Global environmental changes in the high tropical Andes

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Chapter 1
General Introduction
Chapter 1. General introduction

1. Introduction

Upper montane forests, alpine grasslands (paramo and puna) found in the high tropical Andes¹ (Figure 1) contain globally significant carbon stocks (Buytaert et al., 2011; Hribljan et al., 2017), singular biodiversity (Gentry, 1995; Kessler & Kluge, 2008; Sklenář et al., 2014), and play a fundamental role in sustaining the livelihoods of millions of people (Cincotta et al., 2000). The first ecosystem services provided to resident populations relate to food production and water resources for domestic use, agricultural production, and hydropower generation (Bradley et al., 2006; Carey et al., 2017). These essential systems are, however, under threat due to global environmental change (GEC) stressors² (Jetz et al., 2007; Brook et al., 2008; Asner et al., 2010). Although global warming is by far the most widely recognized GEC stressor, land use change (LUC) also has a strong effect on biological diversity and ecosystem functioning (Sala et al., 2000; Báez et al., 2016). The interactions between climate change and LUC are likely to have a significant impact on the Andean biota (Feeley & Silman,

¹ This portion of the Andean change encompass areas above 3000 m asl. Included in this upper region are four major ecosystem types: (i) the paramos of the northern Andes, (ii) the upper Andean forests of the eastern and some of the western slopes of the Andes, (iii) the puna of the central Andes and the dry scrub/forest of high intermontane valleys. This thesis is restricted to the first three ecosystems.

² Global change involves the simultaneous and rapid alteration of several key environmental parameters that control the dynamics of Earth ecosystems across all scales (Bachelet et al., 2001). In this thesis, I focus primarily on two stressors of global change: land use and climate change.
2010b) and ecosystem dynamics (Buytaert et al., 2011) because: (i) many range-restricted species are present, with a high level of species turnover over short geographic distances (Sklenář & Balslev, 2005; Sklenář et al., 2014), (ii) the gradient of decreasing temperature with increasing elevation strongly influence plant communities (Körner, 2003), and (iii) critical ecological functions, such as carbon sequestration, are controlled by low air and soil temperatures (Körner, 2007, 2012). Additionally, these ecosystems have a long history of human uses and in some cases, plant community dynamics are controlled by human-induced fire regimes and cattle grazing such as the lower section of the puna in the Altiplano (Postigo et al., 2008; Monteiro et al., 2011). Humans have been present in the Andean landscape for around 12,000 years (Rademaker et al., 2014) and have utilised the landscape in a variety of ways during this time, including agriculture and extensive cattle grazing (Postigo et al., 2008; Young, 2009), combined with high human population density in the major Andean cities (i.e. 5,200 hab./km²) and a projected average growth of 2.2 by 2050 (Buytaert & De Bièvre, 2012; Goldberg et al., 2016).

The critical role that high tropical mountain systems play in sustaining Andean societies, coupled with the enormous pressure they face due to GEC stressors means that they have been identified as of acute global concern (Brooks et al., 2006; Mittermeier et al., 2011). However, we still have limited knowledge of the responses of the Andean biota and the ecosystems as a whole to these stressors. For instance, there is very little knowledge about how vulnerable high Andean species and communities are to the observed warming rate. Deeper understanding is needed to assess if the intrinsic niche traits of high Andean plants allow species to be identified as being particularly prone to the effects of warming, as well as communities with a higher risk of being confronted to a warming-induced transformation of their species composition. Further, our understanding of the resilience of high Andean ecosystems to recover from land use impacts is still very basic, especially regarding ecosystem dynamics, such as carbon sequestration (Malhi et al., 2010). International cooperation agendas are promoting and financing restoration actions across the tropics, such as the 20 x 20 initiative (https://www.wri.org/our-work/project/initiative-20x20). Many of these

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3 Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes (McCarthy et al., 2001).

4 Resilience is defined in the context of this thesis as the amount of disturbance that a system can absorb without changing state. A concept introduced to indicate behavior of dynamic systems far from equilibrium (Gunderson, 2000).
restoration actions have not been scientifically validated and, in the majority of the cases, any assessment of their impacts on the ecosystem is limited (Chazdon & Guariguata, 2018). Overcoming these knowledge barriers is essential to provide clear guidance for the development of effective conservation plans together with the design of cost-effective restoration actions (Chazdon et al., 2017).

