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Julia Z. McDowell 12/3/2010

Accessing Adaptation:
Multiple Stressors on Livelihoods in the Bolivian Highlands under a Changing Climate

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An abstract of
A thesis submitted to the Faculty of the
Rollins School of Public Health of Emory University
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Abstract

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Smallholder farmers continuously confront multiple social and environmental stressors, including climate change, that necessitate changes in livelihood strategies to mitigate associated harms and take advantage of new opportunities, or adaptation. Vulnerability, meaning susceptibility to harm, is mediated in part by limited access to assets, leading to greater exposure to stressors and a limited capacity to adapt. Exposure and adaptation are interconnected because exposure itself depletes resources available for adaptation, while adaptation to one stressor may erode resources available to respond to future stressors. We present empirical evidence of the process of adaptation to multiple stressors over time through a case study of indigenous farmers in highland Bolivia. We examine how farmers perceive their exposure to stress on livelihoods, their strategies for adapting to these threats, and the influence of past adaptations on vulnerability under increasing climatic change. We find that vulnerability changes over time as stressors, such as land scarcity and delayed rainfall, compound, demanding the expenditure of household assets for adaptation, including water, land, labor, and financial, human and social capital, while influencing access to those same assets. To reduce vulnerability over time, adaptation planning must address constraints on access to key resources, allowing households the flexibility to reduce their exposure and improve their capacity to adapt to multiple stressors.

The disappearance of glaciers due to climate change is impacting water supply in the Andes, but there is little research on how this declining flow will impact water quality. The community of Khapi, Bolivia depends on the Illimani glacier for its water. To investigate the influence of streamflow on microbiological water quality, we collected 69 samples from three points along Khapi's principal surface water source. We built a multivariate regression model to test the association of our outcomes, *e. coli* and total fecal coliform organisms per 100 mL, with streamflow, time of day, month, and sampling point. Streamflow was a significant predictor of total fecal coliforms ($p<.001$), and a near significant predictor of *e. coli* ($p=0.097$). These results indicate that water quality, in addition to water quantity, may be of concern given further climatic change and associated glacial retreat.

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Part I

Accessing Adaptation: Multiple Stressors on Livelihoods in the Bolivian Highlands under a Changing Climate

1 Introduction

Bolivia contributes only .04% of the world's carbon dioxide emissions (CDIAC, 2007), yet rising temperatures are already causing the retreat of glaciers fundamental to the water supply (Barnett et al., 2005; Fischer et al., 2005; Gilbert et al., 2010; Parry et al., 2007; Ramirez, 2001; Vuille et al., 2008). The highlands have also experienced a delayed rainy season with more variable and intense precipitation events (Thibeault et al., 2010). These climatic changes put stress on vulnerable Bolivians, especially smallholder farmers, who are experiencing climate-related crop loss and other insults to their livelihoods (Valdivia et al., 2010). While all individuals and social groups must manage multiple stressors on their livelihoods–including social, economic, climatic, and other threats–the most vulnerable are often more exposed to these risks and are the least able to manage them (Adger et al., 2006). In this way, global inequalities are clear in anthropogenic climate change, whereby those groups most affected by climate change are the least responsible for causing it (Barnett, 2006; Dellink et al., 2009; Roberts and Parks, 2007). This is not coincidental and these social and economic inequalities are inseparable from climate-related vulnerability at all levels of analysis (Ribot, 2010).

Across a wide range of disciplines, vulnerability generally refers to susceptibility to harm (Adger, 2006; Eakin and Luers, 2006; Fussel and Klein, 2006). In the climate change literature, vulnerability is often understood to be a function of exposure to a hazard[1] and the ability to respond to that hazard, or adaptive capacity (Parry et al., 2005; Smit and Wandel, 2006). Because physical hazards themselves do not explain the heterogeneous impacts and responses of affected socio-ecological systems, or why certain groups are more exposed to hazards than others, the social determinants of vulnerability must be considered (Turner et al., 2003). Adger et al. argue that: "the vulnerability or security of individuals and of societies is determined, not only by the likely responses of the resources on which individuals depend, but by the availability of resources and, crucially, by the entitlement of individuals and groups to call on these resources" (Adger et al., 2003). Rather than addressing vulnerability solely as a *function* of exposure and adaptive capacity (Parry et al., 2007), we recognize that social processes determine who can access resources and in this way *cause* certain groups to be more exposed to risk[2] (Tanner and Mitchell, 2008) (Mustafa 1998) (Watts and Bohle, 1993) and less able to adapt (Adger et al., 2004; Smit and Wandel, 2006). Yet vulnerability is also s*ubject* to stressors that change access to resources and it may be *altered* by the way in which people adapt or respond to those stressors (Casale et al., 2010) (Blaikie et al., 1994). This conceptualization recognizes that vulnerability changes over time (Adger, 2006) and legitimizes the agency of vulnerable groups to make decisions about their own livelihoods (Acosta-Michlik and Rounsevell, 2009; McLaughlin and Dietz, 2008), while it also accounts for the limitations imposed by external drivers (Chambers, 1989).

Agricultural systems demonstrate substantial variation of vulnerability, exposure, and adaptive capacity across geographic and socioeconomic groups under a changing

[1] The IPCC distinguishes between the sensitivity of a system to a hazard and the exposure to that hazard (Parry et al., 2007) Here exposure and sensitivity are considered to inseparable, defined by Ford, et al. as the "susceptibility of people and communities to conditions that represent risks" (Ford et al., 2006) but that only become risky if individuals are vulnerable to the harm associated with those conditions.

[2] For more on the relationship of vulnerability and risk, see: (Brooks, 2003).

climate. While rising temperatures will likely increase crop yields in much of the developed world, yields are likely to decrease throughout the global south (Fischer et al., 2005; Parry et al., 2005), where millions are expected to experience climate-related hunger in the coming decades (Lobell et al., 2008; McMichael, 2004). Yet, as Fischer et al. recognize, socioeconomic factors are essential to these projections (Fischer et al. 2005). In recent history, famine and food insecurity are largely attributable more to lack of entitlements or access to resources than to climatic or environmental conditions themselves (Bohle et al., 1994; Schmidhuber and Tubiello, 2007; Sen, 1981; Watts and Bohle, 1993). For example, smallholder farmers are often considered particularly vulnerable to climate-related food insecurity, not due to a higher level of environmental exposure to drought than more commercial farmers, but due to limited infrastructure and inputs, narrow yield margins, susceptibility to market fluctuations, and limited resources to adapt (Brown and Funk, 2008; Morton, 2007).

Limited resources are expended not only for adaptation to climate change, of course, but to respond to a changing suite of stressors (Mortimore and Adams, 2001). Livelihoods approaches to vulnerability analysis account for these multiple stressors and associated damages, placing assets at the center of analysis to explain who is vulnerable, why they are vulnerable, and pinpoint opportunities to assist them (Ribot, 2010). Vulnerability can be reduced by either addressing its root causes (Ribot, 2010) or by improving adaptive capacity (Agrawal, 2010).[3] Livelihoods approaches have recently

[3] Vulnerability reduction and improvement of adaptive capacity are often considered to be synonymous (Adger et al, 2004), though this does not address the exposure component of vulnerability, by which vulnerable populations are often more exposed to risk in the first place. From a livelihoods perspective, and for the purposes of this paper, both vulnerability reduction and adaptive capacity improvement (in the context of multiple stressors) depend upon enabling access to assets, and so it is consistent that strategies to provide sustained access to assets will both reduce vulnerability and improve adaptive capacity.

illuminated the complexities of rural vulnerabilities in a changing climate (e.g. (Mertz et al., 2009; Osbahr et al., 2008; Paavola, 2008; Reid and Vogel, 2006)), but the process of adaptation remains poorly understood (Tschakert and Dietrich, 2010). While it is clear that some vulnerable communities can, and do, adapt to change over time and succeed in reducing their own vulnerability to certain harms (Casale et al., 2010; Nyong et al., 2007), others are unable to do so (Tanner and Mitchell, 2008). A better understanding of the process of adaptation to multiple stressors can help policymakers and practitioners to both support autonomous adaptive capacity and address external pressures that restrict the assets available to vulnerable people (Prowse, 2008 #56).

Using qualitative data from sixty interviews, focus groups, and participant observation in the Palca municipality of highland Bolivia, we examine how farmers experience household-level vulnerability to poverty and food insecurity under a changing climate. First, we unpack the concept of vulnerability by reviewing notions of multiple exposures and adaptation, and adopt a livelihoods approach to access as a unifying framework. We then present the case of Palca, illustrating farmer's perceptions of the changing climatic, social, and economic stressors on their livelihoods and examining how farmers have adapted their livelihood strategies in response to these stressors. We demonstrate how farmers are exposed to multiple stressors that limit the accessibility and availability of key resources, while responses to those stressors also compete for limited household and community assets, constraining options for future adaptation. We suggest that vulnerability reduction can only be achieved by holistic solutions that ensure sustained mechanisms of access to permit households to respond to the wide range of interacting stressors on their livelihoods, climate change included.

