A framework for the science contribution in climate adaptation: Experiences from science-policy processes in the Andes

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As significant impacts of climate change are increasingly considered unavoidable, adaptation has become a policy priority. It is generally agreed that science is important for the adaptation process but specific guidance on how and to what degree science should contribute and be embedded in this process is still limited which is at odds with the high demand for science contributions to climate adaptation by international organizations, national governments and others. Here we present and analyze experiences from the tropical Andes based on a recent science-policy process on the national and supra-national government level. During this process a framework for the science contribution in climate adaptation has been developed; it consists of three stages, including (1) the framing and problem definition, (2) the scientific assessment of climate, impacts, vulnerabilities and risks, and (3) the evaluation of adaptation options and their implementation. A large amount of methods has been analyzed for stage (2), and a number of major climate adaptation projects in the region assessed for (3). Our study underlines the importance of joint problem framing among various scientific and non-scientific actors, definition of socio-environmental systems, time frames, and a more intense interaction of social and physical climate and impact sciences. Scientifically, the scarcity of environmental, social and economic data in regions like the Andes continue to represent a limitation to adaptation, and further investments into coordinated socio-environmental monitoring, data availability and sharing are essential.

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1. Introduction

As effective mitigation of climate change has turned out to be a major political challenge, and the objective of containing warming to below +2 °C in relation to preindustrial levels is increasingly difficult to achieve (Stocker, 2013), adaptation to both negative and positive effects of warming is unavoidable and has become a policy priority. In fact, over the past years, increasing attention has been paid to adaptation, reflected in the negotiations of the United Nations Framework Convention on Climate Change (UNFCCC) (Khan and Roberts, 2013). Adaptation is relevant both for the developing and developed world, and countries have developed adaptation strategies and begun to plan and implement adaptation measures in different sectors, such as water resources, natural hazards or agriculture (Biesbroek et al., 2010; Botzen and Van Den Bergh, 2008; Poussin et al., 2012).

It has been recognized that adaptation is a multi-scale process that needs to consider not only different sources of knowledge but also societal and cultural values, objectives and risk perceptions of different involved actors (IPCC, 2014). Adaptation is place- and context-specific, with local governments and communities playing a key role in the process. How, when and to what degree science should interact and be part of the adaptation process is an ongoing discussion and has also been analyzed for other environmental fields (Moser and Ekstrom, 2010; Paavola, 2008; Pohl et al., 2010). Science plays a particular role in the knowledge production process where other sources of knowledge such as local and indigenous knowledge may also be of substantial relevance, depending on the context (Cash et al., 2003; Ford et al., 2012; Valdivia et al., 2010; Vogel et al., 2007). Research on science-policy interactions has analyzed and proposed different models. A supply driven model, also termed 'science push', foresees that science production is driven by the pursuit of knowledge with limited applicability to solution of problems, and thus often limited use for decision-making (Bielak et al., 2008; Cash et al., 2006; Dilling and Lemos, 2011). In a demand driven, 'policy pull' model the production of scientific knowledge is commissioned by policy in search of practical solutions, but various experiences show that the information asked for may not be coherent with the scientific perspective (Sarewitz and Pielke, 2007). A third approach combines the 'science push' and 'policy pull' models into a co-production, or joint production of knowledge which implies an iterative communication between science and policy (Dilling and Lemos, 2011; Lemos and Morehouse, 2005). Based on empirical evidence, there is increasing agreement that the approach of joint production of knowledge is a more feasible and successful model to achieve environmental solutions (Hegger et al., 2012). The call is out for adaptation research to analyze how decisions are made, and how to facilitate and improve the policy implementation under constraints of time, information, capacity and resources (Smith et al., 2009).

In practice, to date, we observed a strong demand by policy for science to develop and contribute primarily toward a scientific basis for adaptation projects in fields such as physical climate science, climate impacts, vulnerabilities and risks. The scientific basis is thereby understood as the data and information that is generated by science regarding the natural and human systems, typically including observations on the recent past, and projections and scenarios of the future. An analysis of the actual adaptation process that includes adaptation planning and management under consideration of different levels of governance and local actors has been less often asked for and conducted but is nevertheless an essential element (Smith et al., 2009).

This study focuses on the scientific contribution to the adaptation process, and how the scientific knowledge is embedded in the context of the adaptation process with a focus on the tropical Andes. As we will show here, it has become clear that a framework for the production and exchange of scientific knowledge within the multiple dimensions of adaptation planning is an important need. Recently some frameworks have indeed been proposed (see a corresponding assessment in (IPCC, 2014), although some of them may lack specificity in terms of thematic and methodological guidance and regional or local context. Several international organizations and development agencies, as well as technical and scientific institutions in fact have called for methodological guidance. A recent initiative involving the World Bank, the Andean Community of Nations, the Swiss Federal Agency for the Environment, the Swiss Agency for Development and Cooperation, and a scientific consortium of Swiss and Austria based research institutions approached the issue. The focus of the study was on the tropical Andes region, yet with an eye on a possible application of the framework and methodology in other mountain regions. The selection of the thematic scope and scientific disciplines was based on their importance for the Andes region and defined by the involved actors. Accordingly, the focus was on climatology, water resources, agriculture and food security, ecosystems, natural hazards and risks. Social, cultural, economic and political aspects were considered as cross-running issues implying a highly interdisciplinary approach. It is recognized that the thematic scope defined here cannot encompass all potentially relevant aspects but a thematic concentration was regarded necessary for the sake of feasibility.

The objectives of this paper are: (i) developing a framework for the science contribution in the adaptation process in the Andes context; (ii) providing evidence and analyzing experiences for the different stages of the framework; and (iii) putting the Andes experiences and framework in a larger climate adaptation context. These objectives imply a certain hybrid character of this paper, by presenting a framework and discussing its implementation, but also including review elements on the state of methods in different thematic fields in the Andes region and partly beyond the region.

