Revisiting the science and practice of ecosystem restoration in tropical mountains



A thesis presented for the degree of Doctor of Philosophy

School of Geography and the Environment

Tina Christmann

Supervisors: Dr Imma Oliveras and Prof Yadvinder Malhi

Disturbance Ecology Lab & Ecosystems Lab

Worcester College

RHODES TRUST

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"We have all realized that what gives life to humanity is the tree."
– High Andean farmer

"All the resources, the climate schemes, and the payment for ecosystem service schemes, focus on the Amazon. And no one is looking at the Andes. This must be the role of academia and of the researchers – like you."
-Government conservation official



Thesis summary

With an acceleration of restoration initiatives in this UN Decade on Ecosystem Restoration, it is paramount to conduct restoration science and practice in a scalable, long-term and equitable manner and to expand restoration efforts to ecosystems which have so far received less attention.

Tropical mountain ecosystems (TME) such as montane forests and grasslands have been critically destroyed or degraded by human activities. This compromises their habitat functions for threatened biodiversity, their carbon storage and the provision of ecosystem services for human livelihoods in the uplands and lowlands.

Restoration of TME – whether active, passive or mixed interventions – has emerged as an approach to re-create thriving ecosystems. But compared to lowland ecosystems restoration in tropical mountains, particularly in the Andes, remains understudied. My DPhil research looks at how to best inform and implement restoration of mountain ecosystems at three different scales and through three different methodologies. My thesis is framed by the agenda 'Research Priorities for the Conservation and Sustainable Governance of Andean Forest Landscapes' by Mathez-Stiefel et al (2017) which serves as a theoretical structure throughout the thesis.

First, I use a systematic review at the pantropical scale to synthesize research on the state of TME restoration science. Second, I use remote sensing analysis at the continental Andean scale to track forest recovery over 15 years and detect restoration priority areas. Last, I interview restoration stakeholder at a local project scale in Peru to understand motivations, preferences and success factors for Andean Forest restoration.

My **Chapter 2 (Paper I)** is titled *'A synthesis and future research directions for tropical mountain ecosystem restoration' (published in Scientific Reports)*. I review 176 scientific studies focused on ecosystem restoration in mountainous locations across the tropics to identify geographical and thematic research gaps, compare restoration interventions, and consolidate enabling factors and barriers of restoration success. I find that restoration research outside Latin-America, in non-

forested ecosystems, and on socio-ecological questions is scarce. For most restoration interventions success is mixed and generally limited by biophysical factors such as dispersal and microhabitat conditions. I propose five directions for future research on tropical mountain restoration in the UN decade of restoration, ranging from scaling up restoration across mountain ranges, investigating restoration in mountain grasslands, to incorporating socio- economic and technological dimensions.

My **Chapter 3 (Paper II)** is titled '*Disrupted Forest recovery hinders biodiversity conservation across the Tropical Andes' (published in Global Ecology & Biogeography)*. It builds on the knowledge gaps and research priorities identified in the first paper, namely a lack of large spatio-temporal studies using satellite technologies to monitor and inform restoration of mountain ecosystems across the Andes. In this paper, I map forest recovery of Andean tropical montane forests across the continent over a 15-year period using 30m resolution Landsat data. I identify potential recovery sites using tree cover change analysis and develop a method to classify restoration trajectories over a 15-year time frame on a pixel-by-pixel basis using sequences of multi-temporal Normalized-Difference Vegetation Index (NDWI) images. Further, I test the method on well-studied forest restoration landscapes in Peru, Ecuador, and Colombia. I find that the method captures landscape scale dynamics well. However, forest recovery across the Andes is mostly disrupted, arrested or unsuccessful with consequences for biodiversity conservation and provision of ecosystem services. Areas of low recovery identified in this study may be good candidates for active restoration interventions in this UN Decade on Restoration, however, their restoration potential must be determined at a local scale together with mountain communities.

My **Chapter 4 (Paper III)** is titled *'Sowing and harvesting water' – a socio-ecological analysis of forest restoration projects in the Peruvian Andes' (in review at People & Nature)*. Andean Forest restoration is a recent endeavour in the megadiverse country of Peru but knowledge about the motivations and socio-economic and governance conditions that determine restoration success is scarce. Through 75 semi-structured interviews with communities, NGOs and government actors in 11 restoration sites this paper synthesizes motivations, enabling and limiting factors, impacts, and

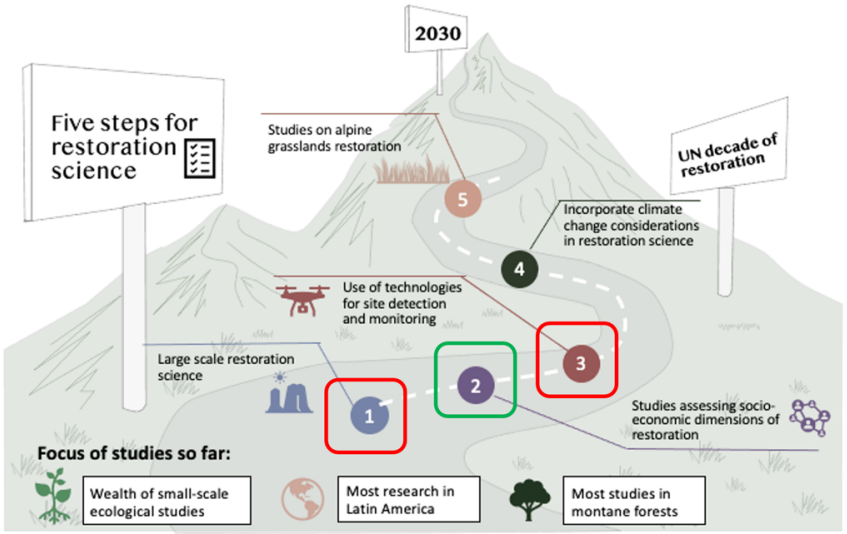
local preferences to inform successful future Andean Forest restoration. I find that communities are motivated by an instrumental desire to restore and improve water resources. Enabling factors for restoration success are mostly social and institutional ranging from high communal resource dependence to support from NGOs to creation of communal conservation agreements. All stakeholder groups favour active Andean Forest restoration and highlight a host of desired useful plant species and restoration priorities. While all projects have opportunity costs for farming, there are various models for community involvement and compensation. I identify a 'payment model' and a 'capacity model' which differ in their project sustainability, social and economic benefits provided and how they create capacity. I conclude by presenting a scaled-up 'Mountain Landscape Restoration Approach' suggesting various restoration interventions in line with the social, ecological, and economic priorities identified by the stakeholders.

I conclude the thesis with a synthesis in Chapter 5 which is structured along a 10-point agenda for the science and practice of Andean Forest restoration. Within these agenda points I discuss some of the overarching challenges and solutions to restoration identified across my research and highlight major gaps and recommendations for the science and practice of Andean Forest restoration and for tropical mountain ecosystems more broadly.

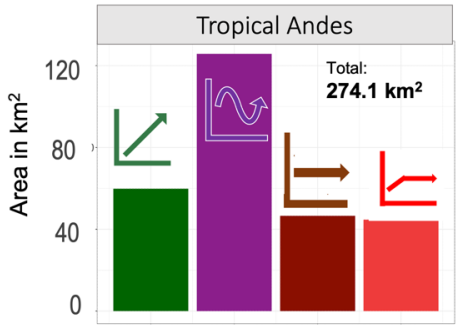
Graphical abstract

Highlights

Paper I
Key knowledge gaps for the restoration of tropical mountain ecosystems include lack of socio-economic research, large spatio-temporal studies and use of remote sensing technologies



Paper II
Most potential forest recovery areas do not recover successfully. Instead, many areas show disrupted, arrested or no recovery. These areas could be targeted for restoration interventions.



Paper III
Andean forest restoration is motivated by water provision and direct benefits. Restoration success is strongly determined by social, institutional and technical factors which vary between stakeholders.

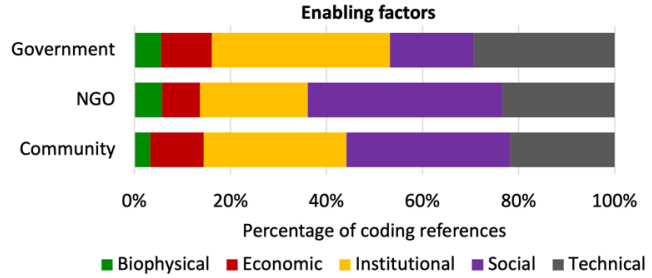


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Outputs of doctorate

My first paper has been published in *Nature Scientific Reports* and I have presented its findings at the Association for Tropical Biology and Conservation (ATBC) conference 2021 in a symposium on 'Young voices for tropical restoration'.

1. ***Christmann, T*** *& Oliveras, I (2021). 'A synthesis and future research directions for tropical mountain ecosystem restoration'. Nature Scientific Reports. Doi: 10.1038/s41598-021-03205-y*

My second paper is published in *Global Ecology & Biogeography*. I presented my second paper at the European Conference of Tropical Ecology in Montpellier through a poster presentation and a lightning talk.

2. ***Christmann, T.,*** *Wilson, S., Armenteras, D., Palomeque, X., Malhi, Y., Oliveras, I (2023). Disrupted Montane Forest Recovery Hinders Biodiversity Conservation in The Tropical Andes. Global Ecology and Biogeography. Doi: 10.1111/geb.13666*

My third paper has recently been submitted to *People & Nature*:

Christmann, T., *Cjuno-Turpo, I., López-Aranda, M., Rondan, V., Ramirez, A., Arenas, M., Mamani, M, Aucca Chutas, C, Recharte, J, Malhi, Y. Cuni-Sanchez, A, Wilson, S.J, Oliveras-Menor, I. (submitted 11th of March 2023). 'Sowing and harvesting water' – revisiting restoration of Andean Forests through a multi-stakeholder analysis. Submitted to People & Nature*

I have written a case study report on my findings together with Instituto de Montana summarizing findings of our interviews for their focus restoration site in Aquia. I am currently writing a policy brief together with local collaborators from NGO, governments, and field assistants to promote a 10-point Andean Forest Restoration agenda.

Additional outputs not presented in this thesis but linked to the doctoral experience include the publication of my MPhil paper in *Ecology & Evolution* and of a review in the *Elsevier Biome Encyclopaedia*. These papers planted the seed for my interest in mountain restoration and the decision to focus my DPhil thesis on remote sensing & restoration in the Andes:

3. ***Christmann****, T. & Oliveras, I. (2021). Nature of Alpine Ecosystems in Tropical Mountains of South America. in Encyclopaedia of the World's Biomes 1–10 (Elsevier Inc., 2020). Doi:10.1016/B978-0-12-409548-9.12481-9.*
4. ***Christmann****, T., Rosado, B.H.P, Delhaye, G., Matos, I.S., Drummond, J.S., Roland, H., Moraes, Y.C., Oliveras Menor, I. (2021). Functional assembly of tropical montane tree*

islands in the Atlantic Forest is shaped by stress tolerance, bamboo presence, and facilitation. Ecology & Evolution. 1–14 Doi:10.1002/ece3.7824.

Together with fellow early career restoration scientists we published a commentary paper in *Biotropica*, following leading a symposium session at the ATBC 2021 meeting:

5. *Gopalakrishna, T., **Christmann**, T., Pashkevich, M., Puttick, R. (2022). Young voices in and visions for tropical restoration science in the UN Decade of Restoration. Biotropica. Doi: 10.1111/btp.13085*

As part of the 'Young voices in restoration' initiative I guest edited a special feature in the journal *Restoration Ecology*. During the 18 months as guest editor, I have edited over 30 papers and written an editorial:

6. ***Christmann**, T., Gopalakrishna, T., Stuart, C. & Amaral V. (2023). Young voices and visions for the UN Decade on Ecosystem Restoration. Restoration Ecology. Doi: 10.1111/rec.13871*

I also published my bachelor thesis paper which gave me valuable statistical and writing skills:

7. ***Christmann**, T., Kowarik, I., Bernard-Verdier, M. et al. (2022). Phenology of grassland plants responds to urbanization. Urban Ecosystems. Doi: 10.1007/s11252-022-01302-y*

During my DPhil I have peer reviewed 4 papers for *Restoration Ecology, Philosophical Transactions* and *Botanical Science*. I was teaching assistant on the master's degree Biodiversity, Conservation & Management, where I gave lectures on remote sensing, GIS, methods training and facilitated various conferences, field visits and workshops. I also conducted a year of fieldwork in Wytham Woods, Oxford, as a fieldwork assistant on ash dieback, measuring forest carbon dynamics.

COVID statement

While the Corona pandemic now creeps into more remote parts of our memory, it has very much shaped my DPhil from start to finish, in both bad and good ways. Back in 2019 I wrote my DPhil proposal as a continuation of my 2+2 DPhil – a 2-year Master which is followed by 2year DPhil. In this model the Master thesis is then used as the first DPhil paper. My Master thesis used functional ecology in a very understudied mountain ecosystem – the mountain forests and alpine grasslands of the Brazilian Atlantic Forest – to make predictions about the fate of this ecosystem under global change. Realizing in the field how severe degradation and deforestation was and is in the Atlantic Forest (my field site even burnt down because of a wildfire…), I decided to do my DPhil looking at the solutions to this crisis. I wanted to study forest restoration, and learn all about it, from the technological side to the ecological implementation of restoration, to the socio-economic conditions for success. I was planning to do two 6-month field seasons in Brazil to familiarize myself with the wider restoration context, to collect validation data for a range of remote sensing monitoring approaches and to use social science methods to model forest restoration opportunities and potential in this highly degraded ecoregion.

Then the pandemic came, and I was faced with the undeniable fact that fieldwork would not be possible, and I didn't know when or if it would ever be possible again. I realized that I couldn't usefully contribute to the science of restoration of the mountain ecosystems in the Atlantic Forest, and that with the Atlantic Forest Restoration Pact under way, things in Brazil were moving fast. That's when I had a rethink about my thesis with my supervisor Imma. I wanted to study tropical mountain ecosystems, because they fascinated me and because the science was still scarce. And with travel restrictions at the peak in 2019/2022 it was clear I wouldn't be able to visit any of these ecosystems.

Together with Imma I decided to start pantropical and conduct a comprehensive and exhaustive desk-based literature review of ecosystem restoration in tropical mountain systems across the world which would then shape the future direction of my thesis. This review opened new opportunities and steered my attention towards the Andes and large scale, long-term approaches of ecosystem monitoring. Again, we used desk-based methods to investigate forest restoration across the mountain range. We developed a new method based on satellite data to track forest recovery and suggest restoration priority areas. I would have loved to collect validation data myself in the field, but in 2021 this was not possible. We reached out to various research institutions, governments, and NGOs to find out whether we could use any of their restoration sites or secondary forest locations for validation, but to no avail. Long-term monitoring of forest restoration initiatives at a

scale large enough to be matched with satellite data did not exist. So, we developed alternative methods, again desk-based but that was the best we could do.

In my last DPhil year (2022) opportunities for international travel finally opened last minute. I decided to use this last chance – the dry season of 2022 – to travel to the Peruvian Andes, to visit forest restoration sites, talk to practitioners and communities and learn from the existing restoration experiences. This was clearly a high-risk approach and last minute as I did not know whether my data collection would work and because it gave me little time afterwards to analyse, write and publish. But I was itching to travel and visit the mountain forests and to get those last puzzle pieces together. The previous years of desk-based research had set me up well: (i) I had the biophysical and continental-scale knowledge of forest recovery and restoration, (ii) I had built a large network of researchers and practitioners across the Andes who advised, facilitated, and helped me before and during fieldwork, and who opened my eyes to both the beauty of the Andes, but also the challenges. So many questions had amassed in my head in the previous three years that the 'short' two months of fieldwork that I spent in Peru ended up being the most valuable and formative period of my academic journey. We worked day and night, conducting 75 interviews in less than 8 weeks, visiting 10 restoration sites and transcribing all our interviews in the field. Luckily, it all worked out and it gave me the on-the-ground understanding of forest restoration in the challenging mountain terrain of a developing country. It connected all the dots for my thesis which has evolved into a multi-scale and multi-method study of tropical mountain ecosystem restoration.

All in all, COVID meant I had to change topic and could not do the classis 2+2 route doctorate, instead I did a DPhil with 3 papers in 2 ½ years. It meant I had to change methods and plans every half a year, but it also directed me towards the Andes which I have fallen in love with. Many times, things were more difficult than they would have been in a non-COVID world, but on the other hand this opened new opportunities and research paths for me. I am glad I didn't lose faith in my ability to adapt and that my long-acquired elite-athlete attitude helped me to keep things moving forward and not lose focus at the fast pace my DPhil had to be done. I am proud with the outcome of the thesis, and I have properly come to grips, with the science, technology, and practice of tropical mountain ecosystem restoration.

Acknowledgements

This thesis and the academic journey I have been through would not have been possible without the ongoing support I received from my supervisors, friends, family, and the fabulous restoration folks across the world. This thesis is for them. It's for the young restoration scientists who have a deep belief and drive to restore and conserve our world's understudied ecosystems, it is for all the kind and inspiring people in academia who make a DPhil enjoyable, it's for the student-athletes who live a not-so-secret double life, and it is for the people that live in and off our world's tropical mountain ecosystems.

To the people who advised, mentored, and guided.

First and foremost, I thank **Imma** for not only being an outstanding supervisor but being a mentor and an academic inspiration. Imma, you taught me that academia does not need to be the soul crushing doom & gloom is often portrayed as. Instead, through your actions and your Disturbance Ecology Lab you exemplified how academia can be an opportunity to grow at one's one pace, to explore an intriguing area of research, to create a collaboration network around the world. And at the same time, you showed me that being human is okay, I've shed tears in front of you and you always knew what to say and how to get me back on track. Imma, you have enthused me to do a DPhil on tropical mountains, nurtured my desire to try a variety of methods in my research, and till the very last moment of this DPhil you have been here for me. But one of the things I have appreciated the most is that you have supported me as a student-athlete, always helping me to find a way to combine academia with elite sport even against the odds and in difficult times. You found an excellent balance of knowing when to give me a nudge and when to step back and you have been a mentor and an incredibly kind and generous academic role-model. Our journey of working together does not end here. After all there are many more mountains to be climbed together out there (academically and literally).

I thank my second supervisor **Yadvinder** for being a very welcoming and open-minded lab leader and for fully embracing my move towards restoration science. Yadvinder, I thank you for giving me directions, for opening your truly global research network to me, for connecting me with people around the world and for your Ecosystems Lab to be a thrilling research group to be part of. Many of the events you organized as part of the OCTF and Biodiversity series provided inspiration, theory, and variety throughout my DPhil. I thank you for always fitting me into your crazy busy schedule, and for reading my drafts on your train journeys and flights to conferences (and for never getting tired of me chasing you for it).

I thank my external advisor **Dr Sarah Wilson** for being an outstanding advisor on all aspects of restoration. Sarah, through your DPhil research entitled 'Replanting a future' focused on community forest restoration in the Ecuadorian Andes you inspired me to look at the social aspects of restoration and you have always helped me give my research both a broad visions and a practitioner-perspective. Your dedication to helping a geeky restoration-DPhil student you've never met in person is greatly appreciated.

I thank **Prof Bruno Rosado** for introducing me to the beauty of montane ecosystems in South America during my masters and for teaching me valuable fieldwork skills and Forró. I thank **Dr Aida Cuni Sanchez** for helping me get my head around how to interviews with communities and how to interpret socio-ecological data. I thank **Prof Ximena Palomeque** for introducing me to forest restoration in Ecuador, and **Prof Dolors Armenteras** and for discussions on restoration in Colombia. I also thank my Confirmation of status assessor **Dr Marc Macias-Fauria** for great feedback on streamlining and improving my Paper II and III. I also thank Dr **Marc Hirons** for giving me advice on fieldwork and data analysis. I thank **Prof Lisa Wedding** for being an exceptionally kind and generous college advisor.

I was fortunate to have the chance to edit a special feature in the journal Restoration Ecology and as such was mentored by **Dr Stephen Murphy** and **Valter Amaral** during the whole process. Valter and Stephen, you motivated us to run and edit a special feature for young restoration scientists and taught us about the perks of editing & reviewing. I also got the chance to teach on the MSc Biodiversity, Conservation and Management and thanks **Dr Chloë Strevens** for this opportunity and the many letters of reference she wrote for me.

To the institutions who funded and enabled

I thank the **Rhodes Trust** for funding my MPhil and DPhil and providing a family and a huge amount of immaterial support to me in all phases of the DPhil. I owe this scholarship a lot – it enabled me to study with the top people in tropical ecology, to discover my passion for restoration science and to have a truly wonderful student-experience in the last few years. The Rhodes Trust helped me with a COVID-extension grant and with fieldwork support through a **Sir Peter Elworthy Grant**, and with that allowed me to finally go and spend some last-minute time in the Andes. Without these grants enabling me fieldwork my DPhil would have lacked richness, depth, and perspective. For problems big and small there was a solution, whether it was financial support with physiotherapy or a laptop loan when my MacBook died after fieldwork.

I thank **Worcester college** for having me as one of their students and for the privilege to enjoy the arguably most biodiverse Oxford gardens and the most delicious veggie food, but also for funding

my fieldwork and providing great academic support. I thank the **School of Geography and the Environment** for helping with research grants and conference funding and for ECI-coffee mornings, a vibrant social scene, and inspiring talks.

To the fieldwork heroes

My fieldwork trip to Peru was a truly multi-personal endeavour and the CRediT statement really doesn't do everyone's contributions justice. Most of all, I thank my two extraordinary research assistants **Isaias Cjuno Turpo** and **Mayte López Aranda**. Isaias, working with you was a delight. Your patience, scrutiny, dedication to the Andean Ecosystems and the way you've helped me navigate logistics and interviews were immensely helpful. I am excited to keep working together and to come visit your newly founded vegetarian restaurant! Mayte, travelling to Ancash with you was great fun and you helped me totally exceed my interview targets. Sometimes we experienced times of illness and homesickness, but together we always made it enjoyable and a laugh – whether it was birthday hikes, falling off horses or surfing in Lima.

I also thank many of our wonderful collaborators in the NGOs who have hosted us and helped facilitate planning, logistics and interviews, namely **Florencia Zapata, Vidal Rondán** and **Mirella Gallardo** from the Instituto de Montaña, **Augusto Ramirez** from CEDES, **Francisco Medina** from Programa Bosques Andinos, **Marlene Mamani** from ACCA, **Florent Kaiser** from Acción Andina & **Constantino Aucca Chutas** from ECOAN. I thank the restoration team from **SERFOR** for introducing us to many restoration contacts across Peru, and the team from **SERNANP** for welcoming us. I thank **Walter** for helping me with logistics and organization in Peru and offering me his room. I also thank lots of fabulous people who facilitated in the field, helping us out with mobility, visits of restoration sites and greenhouses: These people include **Abrahan Córdoba, Jorge Ramos, Jorge Luiz, Elias Damián**, **Adan Damián, Hernán Ibarra, Luiz Zavalla**. I thank the communities of **Kiuñalla, Challabamba, Vilcanota, Cuenca del Mariño, Huaraz** and **Aquia** for allowing us to conduct interviews and for sharing valuable insights and perspectives (and sometimes a dance and a chicha).

To the people who provide friendship, inspiration, joy and relentless support

I had the pleasure to share my DPhil with a wonderful group of friends. During lockdown what really kept me going was my bond with my 'DPhil Ladies' **Olivia, Sarah, Ana, Maryam, and Sophie** – a group of inspiring geographers, who shine with their supporting, humanness, and wonderful attitude. Thanks, **Jasper,** for always being a sounding board for ideas and tirelessly

reading my drafts and opting into my silly morning run offers. Thanks to **Anna** – for being my cycling and department partner in crime – and many coffee chats which took us out of our DPhil bubble and into our beloved sporting world. Thanks to **Eleanor** and **Marcus** for great discussions on satellite data, fieldwork and many cake'o'clocks during our lockdown co-working hours. The DPhil gang from the Ecosystems Lab and Disturbance Ecology Lab really made the last three years a very nice ride. Thanks, **Carlota** for helping me through some stressful phases of the DPhil and for sharing our first big conference experience together, thank Ty for many great chats on how to do interviews and how to deal with the mess of qualitative data. Thanks **Jed** and **Trisha** for being the other crazy restoration guys in the Lab, thanks **Paco** for lots of translation help. Thanks to **Huanyuan** for lots of tech help and to **Laura** for all her wise words on socio-ecological fieldwork. Thanks to all the Postdocs in the Lab, **Erika, Manu, Nikki, Guillaume, Jesus** and **Cecilia** for many informal advice and chats.

I am incredibly grateful to have met my dear friend **Robyn** in the pool and that we decided 'just like that' to be friends. Robyn, together we have conquered the outdoors, baked, and cooked our way through the lockdowns, and you have since been a rock for me. I also owe a lot to **Philip** – who shared the entire Oxford journey with all the ups and downs with me, from leaving in a minibus in Germany to submitting our DPhils. Thanks to my MPhil friends **Charlie** and **Silvia** for inspiring me to give socio-ecological methods a go. Thanks to **Josie** for hyping me up on forward-looking topics such as restoration and rewilding. Thanks, **Max**, for being my sporting buddy and sharing your 'no worries, mate – it will all work out' attitude with me. Thanks to **Lena, Jannik** and **Volker** in Germany, three friends I can always count on. Thanks to **Simon** and **Annie**, for welcoming me to the Arscott family and for being a sounding board for crazy ideas big and small and for shaping my last year of my DPhil. Thanks to **Ioan** for welcoming me at his house and allowing me to spend my lockdown not on a narrowboat but in a gorgeous place on the hills.

I was not one of these people for whom the DPhil was the centre of their universe. I am lucky to have found my communities outside academia and in the sporting community. The **Oxford University Triathlon Club** for providing a fun and friendly escape and balance to academic life. Thanks to **Emilia** for letting me crash at your house lots of times and for creating a long-lasting bond. Thanks to **Justin** for all those S&C and crazy hard track sessions. Thanks to **Flo** for epic midday run-sessions, mad cycle races, Quinoa feasts and nerdy chats about plant science. Thanks to **Christine** for all our chats on our sporting goals and academic projects. Thanks to our club coach George for mentoring me in being a student-athlete and in getting my training on point. Thanks to **Molly** for lots of heart-warming chats during physio treatments. And a big shout out to all the other OUTriC peeps out there, **Emma, Harri, Carys, Kieran, Ellie, Alice, Tom, Mat, Arundathi** and

many others for fun training sessions, social events, and a wonderful triathlon family. A deep thank you extends also to my coach **Jon Cowell** (a DPhil student himself!) for taking me on as a 'sponsored athlete' and his enduring support and wisdom in structuring high level training around a DPhil.

Mum & dad thanks for being always there for me, for always listening to my worries, my mad plans and being patient, supporting & ever loving. And most importantly, thanks to **Oli** for getting me through this and making me come home with a smile every day. Even when things don't go as planned, I can still come home after a long day of DPhil work and training knowing that I am surrounded by the most loving, kind, and exciting human being.

List of abbreviations

ATMF – Andean Tropical Montane Forest

BACI - Before-after-control-impact

C - Carbon

m asl – meter above sea level

LIDAR – Laser imaging detection and ranging

RADAR – Radio detection and ranging

MERESEH – *Mecanismo de retribución servicios ecológicos y hydrológicos* [Mechanism for payment of ecological and hydrological services]

NDVI – Normalized Difference Vegetation Index

NDWI – Normalized Difference Water Index

NGO – Nongovernmental organization

NIR – Near Infrared

PICO - Patient or problem. Intervention or exposure. Comparison or control

PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-Analyses

SDGs – Sustainable Development Goals

SWIR – Short-wave infrared

TME – Tropical montane ecosystems

TMF – Tropical montane forest

Abbreviations of organizations

ACCA – *Asociación conservación de la Cuenca Amazónica* [Association for the Conservation of the Amazon Basin]

CEDES – *Centro de Estudio y Desarollo Social* [Centre for Social Development and Studies]

CIMA - *Centro de Conservación, Investigación y Manejo de Areas Naturales* [Centre for Conservation, Research and Management of Natural Areas]

ECOAN – *Asociación Ecosistómas Andinos* [Association for Andean Ecosystems]

GIZ – *Gesellschaft für Internationale Zusammenarbeit* [German Agency for International Cooperation]

IdM - *Instituto de Montaña* [The Mountain Institute]

MINAGRI – *Ministerio de Agricultura y Riego* [Ministry for Agriculture and Irrigation]

MINAM – *Ministerio del Ambiente* [Ministry for the Environment]

PBA – *Programa Bosques Andinos* [Andean Forest Program]

SERFOR – *Servicio Nacional Forestal y de Fauna Silvestre* [National Forest and Wildlife Service]

SERNANP – *Servicio Nacional Areas Protegídas por el Estado* [National Service of Natural Areas Protected by the State]

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Chapter 1

Introduction and literature review

A global momentum for ecosystem restoration

Many of the world's tropical ecosystems have been destroyed, deforested, or degraded and simply protecting what is left is no longer sufficient (Stanturf, 2020). We must now restore our tropical ecosystems to: (i) mitigate climate change and biodiversity loss, (ii) reduce negative consequences for the people who depend on these ecosystems, and (iii) reach many of the sustainable development goals including reducing poverty and hunger, tackling inequalities, improving life on land and providing clean water (United Nations, 2020).

Ecological restoration has gained substantial momentum in the last decades and is defined as the process of *"the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed"* (SER, 2004). Especially Forest Landscape Restoration (FLR), an approach *"that aims to regain ecological functionality and enhance human wellbeing in deforested or degraded landscapes"* (Besseau et al, 2018) has recently gained traction. FLR is an intentional and multidimensional strategy of restoring the ecological integrity of forested landscapes (Mansourian et al., 2017). In the Bonn Challenge for instance countries worldwide pledged to restore 350 million ha by 2030 of degraded land by using an integrated landscape approach such as FLR (IUCN, 2011). Recently, the proclamation of the UN Decade of Ecosystem Restoration (hereafter UN Decade), which *'aims to prevent, halt and reverse the degradation of ecosystems on every continent and in every ocean'* has added additional impetus to the task of making restoration happen in all kinds of ecosystems around the world, using a suite of different restoration approaches (United Nations, 2020). The UN Decade is a multi-actor partnership including the UN environment program, the Food and Agriculture Organization, and several governmental, private and NGO partners. The vision of the UN Decade is to create *'a world where - for the health and well-being of all life on*

Earth and that of future generations – the relationship between humans and nature has been restored, where the area of healthy ecosystems is increasing and where ecosystem'. As such, the UN Decade links with various global policies, such as the SDGs and the Kunming-Montreal Global Biodiversity Framework. To achieve this ambitious vision of catalysing restoration action, an Action Plan has been set out which outlines pathways, challenges, stakeholders and principles (UN Environment Programme, 2023). Three main pathways are being taken: 1) A global movement pathway to catalyse political will, new initiatives, knowledge exchange and collaboration, 2) A political will pathway to create capabilities for policy reform through incentives and investments. and 3) A technical capacity pathway to strengthen capacities to plan, implement and monitor restoration.

The monumental task of restoring the world's degraded ecosystems, comes with a host of technical, social, economic and ecological challenges - such as planning of the right restoration interventions in the right places, tailoring restoration efforts to be sustainable and successful in the long-term, designing restoration approaches that better involve local communities, as well as better standardized planning and monitoring of restoration through technologies and protocols (Monitoring Task Force, 2020). Against the backdrop of ambitious global commitments, scholars have highlighted the utmost importance of making the UN Decade a Social-Ecological Endeavour (Fischer et al., 2020). The concept of Forest Landscape Restoration (FLR) for instance has emerged as an integrated landscape-scale intervention aiming to restore forest landscape for their ecosystem functions and social benefits for livelihoods and wellbeing (Erbaugh & Oldekop, 2018). FLR aims to create multidimensional landscapes and to be scaled up successfully local stakeholders must be involved in all stages of the project, from selecting appropriate sites, defining restoration objectives and measuring success (Mansourian et al., 2017).

The UN Decade of Ecosystem restoration also comes with a mission to extend restoration science to neglected ecosystems and to focus on restoration priority areas where degradation is high and where biophysical potential for restoration is too (FAO 2021). Often these restoration priority areas

are found in the tropics and coincide with areas with a low human development index (Löfqvist et al., 2022). One such restoration priority area - coined by both high biodiversity and high threats due to past and present degradation - are tropical mountain ecosystems (TME) (Soh et al., 2019). They harbour a range of formations, from montane forests and cloud forests, mountain and alpine grasslands, to azonal systems such as rivers and wetlands. Many global biodiversity hotspots are found in tropical mountain ranges, such as the Eastern Afromontane hotspot, the tropical Andes Biodiversity Hotspot, and the Western Ghats hotspot (Myers et al., 2000). They provide a suite of ecosystem services to local inhabitants, such as water regulation, nutrient cycling and cultural value as well as having global significance for carbon sequestration (Gaglio et al., 2017; Soh et al., 2019).

Many tropical mountain ecosystems worldwide have been altered by human activities causing degradation at all ecological levels from genes and populations to ecosystems (Soh et al., 2019). In the last two decades there's been an acceleration in loss of tropical mountain forests leading to large carbon losses (Feng et al., 2022). Degradation and land use change is particularly prevalent in the largest tropical mountain range - the Andes - where a millennial human legacy coupled with modern global change has impacted precious biodiversity, carbon storage and other ecosystem services such as water regulation and food provision (Pinos, 2020; Zador et al., 2015). Restoration of such degraded and destroyed ecosystems can promote ecosystem service provision and increase connectivity and biodiversity (Soh et al., 2019). A suite of restoration approaches are used in TMEs ranging from passive restoration (natural regeneration) (Davies et al., 2020; Ortega-Pieck et al., 2011; Von Thaden et al., 2018), to assisted approaches such as managing invasive species (Cole et al., 2012) and active restoration (seedling planting or direct seeding) (Atondo-Bueno et al., 2016; Landero-Lozada et al., 2019; Trujillo-Miranda et al., 2018).



Figure 1. 1: A greenhouse in the Vilcanota mountain range, Peru. Here *Polylepis spp* are planted in various community restoration efforts to recover degraded high Andean land.

While there are a wealth of restoration efforts and studies in temperate ecosystems and in lowland tropical ecosystems, comparatively little is known about the challenges and opportunities of restoration in tropical mountain ecosystems (Gleeson et al., 2016). For instance, the science on degradation and restoration of tropical mountains lags far behind the lowlands (Mengist et al., 2020a; Soh et al., 2019). A multidisciplinary agenda setting paper for science in Andean Mountain forests highlighted that critically reviewing exiting restoration initiatives including their bottlenecks and enabling factors is a key research priority, and including socio-ecological dimensions in research and practice is a key priority for achieving sustainability in Andean Forest Landscapes (Mathez-Stiefel et al., 2017).

In this thesis, I aim to address some of these knowledge gaps and challenges related to ecosystem restoration in TME. I revisit the science and practice of TME restoration using a multi-scalar approach, starting at a pantropical scale, then focusing on the Tropical Andes for a satellite data

assessment. I conclude my research with a local scale analysis of ecological restoration projects in Peru and set out an agenda for TME restoration for the remainder of the UN Decade.

Thesis framing and objectives.

Theoretical framing

This thesis is conceptually aligned with the framework by Mathez-Stiefel et al. (2017), which laid out Research Priorities for the Conservation and Sustainable Governance of Andean Forests. The framework is a research agenda which proposes research goals and objectives aimed to guide research that can inform the achievement of the sustainable development goals (SDGs) within Andean forests. It is intended at a range of actors, from policy, research to implementation, all of which will feature in the chapters of this thesis. Mathez-Stiefel's framework integrates the three dimensions of sustainability (ecological, economic and social dimensions) in an interdisciplinary way and as such is based on the understanding that Andean Forest Landscapes are complex socio-ecological systems wherein actors, governance systems, resource units and resource systems interact though feedback and links, resulting in social, economic and environmental settings and dynamics. This socio-ecological system and its links to Andean forest restoration will be explored in depth in Paper III of this thesis.

Mathez-Stiefel's agenda sets out three classes of research priorities:

1) System knowledge priorities which are linked to understanding and describing how socio-ecological systems work. These include assessing the impacts of global socio-environmental change on Andean Forest Landscapes and the impacts of governance and management practices on livelihoods and ecosystem services and studying the interactions between complex social and environmental dynamics.