2 Unpacking Vulnerability

Vulnerable groups are more exposed to stressors and less capable of adapting to them (Adger et al., 2006; Thomas and Twyman, 2005). Adaptation is constrained as multiple stressors, including both physical and social, impact the availability and accessibility of resources, while also demanding expenditure of these resources for response. A livelihoods approach to *access* allows us to follow the process of adaptation to multiple stressors over time, specifically identifying how assets for adaptation are obtained, constrained, and expended, and pinpointing opportunities to reduce vulnerability (Bebbington, 1999; Ribot, 2010).

2.1 Adaptation and Multiple Stressors

In the climate change literature, adaptation refers to the self-adjustment of socio-ecological systems to a climate stressor in order to moderate harm or take advantage of opportunity (Smit et al., 2000). Adaptation implies the reorienting or reinventing of a system to anticipate and avoid damages, but may necessarily include the ability to cope, which often focuses on survival under temporarily constrained conditions (Agrawal, 2010; Cooper et al., 2008; Gallopín, 2006; Pelling, 2010; UNFCCC, 2003). Successful adaptation thus implies that a system both avoids damages from climate stress and is able to cope with damages that do occur, without undermining the capability for future response, often referred to as resilience (Folke et al., 2002; Tompkins and Adger, 2004). Most adaptation choices depend upon the assets available to a household or individual (Agrawal, 2010).

Adaptive capacity, then, is "the set of resources, and the ability to employ those resources, that are prerequisites to adaptation," and may depend upon institutional and social factors (Nelson et al., 2007). Adaptive capacity can improve as individuals and institutions learn to respond to repeated stressors or gain access to resources (Armitage, 2005; Folke et al., 2003; Yohe and Tol, 2002). Alternatively, adaptive capacity can decrease over time with repeated exposure when risk management strategies erode assets for coping, limiting the possibility for long-term adaptation (Agrawal, 2010; Pelling, 2010). Adaptation therefore occurs as a process of constant adjustments and learning that evolves in response to different exposures and past experiences (Nelson et al., 2007; Yohe and Tol, 2002). In this way, adaptation strategies are rarely implemented solely in response to climate change and cannot be understood without accounting for the additional stressors on livelihoods (Belliveau et al., 2006; Bradshaw et al., 2004; Mertz et al., 2009; Pielke, 2005).

Leichenko and O'Brien developed the framework of "double exposures" to analyze the simultaneous effects of environmental change and economic globalization on diverse social groups (2000). The framework recognizes the underlying processes affecting exposure, the responses of affected populations, the outcomes they experience, and the influence of these, in turn, on the processes and exposures themselves (Leichenko and O'Brien, 2008).This double exposures framework has now evolved to address multiple stressors and recognizes vulnerability as dynamic, such that stressors, responses, and outcomes form part of a multidirectional system that changes over time (Belliveau et al., 2006; Handmer et al., 1999; Leichenko and O'Brien, 2008; Liu et al., 2008; Smit and Pilifosova, 2003; Smit and Wandel, 2006). For example, successful adaptation to one stressor may result in greater exposure to other stressors (Belliveau et al., 2006), and coping with one stressor may erode or amass resources available to respond to other stressors in the future (Roncoli et al., 2001). Exposure itself may deplete resources for adaptation or, alternatively, catalyze adaptive actions (Schipper and Pelling, 2006). We therefore understand adaptation and multiple exposures to be necessarily interconnected, and vulnerability analysis must reflect this entanglement.

2.2 Livelihoods and Access

Assessing vulnerability to climate change in the context of multiple exposures is challenging because the same pool of resources must be leveraged to respond to more than one stressor, and the stressors themselves may impact access to those resources currently or in the future. Livelihoods research has characterized many diverse livelihood strategies employed by smallholder farmers to respond to multiple stressors (Bohle et al., 1994). As Bebbington explains: “livelihood strategies are attempts, from existing and often severe constraints, at a continuous management and modification of ... substitutions, tradeoffs and draw downs on different capital assets,” including natural, produced, social, cultural and human capital (1999). Adaptation is similarly dependent upon asset access and management, and the phrase ‘adaptive strategies’ has been used for decades to describe how farmers respond to changing stressors on their livelihoods, from environmental degradation to market conditions (Barlett, 1980).

Multiple stressors, including climate change, impact the availability of assets fundamental to livelihood and adaptation strategies, and also determine who can *access* these assets. Ribot and Peluso (2003) argue that beyond the *right* to benefit from such assets, as is the traditional understanding of property, access implies the *ability* to benefit from capital assets and is a function of power. In the context of climate change, physical stressors may determine the physical quantity and sometimes quality of a given resource, such as water. However, the ability to benefit from such a resource depends on mechanisms of access, such as legal rights or technology (Ribot and Peluso, 2003), and intangible assets like human and social capital, which are impacted by social stressors. In the context of climate change, the ability to adapt depends on access to resources, and thus on the physical and social stressors to which a household is exposed.

A focus on access to assets provides a unifying approach to consider the dynamic complexity of vulnerability and adaptation to multiple stressors. Current decisions on how to allocate assets can limit or expand future options for adapting or coping with stress, but poor households may have few options to change their short-term use of assets in order to prioritize long-term adaptation (Carter and Barrett, 2006; Prowse and Scott, 2008; Tanner and Mitchell, 2008). Likewise, the ability to benefit from one resource, like land, may depend on access to another resource, such as labor, so some households may not be able to fully utilize the resources they *can* access (Berry, 1989). An assets-based approach allows us to trace the effect of multiple stressors, both social and physical, on a household's access to assets (Moser and Satterthwaite, 2010). Adaptation can then be followed as a process centered on accessing and expending assets interlinked with these multiple stressors.

The livelihoods literature on climate change provides some empirical evidence to identify and characterize asset allocation strategies used by rural households to confront multiple stressors, such as agricultural intensification and livelihood diversification (Osbahr et al., 2008). Others have shown how multiple stressors impact household assets and responses (Reid and Vogel, 2006; Young et al., 2010), or how multiple stressors constrain adaptation options (Bryan et al., 2009; Tschakert, 2007). Only a few authors have addressed the complex interactions of multiple stressors and adaptation over time. In the double exposures tradition, Eakin (2005) shows how adaptation to market stressors stemming from free trade policies may heighten vulnerability in the face of climate change for smallholder farmers in Mexico. Belliveau et al. (2006) demonstrate that both free trade policies and responses to those policies heightened Canadian grape growers' exposure to climatic stress and limited further adaptation options. Yet, few authors have addressed the asset-based relationship between adaptation and multiple stressors in rural areas (Prowse and Scott, 2008).

Our research contributes to the growing body of empirical evidence on adaptation to multiple stressors, addressing adaptation as a process of allocating limited assets subject to changing stressors. Using data from qualitative interviews with smallholder farmers in Palca, Bolivia, we present the area of study and its traditional productive system as related to the climate variability characteristic of the region. Relying on farmer perceptions of recent stressors on their livelihoods and corresponding adaptation strategies, we present multiple stressors and adaptation strategies in two periods: one period of increasing social and economic stress, followed by the current period of increasing climatic stress. We focus on assets that participants identified as most affected by multiple stressors and needed for adaptation, including land, water, labor, human capital, social capital, and financial capital. Vulnerability is shown to change over time as households respond to multiple stressors, which impact the availability and accessibility of assets and make competing, and sometimes contradictory, demands on limited assets for adaptation.

3 Methods and Study Area

3.1 Methods

We selected the Municipality of Palca for study because it depends on smallholder agriculture as its primary source of income (INE-PNUD, 2005) and on glacier and snowmelt runoff for irrigated agriculture and household water consumption (Ramirez, 2008), providing the clear physical linkage of climate change to a socially vulnerable group. Yet rather than assuming impacts in advance, we followed a participatory vulnerability assessment framework, aiming to understand how farmers themselves perceive stress on their own livelihoods (van Aalst et al., 2008).[4] Qualitative methods allowed for a nuanced understanding of the complex factors influencing adaptation decisions and vulnerability from farmers' own perspectives (Belliveau et al., 2006).

We conducted sixty semi-structured interviews with heads of household in five rural agricultural communities at different altitudes within the Choquecota River Basin. We first interviewed key informants, including community leaders and respected elders, and then used snowball sampling (Ritchie and Lewis, 2003) to ultimately include mostly landholding[5] men (32) and women (28) from a range of age groups (aged 18 to over 70). Semi-structured interviews began as open-ended discussions (Rubin and Rubin, 2005) of past and present stressors and livelihood strategies. Conversations were then focused

[4] This study composed part of a larger study of Andean agricultural communities' vulnerability under multiple stressors, including water scarcity and climate change, funded by the InterAmerican Institute (Project Title: "Coming Down the Mountain: Understanding the Vulnerability of Andean Communities to Hydroclimatologic Variability and Global Environmental Change") and carried out in Bolivia, Chile, and Argentina. It was also carried out as part of a multidisciplinary study of agricultural adaptation to climate-related water scarcity in the Choquecota Basin, funded by DANIDA (Project Title: "Adaptation to Climate Change in Regions Affected by Retreating Tropical Glaciers").