Accordingly, the paper is organized as follows: we first introduce the Andes region and the policy context within which the framework was developed (Section 2). We then describe the framework, along with its different stages, including the framing and problem definition (Section 3), the scientific assessment of climate, impacts, vulnerabilities and risks (Section 4), and the evaluation of adaptation options and their implementation (Section 5). For Sections 4 and 5 we build on, and review existing experiences from science and adaptation projects in the Andes region, and analyze the use of scientific information in these projects. We emphasize that we concentrate on the science contribution in the adaptation process; other components of adaptation may be equally or more important but are not a main focus here. As such the implementation of adaptation is beyond the scope of this study but we include it in the framework because of its fundamental importance in the adaptation process and cycle. In Section 6 we critically analyze the framework and the related experiences in climate adaptation in the Andes, and identify key gaps and needs, and eventually put this in a larger (global) context. We are well aware that all three subjects addressed in Sections 3–5 would merit a separate study, at least. However, we are convinced that there is an added value of integrating the complete process into one study, even though simplifications will be necessary.

2. Study region and science-policy context

We primarily focus on tropical Andean mountain and high-mountain regions and exclude coastal or tropical forest regions which also form part of all tropical Andean countries and are similarly subject to adaptation interests (Fig. 1). In the tropical Andean mountains areas, the exposure and vulnerability of people to climatic change is generally high due to often extreme conditions such as high climatic variability, steep topography, remote setting and high levels of poverty (CAN, 2008; Magrin et al., 2014; Salzmann et al., 2009). Rural mountain communities in the Andes are in fact often characterized by limited livelihood options and adaptive capacity is confined by limited information, poor access to services and often inequitable access to productive assets (Gentle and Maraseni, 2012; Lynch, 2012; McDowell and Hess, 2012; Sietz et al., 2012; Young and Lipton, 2006). Furthermore, due to their more remote location mountain regions often dispose of only sparse climatic and environmental scientific observations, a deficiency that is particularly pronounced in developing countries. These are important limitations for elaborating a scientific basis for climate change adaptation planning and implementation (Salzmann et al., 2009, 2014).

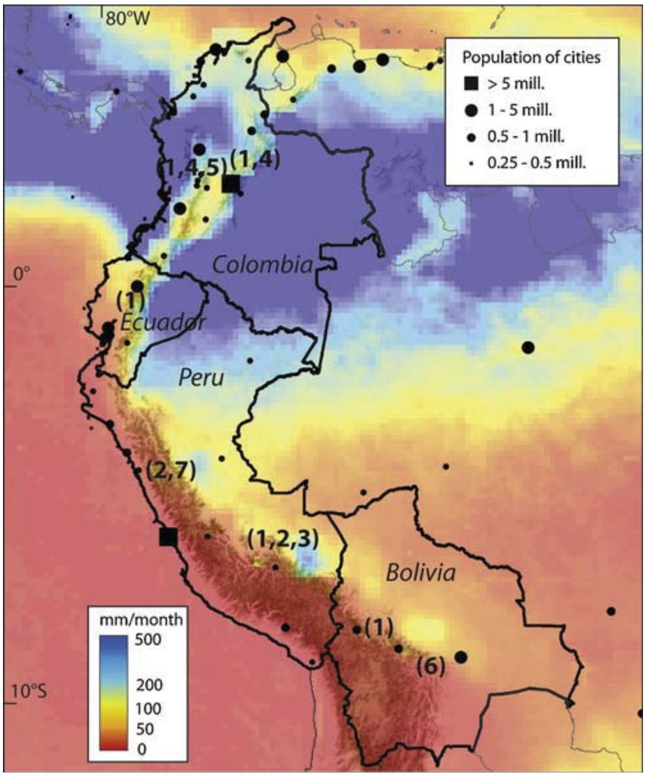

Fig. 1 – Map of the tropical Andes region and countries, indicating the location of the climate adaptation projects analyzed in Table 1: (1) PRAA; (2) PACC; (3) Proyecto Glaciares; (4) INAP; (5) Macizo Colombiano; (6) PPCR; (7) IMACC. Background image is the precipitation climatology for the month of June, based on TRMM 3B43V7 data from 1998 to 2013.

This study was developed in the context of the Adaptation to the Impacts of Rapid Glacier Retreat in the Tropical Andes project (PRAA) and involved the four countries of the Andean Community of Nations (CAN), i.e. Bolivia, Colombia, Ecuador and Peru. The governing and executing political body of the project was the General Secretariat of the CAN. In the CAN, any regional decision needs to conciliate interests and experiences from different actors and realities. This imposes challenges and might require the use of consensus-building approaches and tools. Further actors were the Ministries of Environment of the four Andean national governments, plus a number of technical national government institutions such as the national meteorological and hydrological services, or the civil defense agencies. From Europe a number of Swiss and Austria based universities and research institutions joined the process. The World Bank played a supervision role of the project, and acted as the implementing agency for the Global Environmental Facility (GEF), which provided the Grant funds for the project.

3. Framing and scoping process

A framework is one of the critical elements in a process where science interacts with policy and society (Dewulf, 2013). In our case the framework was developed during a number of face-to-face workshops taking place over more than one year. Fig. 2 displays the result of this scoping exercise visualizing different steps of the adaptation process and the embedment of the scientific contribution in the context of different actors, including local communities, governments and private sector, with essential social, cultural, economic, political and legal dimensions.

