Chapter 1

Technological Solutions for Climate Change Adaptation in the Peruvian Highlands

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Additional information is available at the end of the chapter

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1. Introduction

Climate change is one of the most pressing and complex problems facing humanity. Climate change was first presented as a biophysical phenomenon, one that would manifest itself through sea level rise, melting polar ice caps, and warming temperatures. It has since become an issue of international significance and the subject of ongoing dialogue in both political and academic settings. As the risks of climate change deepen, so too does the contention and confusion surrounding how best to proceed. How we address climate change is continuously redefined and expanded in academia and policy. As the focus has gradually shifted from mitigation to adaptation, the dialogue has shifted to include the social dimensions of climate change, resulting in a sharp rise in research on the human dimensions of climate change. No longer just a biophysical phenomena, climate change has become a lens through which we analyze poverty, inequality, vulnerability, and development. It has created intense debate about who is responsible, who is most susceptible, and how best to prepare for the consequences of a changing climate. To address these questions, climate change scholarship has developed the concepts of vulnerability and adaptation.

The rise in vulnerability and adaptation research has been accompanied by an increase in methodological frameworks and theoretical approaches to understand and assess vulnerability and design and implement appropriate adaptation strategies. Through this work, it has become increasingly apparent that vulnerability to the various threats posed by climate change is not just a function of the threats themselves, but is shaped by the cultural, institutional, and socioeconomic contexts in which these risks occur. Similarly, the capacity to adapt to climate change is influenced by the very same factors. Much of the scholarship on vulnerability and adaptation has focused on those most vulnerable to the impacts of climate change, particularly resource-dependent, agricultural societies. Food production is of fundamental importance to the global community and many agricultural societies will undeniably need to adapt to new biophysical conditions in order to persist. The livelihoods of resource-dependent farmers are inextricably linked to their biophysical environments and there is a great need to understand these relationships to better inform adaptation options.

Within the context of resource-dependent agriculture, institutions and technology have been identified as two factors that shape both vulnerability and the capacity to adapt. To understand how innovation in both institutions and technology can be used to address climate change, the South American country of Peru will serve as a case study and the backdrop to a discussion on the dynamics between vulnerability, adaptation, institutions, and technology. This chapter will focus on the Peruvian highlands, an expansive steppe characterized by vast mountain ranges, tropical glaciers, and indigenous, resource-dependent agricultural communities. Peru's highlands cover a little over 30% of the country and yet contain over 70% of the world's tropical glaciers. Runoff from these glaciers forms the life support system for highland agriculture and for urban consumption in swelling coastal cities such as Lima. Warming temperatures and more variable precipitation have led to accelerated melting, with far reaching implications for agriculture, industry, and urban users. The region is also undergoing considerable socioeconomic changes, as population growth has increased the need for agriculture, mining, and recreation, changing the nature of traditionally rural, subsistence landscapes.

In the last several decades, the role of environmental and humanitarian NGOs in climate change adaptation has become far more pronounced in the region. Often, these NGOs provide resources, assistance, and in some cases, technologies to farmers. They are a part of an emerging network of climate change practitioners focused on preserving the agricultural and cultural traditions of highland communities. In these communities, traditional, pre-hispanic agricultural technologies are being revived and in some cases combined with modern technologies to create innovative adaptation efforts. This chapter will illustrate the dynamics between institutions, technology, and local-scale adaptation efforts. It will present a background on the past, current, and projected changes in the region's glaciers and climate, it will discuss how these changes will impact local communities, and will explore the various methods communities are using in response to these impacts. It will review important theoretical concepts such as vulnerability, adaptive capacity, and adaptation. Andean agricultural communities offer an excellent case to examine the role of technology and institutions in shaping adaptation pathways in agricultural communities. In many regions of the world, climate change impacts are already a reality, underscoring the need to understand how communities are impacted and how they are adapting.

1.1. Why glaciers matter

Tropical glaciers respond quickly to changes in climate and therefore serve as excellent indicators of climate change. Since glaciers are distributed worldwide, they serve as an exemplar of global climatic conditions. Many of the world's glaciers are in close proximity to settlements, causing the effects of climate change to be readily observed by communities [1]. Additionally, alpine glaciers are oftentimes connected to environmental, social, and economic dimensions of communities in surrounding lowlands; consequently, any changes to mountain glaciers have immediate and significant impacts on populations [2]. This is especially true in Peru, where glaciers and the water they provide are intimately associated with indigenous culture, customs, and religion.

In regions where glaciers provide an important source of freshwater, there is growing concern regarding how climate change may alter the relationship between alpine glaciers and freshwater availability. There has been rapid and accelerating recession of mountain glaciers worldwide during the last 50 years, with increasing concern for potential environmental, economic, social, and political implications should these trends continue [3]. Andean glaciers have displayed continued recession, with the most pronounced retreats beginning in the early 1980s. Many of these glaciers have been in existence for centuries, yet they exhibit some of the most rapid mass and surface area losses in the world [4]. Scientists project serious implications in the future if atmospheric warming continues.

1.2. The Cordillera Blanca

The Cordillera Blanca is part of the Peruvian Andes and is the country's largest and most northerly mountain range, covering over 130 km between 8° and 10°S latitude [5]. More than 99% of all the world's tropical glaciers are located in the South American Andes, and roughly 70% of these are found in Peru alone [6]. The Cordillera Blanca is Peru's most extensively glaciated mountain range, with a quarter of the world's tropical glaciers in glacial valleys with elevations ranging from 3000 to 6800m [4,6-7]. The range contains approximately 722 glaciers covering more than 723 km² [9]. Similar to the global trends, considerable glacier retreat has been documented in the Cordillera Blanca over the 20th century [6]. Studies indicate that the Cordillera Blanca has lost over 25% of its coverage since 1970, during which, the average temperature has increased 0.35°C - 0.39°C per decade [8]. Persistent and accelerated glacial shrinkage in the Cordillera Blanca is anticipated for the future, with severe consequences for the region's water supply and those who depend on it [6].

The Cordillera Blanca's glaciers provide the fundamental water source for irrigated agriculture, domestic livestock, human consumption, and hydropower generation in the region [7]. The region's dependence on this resource will invite serious implications in decades to come as scientists expect atmospheric warming to continue to accelerate. Additionally, increased melting causes the formation of glacier lakes at the glacier terminus; these lakes become dammed by unsorted till deposited by the retreating glaciers, leaving nearby developments at risk for glacier lake outburst floods (GLOFs). Consequently, "accelerated melting in the region is of great concern as it poses a threat to the local water resource and increases in the risk of GLOFs associated with moraine-dammed lakes" [7].

1.3. Climate regimes

In the tropics and extra-tropics, moisture availability is governed by the oscillation of the Inter-Tropical Convergence Zone, which creates variations in the amount of moisture received [6]. The climate of the Cordillera Blanca region features low thermal seasonality with an average annual temperature range from 0°C to 9°C, while diurnal variations in temperature are typically greater. In alpine areas, the steep topography also creates a steep temperature gradient. Monthly precipitation displays significant seasonality with the most precipitation falling during the wet season occurring between October and April [5,9]. More than 80% of precipitation falls during the wet season, resulting in higher stream discharge during those months [9]. Glacier mass accumulation occurs during the wet season while ablation, mass loss through evaporation and melting, can occur year round [5,7]. Most melting occurs during the dry season, which is important since this coincides with decreased precipitation. As a result, water is made available from glaciers when it is most in demand [4]. The Central Andes display fairly moist conditions at higher altitudes, while the coastal lowlands experience extremely arid conditions. Thus, the further one travels down Peru's mountain slopes, the more important glacier runoff becomes.