In this thesis, I set out to fill this knowledge gap related to assessing the validity of exclusion grazing practices as a useful restoration tool to sustain alpaca fibre production in the Peruvian highlands, and the effectiveness of passive restoration practices to restore ecosystem functions in the Ecuadorian páramos. I use an integrated research perspective, generating information of mountain ecosystem responses to GEC stressors in the high tropical Andes, using a diachronic approach. Firstly, I analyze the patterns and processes that influence plant community composition, species abundances and species richness, and their relation with the environmental gradients across the high tropical Andes, and then focus on potential future changes. Secondly, I focus on understanding the resilience of high Andean ecosystems to human land uses using carbon stocks, carbon sequestration, and plant species richness as indicators of ecosystem processes. Lastly, I analyse the spatial distribution of species and ecosystem diversity in continental Ecuador and identify priority areas for biodiversity conservation in continental Ecuador, considering the short and mid-term impacts of global environmental stressors.
Figure 1. Major ecosystems of the high tropical Andes: (a) Upper montane forest and ecotone transition towards paramo grasslands; (b) Dry Puna and wetlands (bofedales) in western ridge of Bolivian Andes; (c) wetlands in the western ridge of the Ecuadorian Andes; (d) Upper montane forest landscape in western versant of the Ecuadorian Andes; (e) Alpaca rangeland in the Central Andes of Peru; (f) Páramo glacier landscape in the central Ecuadorian Andes. Photos F. Cuesta (b,c,f) and E. Pinto (a, d, e).
2. The high tropical Andes

The tropical Andes represent the longest and widest extension of mountain areas anywhere in the tropics, occurring from 11°N to 27°S (Josse et al. (2011); Figure 2a). Extending more than 4,500 km in a north-south direction, the high tropical Andes (>3000 m above sea level) show a prominent precipitation and temperature gradient (Fjeldså & Krabbe, 1990) from the humid equatorial Andes to the xeric environments in the central Andes (Josse et al. (2011); Figure 3). Recognized as one of the world’s most important centres of biological diversity and endemism (Myers et al., 2000), the tropical Andes comprise nearly 34,500 described organism of which nearly half (49%) are described as endemics (Mittermeier et al., 2011). Furthermore, a large proportion of their flora consists of unique taxa with restricted geographic ranges that show sharp replacement rates within short distances along environmental gradients (Kessler et al., 2001; Cuesta et al., 2017).

In the high Andes, the remarkable change in topographic configuration from a fragmented landscape in the northern Andes, to a large continuous alpine zone of the central Andes, including a high-elevation plateau (the Altiplano), has been identified as a key driver of high levels of species turnover (beta diversity) along the latitudinal gradient. Together with the island landscape of the alpine systems in the north, the combined effect of a marked thermal seasonality and a progressive reduction in annual rainfall as we move away from the equator line, have been identified as significant drivers of species composition shifts in high Andean plant communities (Anthelme et al., 2014; Cuesta et al., 2017).

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5 The Cuesta et al., (2017) reference corresponds to the third chapter of this thesis.
Figure 2. (a) Map of major landscapes/biomes of the tropical Andes Source: Adapted from Cuesta et al. (2009); and (b) Vegetation profile of major ecosystem types along the elevation gradient. Source: Adapted from Josse et al., (2009).
“(1) Subnival vegetation, (2) Alpine grasslands (páramo/puna), (3) Polylepis forest, (4) Wetlands (Peatlands), (5) Upper mountain forest, (6) Moist Mountain forest, (7) Mesic mountain forest, (8) Piedmont forest.”
Figure 3. (a) Mean annual temperature and (b) Annual precipitation. Source: Cuesta et al. (2011). Climate data source: Worldclim (http://ww.worldclim.org/)
2.1 A global hotspot for biodiversity conservation and climate change mitigation

The ecosystems of the tropical Andes, together with those of the Amazon basin, contain more than 15% of the planet’s biological diversity (Brooks et al., 2006; Langhammer et al., 2007) and regulate the climate of the centre and north of the South American continent (Vuille & Bradley, 2000; Hoorn et al., 2010). The heterogeneity of the bioclimatic and physical patterns of the mountain range explains this enormous biodiversity, which is evidenced in their environmental and edaphic gradients, as well as by their geological and climatic history (Gentry, 1982, 1995; Kattan et al., 2004; Rangel et al., 2018).