2) Target knowledge priorities which are aimed at defining a common vision together with local stakeholders. This priority includes defining sustainability goals and a vision for the management of Andean Forest Landscapes. As part of this agenda point, the importance of including equity and justice concerns, and to define goals and options for restoration together with local stakeholders is highlighted in the framework.

3) Transformation knowledge priorities which encapsulate the required knowledge to coin future transitions and practices. Some of these priorities include to promote robust place-based governance models to support sustainability goals and to promote the sustainable governance of Andean Forest Landscapes at different scales, as well as specifically promoting their restoration.

I chose this framework because it has specifically been developed for a complex socio-ecological tropical mountain system – the Andean Forest Landscape and is as such spatially relevant for the study systems of this thesis. Moreover, the three categories of knowledge – system, target and transformation knowledge are adaptable to ecosystem restoration in a tropical mountain context. The framework is directly relevant for ecosystem restoration, which is one of the transformative actions to achieve sustainability in Andean Forest Landscapes, and is explicitly mentioned in Transformation Knowledge priority 7. For instance, the framework highlights the need to critically review existing restoration initiatives, their bottlenecks and enabling conditions (Priority 7.1), to compare active and passive regeneration approaches (Priority 7.2), to assess the impacts of different restoration practices on livelihoods and ecosystem services (Priority 7.3), to define common criteria for assessment of restoration practices (Priority 7.4), to validate locally adapted restoration technologies (Priority 7.5) and to develop the tools for the restoration of connectivity of he Andean and Amazonian System (Priority 7.6).

Overall thesis aims

The overall aim of the thesis is to revisit the science and practice of TME restoration at three scales and to improve our understanding of ecosystem recovery and socio-ecological restoration processes by using a mix of scientific approaches, from systematic literature analysis to optical remote sensing

to social science qualitative approaches (Fig. 1.2). The papers of the thesis target several research priorities identified by Mathez-Stiefel et al (2017) as shown in Fig 1.3.

The detailed objectives for each chapter, which each constitutes a research paper, are as follows:

Chapter 1:

Provide background literature on the study systems, remote sensing, and socio-economic aspects of TME restoration.

Chapter 2 (Paper I):

Provide a pantropical synthesis of scientific knowledge on ecosystem restoration in tropical mountain ecosystems.

Chapter 3 (Paper II):

Assess trajectories of forest recovery across the tropical Andes using multi-spectral long-term satellite data with the ultimate scope of identifying priority areas.

Chapter 4 (Paper III):

Elucidate motivations, barriers, enabling factors and preferences for Andean Forest restoration in Peru through a multi-stakeholder approach to direct future restoration efforts.

Chapter 5:

Synthesize and discuss the key findings of the thesis and present a restoration agenda for science and practice.

Thesis structure

I start with a general literature review (Chapter 1) to provide context for my three DPhil articles (Chapter 2, 3 and 4). This review presents the study systems, gives a basic summary of restoration approaches in TMEs, and delves into the remote sensing and socio-ecological approaches deployed

in the thesis, before ending on a more specific categorization of the forest restoration context in Peru.

Then, the main body of the thesis (Chapters 2-4) consists of three papers:

- In **Paper 1** (Chapter 2) I deploy a systematic review of 176 articles to synthesize on the state of restoration research in tropical mountain ecosystems (Fig. 1.2). In this synthesis, which sets the stage for the following chapters, I identify multiple knowledge gaps: the need to assess large scale restoration and recovery dynamics in understudied mountain ranges, the use of satellite data for restoration management, and the inclusion of socio-ecological dimensions in restoration science (see conclusions of paper 1 in Fig 2.8).
- These knowledge gaps build the motivation for **Paper II** (Chapter 3), where I deploy remote sensing technologies to investigate recovery trajectories in tropical montane forests across the Andes (Fig. 1.2). I do this by monitoring 15-year forest recovery in potential recovery sites across the mountain range using multitemporal 30m Landsat analysis and a newly developed method of classifying forest recovery trajectories.
- After this continental scale assessment, **Paper III** (Chapter 4) scales down to a national and local scale to assess the motivations, success and limiting factors and preferences for restoration in Peruvian Andean Forests. I do this through 75 interviews with 5 stakeholder groups in 11 forest restoration sites in Peru (Fig. 1.2).

Research from these three geographical scales informs the general synthesis and discussion in Chapter 5, where I discuss challenges and solutions to TME restoration and outline future recommendations for restoration science, practice and policy. The recommendations are structured as a 10-point agenda for Andean Forest restoration.

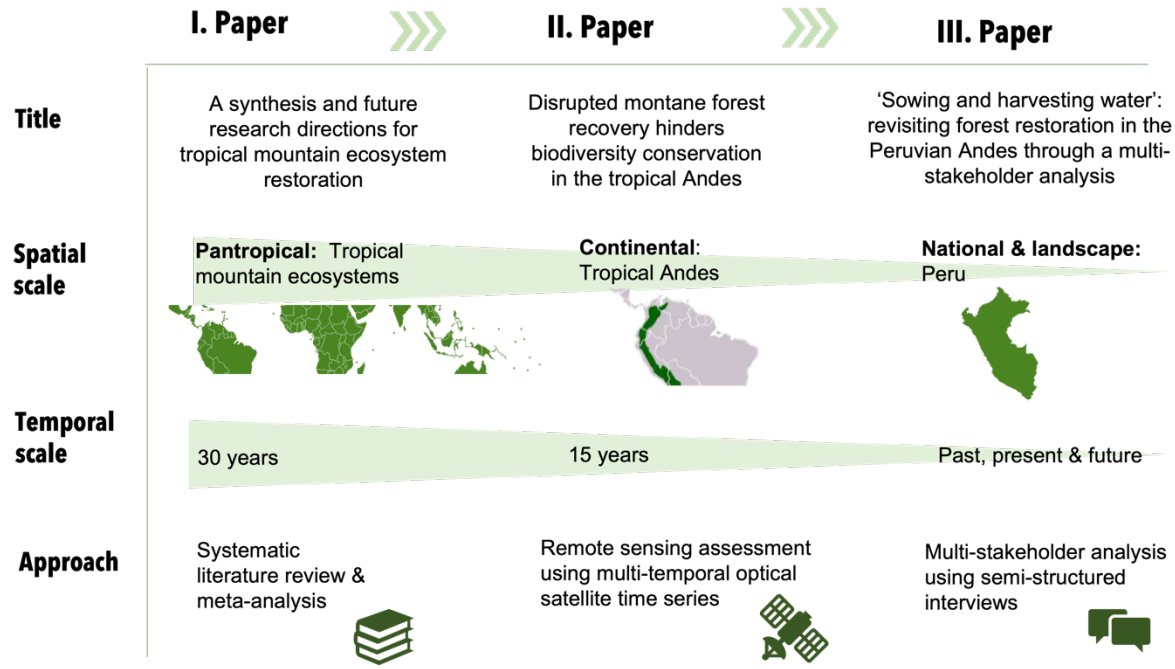


Figure 1. 2: Schematic structure of the DPhil papers and their respective scales and approaches

Knowledge gaps and research priorities targeted in thesis.

This thesis targets several research gaps in mountain ecosystem restoration: geographical, methodological and thematic research gaps.

Geographic research gaps targeted focus on the tropical mountain biome, which is far less studied than the tropical lowlands and the systematic review aims to give this important biome a systematic standing in restoration science. Chapters 3 and 4 of this thesis focus on Andean Forests which to date have received considerably little attention compared to other South American biomes such as the Amazon Forest.

Methodologically this thesis targets the shortfall of large-scale and long-term research of forest recovery in the Andes using remote sensing approaches. This thesis also addresses the underrepresentation of social research approaches and foci in forest restoration science which are crucial to achieving restoration goals and longevity (Löfqvist et al., 2022; Nerfa et al., 2021; Ota et al., 2020).

The thesis links directly to the knowledge gaps and research priorities in the categories System, Target, and Transformation Knowledge (Fig. 1.3) priorities identified by Mathez-Stiefel et al. (2017): For instance, the systematic review in Chapter 2 (Paper I) addresses the research priority 7.1 of reviewing existing restoration initiatives and their enabling conditions, and research priority 7.2 of comparing success of various kinds of restoration approaches. The remote sensing paper presented in Chapter 3 (Paper II) addresses research priorities regarding assessing successional dynamics of forest regeneration, trajectories of tree cover change and past and present landscape dynamics (priorities 1.5,2.2,2.3). The socio-ecological study presented in Chapter 4 (Paper III) addresses research priorities in all fields, such as related to improving local livelihoods, multistakeholder restoration options, upscaling of restoration approaches, critical reviews and validation of existing projects and techniques.

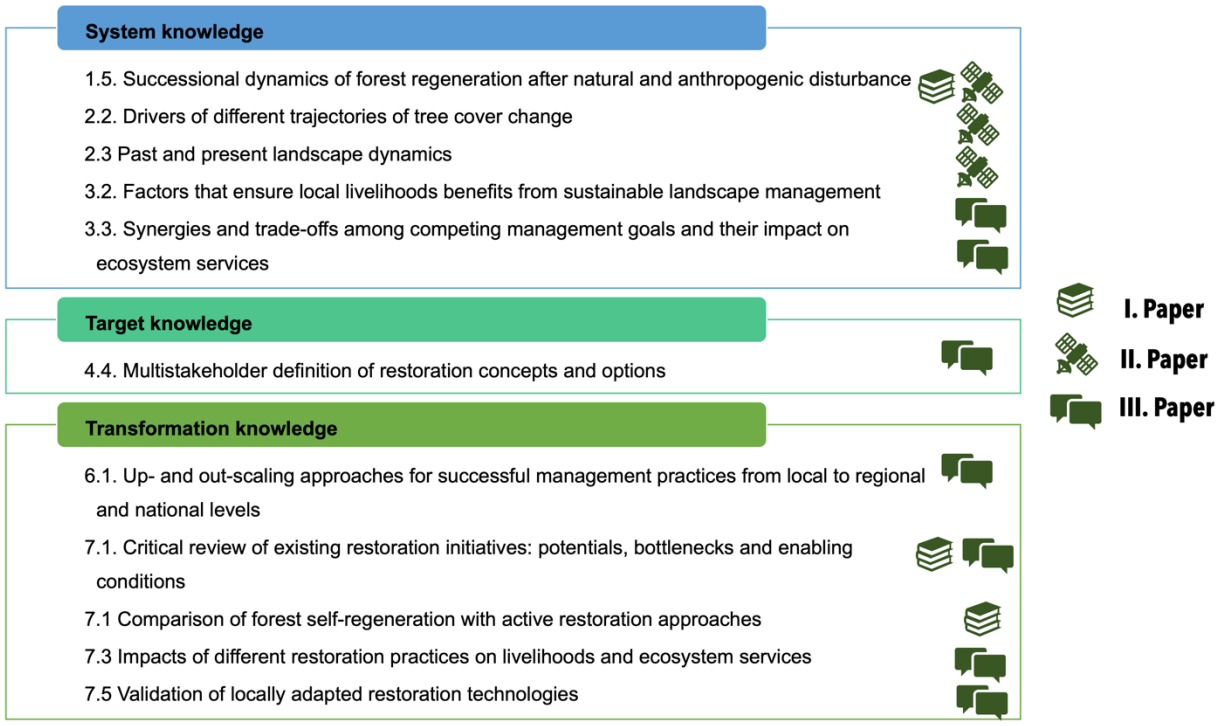


Figure 1. 3: Alignment of thesis chapters with research agenda and research priorities for Andean Forests set out by Mathez-Stiefel et al. (2017)

Literature review

In this thesis I combine methods and theories at different scales from different academic and non-academic fields, namely restoration science, tropical mountain ecology, Andean Forest science, remote-sensing technology, social science, forest governance and on-the ground restoration project work. The literature review offers a broad insight into these theories, methods and study systems and serves as a complementary introduction to the content covered in the subsequent three chapters.

Tropical mountain ecosystems across the world

The thesis focuses firstly on tropical mountain ecosystems (TMEs) across the globe. In this thesis TME are in this thesis defined based on latitude an elevation following Spracklen & Righelato (2014) as ecosystems found at latitudes between 23.5° S to 23.5° N and above an elevation of 1000m asl. The lower elevation threshold can vary between continental and oceanic locations, because of climatological and topographic differences.

TME broadly include montane forests, cloud forests, tree line ecotones, alpine and montane grasslands and azonal formations like peatlands. They can be found in Latin-America, Africa, Asia, Australia and on oceanic islands. TMEs represent a large part of the world's biodiversity, coinciding with many biodiversity hotspots, such as the Tropical Andean Forest hotspot, the Atlantic Forest, the Eastern Afromontane hotspot, the Western Ghats, and the Caribbean islands (Myers et al., 2000).

An in-depth description of these systems is provided in Chapter 2, where I systematically review degradation factors, restoration approaches, restoration success and enabling and limiting factors for restoration in TMEs. Degradation in TMEs is caused by land use change for agriculture, mining or livestock grazing, disturbances such as fires or logging, natural hazards such as landslides and latent degradation factors such as climate change (Soh et al., 2019). These lead to many limitations for ecosystem recovery, such as biophysical limitations or limited seed dispersal. Depending on the ecosystem type restoration of TME involves a range of approaches (Table 1), which are

distinguished by the kinds of ecosystem facets they seek to restore, as well as the wider goals (e.g., biodiversity vs production). Hence, restoration includes a continuum of 'softer' interventions like passive restoration, to 'moderate' interventions such as assisted natural regeneration and more 'intense' such as active restoration or agroforestry involving species introduction (Chazdon et al., 2021). These approaches have different usage and success rates, which depend greatly on the biophysical and local socio-economic context of a place. This theme is further explored in Chapter 2.

Table 1. 1: Restoration terminology used in this thesis.

Terminus	Definition
Ecosystem restoration	Broad term to describe any kind of intervention that seeks to restore an aspect of an ecosystem (e.g., ecosystem structure, composition, or function). As such it can include restoration using native and non-native species and is an umbrella term for a variety of approaches.
Ecological restoration	In this thesis 'ecological restoration' is defined according to the Society of Ecological restoration (2004) as an intervention that seeks to assist the recovery of an ecosystem that has been degraded, damaged, or destroyed. Specifically, the term is used to refer to interventions with native species and ecological objectives such as improving cover and structure, biodiversity, and ecosystem functioning.
Forest restoration	A term to describe the recovery of a forested ecosystem and its ecosystem structure, composition, and function. As such it can encompass various methods, such as passive, active, assisted restoration and agroforestry. Is an intentional activity that seeks to restore ecological forest components.
Forest Landscape Restoration	Interventions that aim to restore forest ecosystem functions at a landscape level and contribute to livelihoods, wellbeing and climate change resilience. Combines a mixture of restoration methods, such as tree planting, natural regeneration and assisted approaches.
Reforestation	An intervention that seeks to restore forest cover. As such it can involve native or non-native species.
Forest recovery	The recovery of a component of a forested ecosystem (e.g., ecosystem structure, composition, or function). Forest recovery can be an intentional or non-intentional activity and is used in this thesis for cases when the type of restoration cannot be distinguished.
Active restoration	A terminus that describes when an active intervention is being used, such as seedling planting, seeding, enrichment planting, transplantation etc. The term makes no distinction between whether native or exotic species are used.
Passive restoration	A term used to describe natural regeneration of sites with minimal human intervention, other than physical and legal protection of sites.
Assisted natural regeneration	A blend of active and passive restoration methods to speed up the process of natura regeneration. Could include for example fencing and fire exclusion coupled with enrichment planting, bird perches or nucleation planting.
Agroforestry	Introduction of trees into a farming landscape with the goal of increasing forest cover and providing local benefits and ecosystem services. Can be using native or non-native species.

Productive restoration	Restoration of an ecosystem with a goal of generating income through a specific species, e.g., timber, fruit species, medicinal species.

Andean Forests (‘*Bosques Andinos*’)

Chapters 2 and 3 of this thesis focus on tropical montane forests (TMF). Across the globe tropical montane forests can be found above 1000m asl in the tropical belt (i.e., between 23.5◦S and 23.5◦ North) and cover 1.22 million km^2 and are largely found on steep slopes (Spracklen & Righelato, 2014). They are also globally significant carbon stores, with a mean biomass of 271 t/ha (Spracklen & Righelato, 2014). Worldwide TMF loss has accelerated in the last two decades due to agriculture conversion, fires and commercial forestry (He et al., 2023). Many of these recent forest losses have occurred in biodiversity hotspots (He et al., 2023). TMFs have a particularly large extent in the Andes summing up to 30.67 million ha (Programa Bosques Andinos, 2021).

Latin-American Mountain ecosystems remain understudied compared to other mountain ranges across the globe (Gleeson et al., 2016; Soh et al., 2019). These Andean Forests, locally referred to as ‘*Bosques Andinos’* (hereafter referred to as ‘Andean Forests’) are part of the Tropical Andes Biodiversity Hotspot which harbours a higher number of species (45,000 vascular plants and 3,400 vertebrates) and of endemism (20,000 vascular plant species, 1,500 vertebrates) than any other biodiversity hotspot (Myers et al., 2000). This high level of biodiversity and endemism is a result of diverse climates, geology, elevation, and topography variation coupled with paleo-climatic history (Zador et al., 2015).

In the last three decades Andean Forests have been largely lost due to deforestation for land use change (Armenteras et al., 2011), exacerbated fires (Oliveras et al., 2014) and overgrazing (Aide et al., 2011). To date, Andean Forests cover about 40-70% of their original extent and by 2050 13-21% of the wet Andean Forests are projected to be lost due to anthropogenic climate changes (Programa Bosques Andinos, 2021). Andean Forests occur in six countries: Venezuela, Colombia, Ecuador, Peru, Bolivia and Argentina, where they provide ecosystem services to an estimated 69 million inhabitants across the mountain range (Programa Bosques Andinos, 2021). Andean Forests

comprise a range of different forest formations mostly spanning from a lower threshold of 1000/1500m asl to the treeline ecotone with the alpine Paramo and Puna grasslands at 3000-5000m asl (Fig. 1.4) (Programa Bosques Andinos, 2021). The lower elevation threshold for Andean Forests varies according to latitude, being around ~1000m asl in Bolivia, and ~1500m asl in Ecuador and Colombia. Further, upper and lower elevation ranges of Andean montane forests vary between the East-West flanks of the Andes and according to local topography.

Andean Forests have distinct bioclimatic conditions: temperatures are lower, decrease with elevation and show high diurnal fluctuations – often with night-time frosts. In the Andes precipitation patterns are highly variable and depend on factors such as topography, seasonality and temperatures. Precipitation tends to decrease with altitudes but peaks at mid-to high elevations around 1500m asl (Arias et al., 2021). At condensation level cloud immersion is a marked property and impacts plant physiology and ecosystem functioning (Bruijnzeel, Mulligan, et al., 2011; Bruijnzeel, Scatena, et al., 2011). Further, UV radiation can be high and impact plant development. These bioclimatic conditions impact plant productivity and carbon (C) stocks of TMFs, in that primary productivity and carbon stocks usually decreases with elevation (Spracklen & Righelato, 2014), while allocation of C to belowground increases, as conditions for heterotrophic decomposition of C are limited at higher elevation (Girardin et al., 2010).

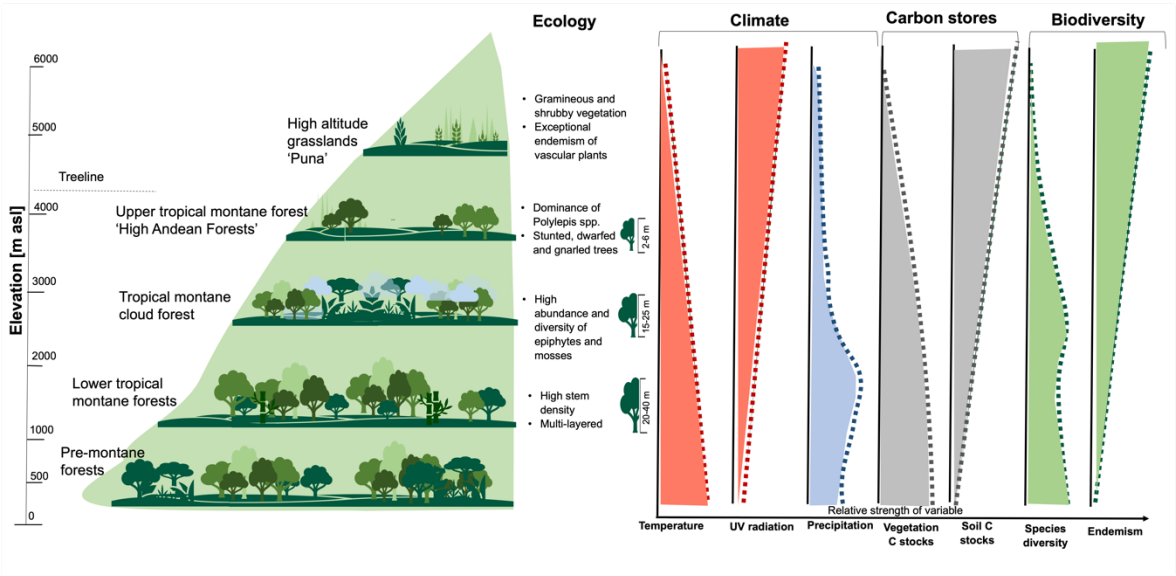


Figure 1. 4: Conceptual classification of the different types of Andean Forests based on elevation belts, ecology, climate variables, carbon stocks and biodiversity patterns. Based on data by (Arias et al., 2021; Girardin et al., 2010; Malizia et al., 2020).

Andean Forests can be broadly classified according to elevation level into pre-montane, low-montane, montane, and upper montane, as well as according to precipitation regime into wet-montane, seasonal montane and dry montane forests (Fig 1.4).

Lower montane forests are situated at 1000-2000m asl and occur below the cloud level. Their vegetation structure is multi-layered and canopy height reaches 20-40m (Gaglio et al., 2017). Frequent plant families in old growth Andean TMFs are *Euphorbiaceae, Moraceae and Myrtaceae, Cyatheaceae, Anacardiaceae, Melastomaceae, Rubiaceae, Annonaceae,* and *Fabaceae* (Aragón et al., 2021). In early succession TMF bamboos of the family *Poaceae* can be found, as well as early succession light wood density species such as *Sapindaceae* and *Fabaceae* are frequent (Calle & Holl 2019). High aboveground biomass provides ecosystem services such as carbon storage, charcoal and timber resources (Aragón et al., 2021; Gaglio et al., 2017). Lower montane forests often coincide with densely populated areas, and undergo strong anthropogenic impacts from deforestation for conversion to agriculture and logging (Armenteras et al., 2011).

Cloud forests, which are characterised by frequent cloud immersion and persistent fog, show a rich understory, a high biomass and diversity of epiphytes and mosses and trees of 15-25m (Bruijnzeel,

Scatena, et al., 2011; Gaglio et al., 2017). As such, they have a role in regulation of the water cycle, preventing erosion and providing habitats for biodiversity. Frequent plant families are *Melastomataceae, Solanaceae, Myrsinaceae, Aquifoliaceae* and *Rubiaceae* (Gaglio et al., 2017). Cloud forests largely experience degradation due to selective logging and conversion to pastures (Aide et al., 2011).

In higher elevations just below the treeline upper montane forests can be found at 3000-5200m asl. These are predominantly *Polylepis* forests, locally calles '*Queñuales*' (named after the indigenous name for the *Polylepis* tree '*Queñua*') – and are composed of *Polylepis spp. (Rosaceae)* which are the highest growing tree species in the world. In upper montane forests trees are short and grow slowly due to temperature limited growth rates (Pinos, 2020). Trees are stunted, often gnarled, and show sclerophyllous traits with intricate adaptations to high solar radiation, frost and wind. Alongside the *Polylepis* trees of the *Rosaceae* family, trees of the *Clusiaceae* (Gaglio et al., 2017) and *Podocarpacea* can occur (Domic et al., 2014; Velez et al., 2017). *Polylepis* forests have a large role in water retention and erosion prevention as they stabilize steep slopes and ensure water is stored and slowly released from the landscape (Pinos, 2020). Main drivers of loss of *Polylepis* forests include overexploitation due to live-stock grazing, unsustainable wood and charcoal harvesting, road expansions as well as fire and herbivory which hinder the regeneration process (Pinos, 2020).

Andean Forests in Peru

Peruvian Andean Forests can be found in several disjunct locations from Northern to Central Peru but make up only 1% of Peru's territory (Ministerio del Ambiente, 2015) and cover 27.76% of Peru's forested area. Across the mountain range, Andean Forest cover 30.67 million ha across South America (Programa Bosques Andinos, 2021). Depending on precipitation regimes they can be classified into dry Andean Forests, humid Andean Forests, and seasonal Andean Forests.

The work presented in Chapter 4 (Paper III) is representative of seasonal Andean Forests in the regions of Cusco, Apurímac, and Ancash, where the recurring dry season between April and

October coins a water-limited ecosystem. At elevations of 2500-3500m asl mixed species Andean Forests are found with various families present such as *Podocarpaceae, Lauraceae* and *Fabaceae*. These turn into cloud forests on the moister Eastern flank of the Peruvian Andes where they harbour an exceptional biodiversity due to their association with several epiphytes, lichen and mosses (Fig. 1.5 A & C). Above ~3500m elevation the Andean Forests appear mostly as mono specific forest relicts (Fig. 1.5 B) and *Polylepis* dominates with the occasional *Buddleja spp*. Above the treeline around 4500-5000m asl still isolated gnarled and dwarfed specimen of *Polylepis* can be found (Fig. 1.5 D).

Andean Forest area in Peru has been greatly reduced and estimates suggest that the current area is only 2% of its potential extent. A mixture of historic deforestation for agriculture and pastures, and recently disturbances such as fire, mining, grazing and exploitation have resulted in a Peru-wide decimation of Andean Forests (Aucca & Ramsay, 2005; Pinos, 2020). Most remaining contiguous Andean Forests are found in protected areas (such as in Manu National Park Fig 1.5 A), otherwise they appear as small relicts in an agricultural matrix.

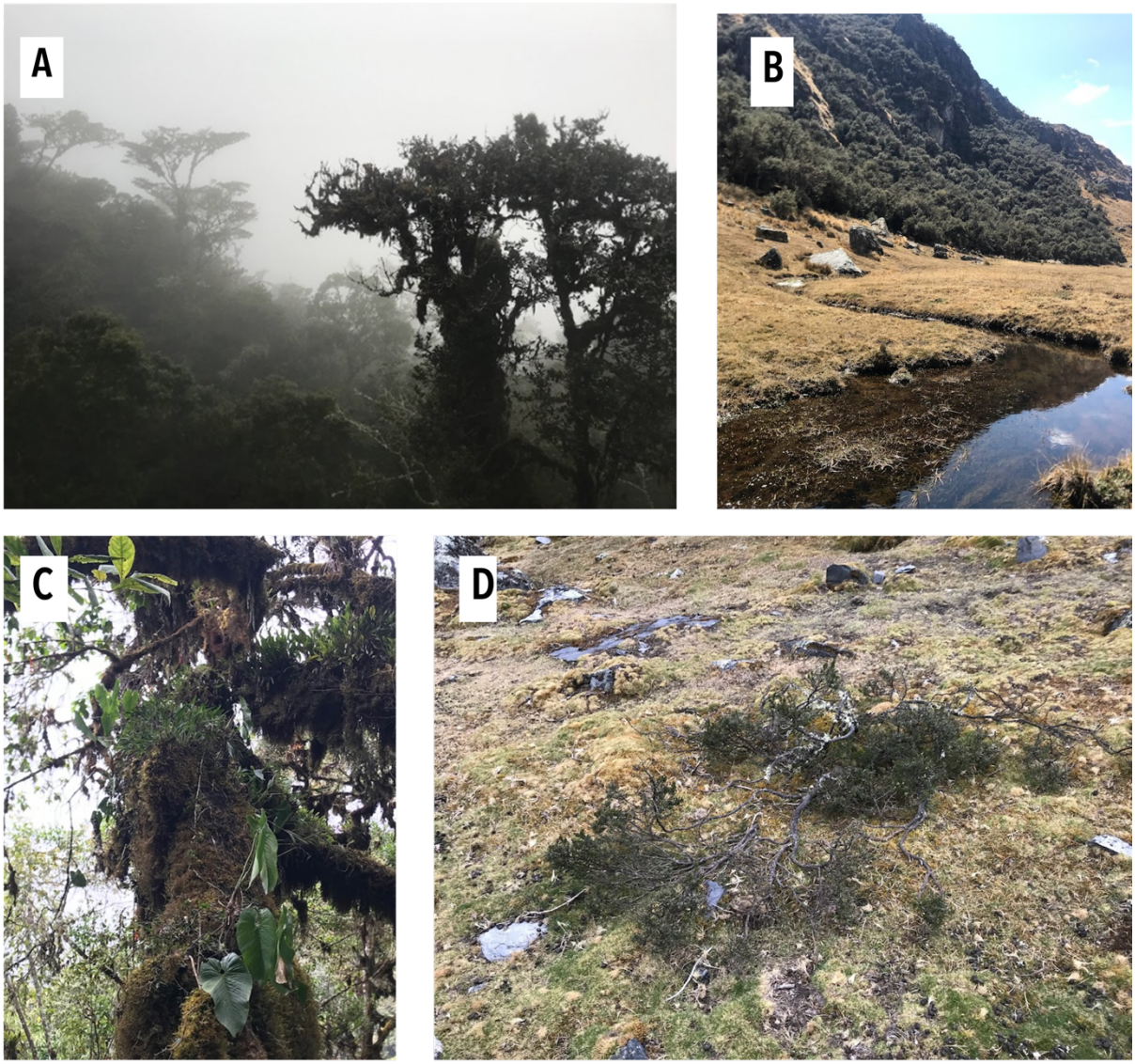


Figure 1. 5: A) A cloud forest at 2500m asl in Manu National Park, (Cusco, Peru) near the Biological Station Wayqecha and near a restoration site from ACCA, B) A *Polylepis* fragment at 4200m asl in the Upper Mariño Basin, (Apurímac, Peru) above a wetland ('*bofedal*'), C) a high Andean tree overgrown by epiphytes and D) A *Polylepis racemosa* at 4200m asl has been wind shaped, dwarfed, and gnarled.

Restoring Andean Forests

Restoring Andean montane forests is a challenging endeavour, due to bioclimatic limitations and poor accessibility of most sites. Recovery of ecosystem structure, composition and biomass in tropical mountain ecosystems, such as Andean Forests, is slower than in lowland forests since they are exposed to climatological, soil and topographic constraints (Guariguata, 2005). Further, in many tropical countries ecological recovery following disturbance is a non-linear process (Decuyper et al., 2022; Middendorp et al., 2016) and often unpredictable (Norden et al., 2015). For instance, repeated disturbance such as cyclical re-clearing results in low residence times of forests (Aragón et al., 2021; Diego Leon et al., 2011) and arrested succession often inhibits forest recovery (Gunaratne et al., 2014; Sarmiento, 1997). Across Latin-America trends of re-clearing of regrowing forests limit the delivery of restoration benefits (Graesser et al., 2015; Sanchez-Cuervo & Aide, 2013; Schwartz et al., 2020).

Recovering Andean Forests provides several co-benefits. For example, allowing tropical montane forests to naturally regenerate (i.e., passive restoration) can lead to substantial carbon gains over a period of 15-30 years, whilst also enhancing bird and beetle diversity (Gilroy et al., 2014). Nonetheless, natural regeneration is not always successful in Andean Forests due to temperature limitations, recurring drought and frost events and disturbances due to herbivory, fire, and other anthropogenic encroachment.

Active restoration interventions are needed in Andean Forests to overcome biophysical limitations. Such interventions include seedling planting, direct seeding, enrichment planting and several other methods of assisted natural regeneration (presented in depth in Chapter 2, Paper I). A key difficulty is that many high Andean tree species cannot be reproduced sexually, which is why vegetative propagation is often required and has emerged as the main strategy to propagate *Polylepis spp* (Mindreau & Zúñiga, 2010). This is a manual and labour-intensive process where branches must be collected from mother trees, prepared, and planted on in the greenhouse until growing a viable

root system. To date, this is the only way of effectively propagating the highest growing species (Mindreau & Zúñiga, 2010).

From a social point of view, Andean forest areas often overlap with areas of established agricultural communities (Aucca & Ramsay, 2005) and of low development index (Löfqvist et al., 2022). This means that often a suite of restoration interventions within the concept of FLR are required to meet local restoation objectives, such as a strategic combination of interventions such as active tree planting, site protection, agroforestry and assisted natural regeneration.

The ecological niche of Andean Forests corresponds to places that are high, mountainous, and often remote and difficult to access. This makes studying forest recovery – whether through active or passive restoration – at a large scale difficult and in recent years some studies have used remote sensing to monitor, predict and prioritize several dynamics of forest recovery in the Andes (Aide et al., 2019; Graesser et al., 2015; Sánchez-Cuervo et al., 2012; Sanchez-Cuervo & Aide, 2013; Schwartz et al., 2020).

Remote sensing for restoration science and practice

For large-scale and long-term monitoring of ecological recovery and restoration, remote sensing (RS) has emerged as a promising technology (Cordell et al., 2017; de Almeida et al., 2020; Reif & Theel, 2017).

Remote sensing describes a range of technologies of data collection from a distance – i.e., with sensor systems that do not touch the study object. Carrier objects for remote sensors include satellites, airplanes, balloons, drones and static terrestrial methods. There are active and passive remote sensing technologies. Active remote sensing works by emitting signals, such as laser signals or radio waves, and detecting the reflection and back scatter of these signals (such as done by LIDAR and RADAR technologies). Passive remote sensing on the other hand relies on detection of reflected signals and wavelengths within the electromagnetic spectrum. This is possible because different surfaces and objects have distinct spectral signatures, i.e., they reflect electromagnetic

radiation in different ways. This also holds for vegetation, with different ecosystem types showing distinct spectral signatures. Within the succession of an ecosystem, e.g., a forest, there is a distinct pattern of progression of spectral characteristics. For instance, as the ecosystem matures and gains biomass reflection in the near infrared part of the electromagnetic spectrum increases. With remote sensing it is possible to, amongst other things, distinguish structure, compositional and functional characteristics of forested ecosystems, such as detecting different species, assessing the vitality and ecosystem health levels of forests and measuring tree dimensions (Camarretta et al., 2019). In restoration science the use of remote sensing has grown in the last two decades. The potential of remote sensing for restoration is vast, ranging from mapping restoration priority areas, assessing potential threats and barriers to restoration, to monitoring restoration progress (Cordell et al., 2017). Many global initiatives are making innovative use of remote sensing for restoration purposes, providing user friendly tools for restoration assessments (IUCN, 2011; Monitoring Task Force, 2020; *Restor*, n.d.; WRI, 2014).

In mountain ecosystems where remoteness, inaccessibility of terrain, and data scarcity are prominent features, remote sensing can provide an easy, consistent, and low-cost method of gathering ecological data (Weiss & Walsh, 2009). Hence, remote sensing can be deployed to investigate recovery and restoration of mountain ecosystems in regions which are otherwise impractical to access.

So far, studies using remote sensing for TME restoration remain scarce and are either on a small spatial scale (Arasumani et al., 2020; Decuyper et al., 2022; C. C. Liu et al., 2019; Wilson et al., 2019), or rely on low resolution continental assessments (Aide et al., 2019; Graesser et al., 2015; Sánchez-Cuervo et al., 2012; Sanchez-Cuervo & Aide, 2013; Schwartz et al., 2020). There has been a trade-off between high-resolution studies on a landscape scale and low-resolution studies at a national/continental scale, likely due to computing limitations. With new high performance and cloud computing methods such as provided by Google Earth Engine it is now possible to carry out high resolution studies at increasing spatial scales (Tamiminia et al., 2020). Studies that are both

high in resolution and large in extent can help steer decision making on land management at national and supra-national scales while still accounting for localized small-scale forest dynamics.