1.4. Climatic changes

Although the impacts from climate change are still uncertain for many parts of the world, alpine regions in tropics and subtropics are already experiencing the ramifications of climate change. Studies conducted on tropical glaciers reveal that they are particularly sensitive to climatic changes [6]. Climate in the tropical Andes has undergone measurable changes over the past 50 years, with an observed temperature increase of approximately 0.1 °C per decade with a general temperature increase of 0.68 °C from 1939 to 2008. A limited number of modeling studies conducted in the region indicate that warming will continue throughout the 21st century, suggesting further warming of approximately 2-4°C [10]. Following the IPCC's Special Report on Emissions Scenarios A2, scientists project that the tropical Andes may even experience extreme warming, on the order of 4.5–5 °C [11]. Warming of this magnitude suggests that an additional 30-50% of existing mountain glacier mass could disappear by 2100 [10].

In addition to the increase in temperature, changes in precipitation are of equal concern, especially in the Peruvian Andes where rain-fed agriculture supports a large part of the population. There are several limiting factors when it comes to assessing precipitation in the Andes, however. Precipitation records are low in quality and have not been collected systematically, hindering detailed assessments of long term trends. Researchers have been able to identify a small increase in precipitation during the latter half of the 20th century. Perhaps of more importance though, are the projected increases in seasonal variability, including the timing and amount of precipitation in both the wet and dry seasons [11].

1.5. Glacier response to climatic forcing

Variations in climate are commonly linked to glacier advances and retreats [12]. Despite some transient advances, glaciers in the Cordillera Blanca have shown continued recession since the mid-19th century [11]. Every glacier has an accumulation zone, where it gains mass, predominantly from snow, and an ablation zone where it loses mass to evaporation, sublimation and melting [4]. The annual equilibrium-line altitude (ELA) delimits these two zones, above which accumulation exceeds ablation [12, 4]. ELAs can be understood through changes in temperature and precipitation; increased temperature and decreased precipitation causes the ELA to ascend, and decreased temperature and increased precipitation causes the ELA to descend [4, 12]. Persistent rising of the ELA of glaciers in the tropical Andes has been documented in recent decades, by as much as 300 meters in some cases [4]. Glaciers of the Cordillera Blanca lost 22.4% of their area from 1970 to 2003. Due to higher temperature increases at lower elevations, much of this loss has been in small, low-lying glaciers [7].

In addition to implications of precipitation and temperature, atmospheric humidity also influences melting and sublimation [11]. A decrease in atmospheric humidity is thought to be one of the major reasons for glacier retreat throughout the tropics at the end of the Little Ice Age. Studies suggest that in the 1930s and 1940s, temperature accounted for one third of glacier retreat in the Cordillera Blanca while factors promoting decreased humidity accounted for the remainder. Alternately, accelerated recession since the 1980s is attributed to increased air temperature and increased air humidity [13]. Observations show that humidity increases during the wet season are particularly responsible for elevated melt rates. In general, however, quality atmospheric humidity records are absent for the Peruvian Andes and most studies suggest that temperature has greater relevance to glacier mass balance [11].

Glacier mass balance is clearly sensitive to changes in both temperature and moisture, and these are also tied to climatic anomalies such as the El Niño-Southern Oscillation (ENSO) [14]. ENSO is identified as the largest influence on interannual variability of weather patterns and climate fluctuations on the global climate regime [15-16]. As a result of ENSO on interannual climate variability in the Andes, mass balance is greatly influenced by Pacific sea surface temperature (SST) anomalies and their impact on precipitation. Due to warmer SSTs in the Pacific, the El Niño period is typically warmer as well as drier. ENSO events have been linked to significant negatives in mass balance, which is attributed to low precipitation, low albedo, and as a result, increased radiation exposure [17]. La Niña periods are characterized by cold temperatures and more abundant snowfall, during which glaciers usually experience balanced or positive mass balances [17-19].

Pacific SST anomalies in the tropics induce large scale forcing on interannual time scales, resulting in negative mass balance during El Niño years and above average results during La Niña years. Changes in the upper-tropospheric flow aloft associated with ENSO conditions determine snowfall magnitude during the wet season, thus, impacting mass balance. “This teleconnection mechanism is spatially unstable and oscillates latitudinally along the subtropical Andes and affects the Cordillera Blanca in most, but not all years” [11]. Therefore, the connection between ENSO and glacier mass balance in the Cordillera Blanca features inconsistencies which have occurred more frequently since the 1970s, when El Niño and La Niña events featured above average mass balances and negative mass balances, illustrating that glaciers in the region are altered through the ENSO events [11]. In addition, climate model research regarding the impacts on climate change on ENSO occurrences suggest climate change will promote an increased frequency of ENSO events along with increased intensity which is expected to be a further detriment to glacier mass balance and seasonal water availability in the future [15-16, 20].

1.6. The future of water in the Cordillera Blanca

The effects of climate change are underway in the Peruvian Andes and many of the Cordillera Blanca's smaller glaciers are projected to disappear within a few decades [11]. Current and projected warming trends combined with the observed changes in glaciers thus far suggest that the retreat of the Cordillera Blanca's glaciers will continue unabated. It is believed that regardless of any mitigation measures the international community takes now to reduce the impacts of climate change, low altitude glaciers will not be able to recover [4]. This continued retreat will alter runoff patterns, the timing of discharge, and will decrease water availability during the dry season [21]. Thus, declines in glaciers will create significant uncertainty and vulnerability for the region's water supplies and the tens of millions of highland communities and lowland urban dwellers who depend on them [21]. Such drastic changes in the Andean highlands are fundamentally altering the relationship between subsistence communities and their surroundings. The impacts are often noticeable, as retreating glaciers leave once white mountains exposed; the black slopes a stark indicator of fundamental change to alpine environments. These biophysical changes are at the heart of a time of drastic shifts in the ecological and social fabric of life in the Andean highlands. Of great importance is an understanding of the mechanisms and factors that shape vulnerability in these communities.

2. Vulnerability: Theoretical development

Vulnerability has its origins in geography and natural hazards research, but it is now used a concept in climate change studies [22]. The biophysical components of vulnerability have been widely studied in both the hazards and risks literatures, where much of the focus is on the biophysical threat itself. The social dimensions are not as well studied, primarily because it is often difficult to quantify these dimensions, but a growing body of work has emerged to address the social aspects of vulnerability. In 2001, the IPCC defined vulnerability as:

The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity [23].