[5] Only a very small number of farmers living in the communities of Palca do not own their own land. These few households tend to depend on livestock, and one was interviewed, while others depend almost solely on mining, and were not interviewed. Some younger households continue to farm parents' land until parcels are turned over to them. These households were considered to be landholding, and were also interviewed.

more specifically toward climatic and water stressors and responses, and perceived changes over the past few decades (methods adapted from (Wandel et al., 2005)). Structured participant observation (Emerson et al., 1995) in the fields, homes, and at community meetings was used to complement the interviews.

3.2 Study Area

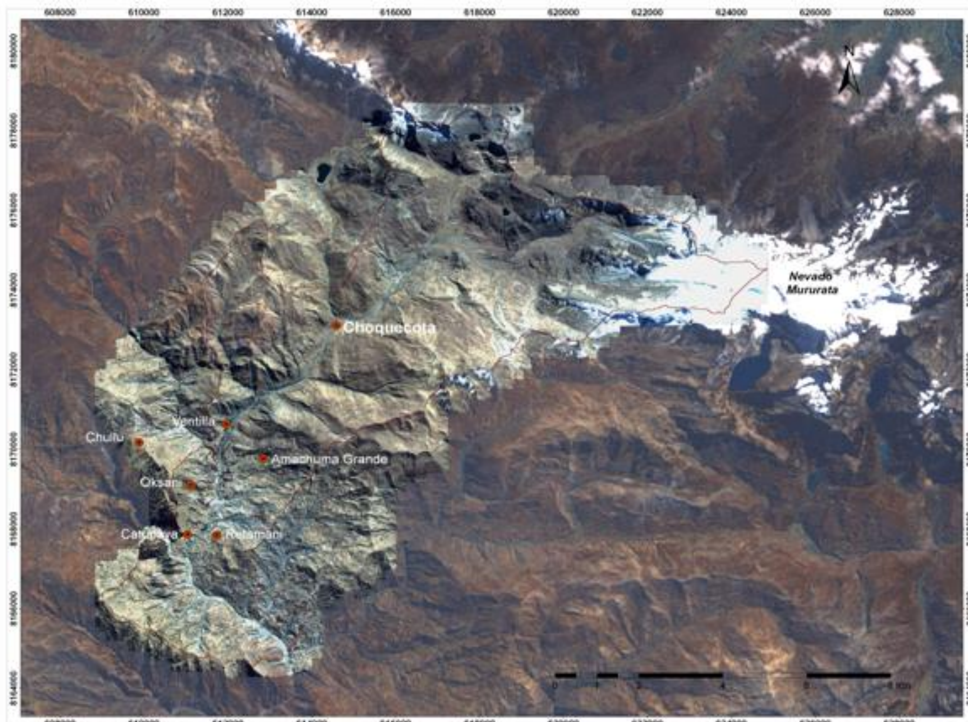
The Choquecota River Basin[6] is located in the Municipality of Palca, approximately 20 km southeast of the capital city of La Paz, Bolivia in a valley at the western base of the Cordillera Real Range in the Andes. The municipality covers 740 km^2 and has a population of around 15,000 inhabitants (INE-PNUD, 2005). Approximately 149 km^2 of this area fall within the Choquecota River Basin (and the surrounding fields linked to it through irrigation channels), ranging in altitude from the peaks of the Mururata Mountain (5628 m) to the valley below (~3400 m) (Castel, 2008).

Almost 70% of the population of Palca depends on agriculture as their primary economic activity and nearly 80% lives in extreme poverty (INE-PNUD, 2005). Much of Palca's population also suffers from high food insecurity (WFP, 2008). Productive infrastructure is limited—only one-fifth of arable lands are irrigated—and there are no paved roads (Ontiverios, 2007). Over 90% of Palca's inhabitants self-identify ethnically as Aymara, and 84% claims Aymara as their first language, while only half is bilingual in Spanish (INE-PNUD, 2005).

This indigenous population once served as *peones* to the wealthy *mestizo* landowners who ran the haciendas of Palca from the Spanish Conquest through the time of the 1952 Revolution (Barragán, 1982). During the agrarian reform that followed, haciendas throughout Bolivia were dismantled and lands were redistributed to indigenous

[6] Also known as the Palca River Basin.

communities, peasants, and displaced miners (Flores, 1954; Sanabria, 1999). Today, the farmers in the Choquecota River Basin live mostly in *campesino* communities, which are governed by indigenous leaders of agrarian unions that oversee social, economic, and spiritual life, though they are subject to the municipal government as well (McDowell and Zeballos, 2008).



Map 1. The Choquecota River Basin (Castel, 2008)

The region is characterized by a sub-tropical, high-altitude climate, with one rainy and one dry season annually. The town of Palca (3,300 m.), the seat of the municipal government found within the Choquecota River Basin, has a yearly average high temperature of 22.4 °C, and an average low temperature of 5 °C (Ontiverios, 2007). The average annual rainfall for the Municipality of Palca is 557 mm, but shows high inter-annual variation characteristic of the region, in part due to ENSO (Garreaud et al., 2003), and seasonal variation, with almost three quarters of the rain falling between November and March (SENAMHI, 2006). Hail and frosts are also common (François et al., 1999). Observed changes include a temperature increase of 0.1°C per decade in the Andes over the past 70 years (Vuille et al., 2008), and recent increases in frost events and more variable, intense precipitation (Thibeault et al., 2010). A primary source of irrigation water for the study area is the Choquecota River, which originates in the peaks of the Mururata Mountain (5,800). Like most Andean glaciers, the Mururata glacier that sustains the river has been shrinking in recent decades, losing nearly 18% of its surface area since 1983, and is likely to disappear within the next thirty years (Ramirez, 2008) .

3.3 Traditional Agriculture and Climate Resilience

Andean farming systems have been managed for centuries to absorb the characteristically variable climate of the region (Dillehay and Kolata, 2004; Erickson, 1999). In Palca, participants indicated several long-standing practices for withstanding climate variability and extreme events. In addition to religious practices to prevent drought and other climatic hazards, such as offerings to the *pachamama*, Palca's farmers focused on assuring year-round availability of foodstuffs through crop diversification, diverse spatial distribution of fields, food storage, communal land and labor, and animal husbandry.

The use of different altitudinal levels (*pisos ecológicos*), and their corresponding microclimates, is an indigenous Andean technique for assuring diversified food production (Murra, 2002). In Palca, tubers, barley, and quinoa are cultivated in rain-fed high mountain fields, while lower-altitude, irrigated, relatively flat plots produce corn, beans, peas, and some potatoes. Families often farm small parcels scattered throughout the basin at different geographic and altitudinal locations. As one farmer says of his fields: [we have] "lots, like confetti—one over here, another over there…" In this way, households and communities assure a varied diet in good years and diversify their risk in bad years across locations and crop varieties. Hail and frost, for example, are often quick, spatially isolated events that affect crops in one area while sparing nearby areas (Valdivia and Dunn, 1996). If one year is particularly dry and high altitude fields give a poor yield, Palca's farming households can depend on limited irrigated crops and food stores to sustain them.

Assuring reserves is a key objective of many Andean agriculture systems (Rist, 2000). Many of the traditional crops, like potatoes, corn, and quinoa, can be dried and stored. One farmer explained of a difficult year: "that's how we made it that year, with a few products we saved." *Kaya* and *Chuño*, dehydrated tubers that can be stored for years, are staple foods in Palca. Livestock represent another way to store and manage resources, while taking advantage of communal grazing land. Small animals like guinea pigs and poultry supplement the household diet, or provide a small source of income. Most families only have a few large animals, like sheep, cows, or llamas, which they can slaughter in times of serious need for economic resources (Valdivia, 2004).

Communal land and shared labor have been an important component of indigenous Andean agricultural systems (Guillet, 1980, 1981). The *Aynoqa,* a traditional crop rotation scheme on rain-fed communal land, requires farmers to switch plots each year on a planned calendar to alternate specified crops with years of fallowing to ensure continuously fertile soils. Other traditions of reciprocity may also serve as adaptive strategies for risk sharing (Valdivia and Dunn, 1996). These practices include the *ayni* (shared work between families and/or neighbors), *la partida* (a type of sharecropping with rights to farm the land exchanged for a portion of the produce), and *trueque* (customary exchange of agricultural and animal products, usually between communities from distinct ecological levels). One mid-altitude community member explains *trueque* with a high-altitude community: "We exchange for food. They usually bring *kaya*, and *chuño* …we usually give them onions." In recent years, changing social and climatic stressors have prompted the abandonment of some of these practices, while others have become even more important.

4 Multiple Exposures and Adaptation in Palca

Palca's agricultural households experience a range of stressors on their livelihoods, many of which have intensified over the past several decades. Communities have been under increasing social and economic stress that has constrained access to capital assets, and farmers have tried to optimize use of limited assets through market-oriented strategies, sometimes increasing exposure to market stressors. More recently, changing climatic stressors have put further strain on assets and challenged strategies for response to both climate and market stressors. While farmers recognize that climatic conditions are changing, they perceive their options for adaptation as increasingly constricted.

