with mixed results (Garrett et al, 2001), but this diversity can help control disease when used with other control measures (Pilet et al, 2006). One of the challenges related to the use of host diversity or specific resistant cultivars is the difficulty in diffusing new material because of potato's low multiplication rate and the perishability of the seed. Some cultural practices such as the combination of minimum tillage and raised beds (named *wachu rosado*, *chacmeo*, *chacma* or *sucacan*) reduce late blight severity (Jacobson and Sherwood, 2001).

Most studies on nutrient management and late blight severity have given mixed results (Forbes & Landeo, 2006), but this line of research has been dominated by a classical reductionist approach in which changes in fertilization were studied for their effect on plant disease. Disease resistance is probably more affected by cultivation systems that promote overall plant health in relation to important biotic interactions with mycorrhizae and growth-promoting rhizobacteria (Artursson et al, 2006). In order to make optimal decisions in the face of new late blight challenges coming from climate change, farmers need to understand basic concepts of pathogen biology and disease epidemiology, and thus capacity building is critical (Nelson et al. 2001, Ortiz et al., 2004).

The challenges that remain include the identification of particular genotypes that fit local conditions and needs (particular market or subsistence needs) and then multiplication and diffusion of these selected materials. The latter is hindered by the fact that potato has a low multiplication rate and by the absence of structured seed systems in Andean countries (Thiele, 1999). In the long run, the most effective adaptive measures against these threats are likely to be resistant plant varieties, higher inter- and intra-crop diversity on the landscape, improved cultural practices, and enhanced farmer capacity for integrated pest management. Also it is important to predict future areas of impact to focus training and intervention activities effectively.

Soils

Altitude profoundly affects the soils' inherent fertility and runoff-erosion behavior. Many soil fertility characteristics (including organic matter content, pH, cation exchange capacity, phosphate sorption and phosphorus availability) show significant altitudinal variations in the Andes, and the soils' resistance to erosion increases dramatically with elevation. Zehetner, Miller and West (2003) found that at higher elevations in Ecuador, cool and humid conditions have favored the accumulation of organic matter and the precipitation of active amorphous materials, leading to the formation of Andisols. At lower elevations, organic matter contents were low, the colloidal fraction was dominated by halloysite, and the soils classified as Entisols and Inceptisols. However, where volcanic ash parent material for soil material is not present, as in much of Peru and Bolivia, elevation trends differ. On non-andic soils in Bolivia, a similar decline in pH occurs with elevation from 2,500 to 4,000 m.a.s.l. likely due to more positive hydric balances and organic matter accumulation (Vaneck unpublished data), but soil texture is defined by a range of sedimentary parent materials and thus soil erosion is a threat at the entire range of elevations.

The observed altitudinal differences in soil development are primarily due to climate. Differences in rainfall and evapotranspiration result in diverse leaching regimes and likely cause the differential formation of allophane or halloysite. At higher elevations, lower temperatures and higher humidity may result in higher rainfall, lower evapotranspiration, greater leaching and less pronounced seasonal drying. Temperature also affects organic matter decomposition causing increased accumulation with elevation and thus resulting in the altitude-dependent formation of different epipedons. Differences in land use and vegetation influence soil formation. Accumulation of organic C and the formation of melanic epipedons at elevations above 3200 m.a.s.l. may result from substantial additions of organic matter from the páramo vegetation, slowed decomposition due to low temperatures, low pH values, and the presence of stabilizing Al-humus complexes. The boundaries among altitudinal zones pertaining to soil formation may shift due to climatic changes over time.

Impacts of climate change in the form of more severe rainfall events, deglaciation, the rise of the agricultural frontier and agriculture intensification will make farming systems more vulnerable to soil erosion, which is already a dominant threat to the agricultural livelihoods of Andean communities. Measured and modeled erosion is as varied as the region's ecosystems, with rates under $5 \text{ Mg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ in perennial páramo and steppe grasslands at the highest elevations to losses in hillside agriculture between 10 and $100 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, and disastrous extremes above $150 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ for steep hillsides where little effort has been made to manage residues or modify slopes (de Noni and Trujillo 1986; Romero 2005; Sims et al. 1999; S. Vaneck, personal communication 2008; Vis 1991).

One simulation study shows that upland páramo and grassland areas of Andean watersheds are stable against erosion under natural conditions (Romero 2005). Under current farming practices, however, advances of agriculture into highland areas and intensification of agriculture will likely lead to an acceleration of soil erosion (Veen, 1999, Valverde et al. 2001). In drier areas of the Andes, vulnerable and overgrazed rangeland, much of it in erosion-prone ecological zones, provides livestock forage and manure for cropped areas. If high-rainfall events increase in intensity due to climate change, all soil erosion models predict that climate change would increase erosion on cropped areas and these rangelands as well.