This definition, as the IPCC recognized in its fourth assessment report in 2007, has been challenged and expanded to include social vulnerability [24]. Brooks provided a critical clarification of vulnerability by distinguishing between biophysical vulnerability and social vulnerability, where biophysical vulnerability refers to impacts of a hazard event, while social vulnerability refers to "an inherent property of a system arising from its internal characteristics" [25]. Accordingly, climate change hazards, such as water scarcity or extreme weather events are the physical manifestations of changing climates.

A variety of disciplines engaged in climate change research are proposing methodological approaches to quantify and assess vulnerability. Assessment of vulnerability includes place-based studies, the development of indicators and, increasingly, scenario-building methodologies and stakeholder-driven processes [26]. A recent attempt to measure vulnerability in the Cordillera Blanca is indicative of the types of variables that are typically included in vulnerability assessments. This method divides social vulnerability into three factors: preparedness, prevention, and response, and divides physical vulnerability into the number of people who may be impacted by the magnitude and trajectory of a hazard event. Each factor is assigned numerical values to allow for measurability and to reduce complexity. These indicators are selected based on academic literature, local conditions, and the availability of data. To maximize mathematical and conceptual transparency, the researchers assigned three classes of scores to each indicator, low, medium, and high. The indicators were then combined to calculate social and physical vulnerability, and combined in total for an integrated vulnerability measure [27].

When the method was applied to the town of Huaraz, it revealed high physical vulnerability and middle to high social vulnerability. Huaraz—an important tourist center—is located in what is known as the Callejón de Huaylas or Alley of Huaylas, which sits in between the Cordillera Blanca and the Cordillera Negra mountain ranges. High physical vulnerability is centered on the Quilcay River and is exacerbated by the outburst potential of Lake Palcachoca and to the high population density of the area. Social vulnerability was attributed to the lack of organized preparedness and prevention practices at a state level and a household level. In addition, preparedness at the individual level was found to vary depending on age, socioeconomic status, and awareness. Integrated vulnerability was found to be highest where exposure, high population density and poverty coincided [27]. The researchers conclude that in order to reduce vulnerability, prioritization of intervention strategies should be based on the underlying causes of high vulnerability in Huaraz: high exposure coinciding with high population density. This method is designed for the scale and conditions of the Cordillera Blanca, but it could be used at other scales if adapted to specific local characteristics and data availability. Studies such as these underscore that while vulnerability is experienced locally, the factors that shape vulnerability occur at different spatial, social, and even temporal scales [28].

There has been significant progress in developing sets of vulnerability indicators to analyze vulnerability at different scales. These indicators can then be used to prioritize adaptation efforts [29]. Oftentimes, these indicators are measures of socioeconomic and political variables [30]. For instance, at a national scale, relevant indicators include literacy rates, life expectancy, governmental flexibility and responsiveness [30]. At a community scale, indicators that measure poverty, inequality, access and representation can be used to quantify vulnerability [29-30]. At a household level, age distribution, labor availability, livelihoods, assets, and resource dependence can shape vulnerability [31]. Thus, vulnerability studies vary immensely on the spatial and temporal scale of analysis and on contextual factors. More and more, the emphasis in vulnerability studies is on the complexities and interconnectedness between social and ecological variables in coupled human-environment systems [32].

2.1. Operationalizing vulnerability: The national scale

Beginning at a large-scale, the first vulnerability for Peru and other nations is the failure to reach binding agreements on emission cuts for carbon emissions and other greenhouse gases (GHG) by the international community. The lack of consensus on emission cuts, witnessed at the 2009 United Nations Climate Change Conference in Copenhagen, is cited for imperiling glaciers worldwide [33]. For many, this ensures that glaciers will continue to retreat rapidly, exposing and exacerbating vulnerabilities in the process. Glacier retreat is a hazard that is associated with a multitude of risks such as loss in minimum ecological stream-flows and reductions in freshwater. These risks affect a variety of sectors, including both urban and rural populations, hydropower production, and the equilibrium of mountain ecosystems [33].

In Peru, reductions in freshwater will greatly affect the livelihoods of people living in the arid coastal plain between the Andes Mountain and the Pacific Ocean [34]. Approximately half of the population, now an estimated 29.2 million, lives along the coastal plain, while one-third live in the mountainous region of the Andean Cordillera, also referred to as the Andean highlands [35]. The largest cities are located in the coastal region and have the greatest economic activity, including Peru's capital, Lima, with 8.7 million inhabitants. For the people living in this region, the primary source of water is from the many rivers that flow down the western slopes of the Andean Cordillera [35]. A key issue, however, is that water resource distribution is highly heterogeneous in Peru: only 1.8% of the average annual freshwater availability flows to the Pacific Ocean, compared to 97.7% to the Atlantic Ocean and 0.5% to Lake Titicaca [36].

Migration to coastal cities is increasing and it is expected that more people will move into the coastal region and place more pressure on water resources as both demand and industry expands [34]. In 1940, 24% of the population lived in coastal regions compared to 65% in the Andean highlands; today, half live along the coasts and 36% live in the highland regions [35]. In 2010, Peru resumed the growth that it had been experiencing before the world recession and ended the year with over 8% economic growth, driven primarily by private investment and high government spending. Delayed spread of growth to non-coastal areas due to poor infrastructure will also aggravate pressure on the coastal region [37]. Ultimately, economic growth, the majority of which occurs along the coast, will exert pressure on the national economy as more investment and action will be needed to address water scarcity. Thus it becomes clear that vulnerability exists along the entire elevational gradient from the Pacific coast to the Andean highlands, but both are linked through national discourse and policy on climate change.

In 2007, then president Alan García promoted water exports to take advantage of the water abundance from melting glaciers. García suggested that excess water could be sold to Brazil. When asked what Peru would do if these water reserves ran dry, he proposed desalination of ocean water [38]. According to Garcia, "We should not pay attention to those who consider melting and disappearing glaciers a threat….the water will never stop trickling down" [38]. This national dialogue reveals conflicts in how experts and decision makers view the consequences of glacial retreat, which may obscure the issue for Andean mountain communities [38]. Andean communities have a lack of understanding regarding the potential consequences that glacial retreat can have on their livelihoods [33]. This vulnerability could be magnified by social inequities arising from differences in how water is governed [39].

The recent increase in flow levels from enhanced glacial retreat has also created vulnerabilities at the local scale. In the short term, glacier retreat has provided a temporary increase in runoff, and populations have quickly responded by taking advantage of these surpluses [11]. Increased water availability has promoted increased agricultural production and development, which has led to sustainability concerns [21]. These surpluses will be a short-lived phenomenon and the eventual decline in water will create adjustment problems for populations that have become dependent on temporarily higher flows [40]. Uncertainty regarding the temporal duration of increased water supplies necessitates consideration for future action if and when the glaciers finally vanish. Thus, priority must be given to studying potential impacts of climate change on water resource management in the region and identifying sustainable adaptation strategies.

2.2 Vulnerability in the Andean Highlands- the Cordillera Blanca

In the Cordillera Blanca, glaciers provide the water necessary to sustain river flows during the dry-season and during extended drought. Inhabitants of the region are dependent on the availability of this water resource for social and economic activities [9]. Water usage can be classified by sector, including consumptive use for agriculture, industry, and households and, non-consumptive use for energy production and mining activities [36]. According to this classification, out of a hypothetical 100 liters supplied by Peru's ecosystems, 51 are used for agriculture, 36 for hydroelectric power generation, 12 for human settlements and industry, and 1 for mining respectively [36].

