Global environmental changes in the high tropical Andes

Cuesta Camacho, F.X.

Publication date
2019

Document Version
Other version

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Other

Citation for published version (APA):
Cuesta Camacho, F. X. (2019). Global environmental changes in the high tropical Andes. [Thesis, fully internal, Universiteit van Amsterdam].

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Summary
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The high tropical Andes harbours vital ecosystems that sustain biodiversity, carbon storage, and environmental service provision for millions of people. They are identified as one of the most vulnerable terrestrial ecosystems to GEC, particularly to climate change and land use conversion. Despite their vulnerability and the importance of global biodiversity conservation and Andean societies, they are among the least studied ecosystems in the world. Knowledge gaps bound understanding of how high Andean ecosystems will respond to the combined effects of both climate and land use change. These knowledge gaps are primarily related to ecosystem functioning and resilience, which is related to the absence of long-term ecological data across the high tropical Andes. Additionally, conservation actions, including restoration, are restrained due to a limited comprehension of the consequences of anthropogenic activities over high Andean ecosystems; thus, particularly important is to understand the relationship between plant community composition and ecosystem productivity (i.e. the mass-ratio hypothesis, sensu Grime 1998) and the use of both ecological attributes to assess ecosystem recovery from human impacts.

In this thesis, I studied the patterns of summit plant community’s across the tropical section of the Andes. As measures of plant community patterns, I used species richness, species abundances, and plant cover. Further, I studied what environmental factors influence plant community composition, species diversity, and thermal niche traits in high tropical alpine ecosystems. Based on the thermal niche traits, I assessed the potential vulnerability of species and communities to climate warming, considering the effect of the climate variability hypothesis (Stevens, 1989) on the species niche breadths. Further, I synthesised the current state of knowledge and assessed the current and projected landscape changes in the high Andes due to the combined effect of glacier retreat and climate warming. I reviewed documented glacier changes and landscape evolution over past decades to millennia and assessed projected future glacier shrinkage until 2100 for two case studies in the Andes of Ecuador and Peru.

I also evaluated the capacity of high Andean ecosystems to recover from land use changes using the aptitude to store and take up carbon together with plant diversity. As a measure for carbon storage, I used biomass stock, i.e. above and below ground biomass per area, and as a measure for carbon uptake, I used biomass dynamics, i.e. the fluxes in biomass over time. For biodiversity, I used plant species richness, species abundances and growth-forms as an indicator of functional diversity (niche complementary theory).
Lastly, I carried out an applied research analysis aimed at informing conservation policy formulation in continental Ecuador through defining critical areas for biodiversity conservation. As surrogates of Ecuador’s biodiversity, I analysed distribution patterns of 810 conservation priority species and 89 terrestrial ecosystems together with above ground biomass spatial patterns. For pressure indicators, I modelled the likely impact of climate change, deforestation, mining and oil concessions, human population density trends and an accessibility model as a proxy of future land cover changes.

The main objectives of my thesis therefore were: (i) understand patterns and processes that influence plant community composition and species diversity in high tropical alpine ecosystems; (ii) determine alpine species and communities thermal niche traits to assess the potential impacts of global warming on the high Andean biota; (iii) assess the expected and observed changes in tropical high Andean landscapes due to the combined effect of climate change and glacier shrinking; (iv) investigate temporal trends in ecosystem recovery after land use practices stopped by analysing changes in vegetation cover, carbon stocks and uptake, and plant community diversity; and (v) to identify priority areas for biodiversity conservation in continental Ecuador, considering the short and midterm impacts of global environmental stressors.

I collaborated with research, conservation and public institutions in Ecuador, Peru, Venezuela, Argentina, Peru, Bolivia and Colombia through the GLORIA-Andes network that manages and monitors high Andean ecosystems through the establishment of permanent vegetation plots. In these locations, I collected data on plant community composition, substrate-type cover, and carbon stocks for different pools. The integration of all the collected information in a single dataset allowed me to generate different measures of biodiversity, carbon stocks, carbon dynamics, and environmental conditions across the high Andes. Further, from satellite images and IPCC climate models (CMIP5), I assessed glacier dynamics and landscape transformation through the 21st century. Priority areas in Ecuador where based on museum and herbaria datasets from the Catholic University in Quito.