The Andes harbour the most extensive continuous surface of tropical mountain ecosystems in the world (Young et al., 2002; Körner et al., 2011). The ecosystem diversity of the tropical Andes includes five macro landscapes or biomes6: (i) páramos, (ii) punas, (iii) montane forests, (iv) dry inter-Andean valleys, and (iv) the salt flats (Cuesta et al. (2009); Figures 1, 2a). On the outer flanks, montane forests constitute the dominant matrix covering an elevation gradient of ca. 3,000 m, from the Andean Piedmont (ca. 500 ± 100 m asl) to the treeline, which varies according to the latitude but which is generally above ca. 3,500 m asl (Körner, 2012). Towards the inner flanks of the Andean mountain range, the forests are delimited by the dry enclaves of the inter-Andean valleys (Figure 2b), which generally have a north-south disposition (Josse et al., 2011). The high and unique biological diversity of tropical montane forests is related to their evolutionary biogeographic history and the strong environmental gradients associated with the tectonic complexity of the Andean mountain range (Gentry, 1995; Kessler et al., 2001; Ledo et al., 2009). Montane forests exhibit high tree species turnover along environmental gradients, particularly elevation, topography, and soil. As a result,

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6 Both ecosystems, páramos and punas, contain peatlands. Tropical high Andean peatlands constitute azonal ecosystems, embedded within the páramo and puna landscapes, as the result of specific geomorphic characteristics that favor the formation of peatlands in mountainous regions, primarily in high mountain valleys and in intermountain basins (Benavides & Vitt, 2014). These mountain peatlands are termed turberas in the Northern Andes and bofedales in the Central and Southern Andes. Peatlands ecosystems store large quantities of carbon, particularly in the soil organic layer (Benavides, 2014; Hribljan et al., 2016). The soil organic layers are formed from alpine vegetation communities (Bosnian et al., 1993; Cooper et al., 2015) that are typically composed of low-stature plants with low aboveground biomass but high belowground biomass (roots). These peatlands also receive large inputs of mineral material, predominantly from volcanic deposition, that has created many interbedded non-peat mineral soil horizons.
these types of forests have very high beta diversity values (Kessler & Kluge, 2008; Homeier et al., 2010; Kessler et al., 2011).

The high tropical Andes, between treeline (ca. 3500 m asl) and permanent snowline (ca. 5000 m asl), harbour both non-seasonal grasslands in the equatorial Andes, known as páramo, and seasonal grasslands in the Central Andes, known as puna (Cuesta et al. (2017); Figure 3). Alpine ecosystems in the high tropical Andes are outstandingly rich in plant species with a high level of endemism (Simpson & Toddzia, 1990; Sklenář et al., 2014). The vascular plant flora of the páramo comprises over 500 genera and 3,500 species of which as many as 60% are thought to be endemics (Luteyn et al., 2002; Sklenář et al., 2005) and is by far the richest and most unique of all tropical alpine floras (Sklenář et al., 2014).

Evolution of the tropical alpine biota is closely linked to Andean orogeny (Hoorn et al., 2010; Sklenář et al., 2011). The alpine habitats where much of this rich flora is found today have been available for plant establishment only since the late Pliocene or early Pleistocene 4–2 Myr ago (van der Hammen & Cleef, 1986; Hughes & Eastwood, 2006) after final uplift of the Andes (Gregory-Wodzicki, 2000). The Andean uplift in combination with the glacial-interglacial cycles (at least 20 of various intensity) during the Pleistocene forced the vegetation to shift altitudinally by as much as 1,500-2,000 m (Flantua et al., 2014) allowing many of the now “isolated páramo and puna islands” to become functionally connected (Hooghiemstra et al., 2006; Flantua & Hooghiemstra, 2018). During interglacial periods, alpine ecosystems contracted and split into small islands (Flantua et al., 2014). Such repeated pulses of expansion and contraction of the alpine ecosystems are believed to have produced a high frequency of recent and fast radiation events (Bell & Donoghue, 2005; Hughes & Eastwood, 2006). As a result of the evolutionary history of the high Andes, the plant communities are composed of many species with narrow ranges (Sklenář & Balslev, 2005; Sklenář et al., 2014), low population densities and genetic variability (Madriñán et al., 2013), and many of them are located in the periphery of their environmental and geographical niche (C. Tovar, personal communication). These ecological traits confer the Andean biota a high vulnerability to GEC stressors (see section 2.2).