Climate change will create vulnerabilites along elevation gradients impact many different sectors along these elevation gradients. Rain-fed subsistence agriculture traditionally dominated agriculture in the Andean highlands, but increasingly, farmers are adopting commercial crop production, which often requires extensive irrigation [9]. Irrigated agriculture is highly inefficient in these regions; for every 100 liters used in agriculture, an average of 60-65 liters end up in the Pacific Ocean [36]. During the rainy season, glaciers accumulate mass and store water that is then released during the dry season [41]. Glacial retreat is accelerating this process, leading to the formation of pools and lakes at the terminus of glaciers. These glacial lakes develop in loose sediment formations and can rupture after tectonic activity or from the impacts of falling ice, which presents another major risk in the form of devastating floods and avalanches [41]. The National Aeronautics and Space Administration (NASA) for example, identified a crack in a glacier overlooking Lake Palachoca, located in the Cordillera Blanca, which led to a warning to cities around the lake of the potential for a devastating flood [42]. The predictions turned out to be accurate; on April 13, 2010 a large chunk of ice fell into a lake in the Cordillera Blanca near the town of Carhuaz [43, 44]. The impact led to the formation of a 23 meter high tsunami that flooded nearby communities with sediment and water and destroyed a water processing plant that supplied water to 60,000 people [43]. Scientists attributed the event to climate change, heavy rains, and possibly an earthquake that occurred one month earlier in the region [43, 44].

The Peruvian government had taken some measures to prevent floods like the one near Carhuaz. A drainage tunnel was constructed for the lake. However, since the volume of the ice chunk doubled in size as it descended, its impact created a splash that breached the lake's 60 foot containment banks. Engineers with Peru's National Water Agency, who oversaw the construction of the drainage tunnel, estimated that the drainage tunnel only protects Carhuaz against 80 percent of icefalls [45]. Local experts have also found that retreat below a lake's surface causes the lake reservoirs to become deeper and longer, leading to an increased potential for disaster despite the drainage [41]. Going back to the NASA findings, it is important to note that some scientists, specifically those at the Peruvian National Institute for Natural Resources (INRENA), felt that more scientific study was needed in order to prove the dangers posed by glacial retreat [42]. The following was the stance taken by the head of the Climate Change Unit of Peru's National Council for the Environment (CONAM), Patricia Iturregui:

We need to make an important effort to plan disaster management and prevention of risks in the future. The most important measures to be taken are to organize local communities and to organize an institutional framework able to respond to these adverse effects. We are in the process of desertification. The retreat of the glaciers is definitely going to mean a shortfall in the water supply in years to come [42].

As this example highlights, how a potential risk is perceived could either hinder or advance action towards its management and prevention. It could also lead to confusion as to what should be considered an imminent danger. Both CONAM and INRENA are important environmental institutions in Peru. CONAM is the central environmental agency charged with all creating and implementing national environmental policy [46]. INRENA serves as the principal agency for the management of natural resources and is responsible for, among other areas, managing soil and water resources [46]. INRENA is also concerned with the impacts of climate change on water resources [35]. One of the most important limitations for CONAM results from its sector-based management arrangement, where sectoral ministries are responsible for both promoting and ensuring compliance of management activities. This arrangement represents a conflict of interest for stakeholders as the efficiency and neutrality of ministries is oftentimes mistrusted [46]. Another big challenge for CONAM is achieving inter-institutional coordination to prevent the ambiguity created from jurisdictional overlap [46]. Lack of resources, staff and administrative capacity are other limitations for both CONAM and INRENA.

Any sector that uses glacial water is vulnerable to hydrological changes, but whether or not these sectors are acutely vulnerable depends on factors not readily apparent. These hydrological changes and the risks they pose will be translated into different outcomes via the particular socioeconomic contexts in which they occur [28]. These outcomes will likely depend on the social inequities present within and beyond communities, and especially, the policies that create them [39]. Access to water is a critical issue in many regions in Peru, especially in highland agricultural communities. One of the issues with water access and allocation stems from that fact that Peruvian water policy defines water as an economic good [39]. Commoditizing water has the potential to create scarcity by excluding particular groups and increasing demand in certain sectors, which ultimately increases competition and deepens these inequalities.

We identified some of the important vulnerabilities, risks, and hazards facing the Cordillera Blanca of Peru. Regional and local vulnerabilities will ultimately have to be assessed based on the local socioeconomic contexts, institutional power-plays, and the value placed on water resources. Though vulnerabilities are communicated, perceived, and measured at different scales, it is clear that vulnerabilities are interrelated. Key stakeholders (including the public) will have to recognize the interconnectedness of these vulnerabilities and risks in order to create suitable adaptation strategies.

3. Adaptation: Theoretical development

Vulnerability is closely tied to another important concept in climate change scholarship: adaptation. Both adaptation and vulnerability have become indispensable to the study of the human dimensions of climate change. When analyzing a particular system's vulnerability to a climate hazard, or set of hazards, the ability of the system to respond, to cope, or to adapt is a complementary consideration. To relate the two, adaptation can be viewed as an attempt to reduce the vulnerability associated with climate change [25]. The relationship between adaptation and vulnerability is not usually linear however [47]. For example, some adaptive measures might reduce vulnerability in the short term while creating vulnerability to a different hazard in the long-term [47].

Adaptation did not make up a significant portion of the early years of international climate change discourse because much of this discourse focused on the mechanisms of biophysical impacts or on strategies to mitigate carbon emissions [48]. In the fourth assessment report of the IPCC, adaptation received more attention. This report defined adaptation as "actual adjustments or changes in decision environments, which might ultimately enhance resilience or reduce vulnerability to observed or expected changes in climate" [48]. Adaptation measures can consist of a range of practices carried out at different scales by many different actors. They include, but are certainly not limited to, policy changes and investment in new technologies or infrastructure at national levels and behavioral adjustments and changes in economic decisions at the household level. There are also temporal dimensions to adaptation. Adaptation can be targeted for current risks or in anticipation of future risks. In addition, adaptation can be further defined by sector, such as practices specific to agriculture, water resources, health, etc. [48]. As in vulnerability, adaptation is also influenced by the hazard in question. Specific hazards may require specific adaptation strategies, and not all systems may have the ability to adapt to all hazards [25]. Thus, adaptation can be highly differential in scope and in purpose.