4.1 Social Stressors and Adaptation

"There isn't much profit in agriculture."

Farmers identified numerous social and economic stressors that have been growing over time, most notably land scarcity, uncertainties in agricultural and labor markets, and institutional marginalization. These stressors limit access to land, labor, financial resources, and human and social capital. In response, farmers have adapted their livelihoods by shifting agriculture toward intensified production of cash crops, incorporating more paid labor, and relying on indigenous institutions.

4.1.1 Land Scarcity

The agrarian reform following the 1952 Revolution reordered the land tenure system, not only of haciendas, but also of traditional indigenous landholding practices (Andersson and Haarstad, 2009). In Palca, individual titles were granted for small parcels in the valley, while most hillsides remained communal. While freedom from the hacienda is celebrated, access to land is recognized as a problem once more. One participant explains that his land belonged to "my father from before, from the time of the hacienda when [President] Victor Paz Estenssoro mandated it…to my grandfather, then my father, and now we are here...we split it between us, piece by piece, with my sister, and now it is all divided." After several generations, most families now have less than one hectare of land, while some have as little as 500 m^2 (Ontiverios, 2007). The tiny holdings are known as "minifundios." A select few farmers have purchased parcels of land outside of Palca, but most participants could not access more land due to insufficient economic resources.

Minifundios prevent the practice of traditional methods of diversification and rotation of crops, which require some plots of land to rest each year, instead planting irrigated parcels twice each year. Though only one community still practices the *aynoqa*, some highland communal areas are still available for household use. A few households have shifted to greater dependence on livestock, grazed on communal lands. Many households have responded by prioritizing crops that yield the most produce per hectare, like the potato, or that bring a high profit in urban markets, like vegetables and flowers, which also fulfill growing needs for cash with increased integration with nearby La Paz.

As one farmer states of his most profitable crops: “it could be the peas, but also the onions. Or maybe the lettuce--in one year it comes up twice.” Some families have switched almost entirely to cash crops, purchasing cheap commercial foods to consume in place of their own produce.

With limited resources for inputs, farmers have strategically intensified production. Limited subsistence crops are still grown on rain-fed land, while irrigated land is dedicated to market-quality produce, including water-intensive vegetables and higher quality traditional crops: “Irrigated potatoes, we sell. Those from the hills are for eating, you know, we store them. . .” As irrigated fields are rarely rotated in the traditional patterns or left fallow, soils become deficient, making fertilizers necessary. Some also noticed a greater presence of pests in the absence of crop rotation, and noted that cash crops were more susceptible and required the use of pesticides. Some cash crops also require new seed to be purchased rather than reused. This intensified system also requires labor to irrigate, fumigate, and fertilize parcels, and take goods to market, while inputs perpetuate the need for cash, creating further dependence on the market.

4.1.2 Market Uncertainties

Reliance on cash crops creates new exposure to agricultural market prices and demand, while the need for income to supplement and sustain agricultural production has lead to greater participation in, and exposure to, the labor market. As one participant explains of the market price for produce: “It goes up, sometimes, it goes down. It isn’t a fixed price.” Some farmers have responded by planting and then harvesting over several weeks, to avoid sale on one day or week of low prices, and saving labor costs by keeping work within the family. Another strategy is timing: “One plants early sometimes in order to earn a little more…so that it is ready in December, and it sells a little better.” Farmers also complained that they did not have a good market to sell to even when prices where good, because the “intermediaries take it away from us,” and farmers receive only a fraction of the value of their produce.

Insufficient land, income, and rural work opportunities, countered by a greater need for cash, push more and more community members to migrate to nearby urban areas, and even abroad. Work options are often limited to low-paying day labor in construction and mining, as one farmer whose son worked in the city explained: “To be a worker, [you are] only just a worker. Only the owners always earn more, you see?” Nonetheless, off-farm work has become an important income source for many families, but not without consequences--migration deprives families of their loved ones and sometimes their most productive members, putting further strain on the labor of remaining women, children, and the elderly for agriculture. Some households now even depend on urban income for agriculture, given the increased inputs needed for cash crops. One farmer explains that she could not buy seeds in time to plant because “we get behind because we don’t have money…My husband went to work, but he did not earn much, and that’s why we are behind.”

The shift to cash crops thus introduces greater exposure to the labor market, as limited human resources are strained to respond to various stressors. At the same time, land scarcity and cash needs have impacted traditional labor practices. Some farmers with insufficient land seek paid work on neighbors’ farms. Some elderly farmers complained that young people were less willing to participate in the *ayni*, instead demanding payment. Still, the *ayni* remains an important coping strategy for tough times: “Today, they are going to help me, tomorrow I have to help them. We do it this way because sometimes there is no money." Such internal sources of social capital prove essential for coping with negligent formal institutions.

4.1.3 Institutional Marginalization

Bolivia's long history of racism continues today, even with the ascension of indigenous President Evo Morales (Kohl, 2010). Many public and private sector institutions are inaccessible to Palca's farmers due to systemic discrimination against indigenous people. For example, decades of intentional exclusion followed by years of bureaucratic ineptitude have left many rural dwellers still cannot obtain the necessary identity cards or official land titles necessary to access services and capital, such as credit. One participant explained of his experience with the bank: "We cannot borrow. There are [loans], but one needs documentation--they ask for a lot of things. We applied to the bank for a sum, but it went nowhere, it resulted in nothing." Other participants feared being tricked by banks or losing their belongings, and some felt their lack of formal education prevented them from accessing and managing loans.

Rural schools are taught in Spanish, seen by Aymara farmers as providing their children with important language skills to participate in the urban economy. However, the quality of the schools is very poor, limiting opportunities for higher education (including urban secondary schools), job training, and better employment: "Schooling here in the provinces is not good—they go to La Paz and then they cannot enroll--in vain, you know?" Options to gain the human capital necessary to improve terms of labor in the urban market are thus seriously limited.

Institutional neglect of infrastructure and basic services was highlighted by participants, yet many felt powerless to hold politicians accountable. Palca's washed-out roads and bridges, collapsing irrigation canals, patchy provision of drinking water, underprovisioned health clinic, and a litany of other deficits are attributed by farmers to the misuse of funds, because the municipal politicians "take the money for themselves!" Yet addressing these failures through formal political channels requires costly trips to La Paz, knowledge of bureaucracy, and Spanish literacy. Even the agrarian unions were often unable to procure assistance: "We go to the municipality and the prefecture, but there is no way to get help. They offer, but they never follow through."

The agrarian unions continue to fulfill primary institutional roles in the communities, from settling disputes to assuring that schools are functioning properly to overseeing infrastructure maintenance. As one union leader charged with overseeing irrigation explains: "In the dry season, [I] see how everything is, if it's good or bad. One has to check to see if it needs work, or doesn't need work." Communal workdays are organized to clean and repair canals, as well as roads, clinics, and school buildings, though lack of economic resources frequently prohibits purchase of even basic construction materials. While these community institutions are important for mobilizing existing community resources, changes in climate are placing new stress on these resources and farmers are finding increasingly limited options for adaptation.

4.2 Changing Climatic Stressors and Adaptation

"It has changed. Sometimes the rain does not fall in its season; sometimes the frost does not come right in its season. Before it was later, but now the frost arrives early, like a punishment. Now the rain falls like it is saying 'I am not going to come anymore.' Already, the sun is very strong. Before, it was not like this."

In recent years, many participants have perceived greater climate variability and change, including water shortages, rising temperatures, and increased climatic variability and extreme events. Climatic stressors impact the availability of water, crop productivity, and the utility of other resources, such as land. Farmers have responded by changing some cropping and water use strategies, but are finding limited adaptation options, as market-oriented production is often more sensitive to adverse weather than are traditional strategies, yet they are necessary to address continuing social stressors.

4.2.1 Water Shortages

A delayed rainy season and decreased flow in irrigation canals have begun to impact production over the past decade. Recently, the rainy season has been delayed, starting as late as November, instead of September. This corresponds to an observed decrease in snowfall in the mountains: “Before, when it used to rain, it used to snow and everything used to be white, but now, no. Now it doesn’t snow.” In the dry season, the communities depend exclusively on water from the irrigation canals derived from the mountain streams for their agriculture, especially for the water-intensive cash crops that have become a fundamental part of the local economy and increased water demand. While the water level of the canals is always reduced from September to November, many perceive even greater water scarcity today. As one farmer explains: “Not as much water runs now. . . Sometimes there is no water at all. No water at all, so we are almost fighting over the water.”

Some farmers have responded to the delayed rainy season and dry season irrigation water shortages by postponing the planting of their plots. In irrigated plots, this means waiting until there is sufficient water in the canals to plant: “If we plant without irrigation, it is not going to produce [anything].” In rainfed areas, “if the rain does not arrive, then one has to plant the rainfed plot in October,” at the risk of an early frost before harvest. These strategies conflict with market-oriented strategies and expose farmers to the lower prices earned late in the season. As rain becomes less dependable and labor becomes more valuable, investment in maintaining hillside fields with low and uncertain yields becomes even riskier. In response, many farmers have abandoned these lands. With less land being cultivated, and more water intensive crops being grown for sale, even greater pressure is placed on irrigated parcels, further exacerbating water shortages and the problems of the *minifundio*.