The tropical high Andes holds vital ecosystems that sustain biodiversity, biological processes, carbon storage, and surface water provision (Buytaert et al., 2011; Vuille et al., 2018). The geomorphology of these ecosystems allows the formation of extensive wetlands or peatlands, predominantly in the central Andes (Josse et al., 2011); these areas are particularly important as reservoirs of
biodiversity and carbon stocks (Dangles et al., 2017). Local human populations are directly dependent upon these peatlands in this region where conditions are so severe as to almost preclude human habitation (Postigo et al., 2008); this ecosystem is used for grazing by their domestic herds of llamas (Lama glama) and alpacas (Vicugna pacos), which are the basis of the local economy (Postigo et al., 2008). Tropical mountain peatlands are an essential carbon sink that typically contains 500-600 megagrams (Mg) of organic carbon per hectare (Hribljan et al., 2017), with even higher values estimated for the wetter Northern Andes peatlands (Squeo et al., 2006; Chimner & Karberg, 2008; Hribljan et al., 2016).

Upper mountain forests are also known for their high carbon contents. The total amount of above and below ground biomass (AGB-BGB) in these type of forests ranges from 154 at low to 67 Mg C ha\(^{-1}\) at high elevations (Gibbon et al., 2010; Moser et al., 2011), and from 7.5 to 28.6 Mg C ha\(^{-1}\) in tropical alpine grasslands depending on the land use history and on the local climatic conditions. Furthermore, a key compartment is the soil organic carbon, which is particularly high in tropical mountain regions, ranging from 300 Mg C ha\(^{-1}\) in the humid puna of Perú (Zimmermann et al., 2010) to 500-800 Mg ha\(^{-1}\) in the wet paramos of northern Ecuador (Chimner & Karberg, 2008; Tonneijck et al., 2010). Patterns of above-ground and below-ground carbon contents are extremely variable at the landscape scale, and more comprehensive approaches are needed to characterize the links between carbon dynamics, biodiversity and environmental services provision under different land use regimes (Mathez-Stiefel et al., 2017).

The ecosystems of the high Tropical Andes thus hold large stocks of carbon. Their preservation and restoration could have a substantial impact on the carbon budget of the region and deliver substantial global benefits. Whether the high Tropical Andes become a net carbon source or sink largely depends on current and future trends in land use and climate change impacts, and the measures that are taken to counteract any negative impacts.

2.2 A global hotspot of environmental changes

The location of and threats to biodiversity are distributed unevenly across the globe (Brooks et al., 2006). The tropical Andes top the list of the most vulnerable areas of the planet due to the combined effects of climate change and habitat loss (Jetz et al., 2007; Báez et al., 2016). Climate change is projected to have substantial impacts on tropical mountain systems (Buytaert et al., 2011; Tovar et al., 2013; Ramirez-Villegas et al., 2014) due to the projected increase in air
temperatures. For example, temperatures in the tropical section of the Andean chain have increased at a rate of approximately 0.04 °C year\(^{-1}\) in the last three decades of the 20th century, in areas above 3000 m asl (Vuille & Bradley, 2000). Furthermore, the high rates of habitat loss and fragmentation of Andean ecosystems due to deforestation and the expansion of the agricultural frontier (Figure 4) in combination with the development of extensive infrastructure and large-scale mining are increasing pressure over Andean ecosystems (Feeley & Silman, 2010b, a; Bush et al., 2015). For instance, Mulligan (2010) estimated that Andean cloud forests had the potential to occupy c. 1.2 million km\(^2\) under current climate conditions, but that for the year 2009 these forests only actually covered 605,317 km\(^2\); equivalent to a loss of 560,499 km\(^2\). The combination and interrelated feedbacks of both GEC stressors (Brown et al., 2013) pose a great dilemma regarding the future viability of the ecological and social systems of the Andes (Agrawal, 2008; Heller & Zavaleta, 2009).