Another closely related concept to adaptation is adaptive capacity, which is the ability of a system to prepare for and respond to climate change stresses [49]. Adaptive capacity can be thought of as a system's potential for adaptation [25]. The capacity for individuals or communities to adapt depends on factors that are not necessarily related to climate, but to socioeconomic factors such as education levels, access to information, resources, and social networks, and even the ability to experiment and innovate [50]. Adaptive capacity can include tangible assets such as financial and technological resources and less tangible assets such as information sharing [51]. Ethnographic studies of pastoral communities in the Andean highlands have shown that livestock ownership is related to the ability of households to adapt to changing and uncertain environmental conditions [52]. Livestock are an important economic asset in these communities, serving as financial capital, a food base, and a means to produce exchangeable goods such as meat, fur, and milk; livestock owners also hold greater positions of power and have more influence in community decision-making, which has resulted in social differentiation based on livestock ownership [52, 53]. During periods of variable weather and/or socioeconomic conditions, households with more livestock are better able to cope by selling or trading livestock or their goods, making livestock a key aspect in the household's adaptive capacity. Households lacking livestock and the associated flexibility lack this capacity [52]. As this case reveals, adaptive capacity depends upon available assets such as livestock and the social, political, and institutional context through which adaptation decisions take place [51, 54]. This context is further characterized by the absence or presence of social networks, institutions, and political influence that may operate at different scales [54]. It is important to recognize that local vulnerabilities and adaptive capacity may be influenced by broader, and in some cases global, forces [55]. For example, international free trade agreements mediated at the national level may remove price supports for local crops, exposing local producers to global market forces and exacerbating local scale vulnerabilities.

Adaptive capacity can be influenced by a variety of factors such as governance, institutions, economic resources, technology, information and skills, infrastructure, and access to resources and services [49]. Poverty is commonly associated with lower levels of adaptive capacity because impoverished communities are typically resource poor and have limited power and representation [56]. Other work has shown that analyzing household characteristics such as education levels and farm vs. non-farm income may indicate why households adopt adaptation technologies and practices [57]. In an in-depth analysis of two rural agricultural communities in Burkina Faso, researchers found that contrasting worldviews within two cultural groups influenced their adaptive capacity through their willingness to adjust behaviorally to changing climates [58]. Studies such as these reveal that deep-seated socioeconomic, cultural, and political forces within communities often shape adaptive capacity. Through in-depth studies of local communities, it is becoming clear that many variables interacting at different scales influence adaptive capacity. Furthermore, adaptive capacity is uneven across and within societies and there may exist barriers and even limits to adaptation. It is important to understand what barriers, limits, or opportunities exist within given societies for adaptation so policies and interventions have a better chance at success [48].

3.1. Pro-poor adaptation as a means for sustainable development

Adaptation may provide broader benefits, beyond its role in reducing vulnerability to climate change. Climate change adaptation is also viewed as a potential pathway in sustainable development (47). There has been a refocusing in vulnerability assessments to shed light on the causal factors that shape household vulnerability, such as income, employment, representation, and access [28]. These approaches focus on impoverished communities and lead to recommendations for "pro-poor" adaptation strategies. To some climate change researchers, herein lies the opportunity to combine adaptation strategies and development efforts. Regardless of whether the goals of adaptation and sustainable development align, development pathways will influence vulnerability and adaptive capacity and vice versa. The manner in which societies choose to develop may lessen or create vulnerabilities to future climate changes, leading to the idea that adaptation and development goals should be combined when possible [49]. Some degree of caution is needed when pursuing "pro-poor" adaptation practices for sustainable development. Since both are promoted in complex social-ecological systems where the drivers that create and maintain poverty and contribute to vulnerability are interrelated and often hard to identify, interventions must be carefully devised so as to avoid creating future vulnerability [47]. This underscores the routinely requested need for systematic and in-depth understanding of the factors that both contribute to vulnerability and facilitate adaptation.

3.2. Resource-dependent, agricultural communities

Agriculture is one of the most fundamental livelihood activities for human societies and climate change is anticipated to heavily impact agricultural systems. Changing climates will not only challenge agricultural systems in the Peruvian highlands, but the more fundamental relationship between humans and these systems will also be tested [21, 59]. Agricultural systems are sensitive to temperature, water availability, crop disease, and extreme weather events, all of which are influenced by climate. Adaptation in agricultural systems aims to promote practices that build long-term resilience to climatic changes. They may include attempts to increase productivity, water delivery and storage, and soil conservation. They may also involve attempts to enhance relations and networks between farmers to create better access to tools, resources, and financial instruments for investment capital [40]. Since climate change is projected to cause further retreats in alpine glaciers and more variability in the timing and amount of precipitation, from the broadest view, adaptation in Peru centers on preparing for the implications of reduced water availability. Rural farmers are one of the most vulnerable groups to changing climates, especially to changes in water availability, temperature, and the timing of precipitation events [21]. Glacial melting and retreat combined with rising temperatures and more variability will shift where crops can be grown, reduce water availability, and will make predictions more difficult [52]. The situation is complex however, because in the short term, glacial melting has led to increased runoff and has opened new terrain to farming and grazing. As the ice continues to disappear however, water availability will eventually decline and with it the buffer that glaciers provide during extended droughts and seasons where the rains are delayed [52].

It is often stated “that all adaptation is local.” Since impacts occur in particular places along defined temporal scales, then responding to climate change indeed will also occur through a locally bound set of actions. Even if a community carries out adaptation in a specific sector, it can be supported, coordinated, or mediated through a network of international funding, national initiatives, and regional collaboration between NGOs and communities. Recent work on climate change adaptation emphasizes that good governance structures can advance adaptation. The social, financial, and political framework within which adaptation occurs can either enhance or undermine adaptation practices. Thus, there are multiple and interacting scales to adaptation, which necessitates careful deliberation and planning in any adaptation endeavor. Adaptation and especially adaptive capacity are influenced by the unique cultural, institutional, and socioeconomic contexts in question, highlighting the complex nature of climate change adaptation.

Though agricultural systems are equally complex, there are several dimensions that are especially relevant to climate change adaptation: local ecological knowledge, technology, and institutions. Indigenous and rural agricultural systems are characterized by local knowledge and practices that co-evolved over time, resulting in systems that are finely tuned to the prevailing biophysical environment. Much of the attention on climate change adaptation in agricultural systems supports technology as a strategy to help farmers increase productivity and conserve resources. However, recent scholarship has recognized that appropriately scaled institutions are a critical factor in technological research, development, transfer, and adoption. In the Peruvian highlands, efforts are underway to develop integrated adaptation that embraces local actions and institutional support. Local knowledge can be used as a foundation to enhance adaptation efforts, warranting further discussion of the relationships between technology, institutions, and agricultural adaptation.

3.3. Technology in adaptation for farmers

Technological research and development are central features of agricultural growth and development [60]. Building of the precedent set in the Green Revolution, technology has been one of the more advocated strategies for climate change adaptation in agricultural systems [61]. Technology can provide an important mechanism for farmers to adapt to changing conditions and has many applications including crop development (new varieties with pest and disease resistance or suitability to temperature and moisture conditions), weather and climate forecasting systems, and management innovations (irrigation, conservation tillage) [62, 63]. Furthermore, technologies are considered farm-level resources and are associated with adaptive capacity [63]. One of the larger challenges in implementing technology in agricultural systems lies in its transfer and adoption, highlighting that technology is not just a strategy, but is also a part of a larger process of research and development, farm-level adoption, and feedback for further innovation [61].