Farmers indicated a great need for more efficient irrigation systems to replace the current earthen canals, which are labor intensive to maintain and suffer large amounts of water loss in transport, but none had the economic resources to install improved systems. One community, through exceptional leadership of the agrarian union, was able to obtain help from an international aid organization for an improved system. Most, however, have adapted by changing their practices. Some farmers now irrigate at night, when there is less competition: "At night there is more water, one has to do nocturnal irrigation." Some canals, which often span several communities, ration irrigation water when it is scarce from August to November and irrigate *por turno,* or in assigned shifts. Others continue on a 'first come, first served' basis, to the detriment of downstream users and with the potential for conflict, as indicated by the abovementioned farmer's concern of "fighting over the water."

Many participants feared increasing water shortages in the future and better infrastructure was widely seen as a solution. In addition to improved irrigation systems, some felt that "a reservoir should be put up there [at the base of the glacier], that way there will be no water shortages." The use of improved inputs, such as short cycle varieties of traditional crops, was also suggested. Lack of knowledge, economic resources, and unresponsive government institutions were cited by participants as principle barriers to obtaining such improvements.

4.2.2 Rising Temperatures

An increase in temperature was noted by most participants over approximately the past two decades, though in a variety of ways: the physical sensation of increased heat, changes in the types of cultivars that grow at a certain altitude, a greater number of pests, and the rate at which soil dries after irrigation. Many perceived that the sun felt hotter[7], as one farmer exclaimed: "It is very hot, very sunny. Look, it's burning us. It didn't use to be like this." Others noted the change in vegetation. While ten or twenty years ago fruit trees only grew in the lowest parts of the basin, now, as one farmer says: "The sun is very strong. For that reason, even peaches can grow! Before, peaches weren't known to thrive, but now, even the *tuna* [cactus fruit] grows." Some farmers wanted to take advantage of this through investment in orchards, but had little experience growing fruit.

Not only plants are surviving at higher elevations—pests that damage crops are moving up the basin. As one farmer from a higher altitude community explained: "There are too many worms in the potato…in the lower parts [of the basin] there are usually worms, and not so much here, but this year almost everything got worms…it is a little hotter, maybe that is the reason." A few farmers acknowledged that the switch to less pest resistant crops, purchasing of seeds from elsewhere, and moving away from traditional means of controlling pests like crop rotation and fallowing, may also have contributed to the proliferation of pests. Farmers have responded by applying more pesticides at significant cost to the households and, potentially, to the health the population. Some

[7] In Aymara, "wali lupiwa" is commonly used to express both "it is very hot" and "it is very sunny," which is the literal translation. Given that in the Bolivian highlands these two conditions almost always coincide, participants often did not verbally distinguish between them, so references to the "strength of the sun" or "the sun is very hot" often referred to either, or both, the solar radiation and the air temperature.

participants also perceived greater sickness in their livestock than in years past, and new infirmities that they did not know how to cure with traditional medicines. Many requested technical assistance to deal with agricultural pests and animal health, and while some assistance was available through NGO's, no government extension services were known to be locally available.

The accelerated evaporation of irrigation water is also seen as an indication of increased heat. As one producer lamented: "Today I irrigate, the day after tomorrow it is already dry . . . I have to work all the time—before, it lasted a week." Because new crops like flowers and vegetables require more water than traditional crops, and there is more dependence on irrigated land, even more water and time are required for irrigation under these new conditions. As in dealing with water shortages, improved irrigation systems were seen as an out-of-reach solution. Irrigating at night helped avoid rapid loss of soil humidity: "In the morning we have to irrigate, from three or four in the morning. We irrigate until the sun comes out."

4.2.3 Climate Extremes

Farmers felt that in recent years some climate events had become more extreme and less predictable, including rainfall, hail, and frost. For example, some participants have noticed an increase in rainfall intensity, while others say it falls in shorter intervals. A farmer explains that while the rain "fell nice and slowly before, now it is very strong, and it even hails." In the past several years, flash floods have swept away entire plots of cropland and caused the collapse of irrigation canals, further compromising already limited infrastructure and uncertain agricultural production: "It carried away everything, it entered houses, when the flood water came. Below I had planted corn and peas, and it washed all of this away."

Many farmers feel that hailstorms have become even more intense, frosts more frequent, and both less predictable. One farmer interviewed explained: "[The frost] is increasing. It isn't usually like this in this season, it is usually cloudy now. The frost is already here a little bit and it is getting worse." When frosts are expected, bonfires are set near fields or straw is laid over fields, but the new lack of predictability has made this strategy less feasible. Likewise, hail has begun to fall outside its normal season: "Before, it was in August, September, October, November. In these months the hail came. But now it comes all the time." Some deal with unexpected hail and frost by gradually planting their fields, a risk smoothing measure also used to protect against low market prices at harvest. This strategy exposes only some plants, rather than the whole field, to late frosts shortly after planting.

But many now feel defenseless: "When the frost or the hail comes, one can't do a thing. With what can we defend ourselves? To its liking it beats down on the quinoa, and destroys it all." Cash crops such as vegetables are especially sensitive to hail, which "destroys the lettuce. The leaves are fragile and everything destroys them." Even when crops were only aesthetically damaged, "…then in La Paz they only want it for cheap." Given limited stores of traditional foodstuffs for consumption, sacrificed in order to plant cash crops, a decline in agricultural prices or an adverse weather event greatly impacts both household income and food security. Greenhouses were seen as one potential solution, though no community members had access to such infrastructure or the means to construct it.

Given uncertain agricultural production, livestock has become even more important. Livestock is usually grazed on communal land, relieving some pressure on small landholdings, and also requires less labor than agriculture. When crops are lost and the yield is low, livestock provides an important wealth store that can be tapped, as one farmer explains of losing crops to a flash flood: "Selling livestock, selling that, we bought corn or beans, or a little bit of rice and noodles and bananas. With that we made it through that year." Other farmers saw livestock as a potential adaptation to less favorable agricultural conditions, but indicated they needed financial and technical assistance to acquire and manage larger herds.

5 Accessing Adaptation to Climate Change

Farmer's in Palca perceive that the climate is changing, and their perceptions are consistent with other farmers in the region (Valdivia et al., 2010; Young and Lipton, 2006), and with physical science observations (Bradley et al., 2006; Thibeault et al., 2010; Vuille et al., 2008). Yet, not surprisingly, farmers also identified numerous non-climatic stressors on their livelihoods, many of which preceded changes in climate. Farmers cited key resources and tools needed for adaptation, including land, water, labor, education, financial resources, and institutional support, which confirm findings of smallholder agricultural adaptation in other parts of the world (Bryan et al., 2009; Eakin, 2005; Osbahr et al., 2008; Reid and Vogel, 2006). As social stressors limited access to these assets, farmers shifted to more intensified, diversified, and market-oriented livelihoods, only to increase exposure to later climatic stress. As stressors compounded, the ability to mobilize assets became constrained, making adaptation choices highly interdependent, and sometimes contradictory. Here, we discuss adaptation options dependent on these key assets as farmers' exposure changes over time. We argue that adaptation to climate change is best enabled by ensuring access to a wide range of resources to allow flexibility in confronting multiple stressors and improving livelihoods.

One key asset highlighted by farmers was land, and larger landholdings have been shown to facilitate adaptation in diverse rural contexts (Eakin, 2005; Reid and Vogel, 2006). As the size of holdings shrank in Palca, options for agricultural production were limited. By intensifying production and adopting cash crops to eke out a living from ever-shrinking parcels, household livelihoods became more sensitive to the interactions of market and climatic stressors, including increases in pests and extreme events that harmed the value and quantity of produce, similar to market-climate interactions noted in Canada (Belliveau et al., 2006). While communal property may reduce vulnerability, (Adger and Kelly, 1999; Kelly and Adger, 2000), most communities did not have sufficient land to practice traditional communal management systems. Communal lands did provide some relief to insufficient private plots, as it was used for grazing animals, though few families were able to acquire enough heads of livestock for subsistence. While accessing more land is economically impossible for most farmers, *benefiting* from existing land is becoming increasingly difficult due to changes in climate, such as decreased rainfall.

Access to water is influenced by both climatic and institutional factors that shape adaptation (Liu et al., 2008; Young et al., 2010).Water stress is growing in Palca, in part attributable to changes in rainfall, rapid loss of soil humidity, and decreased snowmelt, but also due to greater demand for more water intensive crops and the year-round production adopted to maximize output. Yet as rain-fed plots become unsustainable, irrigation water sustains more and more of each household’s agriculture. Poor irrigation infrastructure, limited access to credit, and absent technical assistance all limit access by reducing farmer's ability to benefit from the water that *is* available. The delay in rainfall also constrains some of the strategies adopted to confront market variability, as it is becoming more difficult to plant early to beat the market, while planting late puts crops at risk of frost.