Figure 4. Land use change impacts on high Andean ecosystems: (a) water ditches in a heavily overgrazed paramo at 4000 m asl in the central Andes of Ecuador; (b) Paramos and agricultural frontier in the northern Andes of Ecuador; (c) Deforestation of the Andean forest in the Eastern Andes of Peru. Photos: F. Cuesta (a,c), S. Crespo (b).
2.3.1 Climate change (incl. glacial retreat and associated changes)

Mountain systems are essential for human societies worldwide through their role in Earth system functioning (Spehn et al., 2010) and the direct provision of ecosystem services to resident populations (Huss et al., 2017). Within the mountain systems, the high tropical Andes are a global hotspot region in terms of cryosphere change (Vuille et al., 2018), landscape transformation (Dangles et al., 2017) and enhanced vulnerability of mountain species and ecosystems to climate change (Buytaert et al., 2011; Fadrique et al., 2018).

Tropical high mountain ecosystems are comparatively simple in terms of their biotic components relative to tropical systems of lower elevations and climate-related ecological factors become more dominant with increasing altitude (Körner & Paulsen, 2004). Thus, the effects of climate change may be more pronounced compared to lower altitude tropical ecosystems (Körner & Spehn, 2002). For instance, species range displacement combined with habitat loss due to optimum thermal shifts (Engler et al., 2009; Morueta-Holme et al., 2015; Fadrique et al., 2018) has a significant negative impact on the structure and composition of tropical mountain communities. Range displacement has had particularly major consequences for species that are adapted to the cold-harsh environments at mountain tops, as their suitable thermal ranges have been severely contracted, which has led to a decrease of their abundances in other mountain ranges such as the Alps (Rumpf et al., 2018).

Tropical mountains are characterized by steep environmental gradients, resulting from the compression of thermal life zones. Thus, vegetation patterns and species composition change over short distances owing to climatic constraints (Grabherr et al., 2000). Further, the low relative importance of land use impacts at higher elevations (>4000 m asl) and their location near the edge of species bioclimatic limits makes tropical high Andean ecosystems ideal for studying the effects of climate on the biota and ecosystem functions on a regional scale (Dangles et al., 2017).

Glaciers in the tropical Andes are sensitive indicators of the effects of current climate change in the region (Haeberli et al., 2007; Vuille et al., 2008; Haeberli et al., 2017). Strong glacier shrinking phases marked the last decades: since the 1970’s glaciers in the tropical Andes have lost 20 to 50% of their area and some have completely disappeared (Figure 5a-b) (Rabatel et al., 2012; Schauwecker et al., 2017; Vuille et al., 2018). Glacial recession is also triggering species range displacement and colonization of deglaciated areas (Morueta-Holme et al., 2015;
Moret et al., 2016), as well as ecosystem vegetation shifts (Seimon et al., 2007; 2017). While a wealth of glacier, water resource, and ecosystem related research exist in the tropical Andes, an integrated understanding of cryosphere, ecosystem and landscape changes in the region is currently missing, yet highly needed given the critical role high-Andean ecosystems play for biodiversity and ecosystem service provision.

**Figure 5.** Landscape changes in the high Andes: (a-b) Qori Kalis glacier shrink in the Quelccaya ice cap (Peru) over 30 years (Source: Thomson L., Ohio State University); (c-f) Landscape changes in the water table of Andean wetlands in Cumbres Calchaquies mountain range, NW Argentina (Source: Stephan Halloy).
2.3.2 Land use change