3.4. Institutions in climate change adaptation

Adaptation is the result of decisions made by individuals, by groups within communities, or by organizations, governments, and even international groups on behalf of communities [65]. Thus, adaptation is influenced by the rules and norms that structure decision-making and social interactions, which is to say that adaptation processes are influenced by institutions [66]. In this context, institutions are the formal and informal channels that shape and mediate human behavior [67]. The role of institutions in climate change adaptation has been the focus of recent attention in climate change research, especially those that are involved directly in adaptation practices adaptation practices [68]. Institutions play a critical role in shaping adaptive capacity by supporting and mediating adaptation options and especially by determining how the resources necessary for adaptation flow to different communities [66, 68].

Institutions can operate at a variety of scales from local, to regional, national, or international and they can also emerge within local communities or can be initiated by donor agencies external to the communities that ultimately receive support [68]. Institutions at the national level can promote investments in physical assets such as transportation, water, and energy infrastructure [47]. Local level institutions may influence how resources and information flow to and within communities [66]. It has been shown that institutional factors such as farmer to farmer networks can increase access to information on production techniques and enhance the adoption of various technologies for adaptation [57]. Social networks enable individuals to act collectively, something which climate change practitioners view as necessary to climate change adaptation [65]. Institutions shape the social dynamics of adaptive capacity and adaptation processes are interdependent on these dynamics [65]. The power relationships within communities for example, are oftentimes analyzed in adaptation research because these relationships influence which community actors may or may not have access to representation and resources. Thus, power relationships may create heterogeneous vulnerability even within a community.

Nongovermental organizations are at the forefront of local scale development, conservation, and climate change adaptation efforts. Oftentimes, non-governmental organizations (NGOs) focus on building local capacity and representation, which often entails working within communities and enhancing local institutional capacity [66]. Institutions need to be effectively designed to work within the power and relational dynamics that characterize local groups and some studies show that institutions that fail to take these complex factors into consideration produce weaker outcomes [66, 68]. It is through appropriately scaled institutions that better interactions between farmers, local experts, scientists, and individuals from NGOs can take place. Institutions such as NGOs can be thought of as new configurations that facilitate co-production, the preservation of local knowledge, the integration of expert knowledge, and the sharing of information and technology [69].

It is relevant to consider institutions in the context of technological approaches to climate change adaptation because institutions oftentimes mediate the availability, transfer, and adoption of agricultural technologies. In-depth studies of climate change adaptation on rural farms in Argentina and Mexico have found that financial, technical, or social support is requisite to the adoption of technologies. For example, adoption of irrigation improvement required a combination of tax incentives, technical assistance, and support from the greater community [63]. At the farm level, availability of technology, information, and other resources influence the performance of farmers in terms of productivity and social outcomes [63]. These findings suggest that off-farm institutions play a critical role in agricultural practices in general and are an important consideration in climate change adaptation [66, 70]. Thus, institutions can be thought of as leverage points that determine how technological resources flow to communities [66].

Adaptation is a process through which decisions are made over extended periods of time in response to multiple stimuli that may include climatic and non-climatic dimensions [62]. In agricultural systems, technology and institutions have been identified as two important pathways for building adaptive capacity and facilitating climate change adaptation, especially those institutions that transfer or enhance the use of technology [69]. The broader institutional environment can impose both opportunities and constraints for climate change adaptation, highlighting the need to closely examine how institutions influence adaptive capacity in agricultural systems [63]. The relationship between farmers, technology, agricultural research, and climate change is complex and the following section will use the Andean highlands as a case study to explore these dimensions and to illustrate the role of technology and the institutions in climate change adaptation.

3.5. Local ecological knowledge and technologies

Indigenous populations in Andean regions have always lived in environments characterized by variable weather. To cope with climate uncertainty and risk, farmers developed a suite of strategies tried against the test of time to cope, organize, and adapt to meet these challenges [71]. These strategies exist within long-standing belief systems that are referred to in academic settings as local ecological knowledge (LEK). Local ecological knowledge, also referred to as traditional knowledge or local knowledge, is “gathered over generations by observers whose lives depended on this information and its use” [72]. Local ecological knowledge includes not only the practices, but the social mechanisms behind these practices such as the rituals and institutions that facilitate the sharing and internalization of knowledge [72]. A stark contrast between local ecological knowledge and more modern belief systems lies in the fact that practices built upon local knowledge tends to work within and adapt to environmental limits while modern practices aim to control variability and increase production within agro-ecosystems through the use of high energy inputs and other practices [70, 72]. In the Andean highlands, local ecological knowledge developed from years of observations of and experiences in extreme environments [73]. These experiences led to the development of indigenous crop varieties, irrigation systems, forecasting methods and the cultural and social processes that reinforced these practices. Peruvian farmers developed intimate relationships with their biophysical environments and engage in a number of strategies to cope with variable temperature and precipitation regimes [74]. Since local ecological knowledge in this context contributes to adaptive capacity, it has received attention as an opportunity for climate change adaptation. The following section will introduce aspects of local ecological knowledge in highland communities.

In the Andean highlands, local ecological knowledge is built upon responding to and developing the means to predict climatic variability and this knowledge forms the basis of many of the farming practices of rural inhabitants [21, 70]. Instead of relying on instrumentation to predict weather events, many farmers rely on direct observations of various indicators to determine planting and harvest times. Some groups of Andean farmers forecast climatic conditions by observing constellations. In June, months before the rainy season commences, farmers assess the brightness of the Pleiades constellation to predict the timing of its arrival. When the constellation appears bright, the rains are expected on time and farmers plant accordingly. A dim constellation is thought to mean that the rains will be delayed, and farmers postpone planting to compensate. This annual observation is a part of traditional ritual, but anthropologists who studied the communities were skeptical that it could accurately predict the arrival of the rains. Researchers who have studied these practices however found that there is a fair degree of legitimacy to the practice [75].

During El Niño years, high velocity winds originating off the Pacific Ocean disrupt the flow of moisture-laden tropical air from the Amazon, which delays the onset of the rains and leads to drier conditions. The El Niño winds allow clouds to accumulate over the Andes, which partially obstruct the night sky and cause constellations such as Pleiades to appear dimmer. During normal years, Amazonian air currents deliver the rains as expected and prevent the formation of clouds, causing the constellations to appear bright. Thus, local populations are able to observe these signals from their environment to forecast climatic conditions and plan accordingly. This work is significant because it highlights how worldviews and spiritual beliefs are interconnected with climate and agricultural practices, and all will impacted by climate change. Though some may question the importance of worldviews and subjective beliefs such as these in a discussion of adaptation, others believe that understanding the cultural dimensions of climate change is vital to promoting effective adaptation strategies [76].

The elevation and climate in the Peruvian Andes create a spectrum of microclimates that test the flexibility and adaptability of Andean farmers. To cope with these environmental conditions, farmers have developed an equally broad range of crop varieties for different elevations and microclimates. Potatoes are an important staple in Peruvian highlands and have been cultivated by farmers since the Incan Empire. Potatoes are also culturally significant in the region and some communities pay homage to deities associated with potatoes [77]. There are roughly 2,700 varieties of this important staple crop that are suited to different microclimates and varying water and nutrient requirements. Despite this impressive variety, potatoes are susceptible to extreme cold. Potatoes are typically planted at the start of the rainy season and once planted, soil moisture conditions must fall within a certain range to support growth. If soil moisture falls below a certain level, potatoes may fail to produce strong enough shoots. Potatoes are also susceptible to frosts and if the ground freezes, plants may be damaged or killed. The timing of planting is thus crucial, which necessitates accurate forecasting [75]. Some varieties are more resistant to certain pests [78]. Other tubers such as maca and olluca and the grain-like quinoa were bred to be hardy against frosts and low temperatures and to withstand high altitude environments and the accompanying extreme fluctuations in temperature and precipitation [59]. These crops not only have high resistance to climate related impacts, but are also high in nutritional value [79]. Following Spanish colonization, European crops such as barley replaced indigenous crops [59]. The locally developed techniques and customary practices associated with native crops were lost in some cases as well [59].