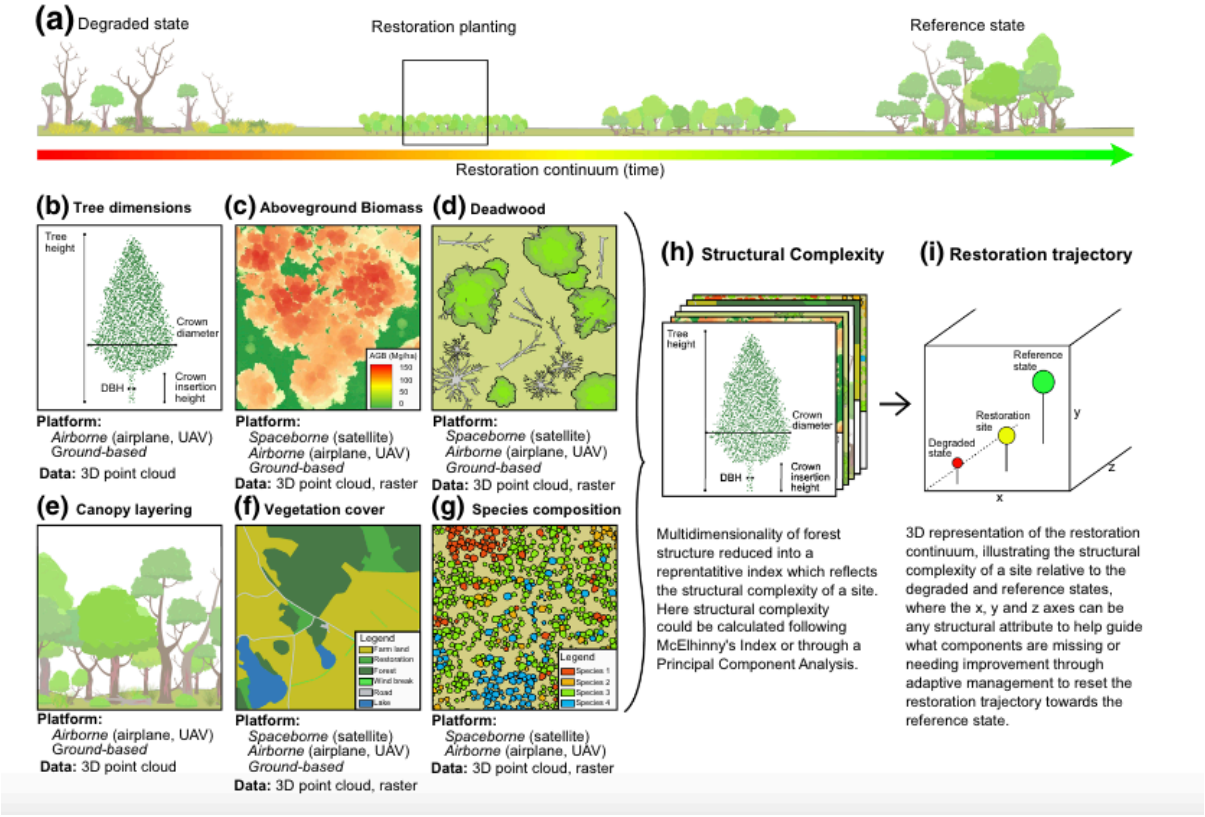


Figure 1. 6: Schematic overview of how different types of remote sensing can be used to monitor forest recovery trajectories (Camarretta et al., 2019). In Paper II of this thesis approach c and f are being used.

A variety of RS approaches have been deployed to monitor forest recovery dynamics and more specifically 'forest recovery trajectories' (i.e., the temporal change of forest components). Assessments of forest recovery using remote sensing are commonly done through various metrics which elucidate the different aspects of ecological restoration, such as land cover and habitat types, landscape metrics such as connectivity and fragmentation, as well as metrics related to biophysical characteristics, such as succession stage, vegetation structure and species composition (Camarretta et al., 2019; Middendorp et al., 2016; Reif & Theel, 2017). Camarretta et al. (2019) for instance present a framework for the use of several RS technologies for restoration monitoring (Fig. 1.6) ranging from laser-based detection of tree dimensions, vegetation structure and species

composition, to modelling of biomass using vegetation indices and classification of vegetation cover using satellite data. With many RS technologies being available on a high temporal resolution (i.e., with imagery every few days to months) and covering large parts of the globe there is a high potential to use such RS technology to accurately monitor outcomes of ecosystem restoration. The potential of remote sensing stands out particularly when several technologies are combined to investigate different facets of ecosystem change and to create a multi-dimensional picture of ecosystem structural complexity (Fig. 1.6). Combining these metrics can support selecting restoration sites, distinguish amongst appropriate restoration interventions for a given area, and help quantify progress through monitoring using indicators related to biodiversity, structure and function (Cordell et al., 2017; de Almeida et al., 2020).

Chapter 3 (Paper II) deploys remote sensing to monitor ecological recovery of tropical montane forests in the Andes over a large spatio-temporal scale using the highest resolution data available for long time periods (30m Landsat data, courtesy of the U.S. Geological survey). I combine time series of vegetation indices, tree cover classification and a novel method of classifying forest recovery trajectories. The study investigates pixel-by-pixel forest recovery trajectories at a 30m scale across Andean tropical montane forests over a 15-year period.

Moving beyond the pixel: Socio-economic aspects of tropical restoration

Remote sensing can help monitor restoration and steer restoration interventions towards degraded or deforested landscapes, such as choosing suitable restoration site given the landscape context and history (Reif & Theel, 2017). Yet, on its own it cannot inform on the best approach for an intervention site as it misses out on other dimensions, such as local socio-economic and ecological context of a site.

Beyond features observable with satellite data, planning and implementing a restoration action needs to account amongst other things for local restoration priorities, livelihood realities and align with socio-economic, cultural, and institutional considerations (Alba-Patiño et al., 2021; Elias et

al., 2021; Fischer et al., 2020; Löfqvist et al., 2022; Ota et al., 2020). To maximize restoration success and effectiveness, including social dimensions of restoration feasibility is key and strategies need to be tailored to the local context (Budiharta et al., 2016; Hopfensperger et al., 2007). Several rule-setting papers, such as the 10 Golden Rules for Ecosystem restoration (Di Sacco et al., 2021) and the 10 People-centred rules for socially sustainable ecosystem restoration (Elias et al., 2021) have appealed to the importance of conducting forest restoration for multiple goals, and including livelihood and equity considerations into the restoration process.

However, so far analyses of how forest landscape restoration projects affect local livelihoods, well-being and resilience remain limited to theoretical frameworks and simple socio-economic studies (Erbaugh & Oldekop, 2018) and this is the same for forest restoration in the Peruvian Andes (Durand & Sevillano, 2017; Joseph et al., 2021).

Chapter 4 (Paper III) focuses on drivers and outcomes of Andean forest restoration with a specific focus on livelihoods, by identifying restoration motivations and objectives, models for local engagement, limiting and enabling factors of restoration, and local stakeholder's preferences for the future. For this, several theoretical frameworks are used – such as the concept of multiple dimensions of restoration success (Budiharta et al., 2016; Cerrón Macha et al., 2018; Le et al., 2012, 2014), the concept of equity and of pathways linking FLR to local livelihood, well-being, and resilience (LLWR) outcomes (Erbaugh & Oldekop, 2018). These frameworks will be briefly introduced and discussed in the following pages.

Equity and ecosystem restoration

Restoration can only be sustainable in the long-term when its goals are aligned with preferences and goals of local people (Di Sacco et al., 2021; Seddon et al., 2021). Trade-offs between socio-economic and ecological benefits are a common element of restoration prioritization and need to be carefully navigated (Budiharta et al., 2016). For instance, in highly populated landscapes intense active restoration interventions which exclude people might not be advisable, instead, integrative

approaches, such as agroforestry, may be preferable (Budiharta et al., 2016; Fedele et al., 2021). In the tropics many restoration priority areas coincide with the areas of low human development index (Löfqvist et al., 2022), meaning that restoration needs to be as much a social endeavour as it is an ecological one (see Fig 1.7).

Incorporating several social equity concerns has been shown to improve effectiveness of restoration and should be at the heart of restoration efforts (Löfqvist et al., 2022). The importance of equity for sustainability has also been placed at the centre of the Sustainable Development Goals, with a specific SDG termed 'Reducing inequalities' and with a recognition of the central role of equity to achieving many other SDGs (United Nations, n.d.).

In the context of ecosystem restoration, equity refers to allocation of benefits ensuring that everyone has what they need for wellbeing, implying more for those who need it (as opposed to equality which refers to giving everyone the 'same share of the pie') (Leach et al., 2018). (Equity-centred restoration has been defined as *"restoration that places the most vulnerable and affected actors (current and future) of a restoration project at the centre of decision making, whilst simultaneously promoting ecological recovery."* (Löfqvist et al., 2022). Scholars have referred to three central dimensions of equity (Fig. 1.7): 1) Procedural equity meaning representation in decision making processes, 2) Recognitional equity relating to recognition of values and identity and 3) Distributional equity, i.e., the distribution of costs and benefits (Löfqvist et al., 2022, Leach et al 2018). Ways of better incorporating social equity and justice into ecosystem restoration are 1) placing livelihoods at centre, 2) incorporating equity and justice into study, design, and implementation, 3) elevating case study knowledge, 4) improving scientific communication around opportunities, trade-offs, and power relations, and 5) adjusting high-level restoration targets to place more emphasis on equity (Löfqvist et al., 2022).

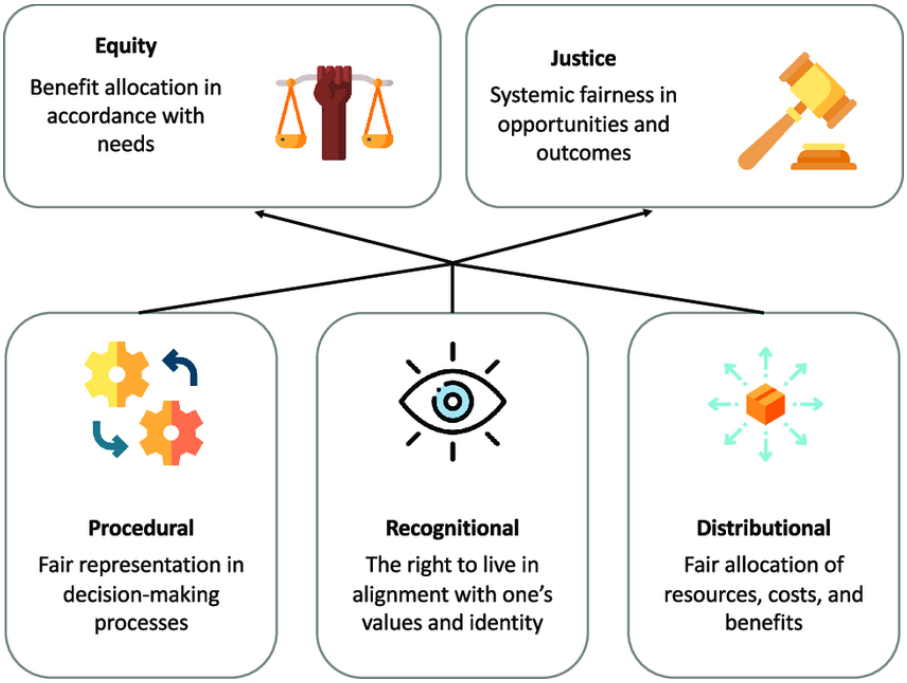


Figure 1. 7: The three dimensions of equity according to Löfqvist et al 2021 and Leach et al 2018.

Conceptual models for drivers of restoration success

Several studies in the tropics have attempted to identify the driving forces for forest restoration success and broadly classified these into technical/capacity, biophysical/ecological, socio-economic, and institutional /governance (Budiharta et al., 2016; Cerrón Macha et al., 2018; Le et al., 2012, 2014).

Le et al (2012) created a conceptual framework for reforestation success assessments. This framework assumes four categories of restoration success drivers, namely 1) Technical/biophysical drivers, 2) Socio-economic drivers, 3) Institutional, policy and management drivers, 4) Reforestation project characteristics. This framework has been applied in a a Philippine reforestation context (Le et al., 2012) and the drivers have been linked to indicators of restoration success, such as environmental and socio-economic indicators. Social factors such as education and awareness campaigns and dependence of local people on the forest were identified as key driving factors for success, while forest protection mechanisms were a key institutional success factor, and incentives and funding are a key economic factor (Le et al., 2012).

A similar study set in Peru and commissioned by the Peruvian Forestry Ministry (SERFOR) used a similar framework to characterize dimensions of restoration success in a meta-analysis of 94 restoration projects across all ecoregions. Cerrón-Macha et al (2019) separated six success and risk factors: governance dimensions, legal dimensions, social dimensions capacity dimensions, ecological dimensions and economic dimensions and showed their prevalence and importance in restoration projects in the different ecoregions. Key success factors were for instance governance drivers such as strategic alliances between communities, public and private actors, legal drivers such as land titling and tenure security, social drivers such as active participation of communities. Capacity drivers such as technical expertise and multidisciplinary experiences, ecological success factors such as appropriate species-site matching and economic factors such as provision of economic incentives. On the other hand, risk factors identified with this framework were from a governance perspective a lack of interest and continuity, social troubles in reconciling communal and individual objectives, lack of capacity to deal with climate-related risks, ecological risks due to frost and dry spells and lastly economic risk factors related to lack of funds for long-term monitoring and management.

Some of these multidimensional drivers of restoration success – especially the social, institutional and economic ones – have also been echoed in continental level (Aguiar et al., 2021) and pantropical studies (Ota et al., 2020).. Across the tropics, key barriers for forest landscape restoration were identified as limited persistence of gains due to institutional weaknesses, limited capacity and threats and over-reliance on support, limited scaling up and limited monitoring, reporting, and learning, poor governance processes and technical challenges such as limited knowledge and poor species selection (Ota et al., 2020). Key challenges for forest landscape restoration in Latin-America include 1) a high dependence on natural resources, 2) land tenure conflicts, 3) divergence in perceptions and values between actors and 4) fragility of public institutions (Aguiar et al., 2021). In light of these challenges several instruments of transformative governance can help improve long-term restoration outcomes, notably knowledge co-production,

polycentric governance, community-based monitoring, participatory mapping, and stakeholder analysis (Aguiar et al., 2021). Hence, policy interventions and future restoration projects need to consider these multi-dimensional drivers of restoration success to effectively achieve restoration outcomes.



Figure 1. 8: Interviewing an alpaca herder in the Peruvian Puna. The interviewee is highly reliant on the land and it natural resources due to subsistence farming and herding.

Linking FLR to local livelihood, well-being, and resilience outcomes

One of the main distinctions between FLR and other restoration interventions is that FLR specifically aims to restore both ecosystem function and contribute to both environmental and social outcomes. These social outcomes can be comprehended as outcomes for livelihoods, well-being and resilience. With a scarcity of evidence on the links between FLR and multidimensional livelihood outcomes Erbaugh & Oldekop (2018) suggest a framework to better conceptualize and practically assess such livelihoods and well-being related outcomes of FLR projects. This

framework consists of three pathways of how FLR is linked to forest ecosystem function and livelihood, well-being and resilience.

Pathway 1 is a direct link whereby and FLR project directly impacts forest ecosystem function, such as through planting of desired species, removal of undesirable vegetation or beneficial site preparation. Pathway 2 is a direct link between FLR project and livelihood, well-being and resilience mechanisms. In this pathway livelihoods, wellbeing and resilience are improved through incentive mechanisms, capacity building and institutional development, Common outcomes and benefits in this Pathway include cash transfers, tenure security, local participation, trainings, employment alternatives. Pathway 3 is an indirect link with interactions between forest ecosystem function and livelihoods, well-being and resilience. In this pathway an improved function of the forest resources results in livelihood benefits over long time scales. For instance reduced soil erosion, improved water provision and regulation and enhanced productivity of the forest create better conditions for the livelihoods of local communities.

This conceptual framework is particularly useful to assess the multidimensional effectiveness of forest landscape restoration of FLR projects and has been specifically designed to counteract the dearth of evidence surrounding livelihood impacts of FLR in complex contexts. It will be used to categorize Andean forest restoration outcomes in Paper III.

The context of Andean Forest restoration in Peru

In Peru, Andean Forests make up 25% of the nation's forested area and about 30% of the Peruvian population lives in the Andes and depend on these forests and the ecosystem services they provide for their livelihoods and subsistence. At the highest elevations, *Polylepis* forests – the highest growing forests in the world – can be found. These are at severe threat, with only and estimated 2% of *Polylepis* forests remaining in isolated patches in hotspots around Cusco, Cordillera Blanca, and Cordillera Occidental (Programa Bosques Andinos, 2021).

Peruvian Andean Forests form part of an intricate socio-cultural landscape which in the past decades has experienced a range of socio-economic changes, such as agrarian reform policies, and an increased access to national and global markets (Solimano, 2003). Since the Agrarian reform in 1968, which restructured tenure and ownership of agricultural land away from wealthy landowners, now the majority of the land is owned by local communities, farming groups and cooperatives (Fonseca Martel & Mayer, 1978; MIDAGRI, n.d.). Hence, local communities now tend to and farm vast tracts of land across the Andes according to traditional knowledge systems and adapted technologies. Agriculture systems are altitude dependent, with different farming systems at different elevations. Maize crops are found between 2800-3300m asl, potato crops between 3300 and 3800m asl and above 3800m asl there is a mix of high altitude livestock (camelids such as alpacas and llamas) and some high altitude crops such as quinoa. Most farming in the Andes is based on subsistence farming with agricultural traditions and techniques adapted to the mountain environment and dating back 5000 years, and including practices such as terracing, local irrigations, crop rotations and traditional use of tools.

To this date, Andean communities face several socio-economic challenges: Economic growth in Peru is slow and the national GDP lies far below the average for Latin America. Governance problems such as political instability and violence, lack of effectiveness and corruption control hinder economic stability, prosperity and peace (Solimano, 2003). Poverty is still prevalent in Peru, with 10% of population living below 1$ a day (International Federation of Red Cross, 2009).

Another challenge is the rural-to-urban migration of the younger generations which seek for improved socio-economic conditions and livelihoods in the cities, leading to depopulation and ageing of rural Andean communities (Aide & Grau, 2004).

To date there are still large income and wealth inequalities in Peru and there is a high level of inequity leading to large vulnerabilities of communities. Peru's population is to 40% classified as indigenous, resulting in a high ethnic diversity (Solimano, 2003). Across the Andes there are several traditional communities *('comunidades originarias'*) encompassing 7% of the national population (Ministerio de Cultura, 2019). These communities have a strong cultural identity, speak their own native language, have ancestral ties to the land and traditional internal social organization. Many of these socio-economic conditions have found to be directly relevant to the success of forest landscape restoration in Latin America in more widely (Aguiar et al., 2021) and in the Andes more specifically (Báez et al., n.d.; Hartman & Cleveland, 2018; Joseph et al., 2021; Wilson & Coomes, 2019a).

In the Peruvian Andes local communities closely interact with the Andean forest through a partly beneficial but also partly exploitative relationship. The forests provide various ecosystem services to local communities, such as food sources for subsistence, as well as regulating and providing clean water and preventing erosion (Aucca & Ramsay, 2005; Pinos, 2020). Further, Andean Forests are substantial carbon stores (Aragón et al., 2021) and Polylepis forests provide habitat for many threatened and endemic species, such as in Peru and Bolivia for 174 species birds (Quispe-Melgar et al., 2020).

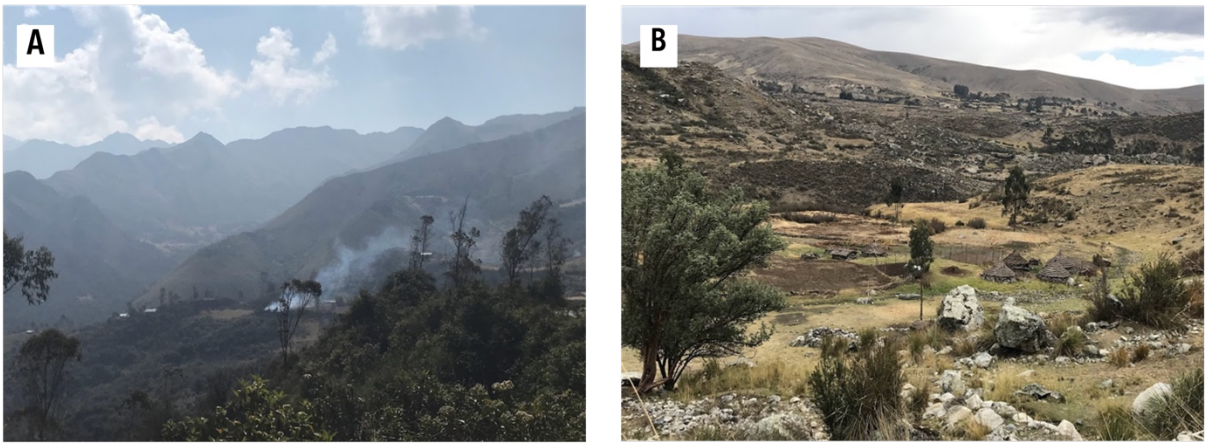


Figure 1. 9: Degradation causes for Peruvian Andean Forests: A) Fires escaped from land clearing, stubble burning, pasture burns or cultural burns and B) Conversion for agriculture and pastures.

However, many anthropogenic drivers endanger Andean Forests in Peru: climate change, land use change and recurring fires transform the Andean landscape and its ecosystem functioning (Fadrique et al., 2018; Manta & et. al., 2018; Oliver et al., 2017) (Fig. 1.9). Agriculture and livestock farming lead to a mosaicked and fragmented landscape, where forests are reduced to smaller less resilient woodland patches (Programa Bosques Andinos, 2021). Climate change causes glacial melting and a destabilization of the water household (Zimmer et al., 2022), as well as a shift in elevation zones due to warming impacting Andean Forest biodiversity and function (Fadrique et al., 2018) Fires, which are being exacerbated by climate change, in conjunction with grazing can cause carbon emission from soil stocks and lead to large-scale landscape degradation (Oliver et al., 2017). These fires, most of which are of anthropogenic origin, have recently increased in intensity, frequency and duration (Manta et. al., 2018). On the other hand, communities in Peru have also shown to actively conserve forests, whether this is by creating private conservation areas, or through informal conservation initiatives (Shanee et al 2014).

Restoration of Peruvian Andean Forests seeks to respond to these challenges by rebuilding and re-joining forest habitats, recovering lost ecosystem services and linking up the forest landscapes using forest regeneration techniques as a measure to mitigate and adapt to climate change (Durand &

Sevillano, 2017). Restoration across the Andes is a recent endeavour compared to neighbouring Andean countries and has only gained momentum in the last decade (Murcia et al., 2017).

Legal context of Restoration in Peru

In Peru, the concept of forest restoration and its legal formalisation can be traced back to the start of the 21st century, when the first Forestry and Wildlife Law ('Ley Forestal y de Fauna Silvestre' Ley No 27308) was declared (Fig. 1.10). This law did not yet refer to the concept of ecological restoration but used concepts such as recuperation and rehabilitation. For instance, it defines 'Recuperation areas' as *'land without vegetation cover or with scarce tree cover, or land with low commercial value, requiring afforestation and reforestation to re-incorporate them into the production and provision of forest ecosystem services"* (Art. 30.2). As such, these early laws had a strong focus on increasing forest cover and providing commercial forestry services. In 2011, a New Forestry law was passed (Nueva Ley Forestal, Ley No 29763) which finally incorporated the concept of ecological restoration and reforestation as a key forest management activity (Art. 3): *"The following are considered forestry and wildlife activities: a) The administration, research, conservation, protection, monitoring, restoration, evaluation, management, use, population, repopulation and improvement of the Nation's forest and wildlife heritage. b) Afforestation and reforestation"*. In this law ecological restoration was first defined as a *'Human-induced process seeking to help restore a degraded, damaged or destroyed ecosystem. Restoration tries to return an ecosystem to its historical trajectory.'*

Since then several decreets have been enacted with relation to forest management and restoration which have more specifically mapped out actors, responsibilities and principles for related to restorations, such as forest management for wildlife (Decreto Supremo No. 019-2015 MINAGRI 2015), forest and wildlife management in indigenous and farming communities (Decreto Supremo No. 021-2015 MINAGRI 2015) and forestry plantations and agroforestry systems (Decreto Supremo No. 020-2015 MINAGRI 2015). This revised forestry law has created a regulatory

framework that since then defines ecosystem restoration in Peru. The government forestry agency SERFOR (Servicio Forestal y de Fauna Silvestre) has been charged with coordinating and overseeing nation-wide restoration programs in conjunction with public authorities, NGOs and the private sector (Cerrón Macha et al., 2018; Murcia et al., 2017). Some of the resulting restoration initiatives have been synthesized in a government report by Cerrón Macha et al. (2018). However, this report has also shown that ecological restoration programs, especially those seeking to restore Andean forests, remain patchy and at a small scale.

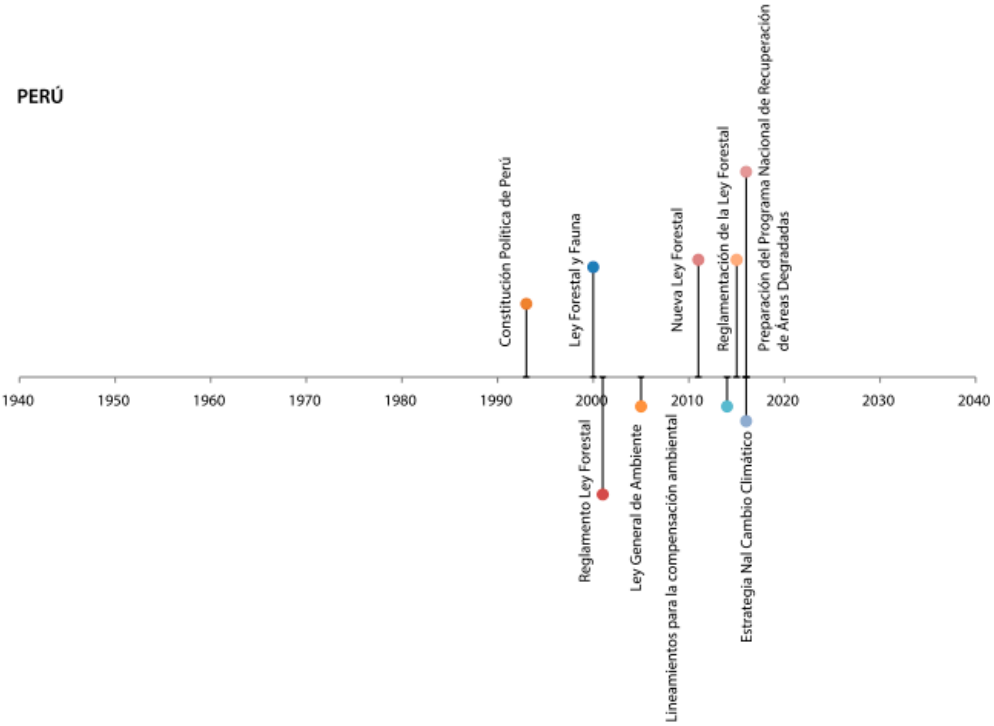


Figure 1. 10: Timeline of legislation of forest restoration in Peru. From Murcia et al (2019).

Restoration stakeholders in Peru

Restoration in Peru is planned and implemented by a range of public and private actors. Mainly these stakeholder groups consist of government actors, NGO actors, private actors (such as mining companies, water companies and tourist companies), academic actors and local communities.

Historically, most large scale restoration programmes have state (34%)-or NGO (43%) led with the private sector and universities taking a minor role (Cerrón Macha et al., 2018). Notably, SERNANP (*Servicio Nacional Areas Protegídas por el Estado*) – the government protected area authority – has been implementing ecological restoration programs in Andean Forests since the 1990s in state protected areas, however these efforts have been rarely documented.

The Peruvian NGO ECOAN (*Asociación Ecosistémas Andinos*) has the longest track record of implementing non-governmental restoration programs in Andean Forests. In the early 2000s ECOAN started the pioneer project in Vilcanota, where local indigenous knowledge and traditions were used to restore *Polylepis* forests. This project is now a showcase project for successful socio-ecological restoration due to its incorporation of ecosystem services, traditional customs, and active participation of communities in all phases of restoration (Aucca & Ramsay, 2005).

Many younger NGOs have begun restoration work in the last two decades, implementing restoration of Andean Forests in the department of Cusco (ACCA - *Asociación de Conservación de la Cuenca Amazónica*), the Cordillera Azul (CIMA - *Centro de Conservación, Investigación y Manejo de Areas Naturales)* and the Ancash area (IdM – *Instituto de Montaña* see Fig. 1.11). Since 2010, international organizations, such as development organizations (German GIZ – *Gesellschaft für Internationale Zusammenarbeit*, Swiss foundation for development HELVETAS) and continental scale NGOs (e.g., *Acción Andina*) have emerged to scale up and support restoration programs across the Andean Forest biome.

Further, private actors are implementing forest restoration such as mining companies who are legally obliged to restore ecosystems as part of their mandate to mitigate and compensate for damaging environmental impacts. Further, water-related stakeholders (some of which are public like e.g. Autoridad Nacional Agua and some of which are private companies) finance restoration through payment for ecosystem service schemes.



Figure 1. 11: The collaborative restoration project in Aquia led by *Instituto de Montaña*. (A) The restoration was implemented by the community directly who grew *Polylepis* in their own nurseries (B) the motivations of the community were identified as being largely tied to improving agriculture and grazing land (C) The project had a string participatory approach with planning and implementation workshops together with the community. (D) Now, 15 years after beginning of the project there is a high level of environmental awareness in Aquia, as exemplified through this mural on nature-people interaction next to the community church.

Across Peru there are restoration projects in a variety of montane forest locations. In a report by the government forestry agency SERFOR, interviews with project managers revealed several common success and risk factors in these projects (Cerrón Macha et al., 2018). These were classified into the following pillars: government, legal, social, capacity, ecology and economy. Common success factors include the creation of strategic alliances, clear land tenure and titling and well as community participation, capacity building and education. Further, the selection of appropriate species for a given site and the provision of economic benefits were identified as driving project success (Cerrón Macha et al., 2018). While these factors give a general indication as to how to plan and implement restoration in montane forests, they were determined through semi-structured interviews only with project managers or conservation practitioners (Cerrón Macha et al., 2018). However, the perceptions of communities on whose livelihoods are inextricably linked to the land and the Andean Forests (about why and when restoration of Andean Forests succeeds) have rarely been studied in a Peruvian montane forest restoration context (but see Durand & Sevillano, 2017;

Joseph et al., 2021) and the community's opinions on what makes a project succeed and the associated challenges remain largely unexplored.

A community-based survey study looking at the socio-economic conditions that drive intention to restore *Polylepis* forests in Peru (Joseph et al., 2021) found that many families had an intention to restore *Polylepis* forests, however this intention decreased with the family's economic reliance on subsistence products from the forests which were seen to compete with restoration. On the other hand, families with higher technological knowledge better understanding of ecosystem services showed a higher intent to restore *Polylepis* forests. A recount of *Polylepis* restoration experiences from the Department of Ancash also showed that socio-economic factors, like land ownership, political boundaries and community organization often matter more for restoration success that biophysical conditions (Durand & Sevillano, 2017). For instance, environmental education of communities was key to instil intrinsic appreciation for forests and a restoration desire, while financial and material incentives did not always succeed in promoting *Polylepis* restoration. Further, they found that clearly stating the restoration objectives and benefits to communities was key to success, as well as post-restoration conservation agreements to minimize encroachment. Beyond that, restoration was more likely to succeed when working will well-organized communities who had low commercial interest (Durand & Sevillano, 2017).

Different restoration stakeholders (e.g., local communities, NGOs, government, private sector, academia) tend to have varying perceptions on what constitutes restoration, on restoration objectives and preferences and on what promotes and limits restoration outcomes (Nerfa et al., 2021). To design and inform restoration interventions it is key to engage relevant stakeholder groups in restoration practice and science through multi-stakeholder approaches. Chapter 4 (Paper III) uses a multi-stakeholder interview approach to study the multitude of motivations, success factors and preferences associated with restoration of Andean Forests in Peru.

First, let us look at the broader pantropical context of ecosystem restoration in TME through a systematic review. This targets one of the Transformation Knowledge gaps identified by Mathez-

Stiefel et al (2017) – Priority 7: A critical review of existing restoration initiatives: potentials, bottlenecks and enabling conditions.

Chapter 2 (Paper I)

A synthesis and future research directions for tropical mountain ecosystem restoration

T. Christmann, I. Oliveras Menor

"Up there in the mountains there isn't water every day, unlike in the greenhouse where we water our plants once a week. So, what we do is to skip weeks of watering and by themselves the plants will adapt. Like a child who we must teach how to walk, so we have to do with the plants."
- NGO technician

This paper has been completed and published in *Nature Scientific Reports* (*10.1038/s41598-021-03205-y*). I conceived the idea and together with Imma I identified the best methodology for the systematic review. I reviewed and analysed the 176 studies and Imma guided me in the data analysis. I drafted the manuscript with inputs from Imma. As per the publisher's author guidelines the method section is at the end of the paper.



Figure 2. 0: View of the Puna grasslands in Apurímac at 4200m asl.

Abstract

Many tropical mountain ecosystems (TME) are severely disturbed, requiring ecological restoration to recover biodiversity and ecosystem functions. However, the extent of restoration efforts across TMEs is not known due to the lack of syntheses on ecological restoration research. Here, based on a systematic review, we identify geographical and thematic research gaps, compare restoration interventions, and consolidate enabling factors and barriers of restoration success. We find that restoration research outside Latin-America, in non-forested ecosystems, and on socio-ecological questions is scarce. For most restoration interventions success is mixed and generally limited by dispersal and microhabitat conditions. Finally, we propose five directions for future research on tropical mountain restoration in the UN decade of restoration, ranging from scaling up restoration across mountain ranges, investigating restoration in mountain grasslands, to incorporating socio-economic and technological dimensions.

Keywords:

ecological restoration, montane forest, mountain biodiversity, mountain grassland, cloud forest

.

Introduction

Tropical mountain ecosystems (TME) are hotspots of biodiversity (Dimitrov et al., 2012; Spehn & Körner, 2005) and endemism (Merckx et al., 2015) and are located in tropical latitudes between 1000m and 4000m asl, and the elevation gradients give rise to a variety of ecosystems including montane forests, montane cloud forests, forest-grassland treelines, mountain grasslands and azonal formations (Table 2.1). TME span across all continents in the tropical belt, and despite their small spatial extent of just over 4 million km^2 (Table 2.1) they provide numerous ecosystem services to people and society, including carbon sequestration, water regulation and supply, timber and food provision, erosion control, and cultural services (Mengist et al., 2020).

Notwithstanding their tremendous biological importance and complexity, TME are still relatively understudied compared to temperate mountain systems (Gleeson et al., 2016). In recent decades, TME have been experiencing increasing pressure from multiple external drivers and stressors, such as anthropogenic pressures due to agricultural encroachment, pasture conversion and population growth (Jacob et al., 2016), exotic plantations (Dhakal et al., 2012; Thijs et al., 2014), invasion by exotic animals (Long et al., 2017) and exotic plants (Elgar et al., 2014; Hooper et al., 2005; Rojas-Botero et al., 2020), as well as accelerating climate change impacts (Krishnaswamy et al., 2013). These drivers lead to severe degradation in TME, impacting all levels of ecological organization, such as disruption of ecosystem services, losses in community diversity, changes in species interactions, reductions of population sizes and lowered genetic diversityClick here to enter text. (Soh et al., 2019). Degradation in TME is far-reaching and ubiquitous: Tovar et al. (2013) projected that climate change will alter 3-7% of tropical Andean biomes, resulting in a 31.4% loss in extent of high-altitudinal Páramo grasslands due to replacement by montane forests by 2039. Further, Helmer et al. (2019) indicate that in the next 25–45 years, reductions in cloud immersion are estimated to diminish 57–80% of Neotropical montane cloud forests. Hall et al. (2009) estimate that

the Tanzanian Eastern Arc mountains have lost 25% of forested areas since 1955, with deforestation rates of 57% in sub-montane forests (800–1200 m).