Plant communities in Andean summits exhibited high community composition turnover. It is therefore essential to understand what determines the spatial variation in plant communities’ composition along the Andes. Therefore, in chapter 3, I looked at the influence of environmental gradients in plant communities’ composition and species richness. I found that the most important abiotic factors
controlling plant communities’ patterns are annual precipitation and maximum air temperatures combined with geographic isolation. Additionally, the degree of community singularity is related to the high degree of recent local speciation driven by the geographic isolation of tropical mountain summits.

Then I looked at how different climate conditions shape species and community traits along the latitudinal gradient of the tropical Andes, in order to assess the vulnerability of alpine ecosystems to climate change effects. In chapter 4, I evaluated these relationships by testing the effect of reduced seasonal temperature variation in the thermal niche traits of species and communities along the latitudinal and elevation gradients. I found that non-seasonal climate conditions on alpine summits in the equatorial tropics select for plant species with narrower thermal tolerances, compared to alpine summits exposed to increasing annual temperature seasonality at higher latitudes, which favours species with broader thermal tolerances. Further, I found that under warming scenarios, alpine species restricted to equatorial latitudes and plant communities dominated by these species are projected to undergo the strongest loss of thermal tolerance. My results confirm the Climate Variability Hypothesis for plant communities across a latitudinal gradient throughout the tropical Andes and, thus, should be considered as essential components in assessments of plant diversity vulnerability to the impacts of climate warming.

I deepened the analysis on the effect of temperature increase in the high tropical Andes. In chapter 5, I scaled from individual species to landscapes to evaluate the combined effect of climate change and glacier shrinking over ecosystems. I found that high Andean landscapes are rapidly changing with major transformations related to glacier loss. Principal landscape transformations can be grouped into: (i) formation of new lakes and drying of existing ones, (ii) alteration of hydrological dynamics in glacier-fed streams and high Andean wetlands, resulting in community composition changes, (iii) upward shifts of species and formation of new communities in deglaciated forefronts,(iv) potential loss of wetland ecosystems, and (v) eventual loss of alpine biota.

In chapters 6 and 7, I assessed the resilience capacity of high Andean ecosystems to land use impacts through analysing temporal changes in carbon storage and carbon sequestration rates. In chapter 6, I assessed the effect of natural recovery (i.e. passive restoration) on high Andean ecosystems after 23 years of cattle grazing practices ceased. I found that ecosystems were able to recover from land use impacts gradually. Higher carbon sequestration rates were correlated
with increased growth-form diversity. In chapter 7, as opposed to chapter 6, I studied the effect of assisted recovery practices on specific functional attributes of a highly degraded system. Specifically, I evaluated how effective herbivore exclusion practices after seven years of implementation, in increasing the biomass of palatable species to maintain the carrying capacity and sustain alpaca fibre production in the Peruvian highlands (Huancavelica). Overall, I found that exclusion practices are positively affecting vegetation coverage and inducing a gradual shift towards a more palatable grassland community concerning the non-excluded areas.

Nevertheless, ecosystem responses to rehabilitation practices varied and the indicators used allowed for the assessment of these variations. For example, vegetation coverage seemed to be increasing at a faster rate for the treatments that provided water, yet, a decrease in species richness accompanied this. Further, I found no significant changes in biomass accumulation among rehabilitation practices, which might be related to the fact that in semi-arid systems, carbon pool responses to exclusion practices take long to occur.

The above chapters (chapters 6 and 7) showed that carbon stocks and its variation in time (i.e. productivity), plant cover and species diversity proved to be suited for detecting Andean ecosystem responses (trends) to passive and active restoration actions within relatively short timeframes.

Lastly, in chapter 8, I implemented a conservation planning exercise aimed at identifying priority areas for biodiversity conservation in continental Ecuador, considering the threats posed by climate and land use change. I found the Ecuadorian system of protected areas has significant conservation shortfalls that require expanding their current size in 2.46 million ha in order to include critical areas in the central and southern Andes, central Amazonia, and the central and southern portions of the coastal plain. Of utmost importance is to preserve the mountain forest of the Eastern versant to enhance landscape connectivity between the Andean piedmont and the Amazonia lowlands.