In our framework the framing, scoping and problem definition, and the definition of the pertinent socio-environmental systems represent the first stage. We identified the following questions that should be addressed at the first stage:

- What socio-environmental systems are at stake and how are they defined?
- Which actors (e.g. local communities, institutions) are involved or relevant?
- What is the social, cultural, political and environmental context of the actors (historically and at present)? What

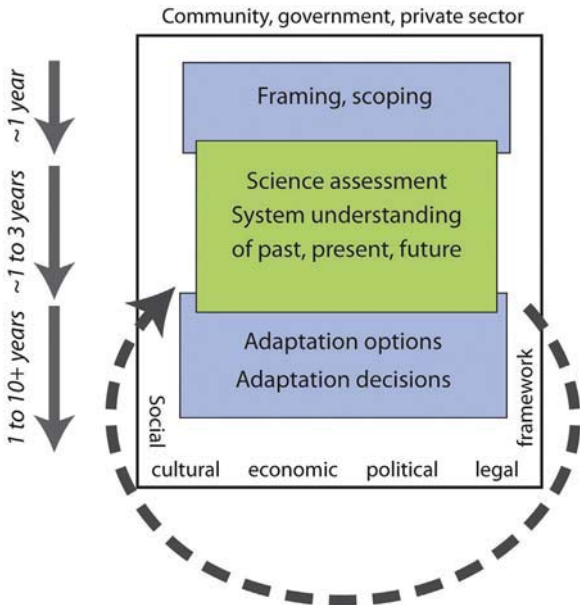

Fig. 2 – Visualization of the framework for a climate adaptation process with science contribution. Three main stages are distinguished and indicated as boxes, where blue denotes processes with a strong policy and stakeholder component, and green with a stronger focus on science. The dashed arrow indicates the iterative nature of the adaptation process. Arrows at the right provide an approximate duration of the respective stage of the framework. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

changes can become important in the future, what are their consequences?

- Are the expectations by the different actors in line with the scientific state-of-the-art, in terms of methods, available data, and time frame?

Studies of the dynamic social, political, cultural and economic context, including perception studies can identify social and cultural aspects of local environmental change and risks (Adger et al., 2013; Carey et al., 2012a,b) that are important for the framing process. The objectives among the actors involved in climate adaptation, in fact, can greatly diverge (Hegger et al., 2012; Weichselgartner and Kasperson, 2010). The definition of objectives and problem framing therefore must necessarily be a joint process that involves a range of stakeholders and actors, where the inclusion of local people and institutions has been shown to enhance adaptation implementation and reduce social conflicts (Dewulf, 2013; Lynch, 2012).

The framing process (first stage) may overlap time-wise with the next, second stage which consists of the scientific assessments. This level is expected to produce the required understanding of the socio-environmental systems, as defined in the framing process, for past, present and future conditions (see Section 4 for more details).

The third stage which may also overlap with the scientific assessment includes the evaluation of adaptation options and eventually decisions on adaptation measures. The close interaction between various actors generated at the first stage of the process (framing, problem definition) is facilitating a more coherent and concerted, and thus useful, process needed for the development of adaptation strategies and measures (Brown and Wilby, 2012; Huggel et al., 2012; McNie, 2007). The open circle in Fig. 2 indicates the iterative nature of this process which represents an important finding from many adaptation experiences in the Andes and other parts of the world, as also emphasized in the recent IPCC 5th Assessment Report (IPCC, 2014).

Fig. 2 also includes an indicative time frame of the different steps of the process. This aspect has often been neglected or underestimated in the past, and experiences (see also Table 1) show that the different time frames of the involved actors can be a major barrier to a successful science contribution in adaptation (see Section 5).

4. Scientific assessments

In this section we focus on the scientific assessment as a main component of the science contribution within the framework process (Fig. 2). We distinguish two main levels that include the thematic studies and can broadly be sketched as observation based (level 1) and projection (scenario) based (level 2) (Fig. 3). The outcome of the first, observation based level, essentially results in an improved understanding of the relevant systems, their vulnerabilities, sensitivities, resilience and adaptive capacities. The identification of critical knowledge gaps and uncertainties is similarly important.

In the second, projection based level, basic information comes from a range of scenarios for the future. How these scenarios are generated (e.g. by participatory methods, analysis of drivers of change, etc.) (Kriegler et al., 2012; O'Neill et al., 2014) should be consistent with the definition of objectives and problem framing. The scenario outcome needs to be translated or propagated into the relevant topics and disciplines. Again, which methods are used for this process essentially depends on the initial problem framing, available data and information, resources available etc. Adaptation involves essential social questions, which should be adequately considered in the scientific assessment and knowledge production. Here we envision the human dimension as running across the different thematic aspects, even though in the structure that follows social, cultural, economic and political aspects are addressed in a separate section. We thereby emphasize the importance of putting the scientific results and models in the respective social, cultural, economic and political dynamic context.

For each thematic aspect (see also Fig. 3) we review and analyze the state of methods and results that has been produced so far in the tropical Andes. This analysis has been done during the aforementioned workshops and additional online meetings involving Andes and Europe based experts. As a result five draft documents were produced, critically revised, discussed, adapted, complemented and brought in its final form that eventually was approved by all four governments of

Table 1 – Analysis of science-policy interaction and context of selected major climate adaptation projects in the tropical Andes with an explicit science component.