Table 2. 1: Definition and description of the five tropical mountain ecosystems, their ecological features, and the total area in the tropics

Ecosystem	**Description**	**Examples of sub ecosystems**	**Elevation**	**Total area (km^2) across the tropics**
Mountain grasslands	Grass-dominated systems found above the treeline. Highly biodiverse with adaptations to strong abiotic stressors, such as tussock growth or conservative functional traits (Christmann & Oliveras, 2020).	Alpine grasslands at high elevations (Andean *Puna* and *Páramos*) Montane grasslands at lower elevations (Western Ghats, *Campos Rupestres*)	*Páramos:* above 3000m asl *Puna:* above 3400m asl (Christmann & Oliveras, 2020) Campos Rupestres: 900-2000m asl	~846,286 km^2 Sum of all tropical-mountain grassland types extracted from (Dixon et al., 2014):
Tree line ecotone	Transition ecosystem between tree life forms and graminoids, forbs or shrubs with aseasonal growing patterns and controlled by temperature and/or land use (Young & León, 2007). Can assume different types of shapes, such as sharp transition, stunted trees, tree island outposts or gradual ecotone (Harsch & Bader, 2011)	Shrublands Sub-alpine *Polylepis* forest High Andean Forest	Variable elevations, dependent on local topographical and climatological positions	No estimates available
Azonal formations	Spatially restricted non-zonal ecosystem that occur due to topographical or hydrological features	Mountain peatlands and bogs Riparian ecosystems Inselberg forests	Variable elevations	No estimates available.

Montane cloud forest (hereafter 'cloud forest')	Forested ecosystem shaped by frequent fog immersion, wetness, and windy conditions. Harbours a distinct tree and epiphyte community with functional adaptations to the mountain hydrology and high elevation conditions (Bruijnzeel, Mulligan, et al., 2011).	Lower montane cloud forest Upper montane cloud forest Sub-alpine cloud forest/'Elfin' forest	Generally, between 1200-1500m asl. But lower boundary of 400m asl on some islands – and of 2000m asl on large mountain ranges (Bruijnzeel, Mulligan, et al., 2011)	~214,630 km^2 (i.e., 6% of all montane tropical forests) (Bruijnzeel, Mulligan, et al., 2011)
Montane forest	Elevation forest with colder temperatures and distinct abiotic conditions to lowland forests. Forests usually show higher stem density, lower DBH, stem length and leaf area index with increasing elevation (Kessler & Kluge, 2010)	Lower montane forest, upper montane forest, dry montane forest, wet montane forest, montane bamboo forest	500 – 3500m asl Montane forests *sensu strictu* 1000-3500m asl Pre-montane forests 500 -1000 m	3,257,275km^2 (Bruijnzeel, Mulligan, et al., 2011)

At the same time, socio-economic drivers have led to migrations of people from tropical mountains to urban areas, abandoning many previously cultivated and inhabited areas (Aide & Grau, 2004; Bender, 2015; Zhang et al., 2004) and creating a large opportunity for ecosystem recovery and restoration across many TME.

Restoration of biodiverse ecosystems, such as TME, has the potential to simultaneously recover lost biodiversity and ecosystem functioning and improve local livelihoods (Di Sacco et al., 2021), and has recently come to the fore of global conservation efforts (IUCN, 2011). Restoration is defined as *"the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed*" (Society for Ecological Restoration, 2002) and, as such, encompasses a broad suite of approaches ranging from passive restoration, to assisted recovery and active restoration. The urgency for global restorative actions culminated in global restoration pledges like the 2011 Bonn

Challenge and the proclamation of the UN Decade of Ecosystem Restoration. Motivations to restore damaged ecosystems include conserving biodiversity (specific habitats or species), enhancing ecosystem processes (such as nutrient cycling), combatting climate change (through carbon storage or adaptation), and providing ecosystem services (such as water regulation or food provision, and for cultural and spiritual reasons (Holl, 2020). While restoration is by no means a replacement for protection of intact ecosystems, it is a useful complementary conservation strategy to recover degraded land, such as in the case of reforestation (Di Sacco et al., 2021).

Thus far, tropical ecosystem restoration has pre-dominantly been focussed on the lowlands, where restoration ecology has been thoroughly studied and synthesized in recent years (Chazdon, 2015; Chazdon, 2003; Ghazoul & Chazdon, 2017; Meli et al., 2017) and various restoration methods have been tested and compared (Meli et al., 2017). On the other hand, only a handful of reviews have addressed restoration questions related to TME, most of which are specific to a single tropical mountain ecosystem type or to a specific restoration context (Aide et al., 2011; Chazdon, 2015; Chazdon, 2003; Ghazoul & Chazdon, 2017; Guariguata, 2005; Holl, 2012; Meli, 2003; Venkatesh et al., 2014).

To the best of our knowledge, there is no pantropical synthesis of scientific knowledge on ecosystem restoration in tropical mountain ecosystems. By completing a systematic review of 980 search entries and a meta-analysis of 176 systematically selected TME restoration studies following the SALSA methodology (Mengist et al., 2020) (see Methods), we address four key questions: (1) When, where, how and why does tropical mountain restoration research take place? (2) What restoration methods are used in TME restoration? (3) What limits or promotes success in TME restoration? We then discuss these questions in the light of climate change in tropical mountains and present research directions for TME restoration research for the upcoming UN Decade of Restoration.

The state of science in tropical mountain restoration

Tropical mountain restoration research reveals strong geographical and research nodes.

Most TME restoration studies came from study locations in Central and South America (67%, Figure 2.1a). Mexico was the most represented country with 18% of all studies, followed by Colombia (13%) and Costa Rica (9.3%).

Half of the Latin American studies took place outside the large mountain range of the Andes, particularly in small Central American mountain ranges such as the Talamanca Mountains (Costa Rica) and Sierra Madre Oriental (Mexico). This Central American focus mirrors the common trend in tropical ecology, where most science continues to come from a few concentrated research locations.

TME restoration studies in Africa were scarce (only 9% of studies, Figure 2.1b), despite the occurrence of prominent mountain ranges such as the Ethiopian and Cameroon Highlands, Tanzanian Eastern Arc mountains, or Mt. Kilimanjaro. Similarly, few studies were conducted in Asian tropical mountains (5% South Asia and 8% in South-East Asia), despite the existence of extraordinarily biodiverse and highly threatened mountain ecosystems such as montane grasslands in the Western Ghats (Arasumani et al., 2018; Raman et al., 2009).

For Mexican TME studies, 97% of first authors came from Mexican institutions. For Costa Rican TME research, 2/3 of funding and authors came from US based institutions (Supplementary 1.1). Funding for Colombian restoration studies was split between Colombian institutions (40%), Global North countries (US, Norway, Germany, UK, together 47%) and supra-national institutions (United Nations, European Union, together 9%).

The number of TME restoration studies remained very low until 2005, followed by a steady increase, reaching maximum numbers in 2020 at the onset of the start of the UN decade of restoration (Fig. 2.1c). Restoration studies in montane forests were predominant throughout, and almost the only ones before 2000. Since 2004 studies in cloud forests and mountain grasslands increased, while studies about the treeline and azonal formations remained anecdotal through the entire period.

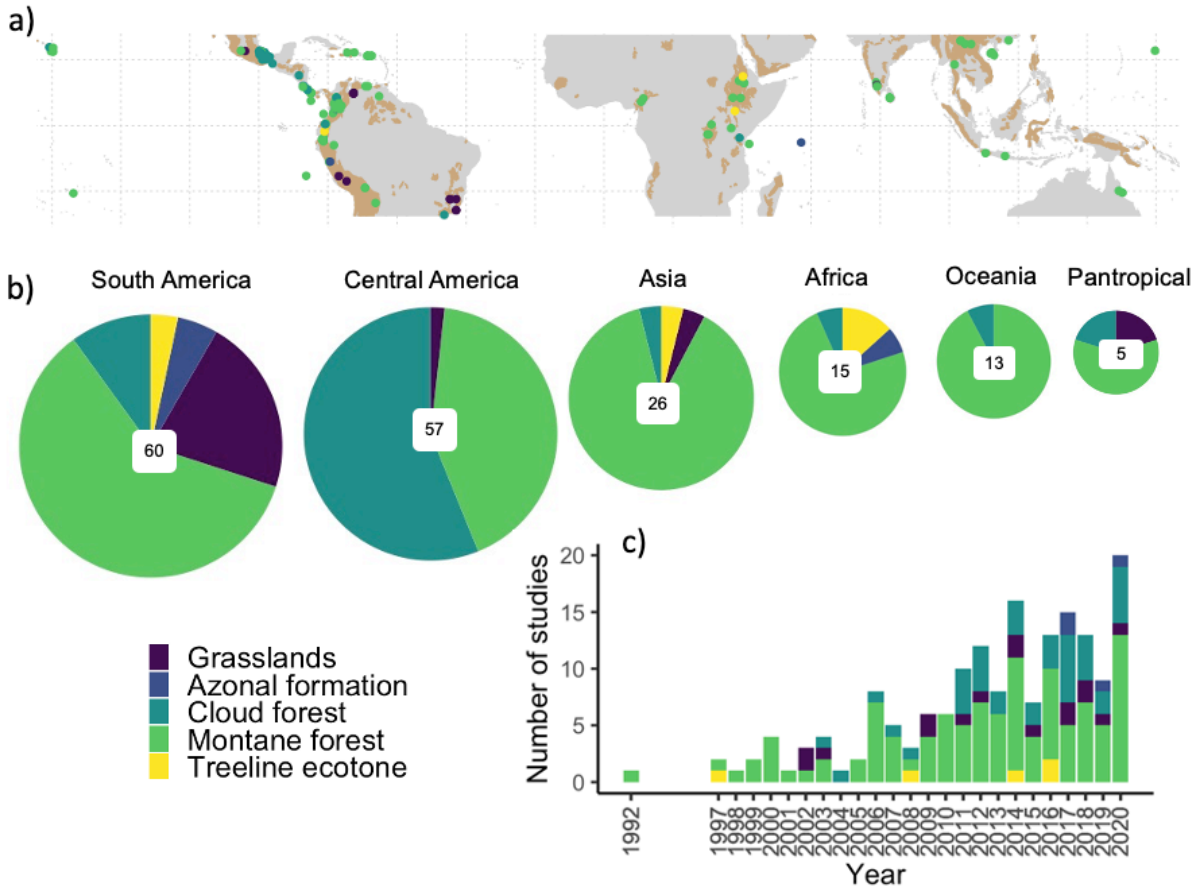


Figure 2. 1: Steady increase in TME studies since the 90s with a focus on Latin-America and forested mountain ecosystems. a) Location of studies in the different mountain ecosystems in relation to the tropical mountain ranges. Mountain shapefile data from Global Mountain Biodiversity Assessment (Körner et al., 2017), base map from R package 'maptools' (Lewin-Koh et al., 2011) b) Ecosystem type pie charts for each geographic region scaled in descending order of total number of studies (number in middle of each pie chart). Pantropical refers to studies carried out in multiple geographic regions, c) Number of studies over time for each ecosystem. All figures were generated in R studio version 3.6.2 (R Core Team, 2019) and using the package 'ggplot2' (Wickham, 2016).

Strong focus on montane and cloud forests

From an ecosystem perspective, we found a strong focus on forested ecosystems with 62% of studies looking at montane forests, 24% of the studies focusing on cloud forests, 9% on grasslands and even smaller percentages for other azonal ecosystems (Fig 2.1b). While this can be explained by the fact that forested tropical mountain ecosystems comprise more than four times the area of mountain grasslands (~3,500,000km^2 vs 846,286 km^2, see Table 1), the flipside of this 'forest focus' is a scarcity of restoration studies in montane and alpine grasslands, many of which rank among the most biodiverse and endemic ecosystems in the world (Christmann & Oliveras, 2020; Le Stradic, Buisson, & Fernandes, 2014; Srinivasan et al., 2015; Vasconcelos, 2011).

The current focus on reforestation and tree planting in the international restoration agenda (Di Sacco et al., 2021; Seddon et al., 2021), exemplified by large international tree planting commitments such as Trillion Trees (*Home | Trillion Trees*, 2020) and the Bonn Challenge (IUCN, 2011), could also contribute to this dominance of forest restoration studies. Less than a dozen studies were carried out in the vast expanses of the *Páramos* and *Puna* (Abadín et al., 2002; Abreu et al., 2009; Bueno & Llambí, 2015; Sarmiento et al., 2012, 2015; Sarmiento & Bottner, 2002) and a few studies in the Brazilian *Campos Rupestres* (Hilário et al., 2011; Le Stradic, Buisson, & Fernandes, 2014; Le Stradic, Buisson, Negreiros, et al., 2014) and Western Ghats (Arasumani et al., 2018, 2020; Raman et al., 2009). We found only 5 studies (2.8%) on restoration in the tree line ecotone (Jacob et al., 2016; Middendorp et al., 2016; Sarmiento, 1997; Venkatesh et al., 2014; Wesche et al., 2008).

We found theme-specific geographic hotspots, such as Veracruz (Mexico) for studies on cloud forest recovery and restoration in abandoned pastures (De Guevara et al., 2012; Lira-Noriega et al., 2007; Muñiz-Castro et al., 2006; Räger et al., 2011; Violi et al., 2008; Williams-Linera et al., 2011). In Hawaii, Mauna Kea was a hotspot for restoration research in montane forest around management of invasive feral pigs (Cole et al., 2012; Cole & Litton, 2014; Gould et al., 2013; Hart, 2010; Ibanez & Hart, 2020; Long et al., 2017; Pinto et al., 2015). Finally, eastern Africa was a hotspot around

agroforestry and productivity restoration on cultivated mountain slopes (Hylander & Nemomissa, 2009; Jacob et al., 2016; Roose & Ndayizigiye, 1997; Uhlig, 1992).

Bias towards short temporal and small spatial study scales

We characterized studies based on the time scale they look at (short < 1yr, medium 1-5 year, long >5 years) and the spatial scale of the restoration project (patch scale <10km^2, local scale 10-100km^2, regional scale 100km^2-10,0000km^2). Most TME restoration studies were short in time and small in space (Figure 2.2). Most of the studies (57%) were conducted in the short-term and in the mid-term (30%). Only 13% of studies were long-term with only six studies lasting more than 20 years (Bingli et al., 2020; Camelo et al., 2017; Carilla & Grau, 2010; Jacob et al., 2016; Middendorp et al., 2016; Wilson et al., 2019), all of which were in cloud or montane forest. Over 33% of the studies were on a patch scale followed by local-scale studies and regional scale studies. There were only 5 pantropical/global assessments, which drew comparisons of restoration processes across distant mountain ranges or across continents (Aide et al., 2011; Byers, 2017; González-Espinosa et al., 2007; Guariguata, 2005; Newmark et al., 2017).

These findings are in line with trends in tropical forest restoration, where "neither the scale of scientific studies nor the restoration projects being implemented have matched the ambitious forest landscape restoration plans that are being proposed" (Holl, 2017). The small spatial scales, often at the stand level, show that TME restoration science is so far a patchy-small scale endeavour.

While most studies were primary research including fieldwork, secondary research made up less than 15% of all studies, mostly as reviews (Chazdon et al., 2020, Diego Leon et al., 2011; Guariguata, 2005; Roose et al., 1993), reports (Hakim & Miyakawa, 2018; Miranda-Castro & Padrón, 2005), model studies (Gilroy et al., 2014; Newmark et al., 2017; Räger et al., 2011) and as five remote sensing studies (Arasumani et al., 2020; Camelo et al., 2017; Chen et al., 2014; Jacob et al., 2016; Liu et al., 2020).

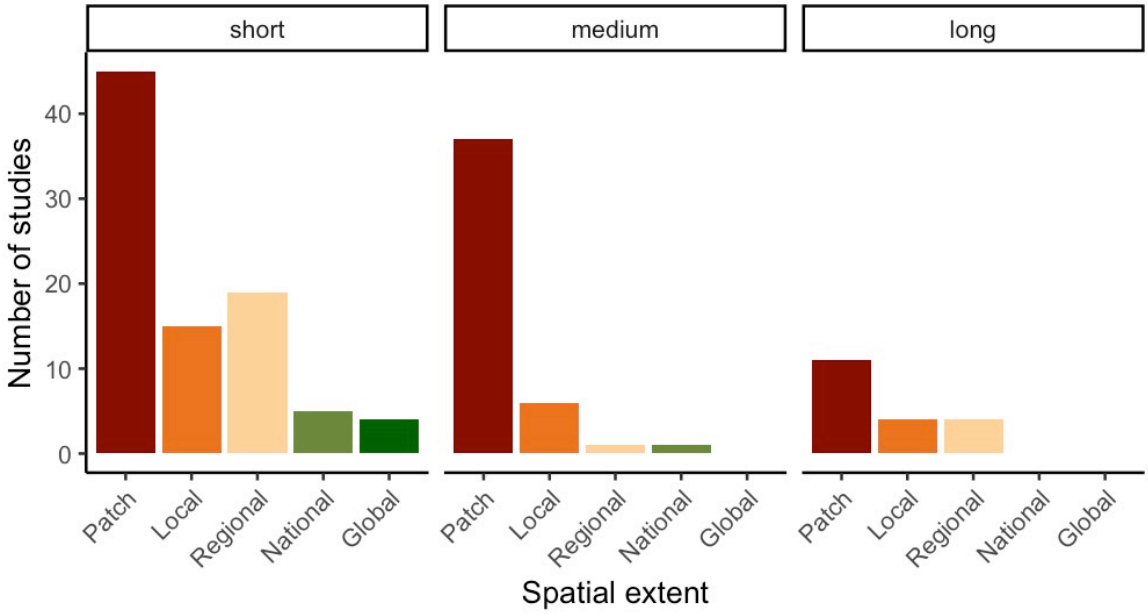


Figure 2. 2: Most TME studies are largely conducted on small spatial scales and in the short term. Spatial categories are Patch: 10–102 km², Local: 102–103 km², Regional: 103–105 km², National: 105–106 km², Global: >106 km². Temporal categories are short term < 1year, medium term = 1-5years, long-term: >5 years. Figure generated in R studio version 3.6.2 (R Core Team, 2019) and using the package 'ggplot2' (Wickham, 2016).

Dominance of ecological goals and metrics

Most of the reviewed restoration studies had an ecological focus, with over 83% of studies addressing ecological goals and research questions. Most restoration studies aimed to recover supporting ecosystem services, with forest structure recovery being the most frequent goal, followed by recovery of a species or a combination of species (i.e., biodiversity recovery) and soil recovery (Figure 2.3). Regulating ecosystem services, especially water and erosion regulation were targeted due to the importance of mountain areas in providing and regulating the hydrological cycle (Crespo et al., 2010; Muñoz-Villers & McDonnell, 2013). Plant community variables such as plant species diversity, vegetation structure and plant recruitment were the most frequently studied (Supplementary Figure 1.2a and c) (Calle et al., 2013; Galindo et al., 2017; González-Espinosa et al., 2007; Lemenih & Teketay, 2006; Posada et al., 2000).

Over 39% of the studies assessed a combination of biotic and abiotic variables or a combination of vegetation and faunal components and as such took a more holistic 'ecosystem approach' (Supplementary Figure 1.2b) (Gunaratne et al., 2010; Le Stradic et al., 2018; Rurangwa et al., 2020; Sanchez-De Leon et al., 2003; Slocum et al., 2006), and 14% of studies assessed animals as part of restoration efforts (Supplementary Figure 1.2c), such as bird communities (Edwards et al., 2017; Newmark et al., 2017; Shoo et al., 2011; Wilms & Kappelle, 2006) or arthropods (Davies et al., 2020; Gutierrez-Chacon et al., 2020; Kattan et al., 2006; Marian et al., 2020).

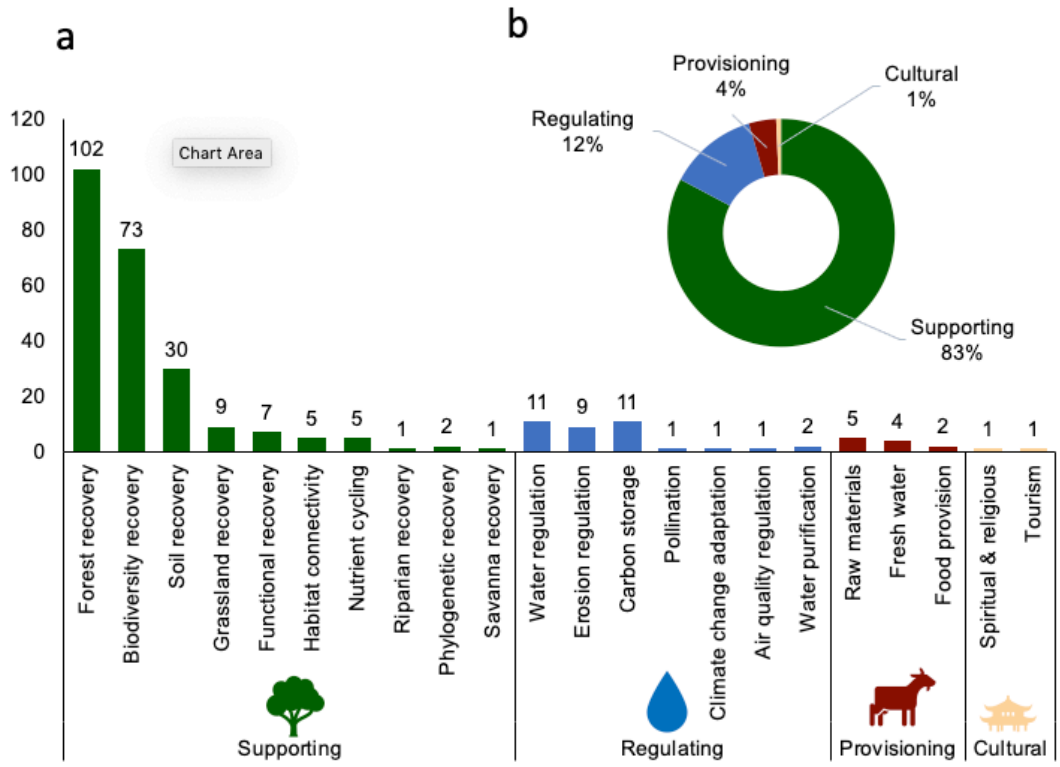


Figure 2. 3: Dominance of supporting ecosystem services as restoration goals. Goals (ecosystem services) and objectives (measurable targets) of restoration studies A) number of objectives for each ecosystem service goal B) grouped into the four ecosystem service goals. Figure generated in Excel.

While many studies assessed compositional variables (such as species richness, diversity, and composition of vegetation structure) the study of functional traits and functional diversity was comparatively underrepresented. In highly diverse ecosystems the inclusion of functional ecology in restoration assessments, such as through measurements of functional diversity, has been shown

to better predict restoration success and trajectories than vegetation composition (Brancalion & Holl, 2016). Incorporating functional trait assessments in restoration research might be especially relevant in tropical mountain ecosystems, due to the strong influence of climate change and the need of species to migrate upslope to track temperatures (Eller et al., 2016; Matos et al., 2020). For example, in a Nigerian montane forest dispersal mode and seed traits of the forest source population played a large role for the colonization of adjacent naturally regenerating pastures, with small animal-dispersed red seeds being dispersed more often and the furthest (Barnes & Chapman, 2014). Hence, to passively restore degraded forest, the functional-trait composition of adjacent parent populations should be studied to determine colonization potential.

Only two studies aimed at restoring cultural ecosystem services and only few studies involved communities or looked at socio-economic variables. This neglect of socio-ecological dimensions is in line with the current underrepresentation of social outcomes and economic cost calculations in restoration of other tropical ecosystems (Dimson & Gillespie, 2020). The international principles and standards for ecological restoration by the Society for Ecological Restoration (Gann et al., 2019) highlight that restoration needs to '*effectively engage a range of stakeholders, and fully utilize available scientific, traditional, and local knowledg*e', as the integration of diverse types of knowledge helps improve ecological, social, and cultural restoration goals. Local and traditional ecological knowledge can aid with species selection, identification of successional trajectories and species interactions, as well as the right choice of management strategies involving cultural practices from prescribed burns to grazing management (Gann et al., 2019). Some reviewed studies made use of local ecological knowledge by consulting local communities about values and preferences for tree species (Wilson & Rhemtulla, 2016) or about land use legacy and age of study sites (Edwards et al., 2017; Jacob et al., 2016; Muñiz-Castro et al., 2006; Van Do et al., 2010). Only a few studies included economic calculations to estimate cost and/or revenue from timber of

restoration plantings (Cole et al., 2012; Joshua Atondo-Bueno et al., 2018; Newmark et al., 2017; Trujillo-Miranda et al., 2020).

Initial degradation due to agriculture and pasture use

Across all TME initial ecosystems degradation occurred mostly due to agricultural conversion and cultivation (53% of all studies), pasture use (51%) or deforestation and degradation (e.g., logging, clearing, selective logging etc, 46%) (Figure 2.4). Plantation use, fire and natural hazards played a substantial role in degradation, too (10-19% of studies). In most studies initial degradation resulted from a combination of multiple degradation causes.

Initial degradation is however site-specific and result in intricate ecological effects posing barriers to restoration, ranging from faunal and vegetation changes, to modified soil and hydrology (Supplementary 1.3). Arrested succession, i.e., an ecosystem being halted in an early successional state, was a prominent effect of degradation addressed across TMEs (Sarmiento, 1997; Sarmiento et al., 2015; Slocum et al., 2006). Reductions in species, functional or genetic diversity or vegetation changes or reductions in vegetation cover or structure were a direct result of initial degradation and particularly prevalent in the highly threatened cloud forests and in montane forests (Gallegos et al., 2015; Gunaratne et al., 2010; Ortega-Pieck et al., 2011; Peláez-Silva et al., 2019; Slocum et al., 2006).

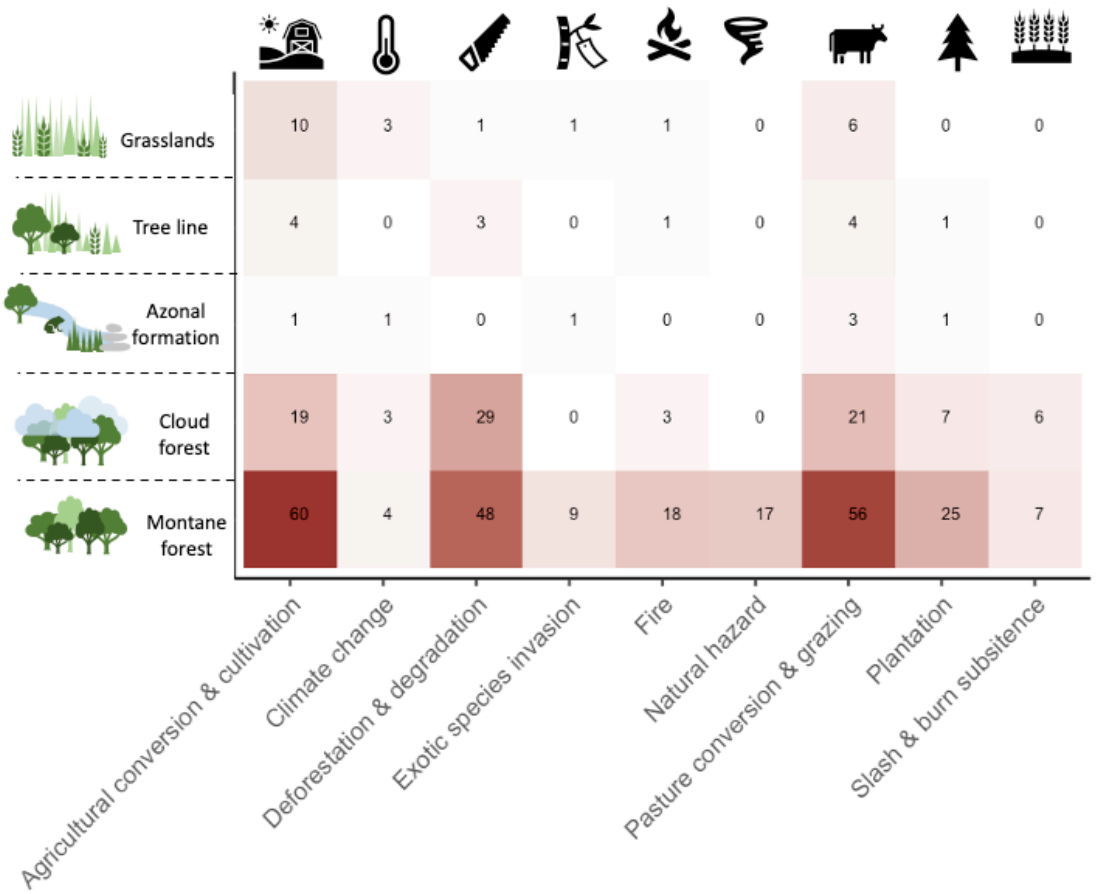


Figure 2. 4: Agriculture, pasture conversion and deforestation are main drivers of initial degradation across TME. Displayed are selected drivers of degradation (mentioned more than 10 times across ecosystems) in each TME (for all drivers of degradation see Supplementary 1.4a, analogous plot for effects of degradation can be found in Supplementary 1.3 and 1.4b). Figure generated in R studio version 3.6.2 (R Core Team, 2019) and using the package 'ggplot2' (Wickham, 2016).

Natural regeneration and seedling planting dominate restoration interventions across TME.

Across all TME, natural regeneration was the intervention most frequently studied (43% of all studies), followed by seedling planting (25%) and invasive plant management (18%) (Figure 2.5 & Supplementary 1.5) and often a combination of multiple restoration interventions was investigated.

Seedling planting was mainly deployed in cloud forest and montane forest (Fig 2.5), mostly using a few plant families (Supplementary Figure 2.5b): *Fabaceae* to enrich the soil with nitrogen, *Myrtaceae* (especially *Eucalypts*) because of fast growth traits and suitability for plantation growth

(Thijs et al., 2014) and *Fagacea*e because of their high conservation value in Costa Rica and Mexico (Bare & Ashton, 2016; Garcia-De La Cruz et al., 2016; Muñiz-Castro et al., 2015; Zhang et al., 2012). 75% of active restoration studies used exclusively native plant material, 17% used non-native material and 8% studied a mix of native and non-native plants (Supplementary 1.6a). Non-native plants were introduced due to easy acquisition, economic viability, fast growth, and facilitative effects for native forest recovery (Borja et al., 2018). In 44% of active restoration studies restoration vegetation was animal dispersed, and in 34% wind dispersed (Supplementary 1.6b).

Plantations were used as a restoration intervention in cloud and montane forests, with exotic plantations frequently studied in montane forest (Fig. 2.5). Direct seeding of species and enrichment planting was most frequently studied in montane forest. A host of additional experimental methods were tested only a few times in the TME restoration studies, such as topsoil, seed bank and hay transfers in the mountain grasslands of the *Campos Rupestres* (Le Stradic, Buisson, & Fernandes, 2014; Le Stradic et al., 2018), applied nucleation, assisted migration (Gomez-Ruiz et al., 2020; Toledo-Aceves & Del-Val, 2020) and inoculation of cloud forest seedlings with arbuscular mycorrhizal (Aide et al., 2011; Urgiles et al., 2009) (Supplementary 1.5a).

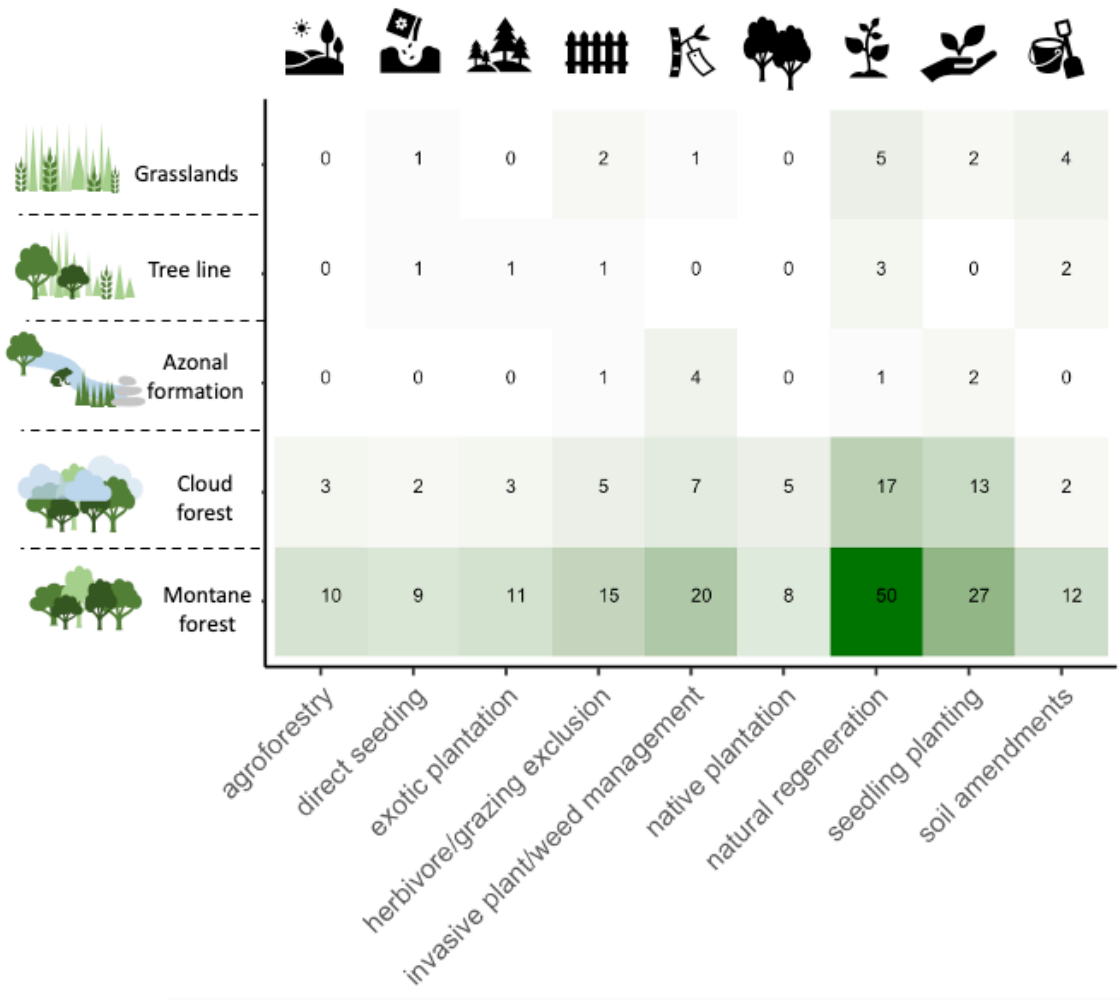


Figure 2. 5: Across TMEs natural regeneration is the most studied restoration intervention, followed by seedling planting and invasive management. Displayed are selected restoration interventions in the tropical mountain ecosystems (mentioned more than 10 times across all ecosystems, see Supplementary 1.5a for all restoration methods). Figure generated in R studio version 3.6.245 and using the package 'ggplot2'46.

Active and passive restoration in mountain forests following agricultural degradation.

In cloud forests, deforestation, pasture use and live-stock grazing caused harsh abiotic conditions following land abandonment and competition by exotic pasture grasses hindered vegetation recovery (Braasch et al., 2017; Hernandez-Ladron De Guevara et al., 2012; Muñiz-Castro et al., 2006; Pinto et al., 2015). Natural regeneration was the restoration method most often studied in these ecosystems, followed by seedling planting and invasive management.

In montane forests, livestock farming, and agriculture create forest-pasture mosaics where forest recovery is limited by seed dispersal, competition with exotic pasture grasses, seed predation and herbivory, and unfavourable site conditions (Holl et al., 2000). This required active restoration interventions through tree or shrub seedling planting (Holl et al., 2000), nucleation planting (Rojas-Botero et al., 2020) or establishment of perching structures (Derroire et al., 2016; Rhoades et al., 1998; Sheldon & Nadkarni, 2013) to jointly overcome biotic and abiotic limitations (Holl et al., 2000). When natural hazards like hurricanes or landslides (Sprenkle-Hyppolite et al., 2016) caused soil erosion, restoration in montane forests was focussed on recovering regulating ecosystem functions, such as erosion regulation, water provision and hazard prevention through catchment management (Borja et al., 2018), restoration of vegetation cover through revegetation and afforestation (Borja et al., 2018; Calle et al., 2013) and natural regeneration (Pang et al., 2018). In montane forests of Hawaiian Acacia invasive species, especially feral ungulates caused degradation. Hence, restoration interventions aimed at recovering native biodiversity through a mixture of invasive control, fencing and landscape zonation (Cole & Litton, 2014; Ibanez & Hart, 2020; Scowcroft & Jeffrey, 1999).