The low-mid elevation ranges (ca. 3000-4000 m asl) of the High Andes have been subject to a long history of human occupation (c. 12000 years; Goldberg et al., 2016) and related land use changes with major transformations after the European arrival to the Americas, leading to ecosystem degradation and loss of functionality (Podwojewski et al., 2002; Brandt & Townsend, 2006). For example, in Andean forests selective logging coupled with annual burning events (Figure 3) translate into biodiversity loss and carbon stock reduction (Fehse et al., 2002; Román-Cuesta et al., 2011). While in paramo and puna grasslands (tropical Andean grasslands, hereafter), extensive cattle grazing and associated burning events have homogenized the vegetation (reduced biodiversity) and resulted in a decrease in above-ground biomass (AGB) and below-ground biomass (BGB) stocks (Hofstede et al., 1995; Ramsay & Oxley, 1996; Keating, 2000; Patty et al., 2010; Catorci et al., 2014). Furthermore, consecutive burning and persistent grazing have been observed to result in a decrease in AGB productivity (Hofstede et al., 1995).

Human activities in tropical Andean grasslands have increased drastically over the last decades (Buytaert et al., 2006; Harden, 2006; Farley et al., 2013). In particular, páramos and puna landscapes have progressively become used more for intensive cattle grazing, forestation with exotic species, cultivation, and human habitation (Figure 6) (Young et al., 2007). There is strong scientific evidence that these activities may have a drastic impact on the ecosystem (Buytaert et al., 2006). Land use practices have a significant, adverse effect on the composition and structure of the vegetation (Hofstede, 1995a; Ramsay & Oxley, 2001), on their above-below ground biomass ratio (Hofstede et al., 1995), on the hydrological behaviour of the system - in particular water discharge and regulation capacity (Farley et al., 2005; Buytaert et al., 2007), and on the chemical/physical properties of the soils (Poulenard et al., 2001; Poulenard et al., 2004; Farley et al., 2013).

Recognition of the societal value of high Andean ecosystems and their ecosystem services have, together with the current threat they face due to ongoing land use and climate change, led to an increased global awareness of the need to restore ecosystems to secure human well-being (Chazdon et al., 2017). Our understanding of how tropical mountain ecosystems recover from land use impacts is still limited, particularly regarding their carbon stocks and uptake (productivity). Furthermore, the available studies (Hofstede, 1995b; Fehse et al., 2002; Hofstede et al., 2002;
Podwojewski et al., 2002; Farley & Kelly, 2004; Román-Cuesta et al., 2011; Farley et al., 2013) are based on a chronosequence design (synchronic approach) instead of a diachronic approach in which non-linear secondary succession dynamics can be assessed. Moreover, to the best of my knowledge, there are no published scientific studies up to date, assessing ecosystem recovering in tropical high mountain forests (>3700 m asl) and tropical mountain grasslands using a diachronic approach.

Figure 6. Land use patterns in the high tropical Andes. (a) Cattle grazing in the puna of the Central Andes of Peru; (b) Pine plantations in the highlands of Cajamarca, Perú; (c) Settlements in the páramos of Colombia; (d) Pine plantations in an upper montane forest matrix in the central Andes of Ecuador; (e) Annual crop fields in the northern Andes (Cajamarca) of Peru. Photos: E. Pinto (a), F. Cuesta (c,d), W. Buytaert (b,e).

3. Research questions

This thesis is embedded in the CONDESAN Biodiversity Program, which focuses on understanding the impacts of global environmental change stressors on ecosystems through the establishment of long-term observation networks of
the dynamics of montane forests (www.redbosques.condesan.org) and the tropical alpine ecosystems (www.redgloria.condesan.org) of the Andes. The thesis covers three major themes. The first one focuses on assessing the vulnerability of tropical mountain summits plant communities to climate change effects across the high Andes (Figure 7). The second one analyses the resilience of high Andean ecosystems to human disturbances in two locations of the Peruvian (Figure 8) and Ecuadorian Andes (Figure 9). The third one focuses on identifying priority areas for biodiversity conservation in continental Ecuador considering the threats posed by climate and land use change.

The specific questions are:

**Patterns (space)**

I. What are the patterns and processes that influence plant community composition, species abundances and species richness, and their relation with the environmental gradients that characterize high tropical alpine ecosystems? (Chapter 3)

II. What is the effect of latitudinal and elevation gradients in shaping species and community niche traits across the high tropical Andes? (Chapters 4).