Project name and duration Main funding/policy institutions	Countries and sectors involved	Objectives	Scientific input (type and methods); interdisciplinary scope	Joint knowledge production process: problem framing and system definition	Use of scientific information for adaptation measures
PRAA[a] 2008–2014 World Bank, Andean Community of Nations, national governments	Bolivia, Ecuador, Peru, (Colombia) Glaciers, water resources, ecosystems, agriculture	To contribute to strengthening the resilience of local ecosystems and economies to the impacts of glacier retreat in the tropical Andes, through the implementation of specific pilot adaptation activities that illustrate the costs and benefits of adaptation	Climate trend analysis National-scale climate scenario projections based on Global Circulation Model from the Earth Simulator at MRI Japan; statistical and dynamic downscaling Local-scale analysis of socio-economic conditions Mostly disciplinary scope	Problems framed under a pilot project approach, defined within a specific water catchment. Connecting knowledge generation community with large users (such as water utility companies, national to municipal governments, NGOs); and beneficiaries (farmers, small-scale irrigation and water supply associations)	Scientific information generated by the project used to better inform specific pilot adaptation measures, as input for policy and planning, such as: provincial government's climate change strategies, land-use planning, and catchment management plans. Scientific information also used for raising awareness through different mass media products
PACC[b] 2008–2012 Swiss Agency for Development and Cooperation, national/provincial gov'ts	Peru: Cusco and Apurímac regions Disasters, water resources, agriculture	To understand vulnerabilities related to climate change, develop tools and capacities to address climate impacts	Climate trend and climate scenario projections at regional scale Sector/system analysis per scientific discipline Interdisciplinary interaction relatively late in process	Broad categories of systems defined, reconciliation process between science and policy during workshops, limited problem framing	Scientific information used for provincial government adaptation strategies. Practical adaptation actions at local level with limited connection to scientific studies.
Glaciares[c] 2011–2015 Swiss Agency for Development and Cooperation, national/provincial gov'ts	Peru, Ancash and Cusco regions Glaciers, water resources, disasters, agriculture	To improve the adaptation capacities in view of glacier retreat in Peru, including the institutional, technical and research capacities	Climate and glacier trend analysis at regional level Scientific basis of early warning and risk reduction at local level Interdisciplinary analysis of socio-environmental systems (incl. ethnographic studies)	Problem framing between science and executing NGO, with involvement of municipalities and local communities. Due to data limitations systems initially only broadly defined, later adjusted.	Local-scale climate risk studies used for adaptation measures; limited use of regional-scale scientific information
INAP[d] 2006–2011 World Bank, national gov't	Colombia Macizo de Chingaza, National Park Nevados Glaciers, water resources, agriculture, health	To support Colombia's efforts to define and implement specific pilot adaptation measures and policy options to meet the anticipated impacts of climate change Efforts focused on high mountain ecosystems and Caribean islands	Climate trend analysis National-scale climate scenario projections based on Global Circulation Model from the Earth Simulator at MRI Japan; statistical and dynamic downscaling Hydrological monitoring and modeling Disciplinary and partly interdisciplinary scope	System definition in line with those defined for Colombia's National Communication to the UNFCCC, i.e. high mountain ecosystems, island areas and human health. Scientific committee involving experts from different disciplines accompanying the process	Scientific information used for, inter alia: (i) maintenance of environmental services and adaptive land-use planning in high mountain ecosystems; (ii) preparation of malaria and dengue early warning system Community-based project components with broad connection to scientific information

Macizo Colombiano 2008–2011 United Nations (UNEP, UNICEF, FAO), national gov't	Colombia, Upper Cauca river catchment Water resources, ecosystems	To support integrated management of ecosystems in view of climate adaptation, land-use planning and empowerment of local actors	National level: generation of climate and water resrouce scenarios; analysis of vulnerabilities and risks in selected catchments Local level: basic information for early warning, including the use of new hydrometerological stations	Framing and problem definition in participatory approaches with local communities Knowledge dialog between different actors	Vulnerability and risk analysis information and related knowledge dialog used for implementation with local communities
PPCR[e] Ongoing World Bank, national gov't	Bolivia, Rio Grande basin Water resources	To support the implementation of Bolivia's Strategic Program for Climate Resilience by strengthening institutional capacity; and supporting its implementation river basin management in three pilot catchments of the Rio Grande basin	Evaluation of water resources in selected river basins under climate change scenarios River basin plans formulated through a participatory process taking into account the impacts of climate change for water resources management for different stakeholders	Framing and scoping by participatory process involving a wide range of stakeholders of the river basin	Use of hydro-meteorological information (observations and projections) for river basin planning process of stakeholders Prioritization of implementation activities according to their relevance for climate adaptation
IMACC[f] 2012–2014 Interamerican Development Bank, Ministry of Environment of Peru	Perú, Ancash Water resources, disasters	To improve people's lives, to implement adaptation measures with public sector involvement and to strengthen regional capacities	Climate and glacier trend analysis at regional level High mountain ecosystem analysis, including water quality and biological indicators Social and institutional system analysis; scientific basis of early warning and risk reduction at local level	Problem framing between science and public sector (local and national level) with involvement of local municipalities and communities	Watershed-scale climate risk studies used for adaptation measures Remote sensing studies to support management plans Development of public investment projects

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[a] PRAA: Adaptation to the Impact of Rapid Glacier Retreat in the Tropical Andes.

[b] PACC: Climate Change Adaptation Program, Peru.

[c] Glaciares project: Climate change adaptation and disaster risk reduction due to deglaciation of the Andes Cordilleras, Peru.

[d] INAP: Integrated National Adaptation Project, Colombia.

[e] PPCR: Pilot Project on Climate Resilience, Bolivia.

[f] IMACC: Implementation of adaptation measures in selected catchments, Peru.