In TMEs at lower, more accessible, and inhabited elevations, restoration often involved land-sharing approaches such as integrative agroforestry practices, through creation of live hedges and fences on working lands (Roose & Ndayizigiye, 1997; Zahawi, 2005), underplanting of seedlings in cardamom plantations (Dhakal et al., 2015) or on-farm tree planting to improve ecosystem service provision (Wilson & Coomes, 2019). On the other hand, in ecosystems less favourable for human inhabitation, land sparing approaches to restoration seemed more common, for instance natural regeneration of cloud forests in pastures (Bautista-Cruz et al., 2012; Davies et al., 2020; Del Castillo & Blanco-Macías, 2007; Pethiyagoda & Manamendra-Arachchi, 2012).

Intense active restoration in grassland following strong land use legacies.

Agricultural conversion most prominently caused initial degradation in mountain grasslands (Figure 2.4), followed by pasture conversion for alpacas and/or cattle, quarrying and mining, and climate change (see Supplementary 1.4a with all degradation drivers). This resulted in strong biodiversity and vegetation change, soil, and hydrological constraints (Supplementary 1.4b).

Commonly, an intense land use legacy reduced restoration success in mountain grasslands – there seemed to be a disturbance threshold beyond which the damage caused by the disturbance was irreversible, mostly related to the soil being too disturbed for native vegetation to recover (Abadín et al., 2002; Sarmiento et al., 2003) or due to low seed dispersal (Le Stradic, Buisson, & Fernandes, 2014; Le Stradic et al., 2018).

Natural recovery was generally poor in mountain grasslands, and more intrusive active restoration interventions were needed to restore ecological functions following degradation, such as soil amendments or species introductions. In the *Páramos* centuries of fallow agriculture coupled with overgrazing left the soils depleted and low in nutrients. Soil organic matter and fertility were restored through necro mass incorporation, manure fertilization and transplantations of mats of nurse plants to provide seed sources and improve soil quality (Sarmiento et al., 2015). Likewise, in the Brazilian *Campos Rupestres*, quarrying and mining led to soil and vegetation losses and species invasion, hindering natural regeneration, and demanding more intense restoration methods (Le Stradic, Buisson, & Fernandes, 2014; Le Stradic et al., 2018). However, even hay or topsoil transfer still proved unsuccessful in restoring the native grassland communities (Le Stradic, Buisson, & Fernandes, 2014; Le Stradic et al., 2018). Similarly, intense restoration methods were trialled and recommended to restore ancient grasslands in the Western Ghats, which suffered species extinction and habitat loss following tree invasion from exotic forestry plantations (Arasumani et al., 2018, 2020; Raman, 2006). For this purpose, Arasumani et al. (2020) used remote sensing to assign

priority areas for restoration and invasive tree removal. Their study was the only mountain-grassland restoration study to date that used remote sensing to inform grassland restoration and showcased a promising avenue of using imagery classification for restoration management.

Despite the apparent difficulty to restore mountain grasslands, the knowledge of tropical mountain grassland restoration seems to be at an early stage compared to tropical mountain forest restoration. Further research will be needed to overcome the barriers in mountain grassland restoration, find cost-effective restoration techniques, and create grassland restoration protocols and knowledge databases.

Mixed success of the most studied restoration interventions

We studied restoration success of studies based on how many of the specified objectives (defined in Figure 2.3) a restoration intervention achieved (low success =no objectives achieved, medium success = some but not all objectives achieved, high success = almost all/all objectives achieved). Objectives ranged from recovery of biodiversity, soil functions, water and erosion regulation, pollination to food provision and spiritual objectives. The three most prominent restoration interventions across all TME (natural regeneration, seedling planting and plant/weed management) showed mixed levels of success, with most studies classified as 'medium success' (Fig. 2.6). In cloud and montane forest, more than half of the restoration interventions showed medium success, about 20-30% high success, and about 10% low success (Fig. 2.6a). Studies with low success were particularly frequent in grasslands and the tree line ecotone.

Of all restoration methods, strategies removing disturbance (invasive plant management or herbivory/grazing exclusion) showed the highest success. Removing invasive feral pigs from Hawaiian montane forest for instance, improved soil conditions and nutrient regeneration and led to large increases in understory vegetation (Long et al., 2017). In Sri Lankan montane forests a mixture of invasive grass removal, creation of fire breaks, protection of individual trees and

isolation of seedling root systems from competitors proved to be successful (Gunaratne et al., 2014), showcasing that often-multiple strategies removing disturbance need to be combined.

Strategies involving planting or seeding had mixed results and a trend towards medium success (Fig 2.6b). For instance, in Mexico mid-to-late successional cloud forest Oak seedlings were transplanted into abandoned pastures and species showed survival rates between 50 to 70% due to lower radiative stress resulting from the prevailing cloud cover (Muñiz-Castro et al., 2015). Planting has been concluded to be a good option to restore forest and soil quality, however its success depends highly on land-use intensity, initial soil characteristics and species choice (Mendoza-Vega et al., 2020).

Agroforestry interventions such as planting of pasture trees or living hedges showed relatively high success levels (~40% high success, 60% medium) and often succeeded in reaching combined goals of reducing erosion, enhancing water quality (Roose & Ndayizigiye, 1997) and improving soil conditions for natural regeneration (Rhoades et al., 1998). Plantations, whether exotic or native, showed mostly medium success. Natural regeneration showed mixed results throughout, and its success was strongly dependent on the local site conditions, on proximity to forest for seed rain and on surrounding and remnant vegetation (Calle & Holl, 2019; Holl, 1999; Meli et al., 2017).

Extensively used TME, such as selectively logged or mixed-plantation systems recovered biodiversity and vegetation structure well under natural regeneration (Liu et al., 2014; Mullah et al., 2011). Abandoned agricultural land recovered more slowly due to habitat constraints, dispersal limitations or competition, and often assisted restoration interventions through weeding, direct seeding or fertilization are needed (Cole et al., 2011; Gunaratne et al., 2011; Sarmiento & Bottner, 2002). In heavily disturbed systems such as pastures invaded by exotic grasses, environmental filtering was strong and restoration success was low without active interventions such as seedling planting (Alvarez-Aquino et al., 2004), systematic planting or soil/seed bank transfers (Rojas-Botero et al., 2020).

Our review showed that active restoration planting generally did not help reach restoration goals more successfully than natural regeneration and a site-specific approach based on landscape and micro-site attributes will be needed in TME to choose adequate restoration interventions, as previously shown for lowland tropical forests (Meli et al., 2017). Deciding on an optimal site-specific approach requires identifying the local abiotic and biotic habitat factors constraints recovery and weighing off costs and benefits of different restoration interventions in the light of finance, time, and labour constraints (Cole et al., 2011).

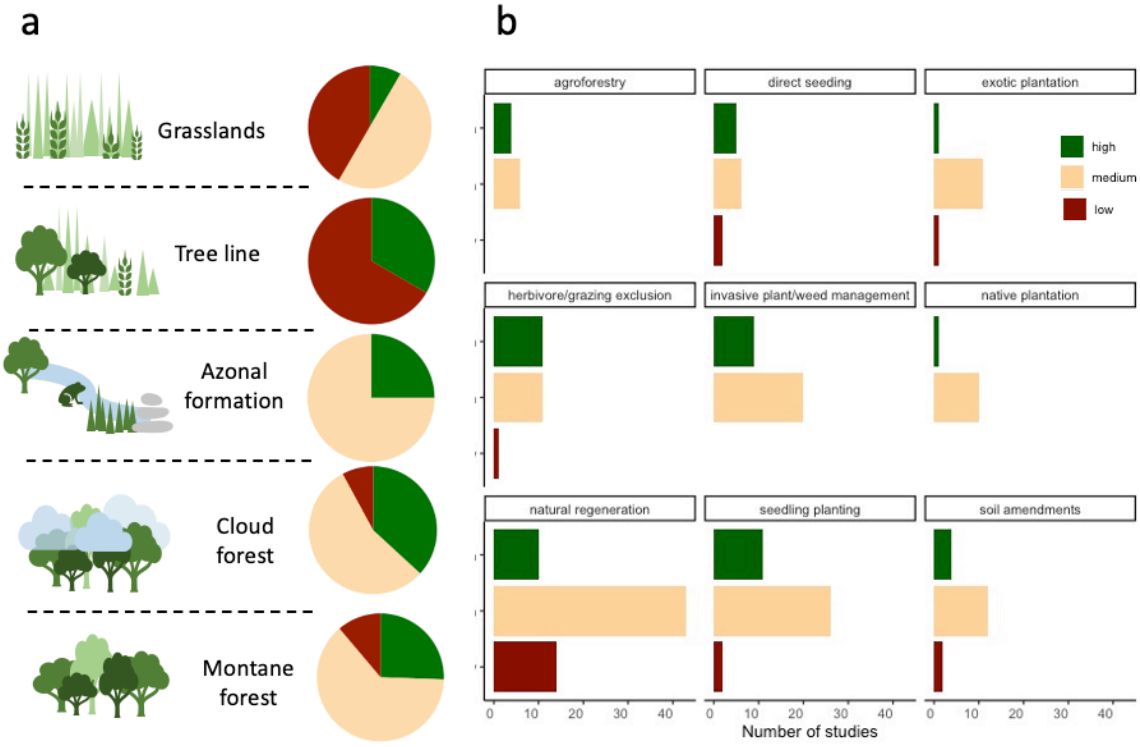


Figure 2. 6: Mixed success rates across restoration interventions. a) Success rates of restoration in each ecosystem b) Success for each of the most prominent restoration interventions (more than 10 times studied) across all ecosystems. All figures generated in R studio version 3.6.2 (R Core Team, 2019) and using the package 'ggplot2' (Wickham, 2016).

Seed dispersal and habitat constraints limit restoration success

Restoration success was mostly limited by abiotic habitat constraints and seed dispersal (Fig. 2.7). Habitat constraints arose because of the harsh mountain environments, with low air temperatures and daily temperature amplitudes that often exceeded seasonal and annual variation (Uhlig, 1992; Wesche et al., 2008), recurring frosts (Joshi et al., 2019), as well as erosion processes due to strong rains, winds, and landslides (Roose & Ndayizigiye, 1997; Singh et al., 2001). These factors, in combination with a naturally rugged topography, contributed to acute losses of vegetation, shallow soils and depleted soil seed banks, making it difficult for vegetation to establish (Pang et al., 2018; Wilcke et al., 2003). As a consequence, this often resulted in recruitment limitation (Diaz-Garcia et al., 2017; Doust et al., 2006; González-Espinosa et al., 2007; Howorth & Pendry, 2006; Thijs et al., 2014).

Limitations due to animal seed dispersal - the most common form of seed dispersion in TMEs (Gomes et al., 2008; Holl, 1999) – were exacerbated by habitat loss, fragmentation and degradation which disrupt seed dispersers' abundances and movement pathways (Cole et al., 2010; De Guevara et al., 2012; Gomez-Ruiz et al., 2020; Middendorp et al., 2016; Pérez-García & del Castillo, 2017). Further, negative biotic interactions such as competition between grasses and ferns, pests, and diseases, as well as herbivory and seed predation compromised restoration success.

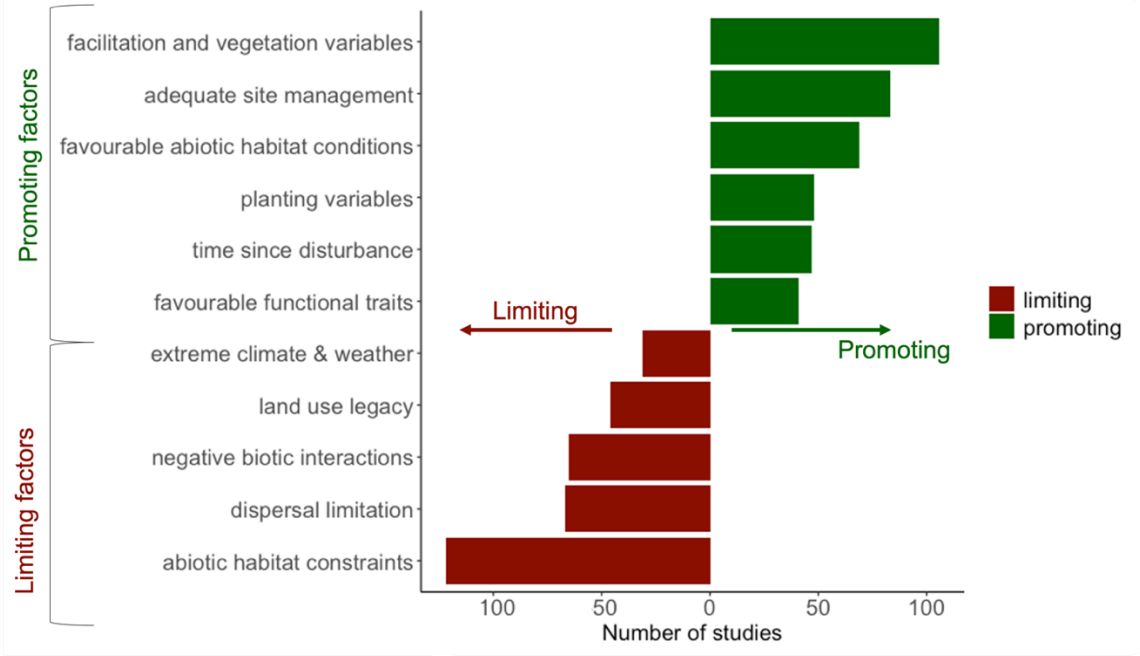


Figure 2. 7: Habitat and dispersal constraints limit restoration success. Factors limiting and promoting restoration success (mentioned more than 30 times across all ecosystems). Factors are arranged on a negative side of the axis if limiting (red), and positive if promoting (green) restoration success (see Supplementary 1.7a and b for bar plots of all limiting and promoting factors in each ecosystem). Breakdown of the top three limiting factors: Abiotic habitat constraints encompasses nutrient, water, light and micro-climate limitation, germination, and recruitment limitation. Dispersal limitation encompasses distance from seed source, lack of dispersers, migration limitation. Negative biotic limitations encompass competitive interaction, seed predation, herbivory, pest & disease. Breakdown of the top three promoting factors: facilitation and vegetation variables include structural complexity, proximity to reference habitat, connectivity, remnant vegetation, intra- and interspecific facilitation. Adequate site management includes invasive removal and control, herbivory control, agricultural management, disturbance removal, site protection etc. Favourable abiotic habitat conditions include beneficial micro-climate, soil conditions, litter properties, light and water availability etc (see Supplementary 1.11 for all categories). Figure generated in R studio version 3.6.2 (R Core Team, 2019) and using the package 'ggplot2' (Wickham, 2016).

The top promoting factors for restoration success were facilitation and vegetation composition and structure that promotes plant establishment and growth, for instance structural complexity of vegetation, remnant vegetation and proximity to natural habitat. As part of this, many studies specifically mentioned facilitation processes which ameliorate micro-environmental site conditions and often contributed to increased restoration success (Bueno & Llambí, 2015; Galindo et al., 2017; Gallegos et al., 2016; Riviere et al., 2008). Facilitative interactions were deliberately employed in restoration studies, e.g. through applied nucleation tree island planting (Cole et al., 2010; Rojas-Botero et al., 2020), exotic plantations to recover native understories (Peláez-Silva et al., 2019),

bracken ferns as facilitators for late succession tree seedlings (Gallegos et al., 2015) or planting to attract seed dispersers (Barnes & Chapman, 2014; Cole et al., 2010; Hernandez-Ladron De Guevara et al., 2012; Holl et al., 2000). Moreover, site management variables related to removing disturbance, such as eradication of invasive species (Bingli et al., 2020; Mohandass et al., 2016), and protection of restoration sites (Jacob et al., 2016; Wassie et al., 2010) were mentioned as promoting success. Furthermore, planting variables associated with the right choice of local planting methods, ranging from appropriate seed bank transfers (Rojas-Botero et al., 2020), shade tree (Townsend & Masters, 2015) and multi-species planting (Liu et al., 2014), and direct seeding (Cole et al., 2011) helped improve restoration outcomes.

Restoring the distinct nature of TME in the light of climate change

Climate change will irreversibly change the ecology of many of the world's tropical mountains (Nogués-Bravo et al., 2007). Mountain ecosystems are projected to undergo 'elevation-dependent warming', a process by which the rate of warming is amplified with elevation (Pepin et al., 2015), resulting in new climate niches. At the same time, many established species will track temperatures through upslope migration, as observed in the Andes (Fadrique et al., 2018). Climate-related limitations such as habitat and recruitment constraints are already a prevalent limiting factor across many of the reviewed restoration studies and may be exacerbated with progressing climate change and its interaction with land use changes (Peters et al., 2019).

This will require designing tailored restoration interventions based on the expected eco-climatic changes for a given TME. However, only four montane forest studies and three cloud forest studies reviewed specifically addressed climate change as an initial degradation factor (Figure 2.3). Tropical montane cloud forests, for instance, are expected to experience shifted cloud and precipitation distributions, resulting in tree mortality and altitudinal migration (Feeley & Rehm, 2015). This may require strategies such as assisting species to migrate upslope to track temperatures

(Gómez-Ruiz et al., 2020; Toledo-Aceves & Del-Val, 2020). Many endemic cloud forest tree species have small population sizes, high habitat specificity and low dispersal, due to lack of habitat connectivity, leading to shifted plant-animal interactions due to climate change which will need to be considered under climate change (Toledo-Aceves & Del-Val, 2020). In mountain grasslands, drought is forecasted to intensify, and a functional eco-physiological approach will be needed to design conservation actions (Matos et al., 2020).

There are still large research gaps in the context of restoration under climate change, such as studies on assisted migration and germination potentials for most species and studies on an ecosystem-by-ecosystem basis on climate change implications for TME restoration. Further, the creation of databases with functional traits that are key to climatic tolerance for tropical mountain plant species will help design restoration interventions that leverage facilitative effects and biotic interactions to improve micro-site conditions and provide local refugia.

Future directions for research

While mountains have long been targeted for conservation due to their unsuitability for agriculture and other forms of anthropogenic use ('High and Far' bias of protected areas (Joppa & Pfaff, 2009)), the UN Decade of Restoration provides a crucial policy window for large-scale restoration beyond tree planting and for the incorporation of many diverse kinds of ecosystems and restoration approaches.

This synthesis is the first of its kind to show the prevailing trends in geographical and ecosystem bias in tropical mountain restoration research, highlighting pre-dominant research methods and scales, and reviewing restoration interventions and limiting and enabling factors for restoration success. However, we found large gaps in tropical mountain restoration research, ranging from underrepresentation of non-forested ecosystems and socio-economic restoration goals to lack of use

of technologies and scarcity of research on implementation and financial viability of restoration projects. Hence, we devise five directions for future research:

1. Given the overwhelming amount of TME studies on a patch and local scale identified here, research on **large-scale restoration** (von Holle et al., 2020) will be needed to scale up mountain restoration to a landscape level. Geo-spatial technologies, such as remote sensing could aid with this, for instance through restoration potential and opportunity assessments for entire mountain ecosystems. Science-based open data initiative like the newly launched portal RESTOR, pave the path for the application of remote sensing for large scale restoration purposes.
2. Studies on the **social dimensions of restoration** in tropical mountains are still scarce. Making restoration a socio-ecological endeavour is especially critical in dynamic social contexts (Fischer et al., 2020), such as tropical mountain ecosystem which are currently undergoing rapid land use changes and are often shared between human use and restoration (e.g., mountain plantations, pastures, and fallow cultivation). Hence, solving questions on land tenure, land abandonment, local preferences, and valued ecosystem services through local participation and partnerships will be key to restoring tropical mountain biodiversity in the long term.
3. Monitoring efforts are a key aspect of the UN decade on restoration (Monitoring Task Force, 2020). Advancing and applying **technologies and monitoring protocols** for tropical mountain restoration could help with increasing restoration success for instance through adaptive management. With most reviewed studies conducted in the short-term, long-term restoration trajectories in almost all ecosystems are uncertain. Drone technologies for instance, could provide exciting avenues for recurring monitoring of recovery of vegetation variables on a patch level in inaccessible and remote mountain areas, while also offering opportunities for assisted regeneration via aerial seeding (Elliott, 2016).

4. Thus far, tropical mountain restoration studies that explicitly consider the **changing climate in mountains,** and tailor restoration interventions to a dynamic future reference state are still scarce. The choice of climate resilient species with the right functional traits will be essential for mountain restoration to thrive under a changing climate. For instance, creating 'functional trait libraries' of reference ecosystems and understanding traits that underpin resilience in a specific ecosystem context will be useful to guide the selection of species and restoration approaches.
5. The paucity of restoration studies assessing **mountain grassland restoration** calls for a better inclusion of these underrepresented systems in future research. Despite the critical importance of alpine grassland systems for water regulation, soil maintenance and biodiversity (Christmann & Oliveras, 2020) and their large extent and degradation status there are very few successful restoration studies in alpine grasslands. The creation of alpine grassland restoration networks and restoration protocols could be a solid next step.

We hope this synthesis will help direct research priorities which can contribute to effectively restore tropical mountains in order to help mountain biodiversity flourish and ensure that communities that depend on their ecosystem services will thrive for decades to come.

Statements and declarations

Data availability statement

The data that support the findings of this study is publicly available on Mendeley Data (DOI: 10.17632/gvy63jydyg.1, URL: https://data.mendeley.com/datasets/gvy63jydyg/1)

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Author contribution statement

TC and IO jointly designed the study. TC conducted data analysis and led the writing of the manuscript under supervision of IO.

Competing interest statement

The authors declare no competing interests.

Methods

We followed the SALSA (Search-Appraisal-Synthesis-Analysis) method which includes the steps of 1) Searching for literature; 2) Appraisal to decide which studies are included; 3) Synthesis and 4) Analysis of studies, as this method has been shown to be applicable to assess knowledge trends and gaps in environmental science research (Mengist et al., 2020). We preferred this method to other established methods such as PRISMA, PICO or BACI, as we review across a wide set of ecosystems, contextual settings, metrics, and restoration interventions, and as such decided not to adopt a purely comparative approach (Mengist et al., 2020).

Literature search

Documents were searched on the databases Web of Science, Scopus and Science Direct (search date 20/10/2021) and on Google Scholar (search date 3/12/2020). We included papers for the period 1988 – 2020, as 1988 marks the foundation date of the Society for Ecological Restoration and 2020 marks the last year before the start of the UN decade for Restoration. We included articles written in any language.

We tested different search strings for Title-Abstract-Keyword (TAK) search of varying length and complexity on the four databases, with the goal of finding a search term that returned a high but manageable number of search hits and enabled high relevance of papers for answering the questions of the review (Supplementary 1.8). We decided on a simple search string that could be applied across all databases despite the different search algorithms. The search string was in English, hence yielding articles which are fully in English, or articles in another language with an English abstract. Our final search string across all databases included a word related to restoration (restor*), to tropics (tropic*) and to mountain environments *(mountain OR montane OR altitude OR alpine OR andes)* (detailed search string specification in Supplementary 1.8), but no word related to specific TME because the nomenclature across TME is not standardized. We decided to include the word 'Andes'

as it is often used instead of another mountain-related word. We further did a top up search in Google Scholar in order to include articles in other languages and from smaller national literature databases that might have been missed otherwise (such as Scielo). However, since Google Scholar only allows for full text search as opposed to TAK search, we only included the first 100 search results.

Appraisal: Inclusion and Exclusion

Our search string yielded a total of 980 articles, of which 532 remained for screening following manual and automated duplicate removal (Supplementary 1.9). First, we performed a title and abstract screening to exclude studies that 1) did not have a focus on ecological restoration sensu Society for Ecological Restoration (2002) and 2) were clearly neither in tropical nor mountain locations. We included studies on all kinds of restoration elements and interventions, including passive restoration (e.g., natural regeneration), assisted recovery (e.g., interventions that involve soil amendments, invasive species management etc) and active restoration (introduction of species, seedling planting, transfer of seed banks etc). Second, we did a full-text screening of the 245 selected articles to exclude 1) grey literature and 2) studies with locations outside tropical latitudes (i.e., outside 23.5°N and 23.5°S) and where study locations were not referred to as montane/mountain/alpine or not situated above 1000m asl. Finally, 178 articles were included in the analysis, most of which in English, and some in Spanish and Portuguese.

Analysis

We synthesized and coded studies using Microsoft Excel, where we extracted tags for the following categories: publication year, study site, study type, initial degradation causes, restoration metrics, restoration methods and success. Each of these categories had additional specific sub-categories. For instance, restoration metrics had the categories: restoration goals; studied response variables; taxonomic groups etc (Supplementary 1.10). Each study could have multiple tags for each sub-

category (e.g., for the restoration goals category each study got assigned as many goals as were mentioned/studied).

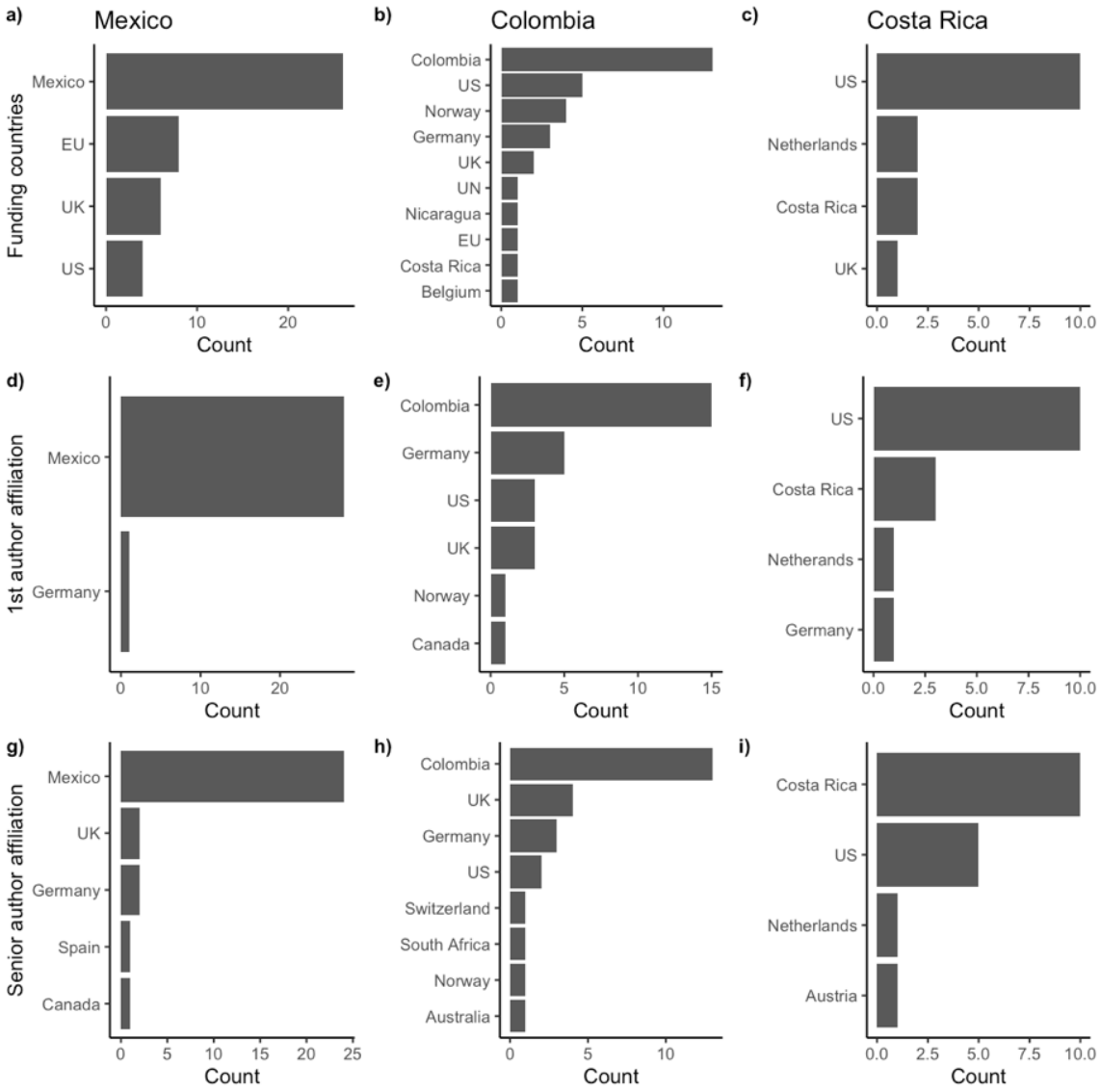
For the top three countries with the highest number of TME studies (Mexico, Costa Rica, and Colombia) we extracted first and last author affiliations and country of funding source to elucidate on funding flows and potential bias in geographical authorship.

As a measure of success of restoration interventions, we qualitatively assigned each study the categories low (no/almost no objectives reached), medium (multiple, but not all objectives reached) and high (all/almost all objectives reached), based on how many of its defined objectives were achieved (e.g., a native plantation intended to improve soil, water, vegetation structure and biodiversity but only improved soil qualities and structure would be assigned a medium value). We realize this metric is quite simplistic, but it allowed for general detection of trends across a multitude of different restoration studies that measured different goals, had different research designs and restoration variables of interest. For the same reason, we decided not to study effect sizes, as the study designs, treatments and measured target variables differed too much to give us adequate sample sizes for specific comparison.

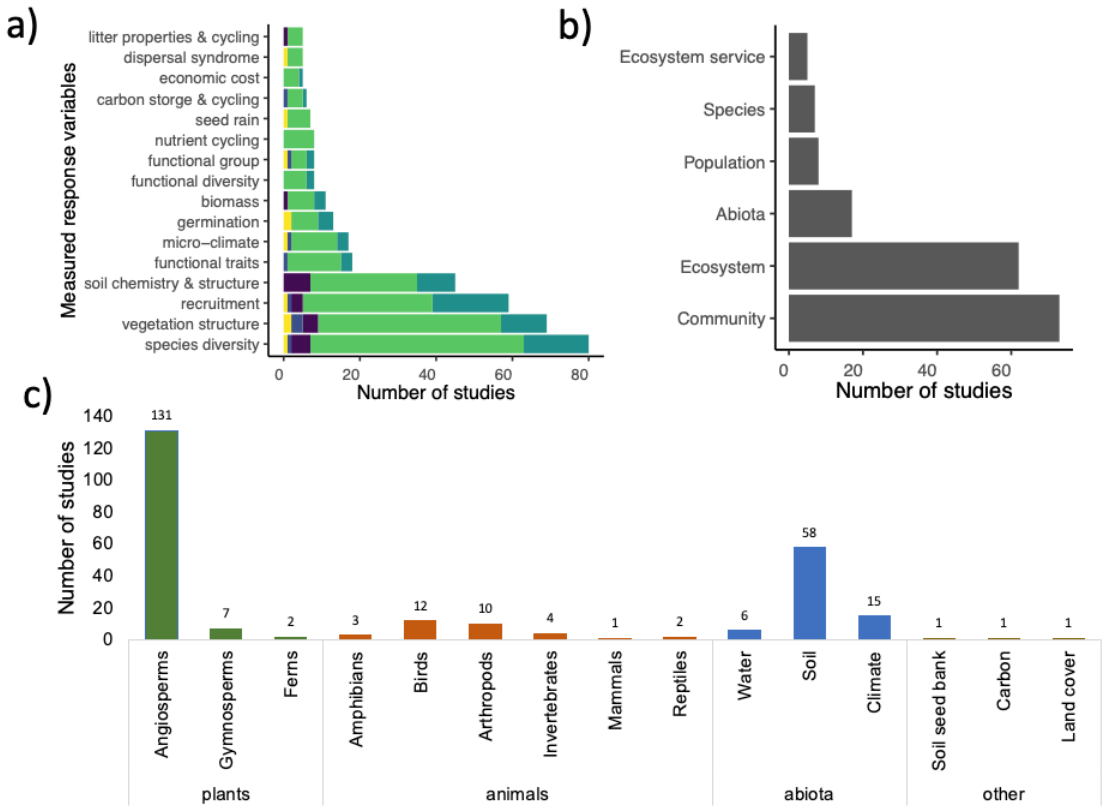
Data analysis and visualization was carried out in Excel and in R studio version 1.2.1335 (R Core Team, 2019) and using the package 'ggplot2' (Wickham, 2016).

Supplementary material

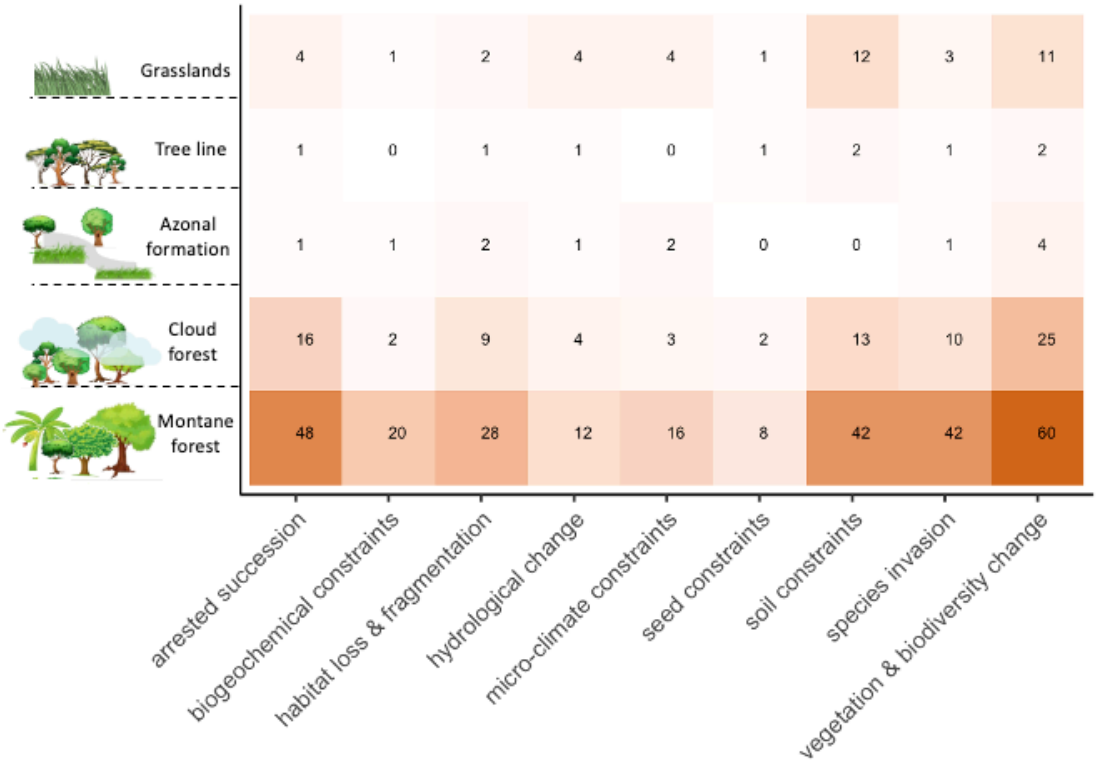
Supplementary results



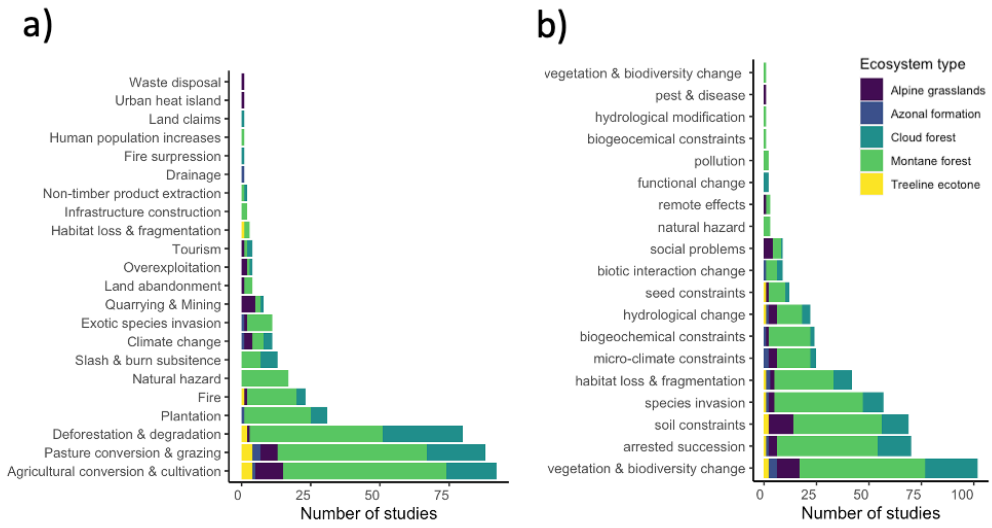
Supplementary 1. 1: Funding and affiliations of studies for the top three countries. a) – c) Funding countries, d) - f) Affiliations first author, g)- i) Affiliations last/senior authors



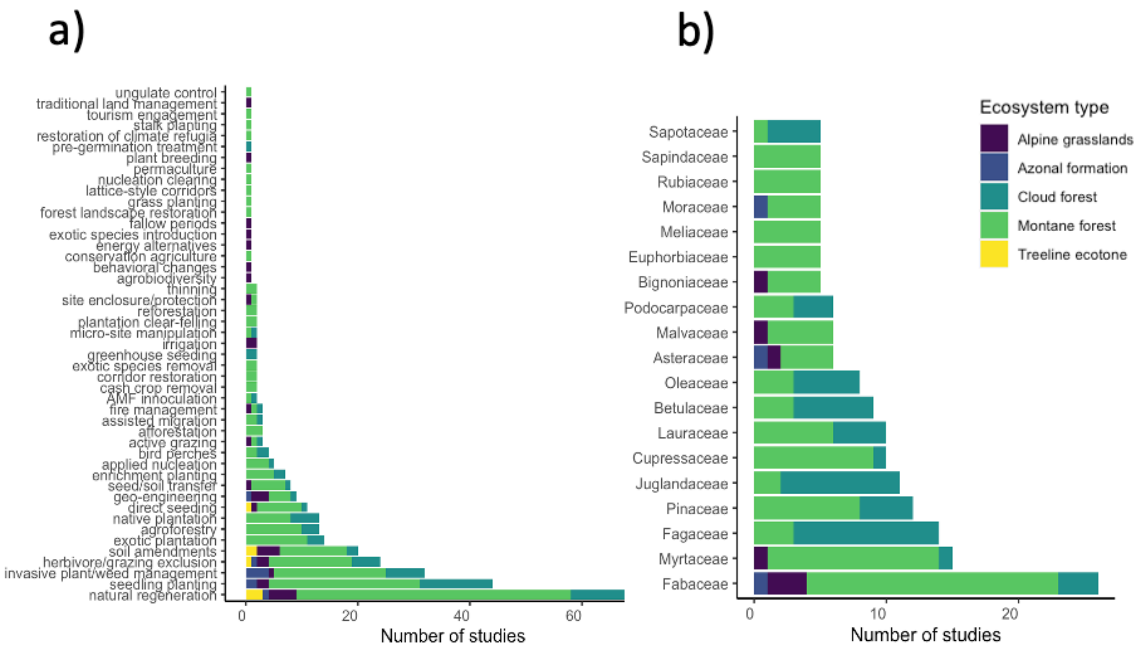
Supplementary 1. 2: A) Measured response variables of restoration studies measured more than 5 times, B) Ecological level of response variable C) Taxonomic group of response variable.