The high tropical Andes constitute a critical region that harbours the richest and unique tropical alpine flora of the world. The ecosystems contained in this region provide essential local environmental services to a large population and global benefits to society such as water provision for human consumption, clean energy (hydropower generation) and climate change mitigation through carbon storage and annual sequestration. Nevertheless, the tropical Andes is included in the
top list of threatened ecoregions worldwide due to climate and land use change impacts. In this thesis, I showed and discussed that conspicuous environmental gradients over short distances largely control species distribution, community assemblages and ecosystem function. These environmental gradients are rapidly changing, such as air temperature, due to climate warming which in turn is weakening the environmental filters that control many of the ecological processes and transforming Andean landscapes at the fastest rate since the Last Glacial Maximum. Additionally, I have tested the capacity of high Andean ecosystems to recover from land use impacts which have proven to be a viable option to increase ecosystem resilience to climate change impacts, conserve biodiversity and secure resource provision for sustainable management of Andean landscapes.
Acknowledgments

E. Pinto
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Acknowledgments

This thesis is written in the first person, and the front cover of this book presents my name only. This is because according to the University of Amsterdam criteria for PhD research, no more names can be added as co-authors of the thesis. Nevertheless, dissertations are the product of a collective endeavour. My thesis committee has provided substantial support during this productive journey as well as many colleagues and friends from the GLORIA-Andes network and CONDESAN who are the intellectual co-authors of many of the chapters of this dissertation.

Throughout these years, the practicality of William D. Gosling’s research helped me structure my own research into a coherent dissertation that can meet the rigorous standards of the University of Amsterdam. William provided encouragement for all my academic endeavours and was patient with my demanding work duties. I owe William his confidence in my research capabilities and he provided me with the perfect balance as a promoter by allowing me significant freedoms as long as I delivered high-quality research. William read numerous drafts of each chapter, provided critical comments and improved the quality of the manuscripts.

Jan Sevink is responsible for my decision of embarking on a PhD program at the age of forty, with a full-time job and three children. I have reached this far because of his constant support. Jan, I’ll be always grateful for your conviction in my research capacities and for your patience with my rough English. Your comments and editions certainly improved the quality of my writing and made me realize the importance of being precise in my concepts and definitions.

Luis Daniel LLambí has become one of my closest colleagues and friends. I owe him the continued support and help to produce the first peer-reviewed article of the GLORIA-Andes network that constitutes the third chapter of this thesis. Luis Daniel helped me understand academic legacies and the importance of theoretical continuities. I owe you the references of J. Grime’s work on the mass-ratio hypothesis and C. Lortie’s on plant community theory.

Harald Pauli, as scientific coordinator of the GLORIA network you have supported the development of the South American node and within this framework you have made substantial contributions to two chapters of this thesis. Your knowledge of alpine systems has been paramount to improve the scope of the manuscripts and to link my research with the international research agenda on the ecology of alpine systems.
Acknowledgments

Carolina Tovar, Marco Calderón, Esteban Pinto, Sisimac Duchicela, Priscilla Muriel, and Gabriela Maldonado. You have been extraordinary work colleagues and unconditional friends. Thanks for all your help during fieldwork, data processing, analyses and continues support during the writing of several of the chapters of this dissertation.

My family has been a cable to earth and a constant reminder of what really matters in life. I am grateful for your unconditional love, support, care and generosity. Julia, María Paz, Sebastián and Carolina, thanks for your understanding of the many weekends in which I had to work instead of play and enjoy life with all of you.

The funding for this thesis came from the EcoAndes Project conducted by CONDESAN and funded by the Global Environment Facility (GEF) through the United Nations Environment Program and from the Andean Forest Program conducted by CONDESAN and Helvetas Swiss Intercooperation, and funded by the Swiss Agency for Development and Cooperation (SDC).
Co-authorship statement
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Co-authorship statement

Chapter 3 Latitudinal and altitudinal patterns of plant community diversity on mountain summits across the tropical Andes


Ecography (2017) 40, 1381-1394

DOI: 0.1111/ecog.02567

FC conceived the idea. FC and MTB wrote the project and obtained the funding to install more than half of the monitoring sites of the GLORIA-Andes Network. FC, PM, LDLL, SH, NA, SB, JC, RIM, SC, AG, LEG, JI, JJ, RJ, LR, NS, DS-D, NT, AT, PV, KY performed fieldwork an collected the baseline information. FC and PM assembled the database. FC and LDLL performed the analysis. FC, LDLL and PM wrote the manuscript. HP and WDG contributed critically to the drafts. FC submitted the manuscript.

Chapter 4 Thermal niche traits of tropical high-elevation plant species and communities and their vulnerability to global warming along a 4000 km latitudinal gradient in the Andes.