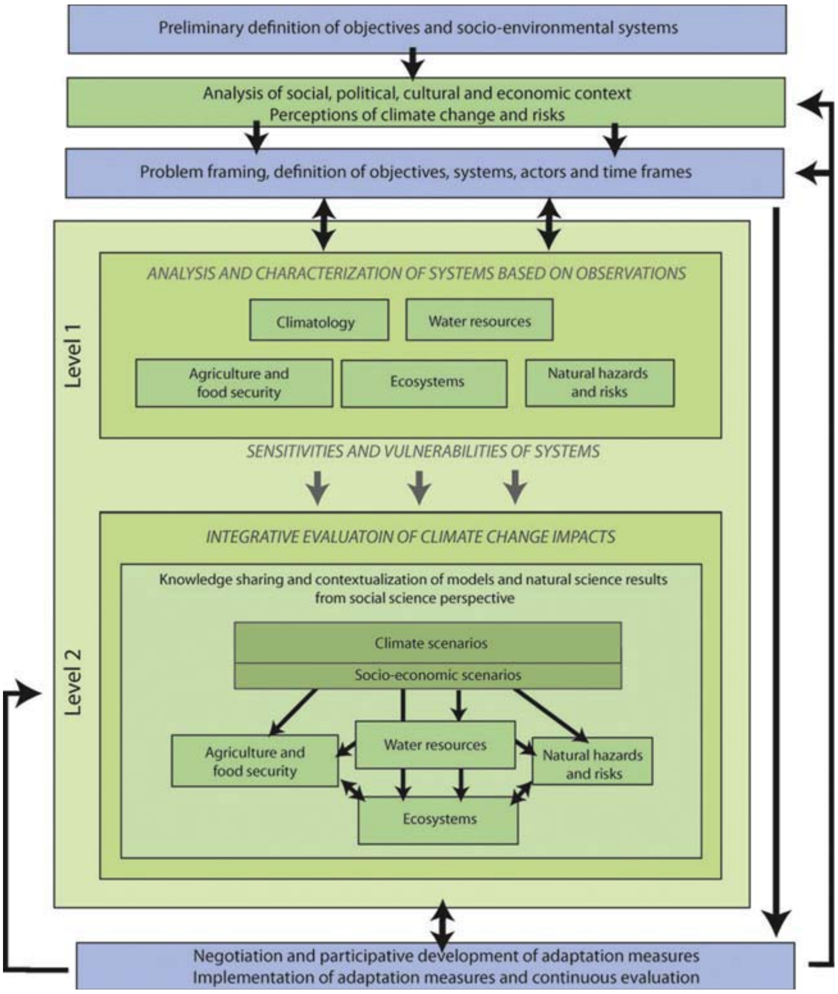

Fig. 3 – Example of a methodological sequence of a scientific assessment. Level 1 refers to observation based studies while level 2 primarily includes projection-based approaches. The main green box corresponds to, and expands on stage 2 (middle box) in Fig. 2. To maintain a comprehensive perspective of the process the intersection with the components with strong policy and stakeholder involvement are shown as well (top and bottom blue boxes). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the Andes countries (for a complete documentation see (AndesPlus, 2013).

Where possible the policy needs in terms of scientific information were considered to highlight the links between science and policy. Due to limitations in space we can provide here only a summary which should be comprehensive, yet to some degree needs to be selective, considering the breadth of research in all the different topics.

4.1. *Climatology*

In line with the general concept of the scientific assessment we distinguish between climate observations and projections. The past climate record is a fundamental basis for any analysis in view of climate change adaptation and at the same time a challenge in the Andes, primarily because of the aforementioned limited availability of long-term, quality-checked climate station data. To cope with limited databases (Schwarb et al., 2011) presented tools and methods for checking and homogenization of climate station data as provided by the national meteorological services, and related to ongoing initiatives on climate services of the World Meteorological Organization (WMO).

Additional data from satellite products such as from the Tropical Rainfall Measurement Mission (TRMM) (Lavado et al., 2009; Scheel et al., 2011; Zulkafli et al., 2013), or reanalysis products (Hofer et al., 2010; Salzmann et al., 2013) have been used in the Andes to complement the ground station data. All these datasets have certain potential and limitations whose discussion is beyond the scope of this study but data quality and reliability is a central issue to all of them.

For climate projections both dynamical and statistical downscaling of General Circulation Models has been performed for the Andes region, for instance with the PRECIS or WRF models (Sanabria et al., 2009; Urrutia and Vuille, 2009), or statistical methods (Minvielle and Garreaud, 2011). Nevertheless, for statistical downscaling long-term, plausible and homogeneous historical data series are an imperative requirement. However, in the tropical Andes long decadal time series without significant gaps or inhomogeneities are quite rare

(Schwarb et al., 2011) and can complicate adequate statistical downscaling.

Climate extremes are essential for the understanding of many climate impacts, and therefore important to analyze. Standard extreme weather and climate indices were developed by Clivar (Climate Variability and Predictability Project), and (Skansi et al., 2013) have found warming and wetting signals over South America, yet with no clear precipitation trends over the tropical Andes. However, from a total of 287 stations, for the tropical Andes only 20 stations over 2000 m asl and 12 over 3000 m asl were available for analysis, highlighting the exacerbation of data scarcity at higher elevations.

4.2. *Water resources*

Water resources are of fundamental importance in the Andes. There is widespread concern that impacts of climate change will negatively affect water resource availability, and people and economy that rely on them (Bury et al., 2011; Buytaert et al., 2011; Vergara et al., 2007). A particular focus is on areas that depend on melt water from glaciers, especially during the dry season in large parts of Peru, Bolivia and Ecuador. However, the exact contribution of glacier and snow melt to runoff is still insufficiently understood.

Hence, both for science and policy a critical question is how to determine present and future water resources and the effects of climate change with a focus on changing glacier contribution to runoff. Glaciological studies in the Andes investigated processes and changes across various scales, from documenting glacier changes from Colombia to Bolivia (Ceballos et al., 2006; Salzmann et al., 2013; Silverio and Jaquet, 2005; Soruco et al., 2009), to energy and mass balance studies on individual glaciers (Favier et al., 2004; Francou et al., 1995; Wagnon et al., 1999; Winkler et al., 2009). A number of hydrological models have been applied to simulating runoff from glacier fed catchments (Baraer et al., 2012; Kaser et al., 2003) including a number of studies that have used coupled climate model data to run hydrological models to estimate changes in future water resources (Andres et al., 2014; Chevallier et al., 2011; Condom et al., 2012; Juen et al., 2007; Lavado et al., 2011). A main limitation for such studies is scarce data availability, especially concerning rain and runoff gauges over climatically and hydrologically significant time periods.

In addition to water quantity, the quality of water is of major importance to local people, and is in fact a major issue, e.g. in relation with mining activities (Bebbington and Bury, 2009). Water is also an eminently social issue and conflicts over water have arisen in many parts of the Andes. Power discrepancies and inequalities play an important role and need to be addressed in water policies and regulations to reduce and avoid conflicts (Carey et al., 2012a,b; Lynch, 2012). From a policy perspective water resource management is a main interest, recognizing the various drivers and stressors, both natural and human, that act on water resources. Available documents and experiences reported during the workshops suggest that recent years have seen enhanced efforts on water resource management by both science and policy, with an increasing number of studies that link across scientific disciplines and institutions (Carey et al., 2014; Harriman, 2014).