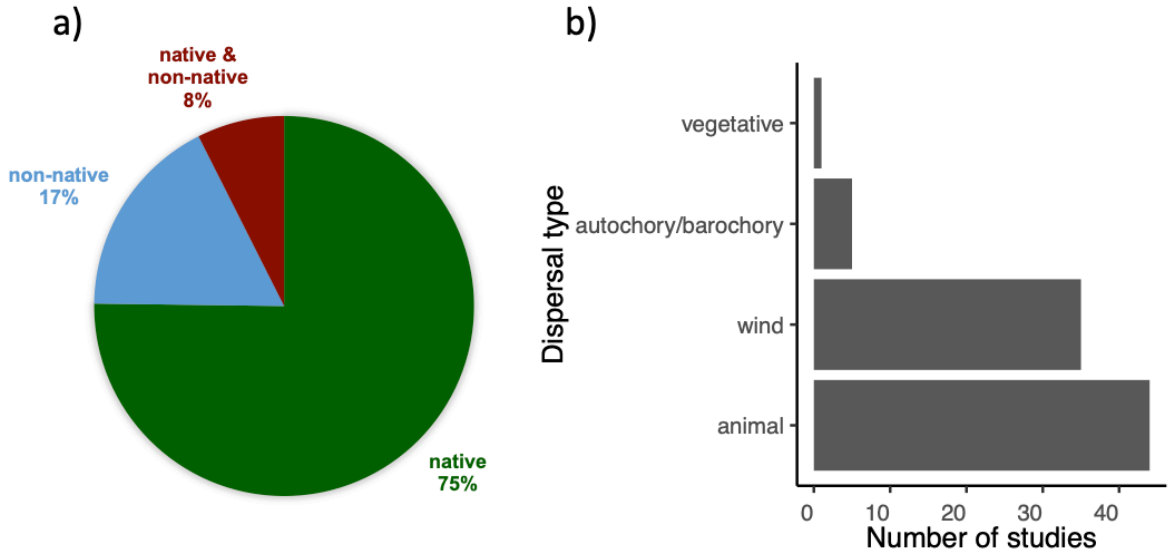
Supplementary 1. 3: Ecological effects of degradation (mentioned more than 10 times) in each ecosystem.



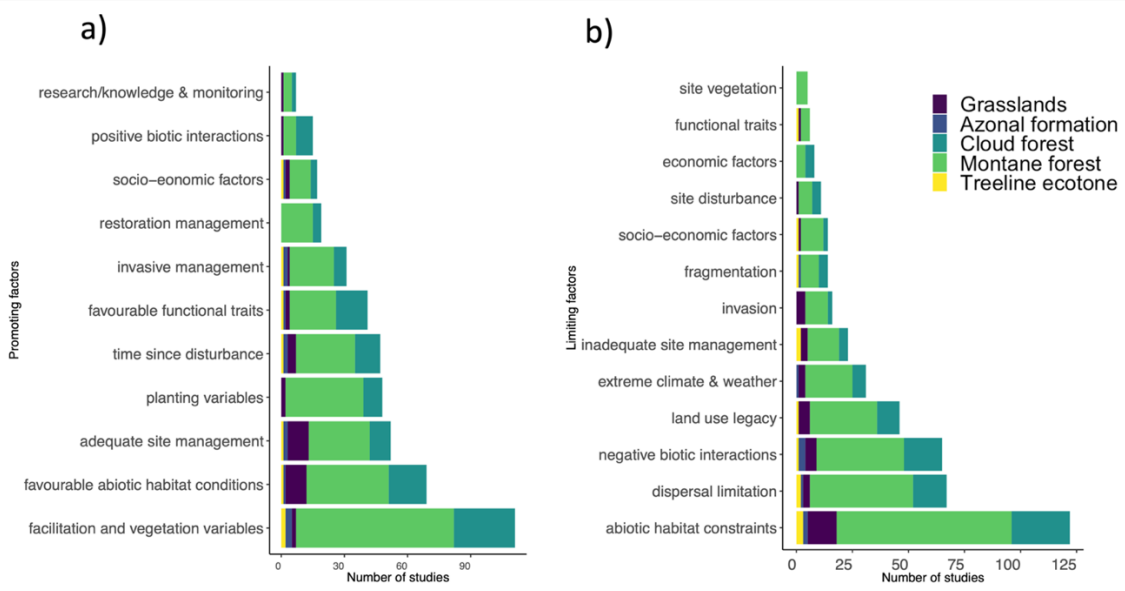
Supplementary 1. 4: a) All drivers of degradation mentioned in studies, b) All effects of degradation mentioned in the studies.



Supplementary 1. 5: a) All restoration methods studied, b) Most frequently planted families (mentioned more than 5 times) in studies with active restoration plantings.



Supplementary 1. 6: A) Origin of planted restoration material and B) dispersal type of planted material



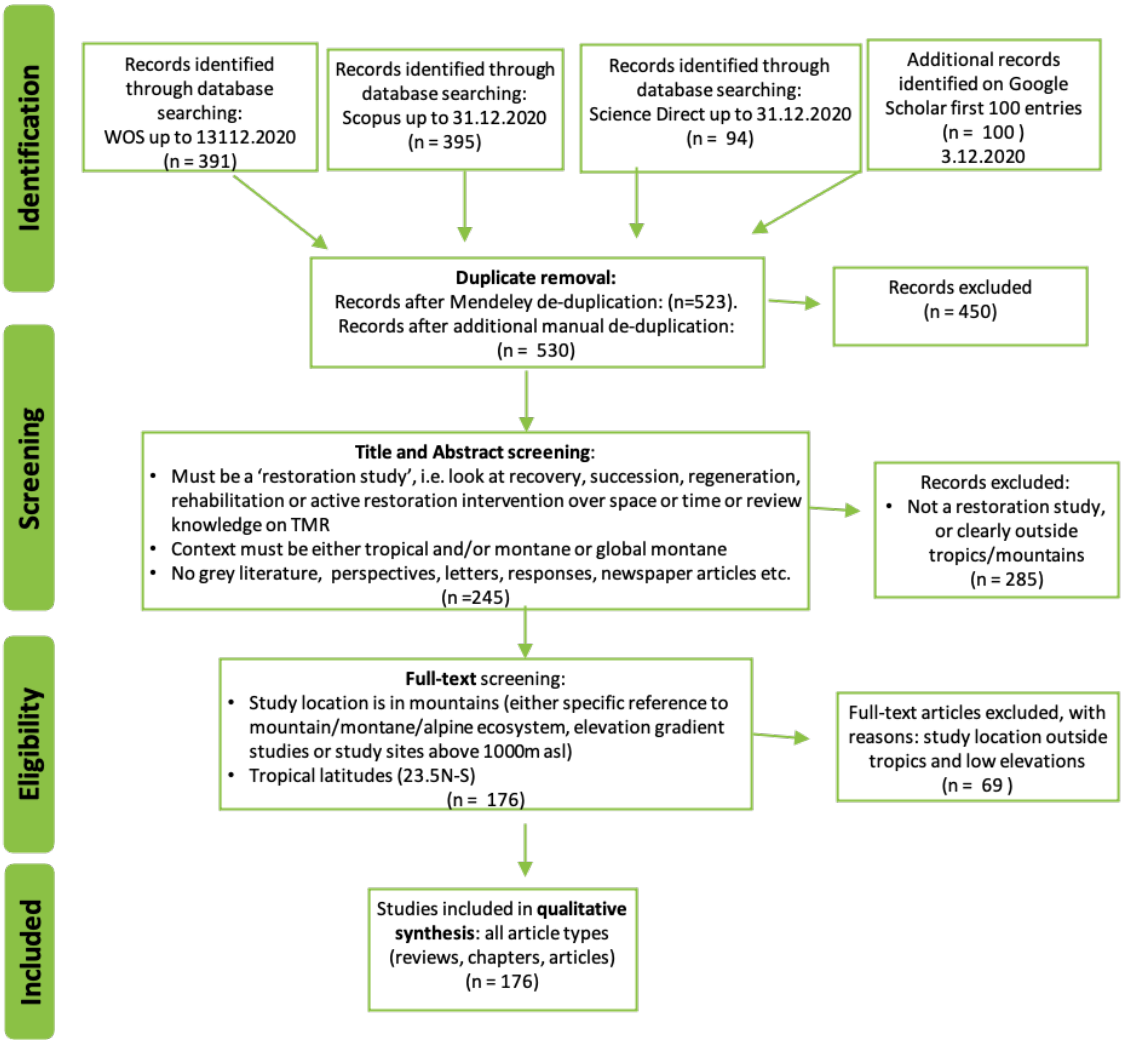
Supplementary 1. 7: All factors limiting or promoting restoration success in each ecosystem. a) Promoting factors, b) limiting factors

Supplementary methods

Supplementary 1. 8: Tested search strings on the four literature databases, including the number of articles per search string. Final search string is highlighted in bold.

Database	Search terms: in title, abstract and keywords of journal articles (research articles and reviews) from 1988-2020	Subject area/Research area	Number of articles
Scopus	restoration OR restor* OR rehab* OR recovery AND tropic* AND mountain OR montane OR elevation OR altitud* OR andes OR andean OR andine	Agric and biol., environmental science, earth, and planetary science	623
	restoration AND tropic AND mountain OR montane OR elevation OR altitude	Agric and biol., environmental science, earth, and planetary science	67
	TITLE-ABS-KEY (restoration OR restor* OR rehab* OR recovery AND tropic* AND mountain OR montane OR elevation OR altitud* OR andes OR andean OR andine AND forest OR grassland OR ecosystem) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (SUBJAREA, "AGRI") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "EART"))	Agric and biol., environmental science, earth, and planetary science	477
	TITLE-ABS-KEY (restoration AND tropical AND mountain OR restoration AND tropical AND montane OR restoration AND tropical AND altitude OR recovery AND tropical AND mountain OR recovery AND tropical AND montane OR recovery AND tropical AND altitude OR restoration AND andes OR recovery AND andes)	Agric and biol., environmental science, earth, and planetary science	10
	TITLE-ABS-KEY (restor* AND tropic* AND (mountain OR montane OR altitude OR alpine OR andes)) AND (LIMIT-TO (SUBJAREA, "AGRI") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "EART"))	Agric and biol., environmental science, earth, and planetary science	395
Science direct	TITLE-ABS-KEY= (restoration AND tropic AND mountain OR montane OR elevation OR altitude)	Agric and biol., environmental science, earth, and planetary science	28,981
	TITLE-ABS-KEY= (restoration OR recovery AND tropic AND mountain AND forest OR grassland)	Agric and biol., environmental science, earth, and planetary science	31

	TITLE-ABS-KEY= (restoration tropical mountain OR restoration tropical montane OR restoration tropical altitude OR recovery tropical mountain OR recovery tropical montane OR recovery tropical altitude OR restoration andes OR recovery andes)	Agric and biol., environmental science, earth, and planetary science	110
	TITLE-ABS-KEY= (restoration OR restore) AND (tropic OR tropical) AND (mountain OR montane OR altitude OR alpine OR andes)	No specification	94
Web of science	TS (topic search, is equal to TITLE-ABS-KEY) = (restoration AND tropical AND mountain OR restoration AND tropical AND montane OR restoration AND tropical AND altitude OR recovery AND tropical AND mountain OR recovery AND tropical AND montane OR recovery AND tropical AND altitude OR restoration AND andes OR recovery AND andes) from 1992-2020	environmental sciences ecology or forestry or geology or plant sciences or biodiversity conservation or agriculture or physical geography or geochemistry geophysics or science technology other topics or meteorology atmospheric sciences or water resources or zoology or biophysics or remote sensing or geography or evolutionary biology	668
	TS= (restor* AND tropic* AND (mountain OR montane OR altitude OR alpine OR andes))	No specification	391
Google Scholar	restor * tropic * mountain OR montane OR altitude OR alpine OR andes no TAK search possible, hence high number of unspecific hits and only selection of the first 100 articles	No option to specify	2160, only first 100 entries selected



Supplementary 1. 9: Prisma (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flowchart of study selection

Supplementary 1. 10: Table for data extraction from articles

Criteria	Category	Tags
Paper details	Study year	Year after 1988
Study site	Country	Name of country
	Geographic coordinates	Latitude (-23.5 to 23.5) and Longitude (-180 to 180)
	Geographic region	S-America, C-America, Asia, Africa, Oceania, Australia, Pantropical studies
	Mountain range	Andes, Himalaya, Wester Ghats, Central Cordillera and more
	Ecosystem	5 broad Ecosystem types (Montane Forest, cloud forest, treeline ecotone, alpine grasslands, azonal formations), and many subtypes like: upper montane forest, high Andean Forest, wet montane forest, dry montane forest, shrubland etc
	Elevation	inm asl
	Climate of site	Mean annual precipitation [mm] and mean annual temperature [° C]
	Protection status of site	IUCN category I-VII
Study type	Primary study	Field sampling, in situ methods, experiment, treatment
	Secondary study	remote sensing, modelling, literature review, databases, reports, syntheses…
	Size of study	Patch: 10–10^2 km^2, Local: 10^2–10^3 km^2, Regional: 10^3–10^5 km^2, National: 10^5–^{106} km^2, Global: >10^6 km^2
	Study duration	Short term (<12 month), mid-term (>=1y-5y), long-term (>=5y)
Degradation type	Initial degradation cause	Pasture conversion and grazing, Agricultural conversion and cultivation, Deforestation and degradation, Commercial plantation, Human induced fire, logging, selective logging, slash and burn, climate change and more (see Supplementary 7 a)
	Degradation effect	arrested succession, biodiversity change and loss, soil degradation, habitat fragmentation, harsh microclimate, invasion by grass change and more (see Supplementary 7 b)
Restoration metrics	Restoration goal	Grouped by ecosystem services (provisioning, regulating, supporting, cultural)
	Response variable measured	Vegetation structure, species diversity, functional diversity, recruitment, hydrology and more (see Supplementary 5 a)
	Successional stage studied ecosystem	Early (0- <=5y), mid (5- <20y), late (>=20y)

	Taxonomic group of response variable	Plant (angiosperms, gymnosperms, other), animal amphibian, birds, arthropods, invertebrates, mammals, reptiles), abiota (soil, water, climate), other (soil seed bank, carbon, land cover)
	Ecological level of response variable	Population, species, community, ecosystem, ecosystem service, abiota (like soil, water, and climate)
	Limiting factors	Distance to forest, dispersal limitation, recruitment limitation, unfavourable soil, unfavourable micro-climate and more (see Supplementary 4)
	Promoting factors	Time since disturbance, facilitative effects, favourable micro-climate, remnant vegetation, proximity to forest, functional diversity and more (see Supplementary 4)
Restoration methods	Restoration intervention	herbivore/grazing exclusion, invasive plant/weed management, natural regeneration, seedling planting, soil amendments and more (see Supplementary 8 for all interventions)
	Type of restoration	Active (planting), passive (natural regeneration and site protection), assisted recovery (some controlling intervention)
	Restoration material: dispersal type	Animal-dispersed, wind dispersed, barochory/autochory, vegetative
	Restoration material: origin	Native, non-native, native and non-native
	Restoration material: taxonomy	Plant family (see Supplementary 8 b)
Restoration success	Success of restoration intervention	Low (did not reach any of its goals), medium (some goals reached, but not all) and high (almost all or all goals reached)
Conclusions (qualitative)	Implications	One paragraph per study with main take away
	Suggestions and recommendations	One paragraph per study with directed recommendations such as restoration methods proposed or critical knowledge gaps that need addressing

Supplementary 1. 11: Detailed specification of categories for limiting and promoting factors.

	Category	Tags
Limiting factors	Habitat constraints	Unfavourable micro-climate/soil conditions, light limitation, water limitation, soil acidity, micro-habitat availability, low seed bank capacity, temperature limitation, absence of soil seed bank, leaching, sandification, recalcitrance, photo-inhibition, unfavourable litter conditions, nutrient excess, nutrient lack, germination limitation, reproduction limitation, species specificity of recruitment, topographic constraints, desiccation
	Dispersal limitation	Distance from forest, lack of dispersers, migration limitation, species colonization capacity
	Negative biotic interactions	Competition by fern/grass/trees/other growth forms, intra-specific competition, seed predation, mammal herbivory, insect herbivory, Pollinator limitation, mineralization of SOM, allelopathy, reduced mycorrhiza, fungal attack, pest and disease
	Land use legacy	Previous clearing of forest or unfavourable use of ecosystem, agricultural or pastoral legacy
	Inadequate site management	Inadequate fire/grazing management, poor waste/resource management, fallow management, vegetation removal, herbicide toxicity, afforestation, agriculture in steep areas, annual cropping, unfavourable exotic species plantation, unfavourable bird perches
	Extreme climate and weather	Recurring fires, intense rainfall, rainfall seasonality, climate change, cloud cover changes
	Socio-economic factors	Divergent stakeholder views, lack of local engagement, trade-offs between restoration goals, poor stakeholder management, poor planning documents, human accessibility of site, absence of legal framework, need for personnel, corruption, poor law enforcement, population pressure, Economic cost, limited funding
	Invasion	Invasion by exotic/non-native plants, re-invasion, proximity to invasive sources,
	Functional traits	Unfavourable seed traits, seed production limitation, fast-growth associated tree mortality, seed dormancy, low resource efficiency of flora
	Site disturbance	Selective logging, wood harvesting, disturbance intensity level, agricultural disturbance, clearing method, timber extraction, livestock disturbance, planting disturbance
	Site vegetation	Structural homogeneity, unfavourable vegetation structure, canopy gaps, unfavourable belowground plant community characteristics
	Inadequate seed treatment	Physical seed damage, inadequate seed treatment
	Fragmentation	lowland vegetation cover, absence of undisturbed forest, surrounding landcover, matrix type, edge effects, forest loss

	Research constraints	Lack of long-term data, lack of regeneration ecology knowledge
Promoting factors	Facilitation and vegetation variables	Facilitation by trees and other growth forms ,Age of tree, complex vegetation structure, remnant trees, remnant vegetation, vegetation cover, dead wood, root biomass, standing dead trees, structural complexity, tree size, suitable canopy cover, in situ propagule sources, floristic diversity, habitat connectivity, proximity to forest, distance from human settlements, distance from human settlement, distance to settlement, proximity to source population, configurational heterogeneity, species turnover, site remoteness, connectivity enhancement, evapotranspiration by vegetation, high phylogenetic diversity on site, water trapping through epiphytes, cloud water nutrient input
	Adequate site management	prescribed fires, management of nurse species, management of exotic plantation, fire management, fertilization, intermediate disturbance, enclosure strength, site protection, disturbance reduction/removal, low deforestation intensity, banning of harvesting, herbivory control, legal site protection, feral pig exclusion, grazing exclusion, land sparing, Fern removal, grass removal/reduction at edge, invasive animal removal, invasive plant removal, pig population control, reproductive control of inhibitor species, removal of invasive seedlings, bamboo control, weed control, competition control
	Favourable abiotic habitat conditions	Adequate micro-climate, light availability, litter amount, soil conditions, thick litter layer, vital soil seed banks, hydrological conditions, elevation, and topographic favouring factors
	Time since disturbance	Time since abandonment or since start of restoration intervention
	Positive biotic interactions	Arbuscular mycorrhiza inoculation, symbiotic inoculation, biotic interactions, positive dispersal feedback, diverse microbiome, gut passage of seeds
	Favourable functional traits	Bird size, frugivorous birds, trait plasticity, wind dispersal, zoochorous fruits, colonization ability, generalist bird species, N2 fixer, nitrogen fixing trees, sapling drought tolerance, vegetative reproduction, vegetative growth, planting of generalist tree species, functional redundancy, N-fixers, plasticity
	Socio-economic factors	Education, training, targeted outreach, benefits to local communities, community care, development of positive relationship, ecosystem services scarcity path, effective communication, local public engagement, locally perceived need to restore, conservation contract, formal relations building, leadership building, visitor education, crisis restoration, capacity building, communal land, learning by example, legal site protection, personal incentives, Financial incentives, broaden market ranges, carbon financing mechanisms, certification, combination of tourism and restoration, ecotourism, high value species, market-based instruments, socio-economic gain, alternative fuel sources, low agricultural site value, private incentives for reforestation
	Planting variables	planting container size, sapling diversity, shrub planting, shade tree planting, seedling planting, seed tree planting, seed bank transfer, seed addition, reforestation, nucleation techniques, native species planting, multispecies planting, forest cover restoration, direct seeding, strip planting, ex-situ

		propagation, vegetation planting, tree planting, seed transfer, initial age of seedlings, large seedling size, enrichment planting, seed burying, root grafting, native species plantations, seedling protection, scarification, seed provenance, generic variation of seeds, frost protection, irrigation, micro-catchment creation
	Restoration management	species-specific approach, site selection, spatial prioritization, use of multi-function value trees, multiple restoration goals, change-adapted restoration planning, biodiversity-carbon-synergies, project specific planning, long rotation times, nitrogen-fixing pasture trees, agrobiodiversity, fallow length, climate resilient crops, agroforestry, water provision technologies, assisted migration, wind breaks
	Research/knowledge and monitoring	Knowledge integration, long-term monitoring, disruptive innovation
	Macro-site conditions	Elevation, rainfall, cloud water nutrient input, climate change effects

Preface to Chapter 3 (Paper II)

The previous chapter found that restoration studies are relatively rare in the tropical Andes, despite it being the largest tropical mountain range in the world. Further, it found a scarcity of studies using remote sensing technologies to investigate various dimensions of ecological restoration, such as mapping of restoration priorities and potential or monitoring of long-term development of restoration sites (Christmann & Oliveras Menor, 2021). One main finding was a lack of knowledge on large-scale and long-term studies for recovery success in tropical mountain ecosystems. It is largely unknown how ecological recovery manifests after disturbance for time frames longer than five years, and where restoration interventions – active or passive – are successful beyond a plot-scale (Christmann & Oliveras Menor, 2021).

The previous chapter identified a series of knowledge gaps in the field of tropical mountain restoration (Fig. 2.8). While the paper partially tackles knowledge gaps and research priorities mentioned in the framework by Mathez-Stiefel et al (2017), it also corroborates the need to dig deeper into some other research priorities mentioned in the framework. Priority 6 in the framework mentions the need to investigate sustainable governance across scales and my paper found a lack of engagement of research with large-scale restoration questions. Further, Research priority 7 in the framework on Landscape restoration practices mentions the need to test the effects of restoration practices on livelihoods and ecosystem services, a priority which aligns with my Step 2 on the need to assess socio-economic drivers and outcomes of ecosystem restoration in Tropical mountains.

This provided my motivation to deleve into three of these knowledge gaps for the following two chapters. Chapter 3 addresses the lack of large-scale assessments on restoration across mountain ranges as well as the gaps in the use of satellite technologies for restoration planning and monitoring to identify potential restoration hotspots (Fig 2.8: Red rectangles). Specifically, Chapter 3 focuses on Andean Forests, an ecosystem in which despite being a biodiversity hotspot of global importance

restoration and ecosystem recovery is still understudied. Satellite data analysis allows investigation of forest recovery at a continental scale. Hence, the following chapter sets out to monitor 15 years of forest recovery across montane forests in the tropical Andes.

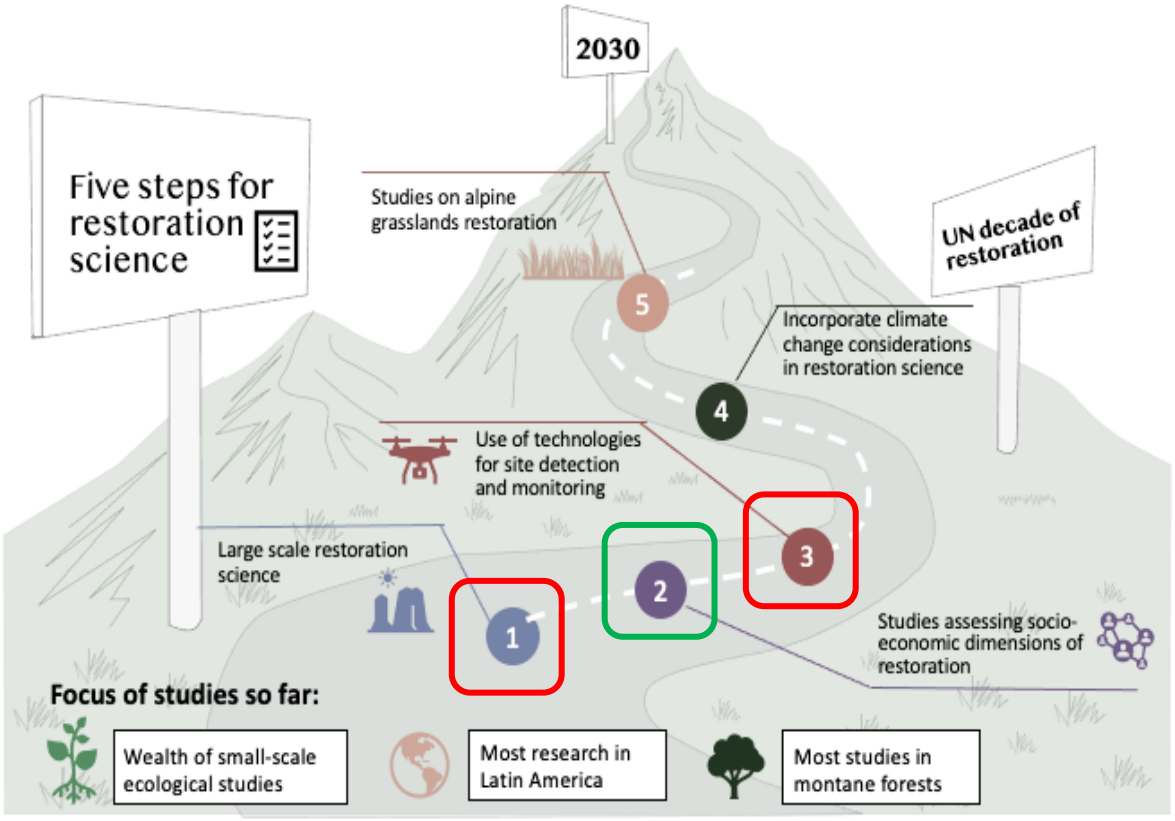


Figure 2. 8: Knowledge gaps identified in Paper I with red rectangle highlighting the knowledge gaps addressed in Paper II and green rectangle gaps addressed in Paper III.

The following paper has been published in *Global Ecology and Biogeography* (*https://doi.org/10.1111/geb.13666*). The idea of the paper was conceived by me and Imma. I carried out all the data collection and analysis with suggestions from all co-authors. Dolors, Ximena, Imma and Sarah further provided local knowledge and data for the case study landscapes. I wrote the first draft and my co-authors helped with the various iterations of the manuscript. Yadvinder advised on the mathematics behind the calculations and provided comments on the final draft.

Chapter 3 (Paper II)

Disrupted Forest Recovery hinders Biodiversity Conservation in the Tropical Andes

T, Christmann, D. Armenteras, X. Palomeque, S.J. Wilson, Y. Malhi, I. Oliveras Menor

"There were problems with the animals. Up there in the mountains they herd alpacas and lamas. To help the tree seedlings grow we built a fence."
– President of Andean farming community



Figure 3. 0: An Andean valley used for grazing and agriculture in the Cordillera de Vilcanota.

Abstract

Aim

Andean montane forests are biodiversity hotspots, large carbon stores and provide numerous ecosystem services. Following land abandonment after centuries of forest clearing for agriculture in the Andes, there is an opportunity for forest recovery. Field-based studies show that forests do not always recover. However, large-scale, and long-term knowledge of recovery dynamics of Andean Forests remains scarce. This paper analyses tropical montane forest recovery trajectories over a 15-year time frame at the landscape and tropical Andean scale to inform restoration planning.

Methods

We first detect 'potential recovery' as areas which have experienced a forest transition between 2000- 2005. Then, we use Landsat time series analysis of Normalized Difference Water Index to classify four 'realized recovery' trajectories ('ongoing', 'arrested', 'disrupted' and 'no recovery') based on sequential pattern of 5-yearly Z-score anomalies for 2005-2020. We compare these results against a tree cover change analysis to validate with other datasets.

Across the tropical Andes, we detected a potential recovery area of 274 km^2 over the period.

Results

Despite increases in tree cover, most areas of the Andes remained in early succession states (10-25% tree cover) and NDWI levelled out after 5-10 years. Of all potential forest recovery areas 22% showed 'ongoing recovery', 61% showed either 'disrupted' or 'arrested recovery', and 17% showed 'no recovery'. Our method captured forest recovery dynamics in a Peruvian arrested succession context and in landscape scale tree planting efforts in Ecuador.

Main conclusions

Forest recovery across the Andes is mostly disrupted, arrested or unsuccessful, with consequences for biodiversity recovery and provision of ecosystem services. Low recovery areas identified in this study may be good candidates for active restoration interventions in this UN Decade on Restoration. Future studies could determine restoration strategies and priorities and suggest management strategies at a local planning scale across key regions in the biodiversity hotspot.

Keywords

cloud forest, forest transition, forest restoration, Google Earth Engine, Landsat time series, natural regeneration, NDWI, Tropical montane forest,

Spanish abstract

La recuperación interrumpida de los Bosques Andinos limita la conservación de la biodiversidad en los Andes tropicales

Los Bosques Andinos contienen altos niveles de biodiversidad, almacenan grandes cantidades de carbono y proporcionan varios servicios ecosistémicos. Después de siglos de talas de bosques para fines agrícolas y de un consecuente abandono de la tierra, existe una gran oportunidad para recuperar estos bosques naturales. Sin embargo, estudios de campo muestran que la recuperación de estos bosques muchas veces es fallida. Además, de momento existen pocos estudios de recuperación de los bosques andinos de larga duración. Este estudio analiza la recuperación de Bosques Andinos a lo largo de 15 años a escala del paisaje y Andino-tropical con el objetivo de informar la planificación de estrategias de restauración.

En primer lugar, detectamos áreas con potencial para la recuperación identificando zonas que han experimentado una transición inicial de cobertura boscosa entre 2000-2005. A continuación, utilizamos series temporales de Normalized Difference Water Index a partir de imágenes satelitales de Landsat para identificar cuatro clases de trayectorias de recuperación (‘recuperación

continuada', 'recuperación arrestada', 'recuperación interrumpida' y 'recuperación fallida') basado en un análisis de patrones temporales de valores de Z entre 2005-2020. Finalmente, comparamos nuestros resultados con clasificaciones de cobertura boscosa y validamos nuestros resultados en tres tipos diferentes de paisajes.

A lo largo de las Andes detectamos 274 km^2 de área de restauración potencial. A pesar de un incremento en cobertura boscosa, la mayoría de las áreas permanecen en un estado de sucesión temprana (10-25% cubertura boscosa) y los valores de NDWI se estabilizan a los 5 años. De todas las áreas con potencial para la recuperación, el 22% muestra 'recuperación continua' mientras el 61% muestran 'recuperación arrestada' o 'interrumpida', y el 17% no consiguen recuperarse. Nuestro método consigue capturar dinámicas de recuperación en áreas de incendio con sucesión arrestada en el Sur de Perú y también en un paisaje con reforestación activa en Ecuador.

Por el momento, la recuperación de los Bosques Andinos ha sido en gran parte fallida, con grandes consecuencias para la biodiversidad y los servicios ecosistémicos. Las áreas de baja recuperación identificadas en este estudio pueden ser candidatas adecuadas para intervenciones de restauración activa en esta Década de las Naciones Unidas para la Restauración de los Ecosistemas. Futuras investigaciones podrían aspirar a determinar estrategias de restauración y prioridades a escala local en regiones clave del bioma Andino.

Introduction

Recovering degraded forest ecosystems is a global priority in this UN Decade on Restoration. Andean tropical montane forests (ATMF) are among the most biodiverse ecosystems in the world (Myers et al., 2000). Historically, Latin American mountain ecosystems remain understudied and assessing trends of biodiversity, ecosystem function and ecosystem services is a key research priority in this decade (Gleeson et al., 2016). However, in the Andes little is known about the success and directions of forest recovery – be it passive or active recovery - due to a lack of restoration knowledge (Christmann & Oliveras Menor, 2021). The inclusion of understudied systems such as ATMFs in restoration science to formulate restoration priorities is vital to ensure their ongoing biodiversity and contributions to humanity.

ATMF provide a suite of ecosystem services to both uplands and lowlands and are a major ecosystem in the Tropical Andes Biodiversity Hotspot (Myers et al., 2000). However, deforestation for land conversion (Zador et al., 2015), wildfires (Aguilar-Garavito et al., 2021; Oliveras et al., 2018), and climate change (Fadrique et al., 2018) have caused widespread ecosystem changes over the last decades. Between 2001 and 2014 50,000 km^2 of woody vegetation in the tropical and subtropical Andes was cleared (Aide et al., 2019). This has severe consequences for people and biodiversity conservation, including a decline in ecosystem services, such as food and medicine, water regulation and provision, and erosion prevention (Gaglio et al., 2017). Further, fires in ATMFs release substantial carbon emissions from burning biomass (Oliveras et al., 2014).