Access to financial capital is limited by multiple stressors, yet is clearly essential to any adaptation, including in smallholder agriculture (Howden et al., 2007). Institutional marginalization limits access to credit, an important climate risk management asset (Bryan et al., 2009). Market-oriented production and increased urban employment provide some income, but market uncertainties make these incomes insecure. Yet cash crops require investment, so households are dependent on unreliable off-farm labor to begin each agricultural cycle. Financial needs limit some adaptation options, as more resilient crops cannot replace the income gained by cash crops and are thus not adaptive to many market stressors. New phenomena, such as fruit trees and vegetables at higher altitudes, provide farmers with some income generating options, but financial resources prohibit adoption of technology and infrastructure improvements to seize these opportunities.

Labor, and the human capital to make it meaningful and fruitful, are essential to livelihoods (Bebbington, 1999; Sen, 1997) and adaptation. Indigenous knowledge can provide human capital important to adaptation ((Berkes et al., 2000) in (Adger, 2003)), but has been challenged in Palca by both social and climate stressors. Land scarcity in Palca has forced the abandonment of some of the very cropping practices, such as altitudinal management, that once served to protect against climate risks. At the same time, institutional racism restricts access to other forms of human capital, such as education and technical assistance, limiting employment and adaptation options. Labor is stretched thin by increased off-farm work coupled with intensified production, while changes in climate require more time dedicated to irrigating and pest management.

Social capital is seen as fundamental to adaptation (Adger, 2003), and strong community institutions have remained important in Palca to confront multiple stressors. Market stressors have lead to some decreased adherence to communal labor practices, though they remain important for coping in times of need. Agrarian unions have mobilized community resources in the absence of external support, though have been unable to hold local government accountable. Furthermore, the combination of water scarcity and municipal neglect has strained the capacity of agrarian unions to fairly distribute water resources without economic resources to improve infrastructure.

These assets have been under increasing stress in recent years, which will likely continue, making adaptation is more urgent than ever. Climate stress is expected to increase in highland Bolivia as temperatures continue to rise, rain falls later and more erratically (Thibeault et al., 2010), glaciers disappear (Vuille et al., 2008), and crop yields decline (Parry et al., 2005). Even under current conditions, Palca's farmers expressed concern the climate stress was exceeding their ability to respond and highlighted the need for external aid. The urgency of external adaptation assistance has been widely recognized in the literature (Adger et al., 2003; Howden et al., 2007; Osbahr et al., 2008). However, a focus on climate change adaptation without addressing underlying vulnerabilities can risk promoting the status quo, keeping the poor from becoming destitute rather than actually improving their well-being (Handmer et al., 1999). As we have shown, climate is only one of many stressors that smallholder farmers must consider when making difficult decisions regarding how to allocate limited assets. The capacity to adapt to climate change is therefore necessarily linked to multiple stressors to which households are exposed and the way in which households respond to those stressors.

In this context, improving adaptive capacity requires increasing access to diverse assets and thereby expanding the choice set available to vulnerable farmers to employ a variety of risk management strategies that are compatible with the multiple stressors on their livelihoods (Prowse and Scott, 2008). This asset-based perspective on adaptation is consistent with longstanding development objectives, such as poverty reduction, and is often considered “mainstreaming” adaptation into the greater development agenda (Golkany, 2007) or merely extending the security enjoyed by much of the world to the most vulnerable (Pielke et al., 2007) In terms of external interventions, access to key resources may be facilitated by investment in technology, infrastructure, and technical assistance, but must necessarily be part of larger reform of institutions that mediate access in the long term(Agrawal, 2008).

Mainstreaming adaptation also requires greater consideration of changing conditions, including in patterns of risk and time spans for action (Mearns and Norton, 2010). In addition to facilitating access to resources, then, adaptation initiatives should consider how households can smooth fluctuations in their livelihoods, such as by supporting risk management strategies (Agrawal, 2010). In communities like Palca, this may mean supporting existing strategies based on indigenous knowledge and informal institutions with additional information and resources (Agrawal, 2008; Kronik and Verne, 2010). Improving institutional capacity to disseminate culturally-relevant climate forecasts, for example, may provide farmers with the information they need to choose the right combination of crops for that season in light of market prices and subsistence needs (Gilles and Valdivia, 2009). Facilitating access to micro-credit, infrastructure and human capital can expand that choice set. In this way, adaptation interventions that do not limit their focus to climate change, but also address access, will ultimately be most effective in improving adaptive capacity.

6 Conclusions

Farmers in Palca confront multiple stressors over time and have employed the assets available to them in order respond. Multiple stressors can compound, however, to greatly decrease the availability of and access to key assets. For example, land made scarce through inadequate land reforms and lack of economic resources becomes less useful due to decreased rainfall. Also, adaptation to a stressor in one time period, such as intensification of cash crops to respond to land shortages, may increase exposure to another stressor, such as market uncertainty, or to a future stressor, such as increased climatic variability. Furthermore, one stressor may impact the availability of assets that farmers need to respond to another stressor, such as the climatic changes decreasing the water supply necessary to cope with increased market integration. Vulnerability can thus increase over time as access to assets is compromised by compounding multiple stressors and the resource base is depleted.

Vulnerability reduction in the face of climate change will only be achieved by ensuring that communities have access to resources to respond to these many stressors on their livelihoods. An access-based approach to adaptation planning would permit communities to confront both climatic stressors and social stressors by broadening their livelihood options. This requires urgent, though carefully considered, adaptation projects as well as broader political reforms to enable indigenous and other excluded peoples to access the assets fundamental to adaptive livelihoods. More work is needed, however, to develop methods to integrate these social determinants of vulnerability into robust adaptation planning.

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Part II

Disappearing Glaciers and Water Supply: Implications for Water Quality in Highland Bolivia

1 Introduction

Nearly one sixth of the world's population depends on glacier-fed watersheds, but since the 1960's, considerable mass in glaciers and ice caps has been lost worldwide, likely due to global warming (IPCC, 2008). In the Andes, glaciers are disappearing at an alarming rate and the water supply they provide is dwindling, with particularly serious implications for agriculture and domestic uses in the dry season (Barnett et al., 2005; Bradley et al., 2006). Water supply is further stressed by higher temperatures and, in some parts of the Andes, by a delayed and more variable rainy season (Thibeault et al., 2010), and increased demand from growing populations and changing agricultural practices (Beniston, 2003).

Water scarcity may be of serious concern for public health for a number of reasons, including greater risk of waterborne disease. It has been posited that climate-related decreases in water supply may lead to increased concentrations of pathogens (WHO, 2003). Yet most of the evidence on water supply and pathogen loads centers on direct precipitation, not glacial or snowmelt. Heavy rainfall may wash diffuse pathogens into surface waters (Ritter et al., 2002). *Escherichia coli*, a fecal coliform often used as an indicator of fecal contamination, was shown to increase by seven-fold after rainfall and snowmelt events in a pond in Michigan (Whitman et al., 2008), and increase two-fold following rainfall events in an urban watershed in Korea (Cho et al., 2010). Yet rainfall may also dilute pathogen loads—*E. coli* counts decreased by 3% with a 1 cm increase in weekly rainfall in Northern Ecuador (Levy et al., 2009). There is also evidence that precipitation extremes are linked to greater diarrhea incidence, including decreased rainfall (Hashizume et al., 2007; Singh et al., 2001) and heavy rainfall events or increased rainfall (Curriero et al., 2001; Hashizume et al., 2007).

These results indicate that precipitation extremes, including scarcity, may lead to poor water quality and negative health outcomes. However, semi-arid regions also depend on other dry season water sources, such as glaciers and snowmelt, that may demonstrate different water quantity-quality relationships. Yet, while many studies address the diminishing water quantity associated with receding Andean glaciers (e.g. (Barnett et al., 2005; Ramirez, 2001; Vuille et al., 2008), few studies examine the potential ramifications of this changing water supply on microbiological water quality, and consequently, public health.