4.3. *Agriculture and food security*

Agricultural production and food security under changing climatic conditions is of essential importance in the Andes, from subsistence farming in the Altiplano region of Peru and Bolivia to cash crops such as quinoa or coffee in the cordilleras of Peru and Colombia. Policy is interested in changing crop yields under climate change, the importance of crop pests and diseases, and more generally how to assess economic output and food security. Climate variability and change act as additional stressors on top of historically developed social, political and economic structures, including land rights, distribution, access and marginalization. In many regions (e.g. the Altiplano) agricultural production is already at its limits and additional stressors can tip the system (Sietz et al., 2012).

Scientific contributions in this field include the application of crop models considering phenological phases and water requirements (Geerts et al., 2006, 2008; Steduto et al., 2009), or the assessment of vectors for pests and diseases (Gregory et al., 2009). Pilot adaptation experiences have been generated at many locations, from Colombia through Peru to Bolivia (Perez et al., 2011; PNUD, 2011).

Large-scale integrated assessment models focusing on agriculture production under climate change scenarios, such as applied in several other regions worldwide (Rosenzweig et al., 2013) are yet largely missing in the Andes.

4.4. *Natural hazards and risks*

Policy makers at different administrative levels and other stakeholders need to know where and to what extent natural hazards and risks are located, both in present and future, and to what extent climate change exacerbates the frequency or magnitude of climatic extreme events and hydrometeorological hazards in general. In the Andes, science has addressed these issues only in a limited way so far. Disaster databases are an important tool to better understand where and when a specific disaster occurs. Across the Andes, Desinventar is a primary database (DesInventar, 2013; Marulanda et al., 2010), complemented by disaster databases at the national level. However, consistency of the disaster record across time and different data sources is limited and represents a barrier to a more comprehensive understanding (Huggel et al., 2014).

A wealth of case studies exist on susceptibility, triggers, and effects of a large range of hazard processes, including rainfall triggered landslides and debris flows, ice/rock avalanches, glacier lake outburst and rainfall floods (e.g. Evans et al., 2009; Pierson et al., 1990; Terlien, 1997; Thouret et al., 1990; Vilimek et al., 2005). Studies that focus on policy relevant aspects such as hazard and risk mapping, or produce a basis for early warning systems are more rare but corresponding efforts have recently been strengthened (Huggel et al., 2010; Künzler et al., 2012; Schneider et al., 2014; Thouret et al., 2013).

Due to widespread poverty in the Andes, the social dimension of vulnerability to climatic hazards is of particular interest to policy and development planners. In fact, there exists a large amount of studies on vulnerabilities, and social and institutional aspects of risk perception and management in the Andes region (e.g. Cardona and Carreño, 2011; Nathan, 2008) but only a few have been published in international journals while the majority are studies performed by local non-governmental organizations or universities that are often difficult to access.

4.5. *Ecosystems*

Ecosystem services can build an important pillar in climate adaptation. How these can be preserved or enhanced under multiple stresses and drivers, including effects of climate change, to secure supporting well-being, reducing poverty and risks, and providing sustainable goods and services is therefore of major interest (Carpenter et al., 2009; Fischlin et al., 2007). Several critical Andean ecosystems, such as *paramos* (high Andean moorlands) or Andean forests, deliver significant benefits in terms of water supply, water flow regulation, and erosion control, to name but a few (Anderson et al., 2011; Buytaert et al., 2011). A good understanding of these services, and how they will be impacted by climate change and economic activity, both qualitatively and quantitatively, becomes thus crucial in the adaptation debate.

Over the past years, several projects in the Andes have generated tangible experiences in ecosystem adaptation and in strengthening the resilience of ecosystems and their services. Some of the most outstanding projects have been the Integrated National Adaptation Pilot (INAP) in Colombia, or the aforementioned PRAA project in Bolivia, Ecuador and Peru, which have been based on science and local knowledge, fostering knowledge generation and dissemination (Andrade et al., 2011) (Table 1). Both initiatives applied a participatory and culturally sensitive approach to promote resilient ecosystems and provide benefits to vulnerable people. In view of a systematic evaluation of adaptation options (see also Section 5) models would be required to integrate bio-physical, social and economic aspects in order to provide stakeholders and decision makers with sufficient knowledge. While in other regions of the world integrated assessment models such as GLOBIOM, G4M or EPIC have been used to assess future scenarios of adaptation options (e.g. strict biodiversity protection, no deforestation) and to support corresponding policy decisions (Havlík et al., 2011; Strassburg et al., 2012), such methods are basically still missing for the tropical Andes. Such models can also deliver better estimates of ecosystem services to set in place appropriate offset schemes, for example the Socio Bosque program in Ecuador, or the environmental service payments in Bogota to protect the nearby paramo in Chingaza. These programs as well as pilot experiences with the EPIC model made in the context of this study indicate the importance of considering the specific characteristics of local Andean ecosystems and agricultural systems from subsistence to export-oriented farming, but also aspects of limited available data when applying such models.

4.6. *Social, cultural, economic and political aspects*

The previous thematic aspects such as water resources, food security or natural hazards and risks have a fundamental social component. For instance, how to respond to which risks does not only depend on the risks themselves but is critically shaped by the dynamic cultural, social, economic, political and environmental context. The social science studies therefore need to run across the thematic aspects, and as such can exert a certain integrative role. Within this process, the impacts of global and national-scale drivers on local processes and the role of local and scientific knowledge for climate adaptation need to be reasonably understood. The number of studies concerning the social and cultural dimension is increasing but yet there is a need to further deepen the understanding of these topics, particularly in their specific local context where concrete adaptation strategies are put into practice.