Andean countries have pledged restoration commitments in the last decade and have started national restoration programmes to recover ecosystem services and biodiversity (Murcia et al., 2017). Identifying priority areas where forests cannot recover without active intervention is paramount in guiding restoration efforts. This study uses satellite remote sensing to identify areas of potential

forest recovery in the tropical Andes and monitors subsequent forest recovery over a ~15-year period to detect recovery trajectories and restoration opportunity areas.

The factors driving forest decline in specific areas of the Andes are well explored – from small-holder land conversion in Colombia (Armenteras et al., 2011) and Ecuador (Palomeque et al., 2017; Posada et al., 2000), to wildfires and anthropogenic fires in Peruvian montane cloud forests (Oliveras et al., 2018; Román-Cuesta et al., 2014). However, the large-scale process and the temporal patterns of recovery following degradation of TMF are not well studied (Christmann & Oliveras Menor, 2021).

In the last two decades, large areas of land have been abandoned in the Andes following rural- to-urban migration, an increase in the remittance economy, and a decline in traditional cultivation methods and farming on marginal land and loss of productivity (Camelo et al., 2017; Gaglio et al., 2017). This enables forest transitions through natural (i.e., passive) regeneration (Aide et al., 2019) as well as creating opportunities for active forest restoration and afforestation (Knoke et al., 2014).

In areas where anthropogenic land use has decreased forest recovery may result in varying degrees of biodiversity and forest structure depending on the ecology of the site, the surrounding landscape, and the degree of previous human intervention (i.e., land use legacy) (Aide et al., 2011; Chazdon, 2003; Holl, 2002). Forest recovery trajectories, in our study defined as the sequential pattern of forest recovery through time, are often non-linear and show dynamics on short temporal scales driven by ecological factors and socio-economic processes (Decuyper et al., 2022). Hence, forest recovery trajectories vary between different geographic locations, as well as within ecological and topographical gradients (Aide et al., 2019; Sánchez-Cuervo et al., 2012).

In this study we classify four broad types of forest recovery trajectories: 1) 'Ongoing recovery' in which abandoned land steadily progress towards secondary forests (Fig. 3.1A) – either through active restoration (Günter et al., 2009) or through passive recovery (Davies et al., 2020; Palomeque

et al., 2017); 2) 'disrupted recovery' (Fig. 3.1B) where forests recover and are then periodically cleared/disturbed (previously called 'reversal of reforestation' see (Piffer et al., 2022; Schwartz et al., 2020)) by, for example, swidden fallow agriculture, (Perez-Garcia et al., 2017), human encroachment (such as logging), or hazardous events like wind throws or landslides; 3) 'arrested recovery' due to ecological inhibitors (Fig. 3.1C) such as invasive grasses limiting forest development to later successional stages (Palomeque et al., 2017; Sarmiento, 1997; Sarmiento et al., 2015) and 4) 'no recovery' due to harsh abiotic conditions or biological constraints limiting recruitment and establishment or later occurring land-use changes (Fig. 3.1D); and 4)

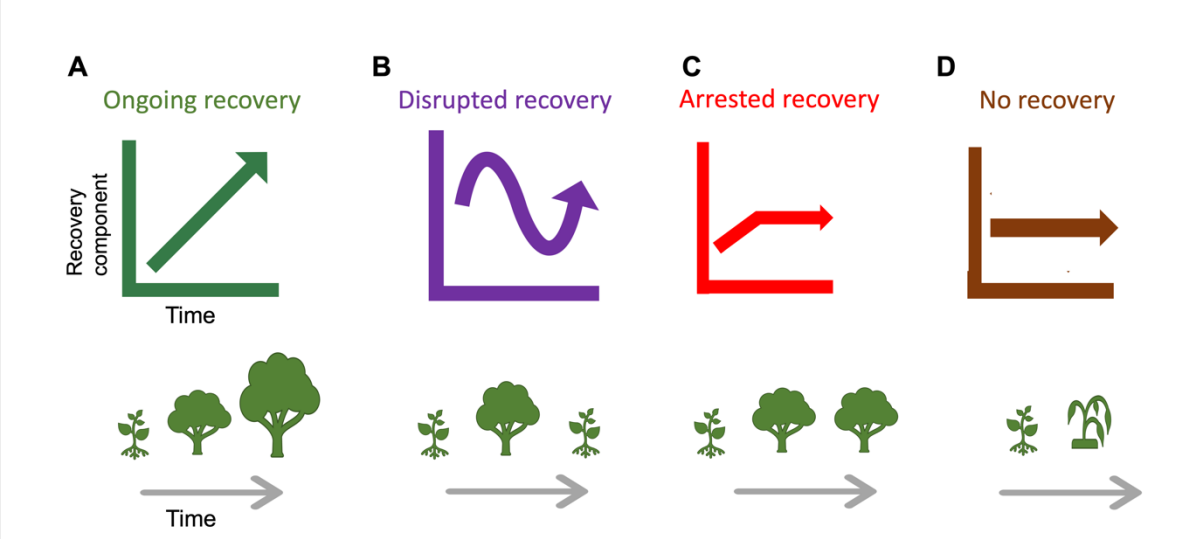


Figure 3. 1: Conceptual framework for four possible forest recovery trajectories in the Andes. The x axis represents time and the y-axis a recovery component, e.g., vegetation structure, biodiversity, ecosystem function.

When ecological barriers to restoration are overcome, forests can recover through natural regeneration, which is the main recovery process in ATMFs (Günter et al., 2007). Natural regeneration often occurs in steep, remote, and high-altitude areas, because land is inaccessible or marginal for agriculture. Natural regeneration is low-cost and often more effective than tree planting in recovering vegetation structure and improving species diversity (Holl and Aide, 2011)

and in the right ecological and social conditions it can create resilient ecosystems which store large amounts of carbon (Cook-Patton et al., 2020).

However, natural regeneration is not always possible as it is strongly influenced by land use legacies, ecological conditions on site, and the landscape context (Aide et al., 2011; Dendy et al., 2015; Gallegos et al., 2016; Holl & Aide, 2011). Generally, forests recover biomass and biodiversity more quickly in areas that are near remnant forests, far from human settlements, and where forests have been recently cleared and soil conditions are favourable (Camelo et al., 2017). Conversely, forests tend to recover more slowly (if at all) where there are dispersal limitations (seed sources and dispersers are absent), land has been heavily used, and where microclimate, soil or topographical conditions are unfavourable. In these conditions forests may experience 'arrested succession' (Rojas-Botero et al., 2020; Sarmiento, 1997; Sarmiento et al., 2015), where an ecosystem is trapped in a resilient degraded state and does not progress to mature forest stages (Aide et al., 2011).

For restoration to be effective, it is crucial to identify areas where forests can recover naturally and where they cannot to strategically inform restoration planning. This practical knowledge can elucidate how to optimally allocate management and resources to maximise restoration goals such as carbon sequestration and biodiversity recovery (Brancalion et al., 2019; Strassburg et al., 2019). Where forests are unable to recover naturally in a timescale that meets restoration objectives, active interventions are needed to overcome barriers of forest recovery (Camelo et al., 2017; Günter et al., 2009; Palomeque et al., 2017). These include protecting regenerating trees and woody species from disturbance, seedling planting, direct seeding, soil improvements, enrichment planting and management of invasive and competitor species (Christmann and Oliveras Menor, 2021). Targeted restoration interventions should be deployed in areas that suffer from arrested succession or where recovery is disrupted, negative or non-existent (Camelo et al., 2017).

Knowledge on recovery trends and trajectories of degraded ATMFs at large spatio-temporal scales remains scarce (Christmann & Oliveras Menor, 2021). For long-term and large-scale purposes earth

observation technologies can be used to explore recovery trajectories of ATMF which are often located in remote and inaccessible areas, precluding extensive field studies. The potential of satellite imagery to reveal recovery trajectories in tropical mountain ecosystems remains underexplored to inform conservation and restoration planning. Remote sensing has been used to monitor forest recovery in mountain areas across the world using approaches ranging from vegetation indices to land cover classifications (Buma, 2012; Leeuwen, 2008; Liu et al., 2019; Liu, 2016).

There are a handful of studies on forest change trajectories using low resolution data on a Latin-American scale (Aide et al., 2019; Chazdon et al., 2020; Graesser et al., 2015) or on a country scale (Sánchez-Cuervo et al., 2012; Sanchez-Cuervo & Aide, 2013). The few remote sensing studies conducted on Andean montane forest recovery have remained at a landscape level (Aragón et al., 2021; Wilson et al., 2019), limiting our knowledge on Andean-wide Forest recovery trends. Time series of publicly available Landsat imagery can provide a cost-efficient and practical mean to monitor forest recovery trajectories over several decades (Decuyper et al., 2022; Meroni et al., 2017) – the period within which ATMF recovery usually occurs (Aragón et al., 2021; Oliveras et al., 2018). The high spatial resolution of 30m of Landsat enables to adequately capture recovery trends of the heterogenous and mosaicked ATMF which are often located within a smallholder landscape with high topographic and abiotic complexity.

Previous remote sensing studies covering the Andes have found that forest recovery is a spatio-temporally varied process: Based on time series and shape-fitting analysis a short permanence of regrowing forests and reforestation reversal was detected across Latin American secondary forests, compromising continental scale carbon stores (Schwartz et al., 2020). Another remote sensing study at the Colombian scale detected woody vegetation recovery areas using Landsat data and found that recovery occurred near remnant forests and with distance from settlements and highlighted the need to evaluate socio-ecological conditions to define restoration approaches (Camelo et al., 2017).

However, montane forest recovery has not been studied across the tropical Andes at a high enough resolution to capture the quality and direction of recovery of individual forest patches to guide conservation and restoration planning in line with the current restoration commitments in the UN Decade on Restoration. Inspired by previous approaches that use change detection algorithms (Decuyper et al., 2022) and multi-temporal before-after comparisons of forest restoration following disturbance (Leeuwen, 2008) we develop a novel method to monitor forest recovery trajectories in a way that is spatially explicit, considers multiple forest recovery trajectories and works in the seasonally and topographically challenging context of the tropical Andes.

This study aims to assess trajectories of tropical Andean Forest recovery through a multi-temporal assessment of Landsat and Global Forest Change data for the period 2000-2020. After identifying potential recovery areas, we use a newly developed trajectory monitoring procedure to monitor forest recovery trajectories for 15 years. This information will help identify restoration opportunities and target active restoration interventions in areas most in need.

Specifically, we ask: 1) What is the potential recovery area for the years 2000-2005? 2) How does forest recovery - in terms of tree cover change, forest recovery trajectory classes and NDWI - manifest in the potential recovery areas for the period 2005-2020? and 3) How do the forest recovery trajectories align with forest recovery trends at a landscape scale (i.e., selected case studies spanning valleys or small protected areas with known on-the ground forest recovery dynamics)?

Methods

Study area

Our study area spans along the tropical Andean belt (on the South American continent down to 23.5° S) and includes areas between 1500 and 3500m asl (Fig 3.2), a realistic elevation range for montane forests across the tropical Andes (Christmann & Oliveras Menor, 2021; Gaglio et al., 2017). We also restricted our analysis to slopes below 30%, as the accuracy of remotely sensed

products and indices is drastically reduced on steep slopes due to geometric distortions and shadows (Weiss & Walsh, 2009). Hence, our estimates are likely conservative.

We zoom into three demonstration landscapes to test how our method of monitoring forest cover trajectories works at a landscape scale: the Intag valley in Ecuador, Iguaque National Park (Colombia) and Manu National Park (Cusco, Peru) (Fig 3.2). These sites have distinct histories of degradation and land abandonment, such as a combination of agricultural, pastoral or fire legacies and span various subtypes of ATMF (Supplementary 2.1) and have all been previously studied (Aguilar-Garavito et al., 2021; Oliveras et al., 2018; Wilson & Coomes, 2019; Wilson & Rhemtulla, 2016). We consulted local ecologists, conservation managers and the previous study authors to evaluate whether our recovery trajectory method accurately represented the forest recovery patterns in these landscapes.



Figure 3. 2: Extent of study and location of case study landscapes

Detecting potential recovery areas

We identified potential areas for forest recovery (hereafter 'potential recovery areas') as areas which had undergone an initial tree cover transition between 2000-2005 prior to monitoring 'realized forest recovery' for the subsequent period 2005-2020 (Fig. 3.3A). We identified these using the 'Tree Cover Multi-Year Global' (Tab. 1) dataset from Global Forest Cover Change

(hereafter 'GFCC') as pixels which had <10% tree cover in 2000 (i.e. below a 10% tree cover an area is commonly considered to be unforested (Putz & Redford, 2010)) which by 2005 had increased to >20% tree cover (i.e. early succession) and hence showed a substantial initial forest transition such as following land abandonment. We chose 20% as a threshold to ensure the change was substantial and not within the variability and uncertainty of the data set. Further, the pixel had to remain over 20% in 2010 and 2015, to exclude pixels which were under a fallow agriculture regime and continuously re-cleared for agriculture or other anthropic purposes. Potential recovery areas hence include any kind of forest transitions following non-forest land uses such as pasture, logging, and agricultural field abandonment, as well as abandonment of settlements, urban and industrial, or mining/extraction areas. Potential recovery areas do not include abandoned plantations or agroforestry systems as these would have a higher tree cover to start with.

Data processing was carried out in Google Earth Engine (GEE) and subsequent analysis in R Studio Version 1.2.1335.

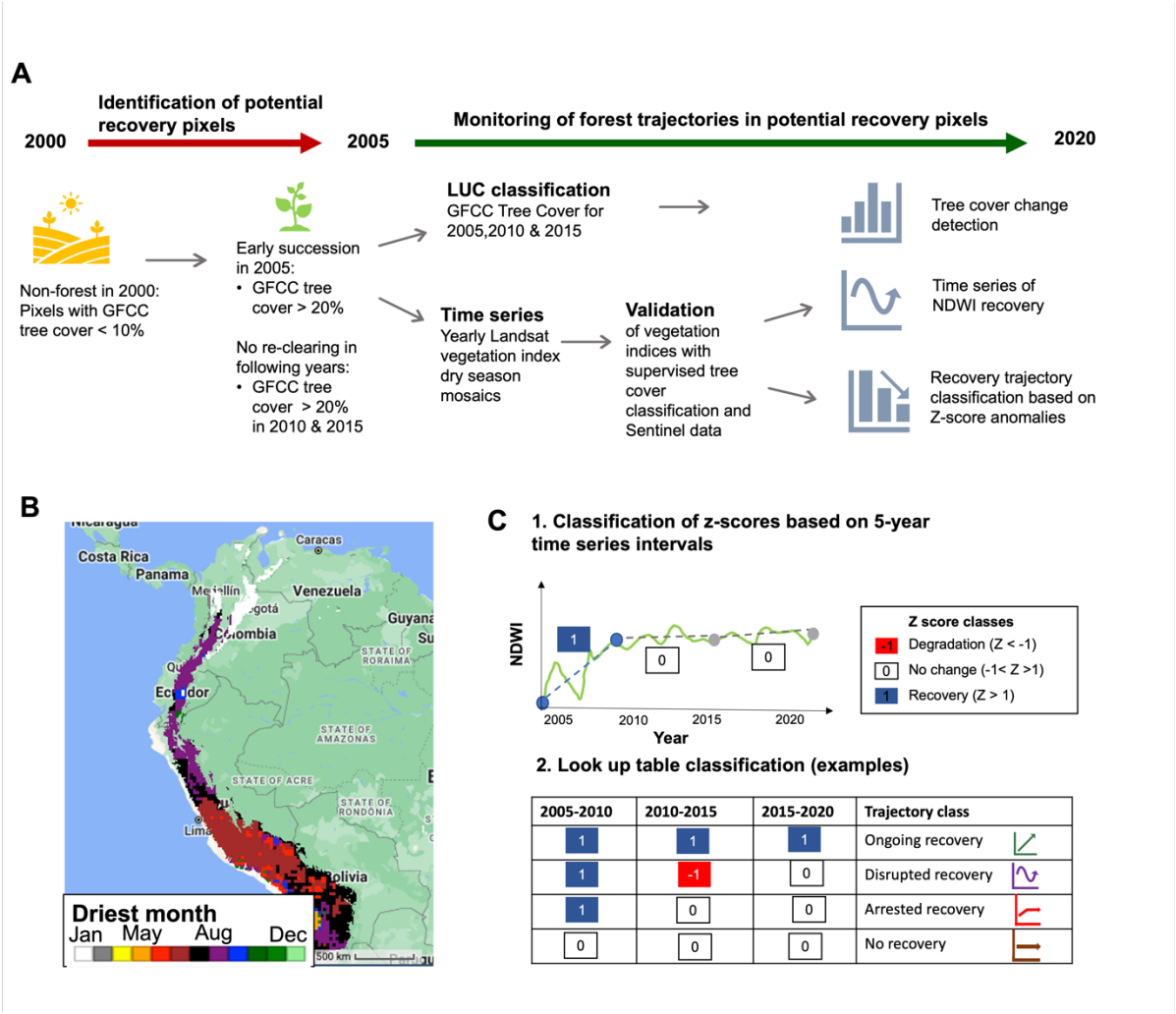


Figure 3. 3: Specification of methods for forest trajectory analysis. A) Workflow to identify potential recovery areas and monitor forest trajectories, B) Driest months in each pixel based on TRMM data. This is the month used for creation of driest month mosaics of Landsat data and C) Classification of recovery trajectories based on Z-score sequence using 1. 5-year time steps from time series and 2. A look up table to classify the recovery trajectories based on sequence of Z-scores. The complete look up table can be found in Supplementary 2.3.

Assessing realized recovery trajectories.

We used surface reflectance layers from Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI as the highest resolution datasets continuously available for our study period and selected 7 bands (Tab. 3.1). We masked clouds and shadows using the quality assessment band and clipped the time series to the potential recovery areas. We computed yearly dry season mosaics on a pixel-by-pixel basis using TRMM data (NASA, 2021) by creating a mosaic for driest month across the period

2000-2020 for each pixel (Fig. 3.3B). This way we generated one image of the most cloud free month per year and obtained an image collection with 20 total images.

We harmonized the time series of Landsat 7 ETM+ and Landsat 8 OLI surface reflectance using a harmonization function with linear regression coefficients (Roy et al., 2016) . We then computed the vegetation indices (EVI, NDVI, DVI, RVI, MSAVI2, NDWI (Xue and Su, 2017). Information of the use of these indices for forest recovery monitoring can be found in Supplementary 2.2.

Selection and validation of vegetation index

To select the best vegetation index to capture on-the ground forest recovery, we validated the Landsat data with higher resolution 10 m Sentinel data based on the Intag case study landscape in two ways: 1) Comparing Landsat vegetation indices with a supervised classification of four forest cover classes derived from Sentinel data to determine which index best represented forest successional stages (Supplementary 2.4-2.7); 2) Using a Spearman correlation of Landsat versus Sentinel data for each vegetation index to investigate which Landsat index best matched the higher resolution Sentinel data (Supplementary 2.8).

These analyses showed that Landsat NDWI (a ration index consisting of near infrared (NIR) and short-wave infrared (SWIR), see Equation 1) was the most representative index because: 1) it showed a high Spearman rho in capturing the successional stages (Supplementary 2.7), 2) it showed a good fit with the higher resolution Sentinel data (Supplementary 2.8), 3) NDWI is sensitive to water absorption and canopy structure and hence a good index to track structural changes during vegetation recovery due to the inclusion of SWIR bands (Liu, 2016) and 4) whilst NDWI is correlated with NDVI, NDWI, does not saturate as quickly and allows to track more variation in denser vegetation environments towards later successional stages and across a variety of montane forests at varying elevations with varying spectral properties. NDWI has been used in previous

studies to help classify recovery and degradation of secondary moist tropical forests (Carreiras et al., 2014), as well as to map drought effects on temperate forest (Wang et al., 2007).

Equation 1: Calculation of NDWI

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR}$$

Our validation was done using supervised classification based on 894 points visually classified using Google Earth high resolution images in one case study landscape (Supplementary 2.6). This is not as accurate as on-the ground data collection but provided a standardized and convenient way of comparing the vegetation indices with forest successional stages. We could not directly validate our method against long-term temporal forest structure data in a variety of restoration sites because long-term restoration efforts in the Andes are rare, have mostly begun in the last decade and often lack regular and long-term monitoring (Murcia et al., 2017).

Table 3. 1: Specification of data sources and sensors

Sensor or product	**Spatial resolution**	**Specification**	**Years**	**Bands**
Landsat 7 ETM Surface Reflectance	30 m	USGS Landsat 8 Level 2, Collection 2, Tier 1	Driest month composites 2001-2012	Blue [B1], Green [B2], Red [B3], Near Infrared [B4], Short wave Infrared 1 [B5], Short wave infrared 2 [B6] (all harmonized using Roy et al 2016), Pixel quality assessment
Landsat 8 OLI Surface Reflectance	30 m	USGS Landsat 7 Level 2, Collection 2, Tier 1	Driest month composites 2013-2021	Blue [B2], Green [B3], Red [B4], Near Infrared [B5], Short Wave Infrared 1 [B6], Short wave

				infrared 2 [B7] and Pixel quality assessment
Landsat 5 TM Surface Reflectance	30 m	USGS Landsat 5 Level 2, Collection 2, Tier 1	Driest month composites 2000	Blue [B1], Green [B2], Red [B3], Near Infrared [B4], Short wave Infrared 1 [B5], Short wave infrared 2 [B6] (all harmonized using Roy et al 2016), Pixel quality assessment
Tree Cover Multi-Year Global	30 m	Landsat Vegetation Continuous Fields	2000,2005,2010, 2015	Tree canopy cover % (i.e., The percentage of pixel area covered by trees)
Sentinel Surface reflectance	10 m	Surface reflectance	Driest month composite of 2021	Blue, Green, Red, Near Infrared, Short Wave Infrared 1, Short wave infrared 2 and Pixel Quality assessment
TRMM Rainfall monitoring	27830 m	Monthly precipitation estimates	For each month between 2000-2020	Precipitation in mm/h

Monitoring of forest recovery trajectories in potential recovery areas

To calculate realized forest recovery trajectories, we used three methods: time series of NDWI recovery, forest cover change detection and our newly developed classification of realized recovery trajectories using Z-scores.

We computed time series of annual NDWI using loess-smoothing functions, since forest recovery tends to show nonlinear temporal patterns (Decuyper et al., 2022). We computed aggregated mean time series for the six tropical Andean countries, as well as for five elevation belts of 500m width between 1500m and 3500m.

We extracted tree cover values from the GFCC dataset for the time steps 2005, 2010, 2015 for all pixels in the potential recovery classes (the data set terminates in 2015). We grouped the tree cover into 5 tree cover classes: 0-10%, 10-25%, 25-50%, 50-75% and 75-100% and assessed tree cover changes between time steps using Sankey diagrams.

Lastly, we computed realized forest recovery trajectories through a look-up table classification of Z-scores for 5-year time intervals since beginning of forest recovery (Fig 3.3 A & C). The use of Z-scores for this purpose is useful as it provides a standardized and relative measure of change accounting for variability and noise of a given pixel and it can help elucidate relative trends over large areas, as opposed to arbitrary thresholds or cut-offs.

Inspired by previous before-after comparisons of recovery using vegetation indices (Bright et al., 2019; Van Wagtendonk et al., 2004), we calculated Z-scores as the difference between the NDWI value of the last and first image of the five-year time interval and dividing it by the standard deviation of the residuals for each year of the given time interval (Equation 2, example of Z-score for 2005-2010 interval). Residuals for each year were calculated as the difference between the observed and predicted NDWI value (Equation 3, example for residuals of 2006).

Equation 2: calculation of Z-score for an exemplary period of 2005-2010

$$Z - score_{2005-2010} = \frac{X_{2010} - X_{2005}}{SD_{(res2006, res2007, res2008, res2009, res2010)}}$$

Equation 3: calculation of residuals for an exemplary year of 2007

$$res_{2007} = X_{2007} - (X_{2005} + 2 \text{ x} \frac{X_{2010} - X_{2005}}{5})$$

We reclassified Z-scores for each time interval in three Z-score classes. A Z-score of greater than 1 or smaller than -1 is commonly considered as a strong deviation from the mean and we decided to use this cut-off to assign one of three classes of change to each 5-year interval: degradation [class -1]: Z-score ≤ -1; no change [class 0]: -1> Z-score < 1; recovery [class 1]: Z-score ≥ 1.

Then we used a look up table to classify the overall recovery trajectory based on the sequential pattern of change of the three 5-year time steps (Fig. 3.3 C, Supplementary 2.3). If a pixel had experienced recovery in each time step, we assigned the class 'ongoing recovery', whereas if recovery periods were interspersed with degradation periods, we assigned the class 'disrupted recovery'. Pixels which had undergone initial recovery followed by no change (i.e., an arrested episode of succession delaying later recovery) were classified as 'arrested recovery'. This differs slightly from the use of the term 'arrested recovery' for initial regeneration phases, as with 30m satellite data we would not be able to track this process at a seedling emergence stage. Pixels without a single episode of recovery, i.e., which either showed stagnation or negative Z-scores during all time steps, were classified as 'no recovery'. The class 'no recovery' hence includes cases of ongoing or repeated degradation as well as instances of no change (Supplementary 2.3).

Results

Forest recovery across the tropical Andes

For the period of 2000-2005 we identified a total of 274 km^2 of potential recovery area. Between 2005-2020 forest recovery was slow and did not quickly progress to higher tree cover stages or high NDWI values (Fig. 3.5A & B). NDWI steadily increased until 2010 before plateauing, a trend observed across different elevations and countries (Fig. 3.9 B, Supplementary 2.9). Lower elevations did not homogenously show higher NDWI values across the Andes (Fig. 3.6B,

Supplementary 2.9A). For instance, in Ecuador and Bolivia highest values were found in the potential recovery areas at 2500-3500m asl (Supplementary 2.9A).

Across all potential recovery areas in the tropical Andes, Colombia represented 42.2% (115 km^2) of all potential recovery areas. Peru made up 25.4% (total 69.8 km^2), Bolivia 12% (33km^2, 0.3%), Ecuador 10% (29 km^2) and Venezuela and Argentina 7% (20.1 km^2) and 2.3% (6.4 km^2) of all potential recovery areas (Fig. 3.4). For all countries the potential recovery area relative to the size of a country's tropical Andean Forests varied between 0.3 and 1.2% (Fig. 3.5): Colombia – despite having the second largest extent of Andean Forests - had the largest potential recovery area of 1% in relation to its national Andean Forest area. Peru had 0.5%, Ecuador had 0.5%, Bolivia had 0.3%, and Venezuela and Argentina 1.2% and 0.6% respectively.

71% of all potential recovery areas did not show 'ongoing recovery' (Fig. 3.4A). In all countries 'disrupted recovery' was the most frequent forest recovery trajectory and the partitioning of recovery trajectories was broadly similar (Fig. 3.4 B-G). Colombia had ¼ of potential recovery areas under 'ongoing recovery' while 'no recovery' and 'arrested recovery' were less frequent. In Peru and Bolivia, disrupted recovery was the most frequent, however arrested recovery was as prominent as ongoing recovery. Partitioning of realized recovery classes between elevations did not vary substantially, other than a slight increase in 'disrupted recovery' area towards elevations of >3000m asl along with a decrease in 'ongoing recovery' (Fig. 3.5C).

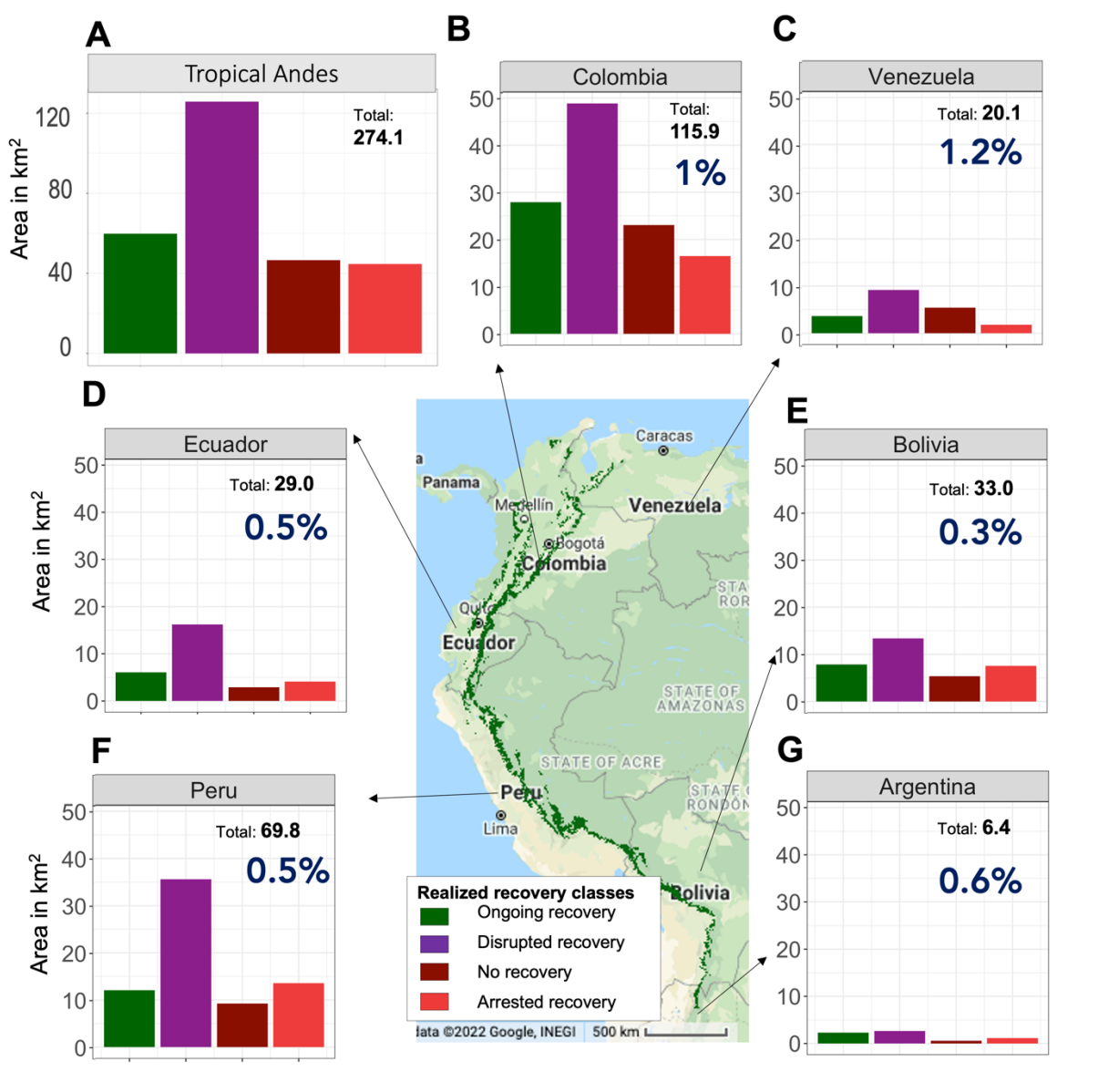


Figure 3. 4: Realized recovery trajectories in abandoned land across the Andes A) For the entire mountain range, B-G) By country. Percentages show potential recovery area in relation to Tropical Andean Forest area in each country. The centre map shows extent of Andean Forests above 1500m in 2020 extracted from the MODIS LUC dataset. The extent of Andean Forest areas differs between the countries and is as follows: Colombia 120,572 km^2, Peru 139,739 km^2, Bolivia 84,992 km^2, Venezuela 16,328 km^2, Ecuador 57,451 km^2, and Argentina 9993 km^2.

The GFCC tree cover change analysis also corroborated these findings (Fig. 3.5A): In 2005 half of all recovery pixels had advanced to medium tree cover classes of 25-50%, however by 2010 and

2015 much of this area reverted to low tree cover stages with 2/3 of the potential recovery areas showing 10-25% tree cover.

In Ecuador more than 50% of the potential recovery areas progressed to tree cover classes above 25% by 2015 and only small proportions reverted to lower tree cover. In all other countries most potential recovery areas stayed below 25% tree cover by 2015 and between 2010 and 2015 most of the 25-50% tree cover areas reverted to 10-25% tree cover (Supplementary 2.9B).

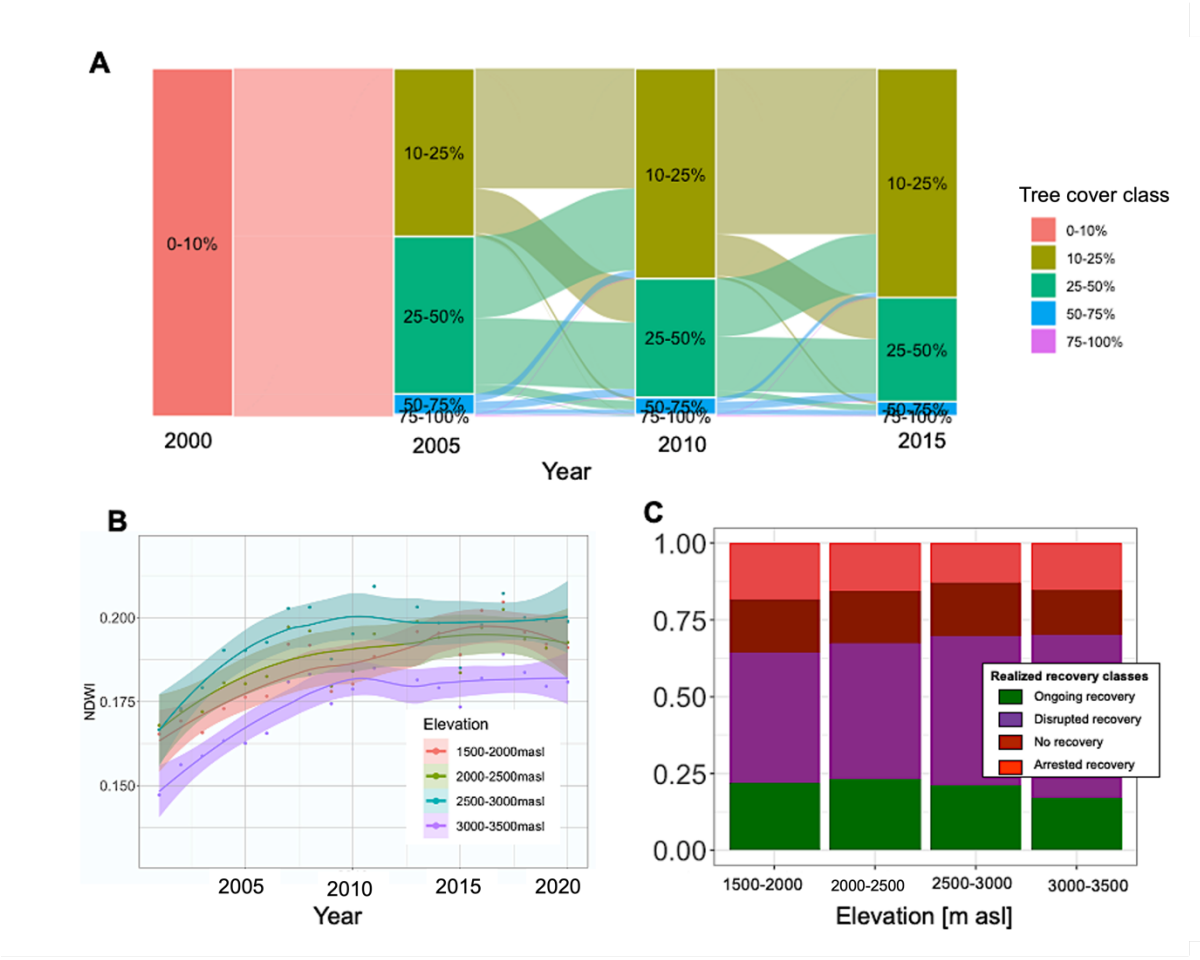


Figure 3. 5: Forest recovery in potential recovery areas of 2000-2005 across the Andes A) Tree cover change 2000-2015 (the dataset terminates in 2015) B) NDWI mean time series in different elevation zones C) Realized recovery trajectories in different elevation zones.

Validation in three forest recovery landscapes

To validate the findings of our large-scale analysis, we zoom into three case study landscapes with known established forest recovery dynamics.