In revision, Journal of Biogeography

FC conceived the idea, wrote the project and obtained the funding to install and establish the baseline information of more than half of the monitoring sites of the GLORIA-Andes Network. FC, LDLL, SH, JC, PM, RIM, SB, KY, NA, PV, JJ, DS-D performed the fieldwork an collected the plant community dataset. FC, CT and CUU, collected all museum records, and assembled the species database. FC, CT and LDLL performed the analysis. FC and CT wrote the manuscript. LDLL, HP and WDG contributed critically to the drafts. FC submitted the manuscript.
**Chapter 5** New land in the Neotropics: a review of biotic community, ecosystem, and landscape transformations in the face of climate and glacier change

*Cuesta, F.*, Llambi, L.D., Huggel, C., Drenkhan, F., Gosling, W.D., Muriel, P., Jaramillo, R. & Tovar, C.

*Regional Environmental change* (2019)

DOI: 10.1007/s10113-019-01499-3

FC and CH conceived the idea, and obtained the funding. FC, FD, PM, RJ performed the analysis. FC, LDDL, CH, FD, PM, WDG wrote the paper. RJ and CT contributed critically to the drafts. FC submitted the manuscript.

**Chapter 6** Carbon sequestration rates indicate ecosystem recovery following human disturbance in the tropical Andes

Calderon, M., *Cuesta F.*, Pinto, E., & Gosling W.D.

*In revision, PlosOne*

FC conceived the idea, wrote the project and obtained the funding. FC designed the experimental layout of the plots. MC and EP led the field data collection. EP and FC consolidated the database. MC and FC performed the analysis. FC and MC wrote the manuscript. WDG and EP contributed critically to the drafts. MC submitted the manuscript. MC and FC are both corresponding authors.

**Chapter 7** Indicators for assessing tropical alpine rehabilitation practices.


*Ecosphere* (2019) 10, e02595

DOI: 10.1002/ecs2.2595

FC conceived the idea, wrote the project and obtained the funding. EP and SD led the field data collection. SD and FC performed the analysis and wrote the manuscript. WDG, EP and KY contributed critically to the drafts. SD submitted the article.
**Chapter 8** Priority areas for biodiversity conservation in mainland Ecuador

**Cuesta, F., Peralvo, M., Merino-Viteri, A., Bustamante, M., Baquero, F., Freile, J.F., Muriel, P. & Torres-Carvajal, O.**

*Neotropical Biodiversity (2017) 3, 93-106*

*DOI: 10.1080/23766808.2017.1295705*

FC conceived the idea, wrote the project and obtained the funding. FC, JF, AM-V, PM, OT-C assembled the species distribution records. FC, FB, MB and MP ensembled the geodatabase. FC, MP, MB and AM-V performed the analysis. FC and MP wrote the manuscript. MB, JF, AM-V, PM, and OT-C contributed critically to the drafts. FC submitted the manuscript.
Biographic sketch
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Biographic sketch

Francisco Xavier Cuesta Camacho was born on the 24th of January 1974 in Quito, Ecuador. In 1998 he finished cum laude his Bachelor’s studies in Natural Resource Management at San Francisco University. In 2003, Francisco moved to Amsterdam to start a MSc in Tropical Ecology at University of Amsterdam, which he finished cum laude in 2005. During 11 years Francisco worked in an international NGO as head of the Biodiversity Department where he led the formulation and implementation of applied research and cooperation programs (e.g. GEF, Swiss Cooperation, USAID) focus on tropical biodiversity, conservation, landscape restoration and long-term monitoring of ecosystem dynamics, with special emphasis on carbon dynamics and functional traits. As part of his ongoing research program, Francisco acts as the scientific coordinator of the GLORIA-Andes Network (www.condesan.org/gloria) and the Andean forest plot network (www.condesan.org/redbosques) aimed at studying the function of tropical mountain ecosystems under environmental change scenarios. As part of his professional experience he has published numerous peer-reviewed articles and books on these topics. His areas of interest are focused on: (1) Diversity and biogeographic patterns in tropical mountain ecosystems, (2) Ecology of Andean tropical plant communities, and (3) Dynamics of Andean ecosystems. In 2015 he started a PhD at University of Amsterdam. During his PhD he remained working as an associate researcher of the Universidad Andina Simón Bolívar University and senior scientist of the Biodiversity Department of CONDESAN. Recently he has been appointed as senior researcher at Universidad de Las Américas in Quito.

Publications

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2018


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**2016**


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