Mining of soil nutrient `stocks will also increase vulnerability of cropping systems to climate change. Excessive nutrient export from crop fields has resulted from shortened fallow lengths, the breakdown of traditional crop rotation/fallow systems, as well as the use of crop residues as forage in systems where forage from rangelands is insufficient (Sherwood, 2009; Wall 1999; Zimmerer 1996). Climate warming will likely aggravate this situation by further decreasing the already low organic matter contents of the Andean soils. In degraded fields where net export and erosion have been severe over the long term nutrient shortages are not easy to redress. This will limit options for soil regeneration and climate risk adaptation through crop residue retention or the adoption of legume crops in systems.

Climate-risk adaptive measures related to soils need to focus on reducing soil erosion losses, increasing access to irrigation for buffering of short-term droughts, and improving the functions of soil to conserve crop-available water and nutrients. Available technologies include: physical soil conservation measures (contour planting, barriers, and terraces), conservation tillage and improved crop residue management, cover crop agriculture, and increased organic amendments through the incorporation of animal manures and composting, water harvesting and micro-irrigation, and alternative multi-use plants for fallow periods. A number of adapted, highly productive highland legume species such as the native lupine *tarwi* or *chocho* (*Lupinus mutabilis*) and introduced vetches (*Vicia dasycarpa* and *V. sativa*) are already in use as grain, green manure, and forage crops, showing promise for farmers to augment soil cover and biological nitrogen fixation in cropping systems (Wheeler et al. 1999).

Discussion and Conclusion

Climate change will likely threaten the delicate balances in ecological, economic and social Andean production systems that have co-evolved over many centuries through design, trial and error. Ancient macro-organizational arrangements like vertical access to multiple ecological zones at different altitude levels (Murra 1975), the domestication of hardy crops (potato, quinoa, lupine beans) and animals (camelids), and production technology (i.e. multi-cropping, rotational systems, legumes for fallow intensification, low tillage systems, terracing) were developed in the Andes to cope with inherent climate variability and make optimal use of ecological niches. Many of these practices are still being used, although at smaller, local scales of coordination (Mayer 2002; Zimmerer 1996).

In addition, farmers use household- and community-level climate risk reduction strategies. These include intercropping many varieties in the same fields; holding as many plots as possible (field scattering) in different zones to maximize altitude, sun exposure and soil fertility differentials; tinkering with planting dates and crop varieties to match changing rainfall patterns; combining crop and livestock production, and taking advantage of long established food processing technology (i.e. freeze-dried potato and oca) (Goland 1993; Regalsky and Hosse 2009). In Huancavelica, Peru, farmers use *a ll apa k uy* as an informal system for climate risk distribution. *A ll apa k uy* (“help in harvesting”) is a pre-Columbian tradition whereby farmers who experience crop failure can offer their labor in exchange for food to friends who had a good crop. It is remarkable that the *a ll apa k uy* payment is at rates considerably higher than the prevailing salaries for similar tasks due to the moral obligation upon which it is based (Crespeigne et al. 2010).

Those traditional systems are generally highly resilient, but the predicted effects, rates and variability of climate change may push local systems beyond their range of adaptability. Furthermore, increased climate variability and change is now happening at the same time that socio-economic factors such as the impacts of markets, governmental policies in favor of externally based technology and population growth pressure are weakening the capacity of local knowledge and organization in agriculture to contribute to a sustainable system (Halloy et al. 2005a). In many communities traditional fallowing rotational schemes that were common in the central Andes (Orlove and Godoy 1986), have been dismantled and replaced with private access to and use of land due to high population pressure. Such disintegration has created more vulnerability among farmers when it has resulted in concentration of crop in one sector, which may actually increase the potential impact of hail and frost, which is often localized. These conditions will likely exacerbate soil degradation, soil diseases and Andean weevil infestation (Parsa 2009). Individual farmers are increasingly using non-farm activities, temporary out-migration and sale of animals to obtain cash as preferred crop failure adaptation strategies (Chaplin 2009; Crespeigne et al. 2010). Poorer farmers are more vulnerable to all forms of climate risk than better-off ones.

There remains much uncertainty about the magnitudes and impacts of climate change at any particular location in the Andes, and therefore it is not clear how best to prepare for the climate impacts. The effects of climate change on crop production and, by implication, on household livelihoods are not all clear-cut, and certainly not all negative (Chaplin 2009). Expected decreases in crop productivity may vary depending on the regions, the temperature regimes, distance to water masses, altitude and also the crops and genotypes involved.

Due to expected changes in water availability, differing adaptability of crops and animals to new environments, and exposure to natural hazards, rural families and their communities are reassessing what, when and where to produce crops and graze animals. An adaptive research and management strategy is required to deal with the unpredictable nature of the changes, which will result from the co-evolving interactions between ecosystems and humans.

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