Many indigenous farmers engage in a practice known as parcel-zoning diversification. One household will cultivate two or more parcels at different elevations or even in different ecological zones to spread the risk in the event of extreme climate events. If a climatic event negatively impacts a parcel in one zone and not the other, the household will still have yields at the end of the season. However, there are constraints to this practice such as the lack of access to adequate irrigation and limits to parcel size [59]. Many households also engage in livelihood diversification so that they do not depend heavily on any one resource [52]. Households will engage in livestock husbandry, tourism, or construction to supplement incomes [52]. The previous strategies are integral components of farming livelihoods, but none is so important perhaps as securing and maintaining adequate water resources.

Andean communities developed irrigation systems to effectively manage and conserve water, a highly fluctuating resource [80]. These systems were developed by pre-Hispanic cultures, most notably, the Incas. These water storage and delivery systems consisted of terraces, ditches, canals, reservoirs, and raised field agriculture known as Waru Waru. Irrigation in the Andean highlands allows farmers to extend their growing season by providing crops an early start in the dry season [81]. Once the rainy season commences, farmers switch from irrigated to rain-fed agriculture. Ceremonious and collective action formed the foundation of these traditional water systems [82]. Maintenance depended on a combination of labor, worship, and pilgrimages to pay homage to mountain springs and gods [82]. These ceremonious and social processes are essential to regulating this extremely scarce resource and ensuring its equitable and efficient distribution [80].

Raised field agriculture, known as Waru Waru, is a farming technique that was used extensively in the Andean highlands prior to Spanish arrival. The system consists of a series of elevated soil platforms embedded in canals. These canals provide moisture in the event of drought and by absorbing sunlight during the day, protect crops against the lethal frosts and low nighttime temperatures that are common at high altitudes. In addition, raised fields also increase cultivated area and soil depth and the nutrient-rich silt that accumulates in canal bottoms can be recycled into the raised beds to augment soil fertility and increase productivity. Because collective labor is often required to construct the canals and beds, the system has also been found to improve social relations by strengthening local capacity and uniting farmers [83]. These attributes make Waru Waru an effective agricultural strategy for variable weather conditions. Despite multiple benefits and being well suited for the Andean region, this type of agriculture was abandoned in many regions after the Spanish conquest.

Indigenous farmers in the Peruvian highlands engage in a variety of practices that are well suited to extreme environments, but climate change is not the only stressor in these communities. Highland communities are also being exposed to socioeconomic changes that challenge the ability of local ecological knowledge and traditional practices to provide adequate livelihoods [21, 52]. Socioeconomic and political factors such as population pressure, global market forces, and national policies that promote commercial agricultural production are rapidly changing rural economies. Migration and the corresponding loss in traditions and native languages further compound these changes. Despite the erosion of such knowledge, local ecological knowledge is regarded as an extremely valuable means for climate change adaptation and many local efforts seek to preserve and in some instances revive it. "Local populations have been coping with climate and social changes for centuries using local knowledge; this local knowledge could be used to supplement technical knowledge to generate a more comprehensive understanding of the problems resulting from climate change" [52].

These past and current practices and the associated beliefs make up a body of knowledge that ties highland communities to their environments. Local knowledge has been fundamental in enabling rural farmers to adapt in the past, and because of this, the strategies, technologies, and belief systems reflected in local knowledge are viewed as a means to enable communities to adapt to the challenges posed by climate change. The following section will provide three cases of institutional and technological innovation that have incorporated local knowledge in adaptation. Each case provides important lessons and together they provide a review of efforts currently underway.

3.6. Technology and institutions in adaptation

Starting in the 1980's, NGOs and governments recognized the potential agricultural and social benefits of Waru Waru and the role it could play in sustainable development and in climate change adaptation. In 1996, through the United Nations Educational, Scientific, and Cultural Organization (UNESCO), 2.5 million U.S. dollars were donated to Peru to implement Waru Waru in Andean communities. The funds were mediated through the non-profit CARE and covered training sessions, capacity building, and construction. Despite the positive publicity and large amounts of external funding, progress reports revealing abandonment of the newly created fields started to appear, which began to raise questions of the appropriateness of the practice. [83] found that some of the NGO's promoting these raised fields offered incentives, such as food, pay, seed, and tools to encourage farmers to participate. Once the incentives were removed however, farmers abandoned projects. Despite good intentions, some fields were built in inappropriate locations or constructed at the wrong time of the year. In some instances, crops that were ill suited to local climatic conditions were imposed on communities by the NGOs and in other instances, agencies provided misleading information to farmers about the expected harvests and risks. Collectively, these factors worked against the widespread adoption of the practice. Erickson noted that fields that were constructed by individual farmers without the incentives from NGOs had more staying power. According to [83], "why they worked or did not is a complex matter and has more to do with social, cultural, and economic factors than with labor or technology issues".

Despite the challenges experienced in the 1980's and 1990's, in 2007, the United Nations Framework Convention on Climate Change (UNFCCC) identified Waru Waru as a potential local coping strategy to climate change because when implemented correctly, it reduces the risks from droughts and frost events and can provide farmers with greater harvest security. Waru Waru was also viewed favorably because of its cultural importance. According to the UNFCCC, local coping strategies are important elements of climate change adaptation. Local coping strategies originate within communities and provide "efficient, appropriate, and time-tested ways of advising and enabling adaptation to climate change in communities who are feeling the effects of climate changes due to global warming" [84]. Though these strategies take place on the local scale, the UN recommends that they be used in synergy with governmental interventions. As Erickson's work revealed however, the successful adoption of Waru Waru may depend on appropriate incentives and empowerment at the local level to ensure that the practices are continued. An effective agricultural practice is but one piece in an adaptation strategy. Other important factors include adequate standards of living, ownership, and especially in agricultural settings, access to markets [83]. This example highlights the issues of scale, goals, and governance in adaptation decision-making [48]. It is important to understand who is making the decision to adapt, what may be influencing this decision including goals or values, and at what scale the adaptation will occur. In other words, institutions that recognize subtleties such as power differences and community perceptions may have greater success than those that fail to do so. The ability of groups to adapt depends on factors that may not be related to climate, but rather to the social context within which climatic changes occur. Factors such as technology, education, information, creativity, and innovation become increasingly important in shaping adaptive capacity and enabling adaptation responses [50]. The Waru Waru system provides a structural adaptation measure, but non-structural components such as the social dynamics that support its functioning are just as important.