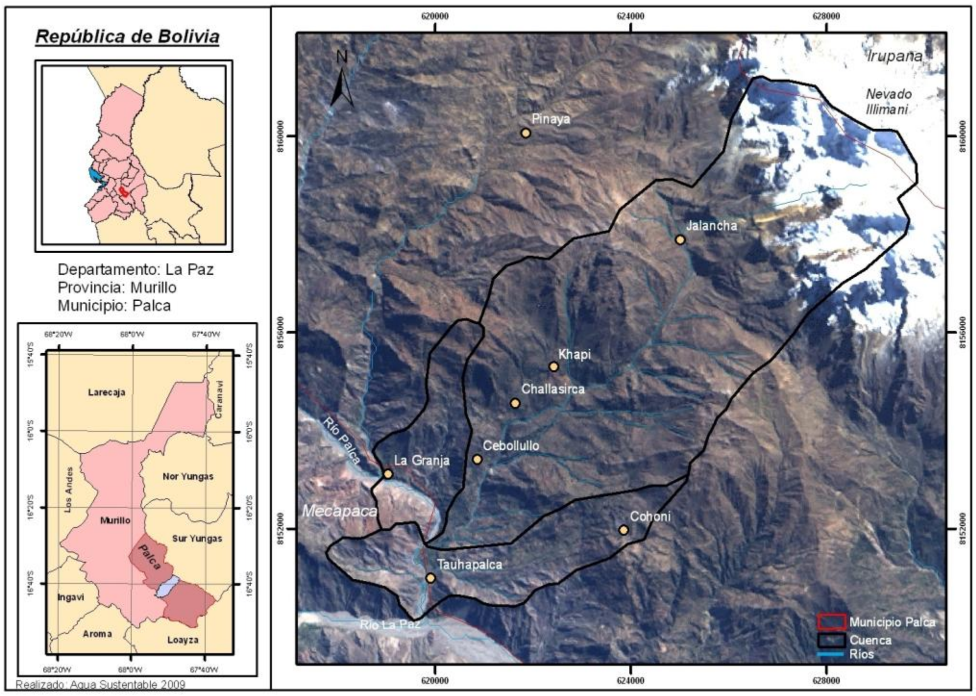
In the developing world, two important drivers of microbiological contamination of surface water are agriculture and open defecation. In rural communities, climate change may alter the dynamics and characteristics of agricultural effluents, including increased runoff and higher concentrations of pathogens in these effluents, yet the environmental fate of pathogens is uncertain (Boxall et al., 2009). In rural Bolivia, surface waters often serve for both consumptive and agricultural purposes, as coverage of improved water and sanitation is extremely low, at 67% and 9%, respectively (WHO and UNICEF, 2008). As water supply decreases with climate change, declining water quality could pose increasingly dangerous health risks.

We address one dimension of the potential public health impact of receding glaciers by assessing the relationship between streamflow and fecal coliforms in a glacier-fed water source in highland Bolivia. We present results from water samples collected in the dry season under increasingly water scarce conditions, and statistically assess the association between *E. coli* and total fecal coliform counts and streamflow in the presence of temperature and time variables.

2 Study Site

The agricultural community of Khapi, a village of approximately 200 inhabitants is located on the slopes of the Illimani Mountain in the Municipality of Palca, Department of La Paz, Bolivia. The region is characterized by a sub-tropical, high-altitude climate, with one rainy and one dry season annually. The average annual rainfall for the Municipality of Palca is 557 mm, but shows high seasonal variation, with almost three quarters of rain falling between November and March. (SENAMHI, 2006) Little to no rain falls from June to August when farmers depend on the Illimani glacier for irrigation water to produce crops. A mountain stream originating at the base of the glacier was diverted to an earthen canal, bringing water flowing through agricultural fields some 7 kilometers to the community (see Map 2). This primary irrigation canal is the main source of water for agricultural and domestic, non consumptive uses in the community, such as laundry.

According to the 2001 Government Census, 77.65% of residents in the Palca Municipality lived in extreme poverty (INE-PNUD, 2005). Two week diarrhea prevalence prior to water sample collection was 27% of children under five (McDowell, Unpublished Data). This unfortunately high burden of disease may be explained by lack of infrastructure and drinking water practices. No households have latrines, and open defecation is commonly practiced. While most households have water taps piped from a high mountain spring, irrigation canal water is also consumed, especially by children and when workers are away from their homes in the fields. Livestock is commonly found in and around the irrigation canal, even far up the mountain near the source, where animals are left to graze.



Map 2. The Illimani River Basin

3 Methods

3.1 Data Collection

Water samples were collected from the primary canal of Khapi over one week in July and one week in August of 2009, to account for potential influence of the ongoing dry season, which begins in June. Water was sampled three to five times per day at three different locations along the canal. The canal locations included a point near the source in the high mountains (point 'One'), a point just before passing through the village, though after passing by several fields ('Two'), and a point just beyond the village ('Three'), meant to capture a variety of levels of contamination from agriculture and domestic activities. 120 samples were collected, 20 at each site during each month.

At the time of sample collection, streamflow was measured using a partially submerged foam ball, a stopwatch, and a measuring tape. Three iterations of these measurements were made and the average was reported. Water temperature (in degrees Celsius) was also recorded immediately prior to the collection of the sample at the sample site. Samples were collected directly from the flowing canal in Whirl-Pak bags and stored in Styrofoam coolers with ice packs for transport to the laboratory in La Paz. Samples were processed in the laboratory[8] within 12 hours of collection.

The IDEXX system was used to process samples, using a Coli-lert 18 medium in the sampling trays, which were sealed and incubated at 44 degrees Celsius. Trays were removed from incubation after 24 hours. Yellow cells, even those light yellow in color, were considered positive for fecal coliforms (FC). A UV light was then applied to the trays, and those cells with phosphorescence were considered positive for E. Coli (EC). The most probable number of fecal FC and EC organisms per 100 mL was determined based on IDEXX statistical most probable number charts. Of 120 samples, problems with incubation equipment prevented reliable results on 51 tests, limiting the final number of reliable test results to 69 samples over 4 days in July and 3 days in August. Other variables considered were the day and month of sampling and the sampling time (measured as minutes from 4:00am, the time at which use of the irrigation canal generally begins).

[8] July samples were processed at Sumaj Huasi and August samples were processed at the Universidad Mayor de San Andres laboratory.

3.2 Data Analysis

Results were entered into Microsoft Excel and imported into SAS 9.2 for analysis. Both outcomes (EC and FC) were assessed for normality. Data for neither variable were normally distributed. Data were instead highly right-skewed given a few outliers with extremely high values (Figure 1). Though still right-skewed, normality was best achieved by taking the log of EC and FC, which is also a common way of displaying microbiological data. This log distribution was used in the analysis and the final model (Table 1).

Overall descriptive statistics of the continuous variables and the raw outcomes were produced. Water quality can change as it flows downstream and pollutants can be introduced, so differences of the primary variable of interest (flow) and the covariates were tested at the .05 alpha level across sample points using ANOVA. To consider the on-going effect of the dry season not captured by other variables in the analysis, differences in flow and the covariates across months were also considered using a t-test at the .05 alpha level. Sample size was insufficient to test for differences across days. The univariate associations between each of the outcomes (logs of FC and EC) and each of the variables was tested for significance at the .05 alpha level using simple linear regression.

Those variables found to be significantly associated with each outcome were included in an adjusted multiple linear regression model for that outcome. Collinearity was tested by creating continuous dummy variables for the categorical variables, with variables with a variance inflation factor of 10 showing evidence of collinearity and requiring removal or adjustment of the model.

The adjusted model was run for both FC and EC using multiple linear regression, and the significance (at the .05 alpha level) and parameter values of flow were compared with those of the univariate models for flow. Parameter changes of more than 10% were considered evidence for confounding of the effect of flow by the additional covariates. The significance of flow in final models was used as to determine whether or not flow is an independent risk factor.

4 Results

There was a mean of 129.8 FC per 100mL in all samples, with a median of 41.0. There was a mean of 1.79 log FC compared with a median of 1.61. For EC, there was an average of 74.6 organisms per 100mL, and a median of 24.3. The mean log E. coli was 1.57 compared with a median of 1.44. The average flow for the channel, across all points and samples, was 34.6, while the mean temperature was 8.5 degrees Celsius and the mean time of collection was 509 minutes past 4am, or about 12:30 pm (Table 2).

Table 1. Measures of Normality for the Outcome Variables

	Mean	Median	Kurtosis	Skewness
FC (n=69)	129.8	41.0	8.89	3.03
Log of FC (n=69)	1.79	1.61	-0.34	.64
EC (n=68)	74.6	24.3	14.89	3.54
Log of EC (n=64)*	1.570	1.44	-0.82	0.44

There were five samples in which there was no* E. coli*, so the log could not be taken.

Table 2. Descriptive Statistics of Risk Factors and Outcomes

	Mean	Median	Standard Deviation
FC (n=69)	129.8	41.0	208.25
Log of FC (n=69)	1.790	1.613	0.499
EC (n=68)	74.618	24.300	119.295
Log of EC (n=64)	1.570	1.439	0.527
Flow (n=69)	34.557	29.890	23.201
Temp (n=62)	8.6	8.4	2.8
Time (n=69)	509	510	113

The ANOVA tests show that Point 3 had significantly worse microbiological water quality than Points 1 and 2, as measured by both crude and log FC and EC counts per 100mL, while Points 1 and 2 showed no difference (p <0.0001). In contrast, flow was significantly higher at Point 1 when compared with Points 2 and 3 (p <0.0001). Temperature and time of water samples was not significantly different across points (Table 3).

Table 3. ANOVA Test Results for Differences across Sampling Points

Variable	**Point 1 (n=23)**	**Point 2 (n=21)**	**Point 3 (n=25)**	**P-Value**
FC	49.5 [3]	51.676[3]	269.28[12]	<.0001
Log of FC	1.53[3]	1.56[3]	2.22[12]	<.0001
EC	24.0[3] (22)	27.2[3]	158.9[12]	<.0001
Log of EC	1.25[3] (18)	1.28[3]	2.04[12]	<.0001
Flow	60.3[23]	25.5[1]	18.5[1]	<.0001
Time	510	496	512	.7717
Temperature	9.6 (20)	8.0	8.1 (21)	.1578

Where data were missing for a variable (n).
Superscripted numbers indicated the other points from which that point is different.