There is a considerable interest of policy makers and adaptation projects for so called ‘tool kits’ to assess perceptions and vulnerabilities in community based approaches, such as e.g. CRISTAL and CVCA (Dazé et al., 2009; IISD, 2012). These tools offer a rapid appraisal to analyze risks and vulnerabilities within communities in a specific context. Nevertheless, data collection methods of these toolkits are often not suitable for adequately understanding decision-making processes, power relations and open and/or latent social or political conflicts within or between institutions. Such issues are often related to trust and distrust among the actors and institutions, and specific interests and cultural values, within or between institutions, and their understanding thus requires consideration of the full range of actors, including the powerless ones.

For providing a sound scientific basis for climate adaptation though, there is a need to apply more in-depth methods such as ethnographies, participant observation, narrative and historical analysis, or mental models to explore knowledge systems (Adger et al., 2013; Barnes et al., 2013). These methods allow to identify social, cultural, political and economic aspects that are crucial for the adaptation process, but also particularly important for joint knowledge production processes because they facilitate the recognition of differences in actor perspectives (Hegger and Dieperink, 2014). Furthermore, a mutual understanding of the cultural, social, political and economic background, of the constraints that the actors face on the adaptation pathway and the perceptions they have, enhances trust among them. However, as stressed byAdger et al., 2013 there is no simple blueprint in terms of methodology, and the consideration of multiple and marginal voices into decision-making is highly challenging.

5. Adaptation options and implementation

Development and evaluation of adaptation options, and their implementation represents the third stage of the framework (Fig. 2). It is a broad, complex and young field but with a rapidly growing body of literature which we cannot capture here in its full breadth. Obviously, the implementation of adaptation measures is beyond the scientific contribution to adaptation and therefore basically also beyond the scope of this study. Here we focus instead on the analysis of recent major climate adaptation projects in the tropical Andes where there has been a science contribution. We consider this particularly worthwhile because the documentation of this process across adaptation projects in this region is underdeveloped despite recent efforts in the IPCC (Magrin et al., 2014).

As indicated in Fig. 2 adaptation decisions are not taken in a vacuum but in a dynamic social, cultural, economic, political and legal context. Climate (change) typically represents one among many drivers of change, and stressors, resulting in risks (or opportunities) that are perceived differently by different actors and stakeholders. Most projects analyzed here concentrated on adaptation measures that can be viewed as vulnerability reduction, and enhancement of adaptive capacities and governance. In several cases climate variability and extremes were considered a more immediate priority for the stakeholders as compared to longer term climate change projections. All the projects have local and national scale components and address multiple sectors, with water resources being a dominant issue in many projects, reflecting the importance of water for the Andes region. In several projects scientific information was used to support the development of national or provincial adaptation strategies. Efforts were also made to use scientific information for evaluation of adaptation options but difficulties were found at the local level, mainly because scientific assessments struggled with the lack of available data, especially over longer periods of time. Instead, several projects applied more practical approaches, applying participative methods and tools with local communities (see also Section 4.6). Especially for water resources, and agriculture and food security, many projects implemented such adaptation strategies with local communities but with limited or no connection to science. Yet, there are some examples where science has substantially contributed to the implementation of adaptation measures, e.g. for early warning and risk reduction measures (Schneider et al., 2014). Furthermore, many projects implemented adaptation measures to improve environmental monitoring networks. Science and different levels of policy and other actors usually jointly evaluated options, and decided on, where and what sort of equipment to install.

One important barrier to successful adaptation implementation we have seen across most projects are different time frames between policy and other actors, and science. Policy and decision makers at various administrative levels are often insufficiently aware of the time needed to produce a solid scientific basis, and hence, scientists were unable to meet the time frames expected from policy makers or adaptation practitioners. The time periods in Fig. 2 are indicative and essentially depend on the respective context and projects. In the Andes countries, more than in Europe or the U.S., the terms of local, provincial and national governments exert a major influence on adaptation planning and implementation, and science cannot act independently of those terms in a concerted adaptation process. The terms are typically 4–5 years, and ideally are considered in the process. Eventually, it is important to recognize the iterative character of the adaptation option and implementation process. This is especially important in view of the uncertainties inherent to the scientific knowledge and socio-economic processes (Webster and Jian, 2011), and thus represents a strategy to manage uncertainties (Gersonius et al., 2013; Hallegatte, 2009)

6. Discussion

6.1. *Reflection on Andes experiences*

The framework for the science contribution in climate adaptation that was developed with the Andean governments distinguishes three main stages (Fig. 2): (1) framing and problem definition; (2) scientific assessments of climate impacts, vulnerabilities and risks with an interdisciplinary perspective; and (3) adaptation option evaluation and implementation. This framework is basically in line with similar concepts that have been assessed and developed recently by the IPCC (IPCC, 2014), where the complete adaptation process is framed under a risk management scheme with multiple feedbacks and iterations. During the assessment of the state-of-the-art in this field in the tropical Andes region we have identified the following gaps and key issues, as related to the aforementioned stages of the framework:

- There is a need for more consistency in common problem framing, terminology, objectives, timeframes, and type of results between science, and policy and local actors (stage 1);
- There is a need for a more sustained interaction and communication of science with the diverse range of actors that have a stake in adaptation (stages 1 and 3);
- Limitations in data availability and data sharing continue to persist, both at country and regional Andean level. Equipment for environmental monitoring is often insufficient but recently improving due to multiple efforts (stage 2);
- The interdisciplinary scope of science studies and the interaction among disciplines are predominantly not yet developed to a level that allows scientists and policymakers to approach the problems in their full complexity (stage 2);
- There is a lack of appropriate monitoring and evaluation tools, which renders the learning and stock-taking process of the different experiences challenging (stage 3).

Some of the above points are relevant beyond the Andes region and are taken on in the next section. Other issues such as limited environmental monitoring data and networks are also a limitation in many other regions, and exacerbated in mountain and high mountain regions (Salzmann et al., 2014). Methods that were developed in regions with dense monitoring networks need to be adapted. Examples of studies with methods adapted to the Andean context in the field of climatology and water resources, for instance, were presented by (Buytaert et al., 2009; Lavado et al., 2009; Salzmann et al., 2013; Scheel et al., 2011) in terms of combination of multiple datasets, and by (Buytaert and Beven, 2011; Chevallier et al., 2011; Condom et al., 2012) in terms of appropriate complexity for modeling studies.