**Trends (time)**

I. How do high Andean landscapes change due to glacier retreat and climate warming? (Chapter 5).

II. To what extent and at which rate do ecosystems in the high Andes recover from human disturbance in terms of their carbon storage, biomass productivity and species richness? (Chapter 6-7).

**Actions (conservation, restoration/rehabilitation)**

I. What indicators are sensitive enough to assess ecosystem recovery from human disturbances in the high tropical Andes? (Chapter 7).

II. What are the most important areas for biodiversity conservation in mainland Ecuador, considering multiple drivers of environmental change? (Chapter 8).
Figure 7. Study area and distribution of the 13 monitoring sites that include the 49 studied summits that are part of the Chapter 3, 4, and 5. Each site comprises four summits except for Sierra de la Culata (Ve) and Podocarpus (Ec), with three summits each. Photos: F. Cuesta.
Figure 8. Study site location (Chapter 6, Yanacocha Reserve): Carbon stocks data collection. Photos: E. Pinto.
Figure 9. Study site location (Chapter 7, Huancavelica): Vegetation and carbon stocks data collection. Photos: E. Pinto.
4. Thesis outline

Climate change and land use change are the primary GEC stressors of the biota and ecosystems of the high tropical Andes. I try to disentangle these by: (i) analysing the effect of climate change on well-preserved systems (i.e. high Andean summits) with no recent evidence of human impact, and (ii) assessing the resilience capacity of high Andean ecosystems to recover from the impacts of land use change related to extensive cattle grazing combined with burning and timber extraction.

The overarching focus on climate change in the high tropical Andes is explored from the perspective of understanding which environmental variables explain plant \textit{alpha} and \textit{beta} diversity patterns across the Andean chain in summit areas, free of human use. The data gathered allow identifying specific climatic variables as critical factors to assess climate change effects on the high Andean biota across the Andes. Further, the capacity of degraded high Andean ecosystems to recover from prolonged periods of agricultural uses is analysed, using carbon stocks, carbon dynamics (productivity), and plant diversity as indicators of ecosystem functionality.

This thesis consists of nine chapters covering the introduction (two chapters), the scientific content (six chapters), and a synthetic overview (one chapter). First, I set the scene for this research in the general introduction (this chapter) and a position paper, setting out the theme of Andean conservation and ecological restoration (chapter 2). I then present six research chapters (chapters 3-8) covering: (i) spatial patterns and processes (chapters 3-5), (ii) temporal trends in environmental change (chapters 6-7), and (iii) conservation actions for Ecuador’s biodiversity (chapter 8). The thesis is concluded with a general discussion and summary (chapter 9).

In the first two chapters, I focus on presenting a conceptual framework for understanding the importance and relevance of studying the effects of climate and land use change in the tropical Andes. Further, in chapter 2, I present a position paper to guide restoration actions in Andean landscapes, highlighting the relevance of establishing long-term monitoring systems together with the importance of identifying appropriate indicators to assess the impacts of restoration actions.

In chapters 3 and 4, I focus on understanding plant \textit{alpha} and \textit{beta} diversity patterns in high Andean summits areas and relate those patterns to assess plant communities’ vulnerability to climate change effects across the high Andes.
Specifically, in chapter 3, I look at patterns and processes that influence plant community composition, species abundances, and species richness in high tropical alpine ecosystems. Then, in chapter 4, I focus on species and community ecological niche trait patterns across the high Andes to assess their potential vulnerability to climate warming.

In chapter 5, I synthesize the expected and observed major changes in tropical high Andean landscapes and ecosystems due to the combined effect of climate change and glacier shrinking (chapter 5). I then assess temporal trends in ecosystem recovery after human land use ceased by analysing trends in vegetation cover, carbon stocks, carbon uptake, and species richness in two sites in the highlands of Peru and Ecuador (chapter 6 and 7).

In chapter 8, I use conservation planning analysis to define conservation priority areas in Ecuador considering multiple drivers of environmental change. Finally, in the general discussion, chapter 9, I provide answers to the main research questions by synthesizing the results of the individual research chapters and highlighting major research knowledge gaps regarding high Andean ecosystems dynamics and their links with GEC stressors.
5. References