T-tests showed that water temperature was significantly lower in July compared with August (p < 0.0001), while flow was significantly higher in August than in July (p =.018). There were no significant differences in monthly log or crude FC or EC levels, nor in time (Table 4).

Table 4. T-Test Results for Monthly Differences

	August (n=36)	**July**	**P-Value**
FC	85.6	178.1	0.077
EC	57.1	93.2	0.227
Log FC	1.68	1.91	0.060 (Pooled)
Log EC	1.53(31)	1.61	0.560 (Pooled)
Flow	40.8	27.7	0.018 (Pooled)
Temperature	10.1 (34)	6.7 (28)	<.0001 (Pooled)
Time	502	518	0.543 (Pooled)

Where data were missing for a variable (n)

In univariate models, Log fecal coliforms were significantly associated only with flow (p <0.0001) and point (p <0.0001), though month bordered significant (p=.054). An increase of 1 liter per second was associated with a 0.011 decrease in log FC, or 1.025

fewer organisms per 100mL (Table 5). Log EC was significantly associated with flow (p <0.0001) and point (p <0.0001). An increase of 1 liter per second was associated with a -0.01 decrease in log EC, or 1.024 fewer organisms per 100mL (Table 6). The day of collection, time of collection, and water temperature were not significant for either log EC or log FC. Significant variables were put into adjusted associative models for EC and FC with flow, and there was no evidence of collinearity, as no variables had VIF's greater than 10.

Table 5. Unadjusted Associations between Risk Factors and Log Fecal Coliforms per 100mL

Variable	N	R^2	F Statistic	P-value	Parameter Estimate
Flow	69	.2434	21.56	<.0001	-0.011
Time	69	.02416	1.66	0.202	0.001
Temp	62	.0000451	0.03	0.870	-0.004
Month (July as reference)	69	.0519	3.67	0.060	-0.226
Day (Seven as Reference)	69	.0995	1.14	0.349	--
One				0.911	0.035
Two				0.056	0.340
Three				0.973	0.007
Four				0.422	0.188
Five				0.639	-0.081
Six				0.670	-0.158
Point (One as Reference)	69	.435	25.4	<0.0001	--
2				0.746	0.037
3				<0.0001	0.697

Table 6. Unadjusted Associations between Risk Factors and Log E. coli per 100mL

Variable	N	R^2	F Statistic	P-value	Parameter Estimate
Flow	64	0.221	17.62	<.0001	-0.011
Time	64	0.011	0.66	0.419	0.001
Temp	58	0. 002	0.13	0.717	.009
Month (July as Reference)	64	0.006	0.34	0.560	-0.078
Day (Seven as Reference)	64	0.044	0.44	0.847	0.126
One				0.709	0.126
Two				0.208	0.243
Three				0.676	-0.089
Four				0.783	0.070
Five				0.746	0.069
Six				0.982	0.009
Point (1 as Reference)	64	.5237	33.54	<0.0001	--
2				0.757	0.037
3				<0.0001	0.795

The adjusted model for log FC included flow and point, and was significant at the .05 alpha level (p<0.0001), with an R^2 of 0.481. Flow remained a significant risk factor (p=-0.019) after adjustment, though the parameter estimate (-0.008) changed by approximately 27.4% from the univariate parameter, indicating the presence of confounding by point (Table 7). The adjusted estimate associated a flow increase of 1 liter per second with a 1.0 fewer organisms per 100mL. Point was also significantly associated with log FC (p<0.0001). Specifically, Point 3 showed a strong association with FC, with an increase of 0.38 log FC, or 2.4 additional organisms associated with samples from that location (p=0.033).

Table 7. Adjusted Model for Flow and Log Fecal Coliforms

Variable	Parameter Estimate	P-value
Flow	-.008	<.0001
Point	--	0.019
2	-0.232	<0.0001
3	0.374	0.147

Table 8. Adjusted Model for Flow and Log E. coli

Variable	Parameter Estimate	P-value
Flow	-0.0055	0.097
Point	--	<0.0001
2	-0.169	0.323
3	0.551	0.004

The adjusted model for log EC and flow included point, was significant at the .05 alpha level (p<0.0001), and had an R^2 of 0.545, also indicating moderate predictive ability. However, flow became insignificant in association with EC (p=0.097), while Point remained significantly associated with EC (p<0.0001). As with FC, log EC was associated specifically with Point 3, which yielded an increase 0.55 log EC, or 3.5 organisms, in 100mL samples from that point (p=.004) (Table 8).

5 Discussion

The two dependent outcomes of EC and FC and the primary independent variable of stream flow were significantly different across points. Point 3 had by far the worst water quality, though this may have been thrown off by the two outliers found there. Point three also had the lowest mean flow, though it was only significantly different from Point 1. That the lowest flow and worst water quality are found at Point 3 is not surprising—the Point is near the end of the canal, after the water has been siphoned off for agricultural and domestic use, and after passing through both agricultural fields and the town. Point 2 was tested after passing through agricultural fields, though no households, which may explain the lower flow, but also indicates that the sources of contamination may important determinants of FC and EC counts.

Month appeared to have little influence on EC and FC levels, though water temperature was significantly lower in July, as would be expected given the generally colder weather in that month compared to August. On the other hand, flow increased in August. This may be due to one snowfall event that occurred prior to sampling in August, or to increased glacier melt during this month due to higher temperatures. However, on no sample collection days were rain events recorded, thus eliminating potential confounding of rain washing contaminants into the canals, or temporarily increasing streamflow.

Not surprisingly, only flow and point were significantly associated with the log FC and log EC. As hypothesized, increases in flow were associated with decreases in both FC and EC. However, in the final models, only FC was associated with flow. Flow ceased to be significantly associated with EC. This difference may lie in the differences between the two indicator organisms being tested. While the fecal coliform test detects a multitude of thermotolerant coliform species found in feces, the test for *E. coli* detects only one specie. It is possible that other, biologically-driven factors may be more important than flow in determining *E. coli* survival in surface water, while flow is a good general indicator for a broader indicator organism test like fecal coliform detection.

6 Conclusions

Flow seems to play a role in determining channel water quality in Khapi, Bolivia. However, better quality data, additional measurements and a larger sample size would be needed to confirm this finding. Given the clear importance of the location of the water sampling, analysis could have been improved if stratified by point, but the small sample size did not allow for further stratification. A greater number of samples at each point, and possibly more locations along the canal for sampling, could have enhanced analysis. Also, sampling over a longer time frame to capture the potential impact of seasonality, precipitation, and snowmelt, would also have been helpful in characterizing other potential drivers of microbiological water quality. Collecting information on the concentration of animals grazing at various points along the stream would also have provided potentially useful information to include in the analysis.

Additional factors that influence water quality were also not considered. The effect of acidity and salinity, for example, is known to affect water quality. UV intensity is also an important determinant of water quality that was not assessed. The presence of heavy metals or other pollutants was also not tested, but may have an impact on microbe populations. There were clear limits to the data collected, as well. The water quality equipment used was not ideal, and some error may have been introduced in the testing and sampling procedures.

These limitations likely biased our findings toward the null, however, and so the positive association between flow and microbiological water quality is likely even stronger than reported here—the higher the flow, the lower the concentration of potentially pathogenic microorganisms. Given the community's use of the canal for both irrigation and drinking, and the projected decline in flow as the glacier retreats, this finding is cause for concern. Should water quality continue to decline, the water may be inadequate even for irrigation of the vegetable crops currently grown.

Further study into the impacts of reduced flow could inform guidelines for water use and treatment in Khapi, Bolivia. However, some recommendations were made to the community during the course of this research to prevent negative health outcomes in the short term. First, children and adults should stop drinking untreated canal water immediately. A more intensive education campaign to discourage drinking of canal water is necessary to explain these hazards to the community. For those that do not have taps, these should be installed as soon as possible by the municipality. This is, however, unlikely given the political and economic circumstances of the area, so appropriate point of use water treatment should be introduced immediately until adequate infrastructure is accessible. To improve canal water quality, livestock should be kept away from the canals, and clothes should not be laundered inside the canal.

While the retreat of the glacier and delay of the rains cannot be controlled by the community or its government, some changes in water management could help mitigate the serious water shortages that are likely to occur in coming years. More efficient water transport and irrigation require serious infrastructure investments that are out of reach of economically poor community, however. Additional options to improve water quality, such as sanitation facilities to provide an alternative to open defecation practices, also require expenditures beyond the means of most households. The deleterious impacts of climate change on water supply could thus be largely mitigated by basic investments to the water and waste management of Khapi and the surrounding communities. While perhaps outside the community's means currently, further study may illustrate that the gains in health, agricultural production, and food security that could result might offset these costs, particularly if water supplies are to become less reliable in future years.

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