The identification of methods that are adapted to the Andean context, or locally developed, was one of the important issues for the scientific assessment of impacts, vulnerabilities and risks (stage 2, Fig. 3). The process of achieving a consensus between Andes and Europe based experts from science and governments on methodologies and concepts in each thematic field was not straightforward and a challenging science-policy process in itself. It was started by a presentation of an initial compilation of methods by the international research team to the Andes experts, primarily along disciplinary lines; followed by a comparison with locally/regionally (Andes) available methods. Methods adjusted to the Andean context were then jointly identified and defined through a review process of several draft documents, which concluded in a final document that was eventually officially approved by the four national governments of Colombia, Ecuador, Peru and Bolivia (AndesPlus, 2013).

The appropriate consideration of a rich and steadily growing Andean experience represented a major challenge through all stages (1)–(3). However, much of the knowledge production and adaptation processes in the Andes are, however, not sufficiently documented and rarely published in international journals. Well-established, long-term, sustainable monitoring and evaluation schemes of experiences are also broadly lacking as indicated above. The recapitulation of these experiences with local experts was a fundamental aspect but also a challenge. For instance, many adaptation experiences have a practical focus, often implemented by non-governmental organizations, with methods that are not necessarily in line with standards of scientific rigor. We have found that the distinction between scientific and practical approaches in adaptation is often not clearly defined, and hence, the integration of such diverse approaches is demanding.

6.2. *General implications of Andes experiences*

Adaptation planning is often categorized into top-down and bottom-up approaches where the first one typically refers to climate scenario and impact driven assessments, and the latter starts with vulnerability assessments, often with qualitative and participatory methods, based on which adaptation option are then evaluated (Wilby and Dessai, 2010). Recent research suggests that in fact the integration of the two approaches is a more successful model (Bhave et al., 2014). Our framework in inline with these proposals as it combines important elements from both approaches. Some of the thematic scientific assessments (see Figs. 2 and 3) include elements of a top-down approach while the framing and problem/objective definition is reflecting aspects of a bottom-up approach. Furthermore, the integrative and cross-thematic nature of the social aspects in our framework contribute to ensure an appropriate consideration of the human dimension of adaptation. Top-down approaches have been criticized to neglect this dimension. It is interesting to note that our analysis of adaptation projects in the tropical Andes (Section 5) has shown that often some sort of blended approach is applied, motivated or constrained by the lack of local data. Some of those project activities were decoupled from science. While actually not all types of adaptation may need a scientific contribution we consider that science can often enhance the joint knowledge production process. In-depth social science studies, for instance, are able to shed light on power relations, interests and values of various actors and institutions, thus contributing to socially more concerted adaptation. However, we also recognize that in this context the science-policy process can be particularly delicate as important political interests may be at stake.

More generally, we note that there is a rich and growing literature on the production of knowledge based on scientific understanding and a range of other sources in an environmental and climate adaptation context. Scholars reflect on both theoretical and practical aspects, with a majority of studies based on experiences from Europe and North America (Cash et al., 2006; Dilling and Lemos, 2011; Hegger et al., 2012; Lemos and Morehouse, 2005). Similar experiences from regions such as South America are available yet to a lesser degree although they are of great importance for regional, national and local adaptation policy (Lynch, 2012).

Recent research has identified a number of functional, structural, and social barriers to a joint problem framing and knowledge production, that accordingly may be grouped in (1) divergent objectives, needs, scope, and priorities; (2) different institutional settings and standards, and timeframes; and (3) differing cultural values, understanding, and mistrust (Hegger et al., 2012; Weichselgartner and Kasperson, 2010).

Concerning the first group of barriers our analysis of major adaptation projects in the Andes has shown that in practice reconciliation of objectives and scope is only rarely done to the extent it would be beneficial (Table 1). A complicating factor thereby is that the aforementioned three groups of inhibiting factors are highly interdependent, i.e. reconciling objectives and needs cannot be achieved without addressing differences such as in terms of institutional settings, time frames, cultural values and trust.

While some of these issues can be approached in a more systematic way (e.g. time frames), this is much more difficult for others (e.g. cultural values and trust) which makes the process not fully controllable or predictable. In the Andes, as well as in other regions, climate adaptation takes place on the regional, national or local level, with a variety of actors (e.g. CAN, international cooperation, development banks on the regional level; local governments/communities, non-governmental organizations on the local level). Accordingly, there is a wide range of aspects to consider when objectives and needs are reconciled on the different levels and between actors. In our framework (Figs. 2 and 3) we have not explicitly distinguished between the different administrative and spatial levels, mainly to maintain its general applicability and constrain the complexity. In fact, given the current discussions in literature, and based on our own experience in other regions, we anticipate that the framework may be useful beyond the Andes region.

7. Conclusions and recommendations

In this paper, we have presented and analyzed a framework for the science contribution embedded in the broader climate adaptation process. It was developed in a joint process involving representatives of the four governments of Colombia, Ecuador, Peru and Bolivia, the CAN, the World Bank, and scientists both from the Andes region and Europe. Three main stages, from problem framing and scientific assessments to adaptation implementation, are distinguished. Appropriately putting the process into the respective dynamic social, cultural, economic, political and legal context is of fundamental importance but highly challenging. Clearly, more research on analyzing and documenting such processes and experiences is needed.

The consistency of many elements analyzed here for the Andes with the recent assessment by IPCC, 2014 indicates that while adaption is often a local process, aspects of science-policy interaction in the frame of adaptation are of more universal significance. Specifically, our study underlines the importance of joint problem framing, definition of socio-environmental systems, time frames, and a more intense interaction of social and physical climate and impact sciences. Scientifically, the scarcity of environmental, social and economic data in regions like the Andes continue to represent a limitation to adaptation. Investments into socio-environmental monitoring can therefore be seen as a viable low-regret adaptation measures.

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