As discussed previously, the preservation of crop diversity is viewed as crucial for climate change adaptation. Agricultural diversity, or agrobiodiversity as it is sometimes referred to, has an important role to play in climate change adaptation [64]. Maintaining crop diversity and variety may help buffer the risk of climate variability and extreme weather events. Some varieties may be able to withstand different temperature conditions and rainfall patterns and it provides farmers with more options in the event of climatic uncertainty. Agricultural diversity can contribute to more diverse, adaptable, and ultimately resilient agro-ecosystems. Seedbanks that store crop varieties and the agricultural science extension programs where they are tested under experimental conditions are two important agricultural strategies for climate change adaptation. The presence and availability of technologies certainly is of importance, but the deeper questions include what technologies farmers choose to use, what factors, either external or internal, induce farmers to adopt certain technologies, and what other factors will influence the ultimate success of these technologies against changing climates. With the assistance of NGOs, farmers in Cuzco province are encouraged to test potato varieties to identify which varieties are best adapted for local conditions. In addition, farmers diversify along elevation gradients to identify which varieties work best at certain elevations [78]. These efforts have become an important mechanism for risk management and increasingly, in climate change adaptation [21]. They also provide an important lesson on the relationship between poverty and adaptation. Typically, resource-reliant communities are viewed both as acutely vulnerable and lacking in adaptive capacity, but Andean farmers have confronted climatic variability for centuries through the careful selection and cultivation of crop varieties [85].

Much of the more recent technological research for climate change adaptation surrounds one of the Andes most well-known indigenous crops: the potato. The Potato Park (El Parque de la Papa) in the southeastern portion of Cusco province in southcentral Peru has become an internationally recognized exemplar of collective action in agricultural research and preservation. The park spans an area of 29,000 acres and is home to over 6,500 members of six indigenous communities. Formed in 2000 by the Cusco based NGO, the Association for Nature and Sustainable Development (ANDES), the park's mission is to preserve Andean agricultural and cultural diversity to promote local rights and livelihoods. Traditional knowledge, in the form of agricultural practices and the customs and beliefs associated with these practices, is viewed as essential to the survival of indigenous communities and culture. The park has provided a shared mechanism for agricultural research and information sharing founded on co-production. Local communities elect individuals to network with other communities to share and transfer new information as it develops. Research within the park is participatory and focuses on identifying distinct varieties, breeding, and crop improvement. In more recent years, the park has widened its scope to work with other NGOs, the Peruvian government, and with the international agricultural community. Dozens of community seed banks and indigenous conservation associations similar to the Potato Park are forming, and they too are organized by NGOs that operate at local, regional, and national levels. The potato park represents both social and technological innovation and is an example of how indigenous communities are complementing local knowledge with social innovation and modern tools to protect indigenous social-ecological systems [64].

A third case of institutional and technological innovation is exemplified by the work of the Asociación Andina Cusichaca (AAC), an NGO founded in 2003 in the southcentral Andean highlands. The organization is best known for its work on rehabilitating prehispanic agricultural terraces and canal systems using locally sourced materials. These terraces prevent surface runoff and soil erosion, create a favorable microclimate for growth, and enhance productivity. Thus, they provide an effective way to buffer the risk of extreme frosts and prolonged droughts, which makes them suitable as an adaptation strategy. The ACC has devoted time and energy into cultivating local involvement and leadership. It provides information sessions, classes, and specialized knowledge exchange sessions on a regular basis. The AAC also offers internships to local youth, creating links to younger generations, which will ensure that knowledge persists within communities.

The AAC created a training program to instruct local residents on how to restore and maintain the systems. This training is ongoing and participants have traveled to other districts and have been involved in regional and even national seminars on rehabilitation. The revival of the canals and terraces has also renewed traditional water festivals and canal cleaning ceremonies that had disappeared in some districts. Now farmers in some districts are beginning to rehabilitate terraces on their own, an indication that communities are reinstituting pride and belief in Andean traditions. This is yet another example of the relationship between institutions and technology; when strengthened, the ties between community members can enhance the success and sustainability of technological solutions.

These three examples make the case that technological change that is grounded in local knowledge and mediated through local networks can increase the adaptability of agricultural systems faced with climate change. They also support the notion that adaptation requires approaches where traditional knowledge systems and science are integrated within institutions that create avenues to transfer information while empowering local communities. The role of institutions in the adoption of new technology may be as important as the technology itself. In some instances, changes in agricultural practices simply cannot be made at the individual level and require community and outside support [64]. Future research on the institutional dimensions of climate change adaptation is needed to assess the social and ecological outcomes of these institutional arrangements on both short and long term horizons. Practitioners and researchers alike may wish to identify what features are best able to facilitate technological transfer and adoption and ultimately, what features are best able to enhance the adaptive capacity of local systems.

4. Conclusion

The future of Peru's tropical glaciers appears bleak, as glacial retreat is projected to accelerate. Increase in atmospheric temperatures is projected to continue, accompanied by decreases in precipitation, raising serious concerns for water availability. There is a need for continued and expanded research throughout the region on glacial mass balance studies, climate change impacts, ENSO occurrences, and glacier behavior. This research will allow for better knowledge of climate forcing on glacier mass balance, which can inform better management of water resources. These biophysical changes present formidable challenges to the social-ecological systems in highland communities. Though these communities have always existed on the edge of climatic extremes, climate change combined with socioeconomic changes may push communities beyond their range of adaptability [21]. Migration between areas and to major cities has led to the loss of local ecological knowledge [86]. In addition, the pressures of globalization and the rise of export agriculture have caused local knowledge to erode as traditional crop varieties are replaced with fast-growing, imported varieties for export markets [87]. Despite these complex and dynamic challenges, indigenous knowledge and technologies may contain great potential for some communities, which will benefit from continued and renewed attention on how to create appropriately scaled institutions to support their full integration.

Technology in and of itself is no silver bullet. However, institutions that are sensitive to local contexts and receptive to changing conditions can provide an avenue for the revival of old technologies and the integration of new ones in agricultural systems. The relationship between technological innovation and institutional change within farming communities, and especially, the processes and channels by which it occurs presents an important direction for future analysis. Climate change adaptation in the Peruvian highlands displays a continuous process of innovation made possible by enhancing, and in some instances reviving, traditional knowledge and technology. These intersections represent an area of rich study and future insights into the capacity of communities to adapt to climate change.

Vulnerability and adaptation in the Peruvian Highlands are interrelated and dynamic. Both the biophysical and social environments in this region are rapidly changing. Agriculture in the Andean highlands will need to undergo measurable shifts to less water intensive crops and more efficient irrigation practices, and in many instances, this shift will continue to be mediated through institutions and technology. A fusion of local ecological knowledge, technological innovation, and renewal of old technologies complemented by institutional support may offer the best mix of strategies to help communities to adapt. The retreat of glaciers has significant implications for Peruvian society as a whole. Though the most vulnerable are often considered ill equipped to adapt to climate change, inhabitants of the Andean highlands have adjusted to harsh climatic conditions for millennia. Despite a bleak picture, there are opportunities for experimentation with adaptation strategies in the Andes, which can offer important lessons and insights on the ability of human societies to meet and overcome the many challenges of climate change.

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