Intag valley

In the Intag valley (Ecuador) mean NDWI increased over 20 years (Fig. 3.6A). Ongoing forest recovery was the dominant trajectory (Fig 3.6 C and D). Likewise, the tree cover analysis showed a steady increase towards higher successional classes in each time step so that by 2015 90% of areas were either in mid (25-50%) or later succession (>50) stages (Fig. 3.6B). Areas of ongoing recovery were distributed across the case study landscape, and watershed areas which had undergone community tree planting, show instances of successful ongoing recovery, such as the core area of the watershed reserve El Paraíso (Fig. 3.6D).

Cusco - Challabamba

Surrounding Challabamba, north of Cusco (Peru) NDWI timeseries showed an initial decrease followed by a logistic increase with highest NDWI values after 10-15 years since abandonment (Supplementary 2.10 A). Tree cover trajectories showed an initial progression to early succession stages by 2005, followed by a reduction in mid succession classes and a reversal towards 10-25% tree cover in 2010 and 2015 (Supplementary 2.10 B). Most areas showed 'disrupted recovery' (Supplementary 2.10 C), such as near forest clearings and quarries or 'arrested recovery' in pastures (Supplementary 2.10 D).

Iguaque

In Iguaque National Park (Colombia) mean NDWI timeseries showed slow recovery trends over the period of 15 year (Supplementary 2.11 A). The majority of pixel were classified as 'arrested recovery' and 'no recovery' (Supplementary 2.11 C), which were mostly located at the outskirts of

the park, adjacent to roads and in proximity to pastures, while ‘ongoing recovery’ areas were found nearby forests (Supplementary 2.11 D). Areas which initially showed a rapid succession to 25-50% by 2005, later often reverted to lower succession classes (Supplementary 2.11 B).

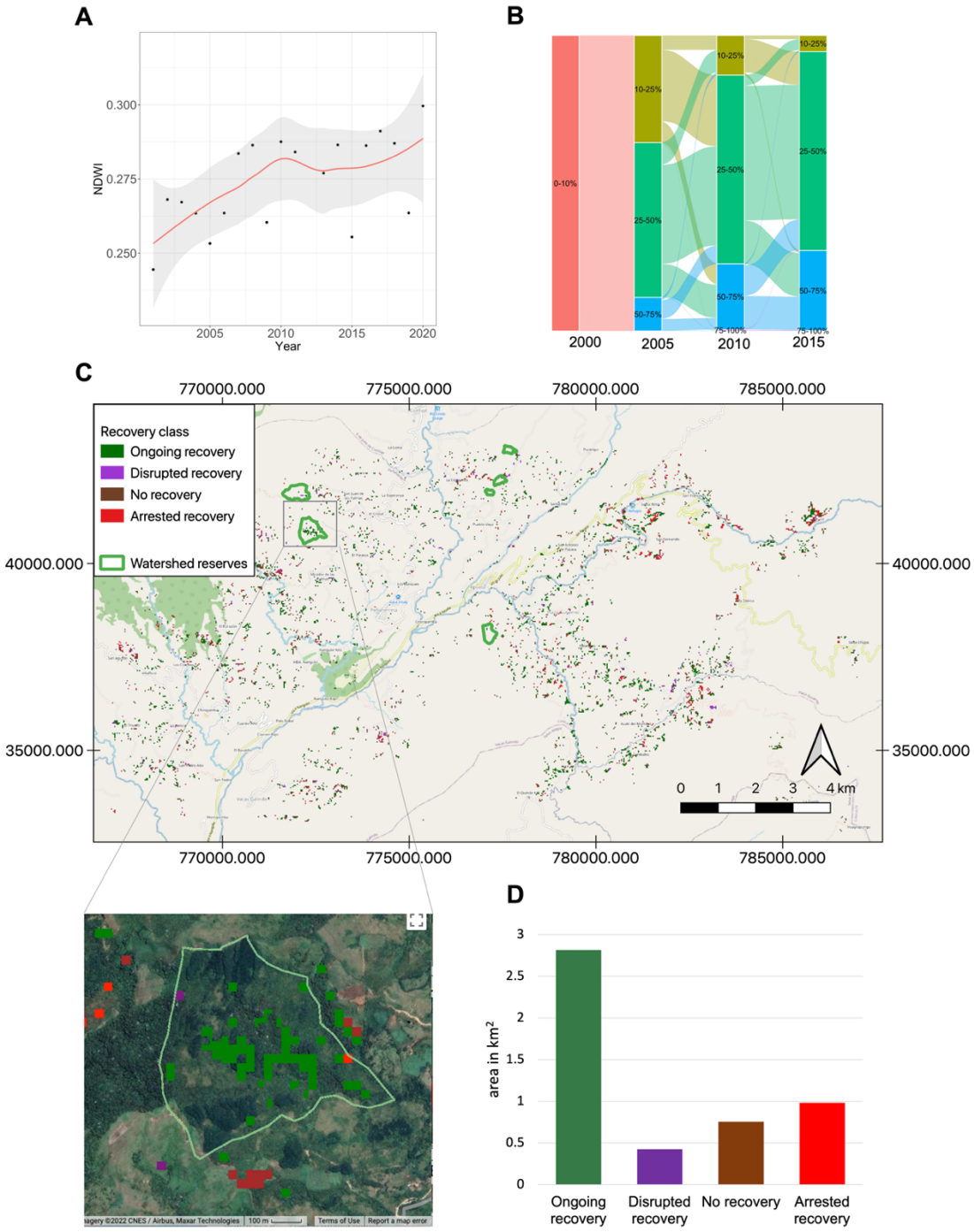


Figure 3. 6: Forest recovery trajectories in the Intag valley (Ecuador). A) NDWI time series in potential recovery classes, B) Tree cover change in potential recovery areas, C) Map of recovery trajectories across the landscape and zoom into the restored water shed reserve El Paraíso and D) Area in each recovery trajectory classes

Discussion

Across the tropical Andes, most forests in potential recovery areas experienced arrested or disrupted recovery, preventing progression to a fully reforested and biodiverse state. Our novel method allowed us to monitor recovery of montane forests across the tropical Andes at a fine scale and to classify four distinct types of forest recovery trajectories. Using the highest spatial resolution available for the period allowed us to examine small scale recovery dynamics of montane forests between 2005-2020 and to corroborate findings from previous coarse scale studies on Andean Forest change dynamics (Aide et al., 2019; Graesser et al., 2015; Sánchez-Cuervo et al., 2012; Sanchez-Cuervo & Aide, 2013).

Subsequently, we elaborate on the validity of our methods and delve into the potential reasons for and consequence of unsatisfactory forest recovery trends across the Tropical Andes Biodiversity Hotspot.

Validation of our method

Our own adapted version of a Z-score to classify recovery trends in each 5-year interval allowed us to look at short-term temporal dynamics within the 15-year time series accounting for residual variability of NDWI between time steps to establish 5-year forest recovery trends by detecting anomalous deviations in NDWI. Our pre-processing of data layers that involved driest month pixel selection and exclusion of steep slopes helps minimize cloud effects and geometric distortions – two common challenges of mountain remote sensing (Weiss & Walsh, 2009). This gives us confidence that the yearly median mosaic values of NDWI are as accurate as possible and can feed into a reliable Z-score computation. The findings from our realized recovery classification align with the Global Forest Cover Change dataset, which shows analogous instances of disrupted recovery through frequent shifts between low and high tree cover classes between 5-year intervals.

Using a 15-year period and 5-year time steps to construct realized recovery trajectories, our method captures a crucial initial phase of ATMF succession, where early successional pioneer species should be superseded by later succession species resulting in a mixed layer canopy with complex vegetation structure. While tropical montane forests take several decades to fully recover biodiversity, biomass and vegetation structure following disturbances (Aragón et al., 2021; Oliveras, Malhi, et al., 2014; Trujillo-Miranda et al., 2018), yearly gaps in Landsat data coverage pre 2000 did not allow us to reliably extend this analysis into the last century to track longer term recovery dynamics.

Based on our three case study landscapes, disrupted recovery predominantly happened near anthropogenic or disturbed areas, such as near infrastructure or settlements and at the outskirts of protected areas. This aligns with forest recovery being higher with increasing distance from human areas (Camelo et al., 2017; Wilson et al., 2019), while near pastures and agriculture recovery is slow in restoring forest structure and biodiversity (Günter et al., 2009; Palomeque et al., 2017; Rojas-Botero et al., 2020; Sarmiento, 1997).

Across the Intag landscape in Ecuador, our recovery classification method detects 'ongoing recovery' pixels near restored watershed reserves and on farmland. This matches remote sensing findings on forest transitions in the area due to a perceived ecosystem scarcity, and a net gain phase in forest cover in the new century. Forests regenerated on pastures and farmers planted trees and practiced assisted natural regeneration on their land in areas farther from roads, on steeper slopes, at lower elevations, and near watershed reserves (Wilson et al., 2019). Further, the mosaicked nature of the landscape with pastures interspersed with gallery forests, tree islands and remnant trees might facilitate montane forest succession and lead to frequent instances of 'ongoing recovery', as they provide micro-climate shelter and attract seed dispersers (Aide et al., 2011). On the other hand, trajectories of 'disrupted recovery' also occurred, likely due to use and interaction of local

inhabitants with the forest in the more accessible location such as for wood and timber extraction or re-clearing of regrowing forests for pastures and agriculture.

In the Iguaque National Park our method found few potential recovery areas, which aligns with the area being a conservation area where forest cover should be more constant through time due to use restrictions. 'Ongoing recovery; areas are likely a cause of natural regeneration as there were no reforestation efforts in Iguaque at the star of the century. We found mostly 'arrested' or 'no recovery', with early or mid-succession tree cover stages by the end of the study period. Interacting natural disturbance could be reducing forest recovery, such as El Niño episodes causing wildfires in 2010 and 2012 leading to reduced biomass and eventually cause tree mortality of some species (Aguilar-Garavito et al., 2021; Salazar et al., 2020) leading to years of stagnation or partial reversal of forest recovery. Moreover, several disturbances likely inhibit forest recovery: invasive pasture grasses like those in the genera *Melinis* and *Andropogon* dominate highly disturbed and burnt areas, and increasing visitor pressure leads to trampling and disturbance of young vegetation and destabilization of soils near hiking trails (D. Armenteras, personal observation). Further, seed dispersal is limited due to large distances between forest patches, leading to arrested succession (D. Armenteras, personal observation).

In the Cusco case study landscape, 'disrupted' and 'arrested recovery' prevailed with most pixels remaining in early tree cover stages, supporting field findings on low biomass recovery following wildfires and anthropogenic disturbance (Oliveras et al., 2014) and slow recovery of above-ground biomass following land abandonment of agroforestry systems (Aragón et al., 2021). It was concluded that Peruvian montane forests take more than 15 years to recover biomass post wildfires (Oliveras et al., 2014), a period extending above our study length.

Recovery trends across the tropical Andes

Across the tropical Andes an area of 274 km^2 made an initial forest transition between 2000-2005. These potential recovery areas theoretically harbour large opportunities for forest, biodiversity, and carbon recovery; however, this potential is currently not being realized.

Rather than progressing from initial recovery into later forest stages, most ATMF did not show progression of tree cover during the 15-year study period. Instead, most of our potential recovery areas deviated from a continuous ongoing recovery aligning with findings on nonlinear forest recovery through time (Decuyper et al., 2022; Schwartz et al., 2020). Previous work using 250 m-MODIS data found frequent reversals of reforestation across 11% of Latin American forests, indicating a short permanence of regrowing secondary forests (Schwartz et al., 2020). Some continental low spatial resolution scale studies have shown a net gain of woody vegetation across the tropical Andes, attributed to forest gain in abandoned pastures (Aide et al., 2019). But our analysis found that over a 15-year period initial vegetation gains manifests as 'disrupted', 'arrested' or 'no recovery'. This is likely due to the higher resolution of our study better capturing smaller scale patch dynamics compared to regional aggregation methods.

The disrupted recovery we observed is likely due to ecological factors interacting at different scales. At a continental level, forest recovery trajectories might be driven by extreme climate events like droughts and heatwaves which can cause tree mortality during forest succession (Hartmann et al., 2022) and might lead to continental scale trends of 'disrupted recovery'. El Niño Southern Oscillation cycles have been shown to impact forest recovery (Wigneron et al., 2020), as observed in our case study landscape in the Colombian Iguaque National Park during the 2014 El Niño period (Aguilar-Garavito et al., 2021) a period that coincided with a low point of NDWI values in our time series.

Regionally, forest recovery strongly depends on the socio-ecological system: 'disrupted' and 'no recovery' areas might result from escaped fires from the management of grazing resources by

pastoralists or land clearing (Oliver et al., 2017; Oliveras et al., 2014), land use changes following forest regrowth in community owned land, such as selective extraction of fast-growing trees and other species for firewood, charcoal, timber, or non-timber goods. Such extraction can create gaps in the forest and reduce forest cover, changes likely to be picked up by NDWI which is sensitive to forest degradation and hydric stress (Wang et al., 2007). A previous study suggested that reforestation reversal in the Colombian Andes might be due to recolonization of remote areas following the national peace process, highlighting the need to assess socio-political processes to understand underlying drivers of forest recovery (Aide et al., 2019).

Locally, agricultural legacies create biotic and abiotic conditions which inhibit forest succession on abandoned land (Martinez-Ramos et al., 2016), such as soil compaction and degradation, invasive grasses, herbivory, and frost exposure inhibiting seedling establishment and leading to the here identified 'no recovery' trajectory (Holl et al., 2000; Scowcroft & Jeffrey, 1999). Further, 'disrupted recovery' could be caused by repeated disturbance in the system, such as fires set by pastoralists to manage grazing resources – shown to have a significant impact on montane forests in Peru (Oliveras et al., 2018). Further, low protection of recovering areas from livestock due to lack of fencing is likely to cause 'disrupted recovery' as regrowing seedlings are predated on. 'Arrested recovery' of Andean Forests has been extensively detected on a plot scale (Palomeque et al., 2017; Rojas-Botero et al., 2020), and we find that this ecological process occurs across the mountain range, with 'arrested recovery' hotspots in Peru and Bolivia. Much of this arrested recovery could be a consequence of slow tree establishment following pasture abandonment due to harsh edapho-climatic conditions (Guariguata, 2005) and competitive interactions with invasive species (Aide et al., 2011).

An opportunity for intentional forest restoration

With 196 km^2 (71%) of potential recovery areas showing 'arrested', 'no recovery', or 'disrupted recovery', there is a large opportunity to use active restoration to overcome barriers to forest recovery in the Tropical Andes Hotspot. This might include protecting regenerating areas through fencing, direct seeding, and/or planting trees.

Restoration resources are limited but commitments are high, hence prioritizing where to focus restoration actions is essential. The methodology presented here can help identify priority areas for interventions, where further studies of restoration potential at the regional scale could be useful. Especially in Peru, Bolivia, and Colombia, trajectories other than 'ongoing recovery' are frequent and regional-level assessments could help identify reasons for low forest recovery and devise appropriate restoration methods.

While there are some recent emerging tree planting efforts – both through exotic plantations and ecological reforestation in the Andean countries (Cerrón Macha et al., 2018; Murcia et al., 2017), most observed forest recovery during our study interval is likely due to natural regeneration given the tropical-Andean scale and many remote locations. Natural regeneration can produce biodiverse, and structurally complex rich forest systems, usually on time scales of several decades. However, it is also a slow and unpredictable process (Norden et al., 2015), which shows variable success rates and often results in arrested succession (Holl & Aide, 2011) as we observed in the current study with little recovery after 15 years.

Various restoration techniques of the restoration continuum are advisable depending on the nature of the barriers that hinder forest recovery (Chazdon et al., 2021). The first step is to determine which biophysical limitations and socioeconomic factors lead to a failure of forest recovery. Techniques of moderate or intense assisted recovery might be useful to boost forest recovery where landscape and micro-site conditions are not favourable to natural regeneration (Chazdon et al., 2021), for instance, in topographically complex and fragmented mountain landscapes, where propagule

sources are lacking due to large distances from remnant forests (Aguirre et al., 2011; Günter et al., 2007), and where previous land use intensity was high (Holl & Aide, 2011). In 'no recovery' and 'arrested recovery' areas where the main limitations have been identified as biophysical, both active interventions (seedling planting, management of invasive grasses, shading seedlings from high solar radiation) and assisted natural regeneration techniques which blend active and passive approaches (fire protection, fencing from herbivores, enrichment planting) can be useful in speeding up recovery (Shono et al., 2020). When 'arrested recovery' happens at early successional stages on pasture sites managing competitive interactions which inhibit forest recovery can help forests to recover (Palomeque et al., 2017), as can enrichment planting or direct seeding of shade tolerant target species in later successional stages (Cole et al., 2011; Florentine & Westbrooke, 2004; Palomeque et al., 2017).

Where recovery is limited by social factors, active techniques need to be determined based on the drivers of forest clearing. For example, if uncontrolled grazing limits recovery, fencing or picketing could be used to control disruption from livestock. If conversion to pastureland is common, working with landholders to introduce silvopastoral systems could be a viable option to increase forest cover - living fences using native woody species and/or pasture trees like *Inga spp or Alnus acuminata* from the Fabaceae family can improve soil fertility, provide shade for livestock and products for local households (Rhoades et al., 1998).

If forests are cleared for agriculture, as is likely in many 'disrupted recovery' areas, locally appropriate measures could be taken to decrease disruption, including introducing agroforestry systems, creating incentives to allow forests to recover (payment for environmental service schemes, tax incentives), and limiting disturbance of surrounding areas by creating firebreaks, controlling grazers, and limiting the spread of invasive species. Creating or improving regulations aimed at protecting regenerating areas could also be critical in potential areas for restoration.

Avenues for further research

Further research could elucidate drivers and solutions for forest recovery. Due to the mosaicked nature of Andean ecosystem dynamics high-resolution land use classifications need to be used to establish environmental conditions related to land use history and landscape connectivity. In the future the recently launched Dynamic World classification on a 10 m resolution could be used for this purpose. As of now however this dataset only dates 7 years back and does not allow to construct a sufficiently long land use history to capture legacy effects. In the future, our method could be re-applied and refined using these higher resolution datasets to establish more fine scale potential recovery areas and track future forest recovery during the UN Decade of Restoration.

While we picked 5-year time steps to compute intermediate recovery, this could be adapted for shorter term recovery dynamics such as for landscapes where recent forest recovery dynamics like tree planting efforts need to be evaluated. Due to the large extent of our study, we stuck to three five-year time steps to provide a simple look-up table instead of deploying complicated method like shape recognition algorithms or computationally limiting calculations.

Reforestation efforts in the Andean Forests have gained momentum in the last decade (Murcia et al., 2017) with a range of organizations seeking to restore these precious ecosystems to improve livelihoods, increase ecosystem services and improve biodiversity (Programa Bosques Andinos, 2021; Cerrón Macha et al., 2018). Together with local and regional scale assessments of the biophysical and socio-economic factors limiting forest restoration success, and comprehensive restoration feasibility studies our analysis could help steer efforts and tailor restoration strategies to areas where forest recovery is compromised.

Conclusion

With an increasing global push for ecosystem restoration, forest transitions in the Andes harbour large opportunities for intentional forest recovery. With 73% of potential recovery areas not undergoing expected forest recovery over a 15-year period, natural regeneration by itself is not a sufficient solution to restore biodiversity and ecosystem services. While many small-scale field studies across the tropics have shown that montane forest recovery is often unsuccessful, our study demonstrates that this trend also translates to the continental scale.

Active restoration or assisted interventions are needed to speed up forest recovery, and managements' decisions will need to be tailored on a local or regional basis to choose the best methods to overcome regional and local barriers to forest recovery. With many international partnerships and the private sector pledging to restore ecosystems for carbon, livelihood and biodiversity goals, suitable areas need to be found where active restoration can make a positive on-the-ground difference and outperform natural regeneration.

We show that long-term time series of satellite data can aid with monitoring forest recovery across large mountain ranges and can help locate priority regions for intervention. Many other highly biodiverse tropical mountain ranges beyond the Andes exhibit difficult biophysical and socio-economic conditions for forest recovery and this method can be applied across the globe to identify restoration hotspots and steer management interventions.

Our method is simple and can be repeated for later periods to detect recovery trajectories of subsequent time steps and restoration priority areas for the future. Poorly recovering Andean montane forests, which show trajectories such as 'no recovery', 'disrupted recovery' or 'arrested recovery' could be suitable target sites for creating active restoration interventions which will need to be co-designed with local mountain communities to deliver holistic restoration goals.

Supplementary material

Supplementary 2. 1: Specification of the three case study landscapes for landscape scale assessment

Name	Coordinates	Elevation [m asl]	Land use history	Dry season months	Local expert
Challabamba (Cusco, Peru) Buffer zone of Manu National Park	13.2 S 71.65 W	3000-3600	Recurring anthropogenic fires, large trend of land abandonment followed by various kinds of vegetation recovery	July-August	I. Oliveras Menor
Intag (Ecuador) valley community tree planting, Ecuador	0.34N, 78.6W	1500-3500	Large parts used as pasture, later community reforestation projects in watershed reserves by local NGO	June-September	S. Wilson
Iguaque National Park (Colombia)	5.68N, 73.46W	1500-3800	Historically agricultural use followed by abandonment. National Park protected since 1977. Recurring wildfires (Aguilar-Garavito et al 2020)	January-February	D. Armenteras

Supplementary 2. 2:The Vegetation Indices used in this study and the facets of recovery they monitor.

Vegetation Index	**Facets of recovery**	**References**
Normalized Difference Vegetation Index (NDVI)	Track vegetation cover and vegetation greening in early vegetation succession stages. However, it often saturates, i.e., reaches maximum values, in highly vegetated forest systems.	(Liu et al., 2019; Meroni et al., 2017) (Pickell et al., 2016)
Enhanced Vegetation Index (EVI)	Used to determine vegetation greening and structure under high vegetation conditions.	(Valtonen et al., 2021)
Near Infra-Red (NIR)	Is sensitive to forest successional pathways following disturbance	(Negrón-Juárez et al., 2020)
Normalized difference water index (NDWI)	It allows assessment of vegetation water content and vegetation structure due to its inclusion of short-wave infrared	(Dupuis et al., 2020)
Soil adjusted vegetation indices (e.g., MSAVI2)	It allows separation of soil related effects and is hence useful during early succession of forests while open soil might still be visible.	(Xue & Su, 2017)

Supplementary 2. 3: Look up table for classification of realized recovery classes based on Z-score sequence.

	Recovery class	Description	Z score 2005-2010	Z-score 2010-2015	Z-score 2015-2020
1	**Ongoing recovery**	Recovery in last time steps	1	1	1
			0	1	1
			1	0	1
			0	0	1
			-1	0	1
			-1	1	1
2	**Disrupted recovery**	Decline following recovery	-1	-1	1
			0	-1	1
			1	1	-1
			1	-1	1
			1	-1	0
			1	0	-1
			1	-1	-1
			0	1	-1
			-1	1	-1
3	**No recovery**	No recovery in any time step	0	0	0
			0	-1	0
			-1	0	0
			0	0	-1
			-1	-1	-1
			0	-1	-1
			-1	-1	0
			-1	0	-1
4	**Arrested recovery**	Recovery followed by stagnation	1	1	0
			1	0	0
			0	1	0
			-1	1	0

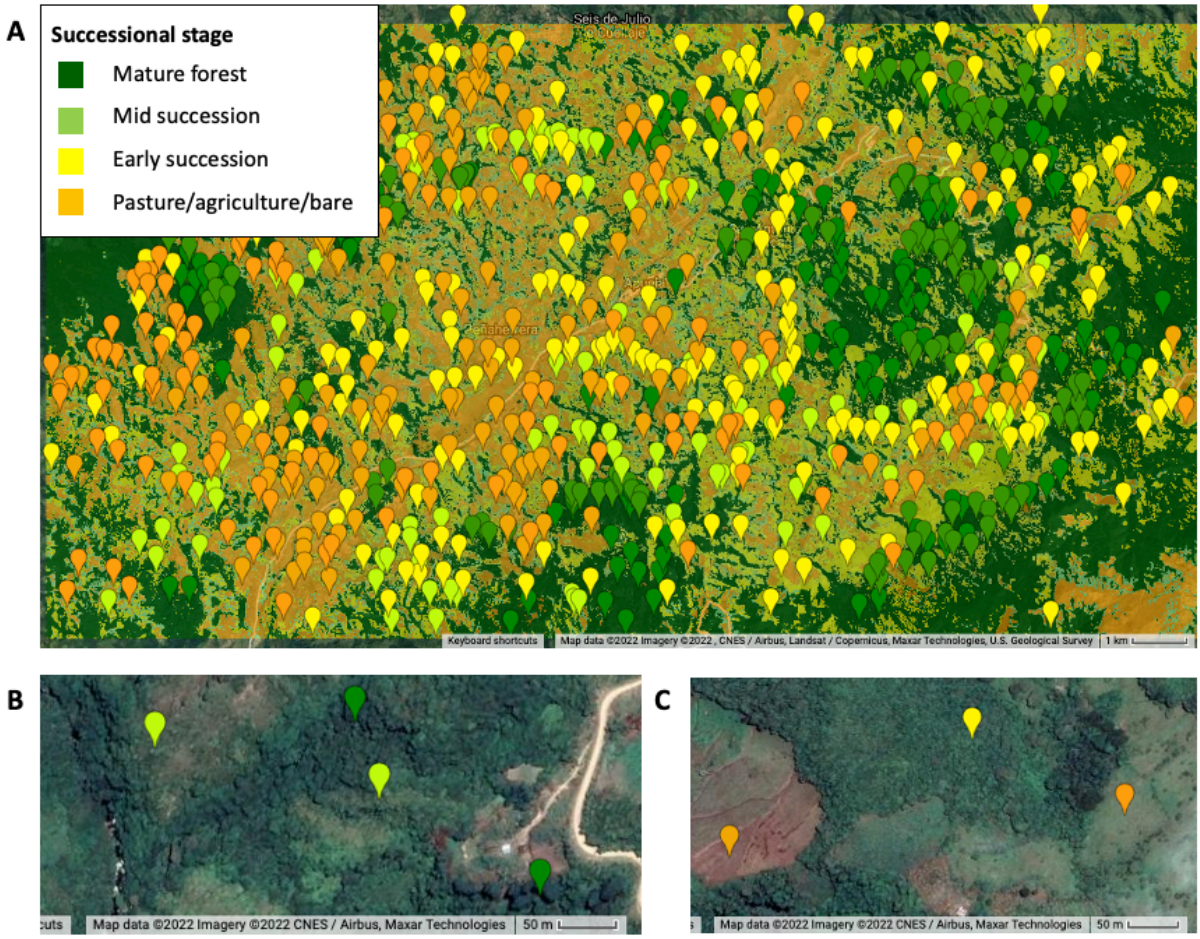
Supplementary 2. 4: Validation against Sentinel data

We created a supervised classification of forest successional stages based on a 10m- Sentinel dry season 2021 cloud free composite for the Intag case study landscape. We used Google Earth high resolution data to visually classify a training dataset of 894 points and then used 80% of the points to train a Random Forest classifier with 500 trees using the bands 'BLUE', 'GREEN', 'RED', 'NIR', 'SWIR1', 'SWIR2' and the vegetation indices 'NDVI', 'EVI', 'NDWI' and 'MSAVI2'. We assessed accuracy of the classification against the remaining 20% and achieved an overall accuracy of 74.5% (Supplementary 4). We then exported the classified successional stages for all pixels in the potential recovery classes and statistically assessed how the Sentinel vegetation indices of the 2021 composited matched up with the successional stages. All the ratio indices (NDVI, EVI, MSAVI2, NDWI, RVI) had a strong positive relationship of Spearman rho > 0.66 with the forest succession classes and these indices increased along with the succession trajectory (Supplementary 6 A & B). SWIR1 and 2 have a strong negative fit and decrease along the succession trajectory. A Principal Component analysis further showed that the succession classes were ordered along the strong first PC axis which explained 62% of variation and was correlated to NDVI, EVI, MSAVI2, NDWI, RVI (Supplementary 6 C).

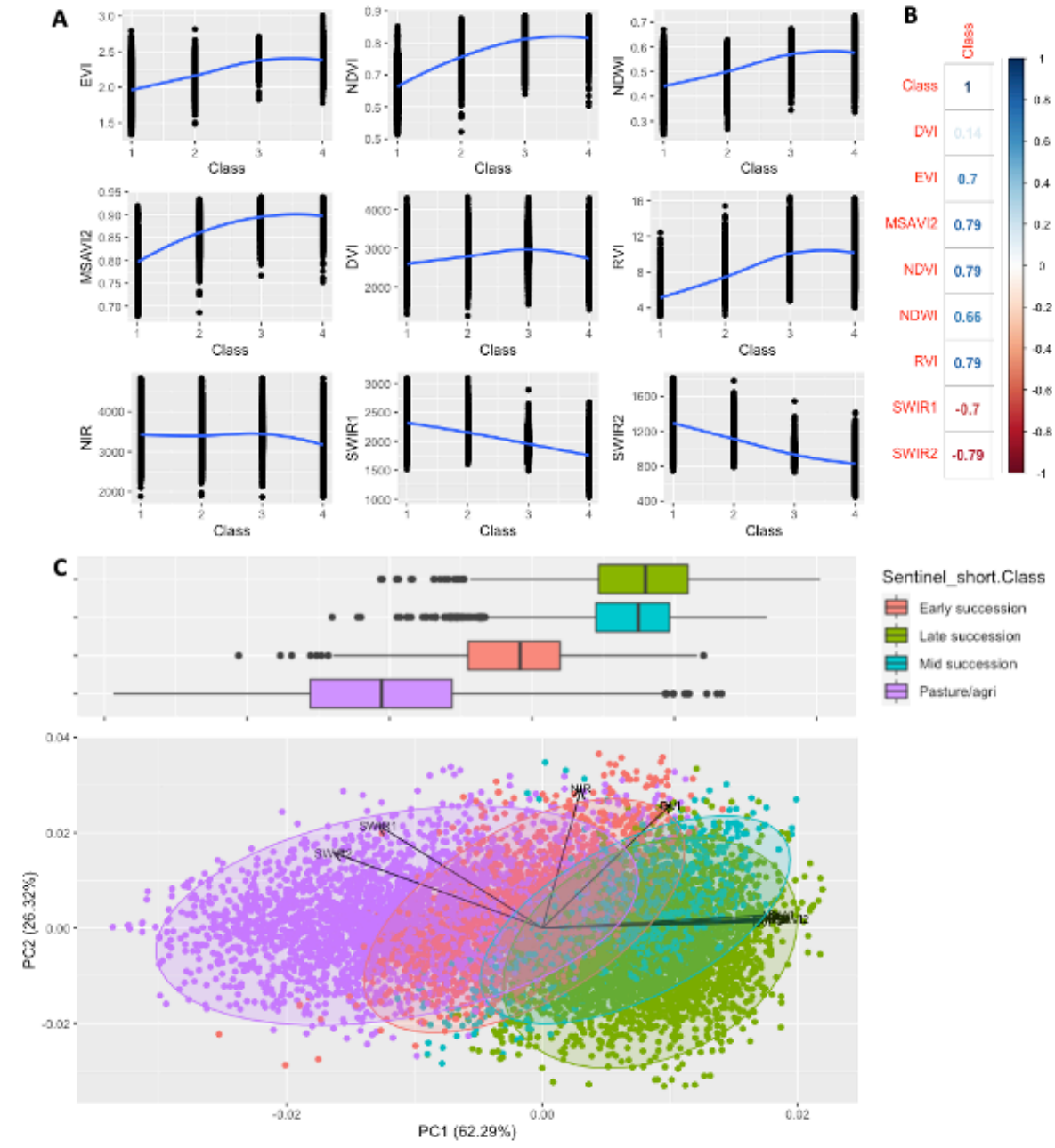
We then assessed whether the lower resolution indices from Landsat sufficiently well captured smaller scale forest dynamics in the potential recovery areas, as seen by higher resolution data, by validating Landsat 30m data against Sentinel 10m data. For this, we computed Spearman correlation of Sentinel surface reflectance dry season composites for the year 2021 against corresponding 2021 Landsat dry season composites, which we reprojected to Sentinel resolution and dimensions (Supplementary 7). Despite the difference in resolution between the datasets, results show a satisfying fit of the Landsat bands NDVI (rho = 0.44) and MSAVI (rho = 0.45) and a good fit of NDWI (rho=0.53) with the respective Sentinel bands.

Supplementary 2. 5: Error matrix for the successional stage classification of the Intag case study landscape classes using Sentinel composite from the dry season 2021. The classification was done using the bands BLUE', 'GREEN', 'RED', 'NIR', 'NDVI','EVI','SWIR1', 'SWIR2',

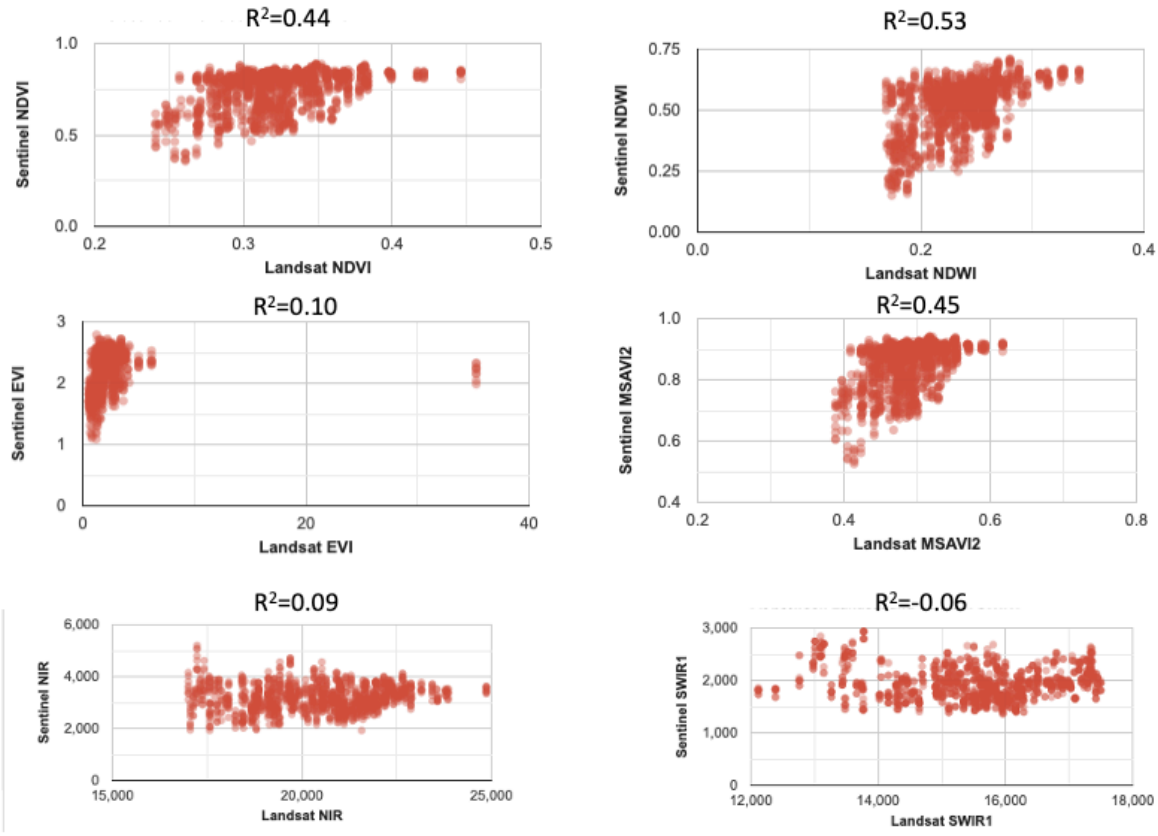
Successional class		Reference data					
		Bare & pasture	**Early succession**	**Mid-succession**	**Mature forest**	**#Classified**	**User accuracy**
Classified data	**Bare & pasture**	58	2	1	2	63	*0.9206349*
	Early succession	6	16	7	4	33	*0.4848485*
	Mid-succession	8	10	8	4	30	*0.2666667*
	Mature forest	1	4	1	64	70	*0.9142857*
	#Classified	73	32	17	74	196	
	Producer accuracy	*0.7945205*	*0.5*	*0.4705882*	*0.8648649*		Overall accuracy: 0.745



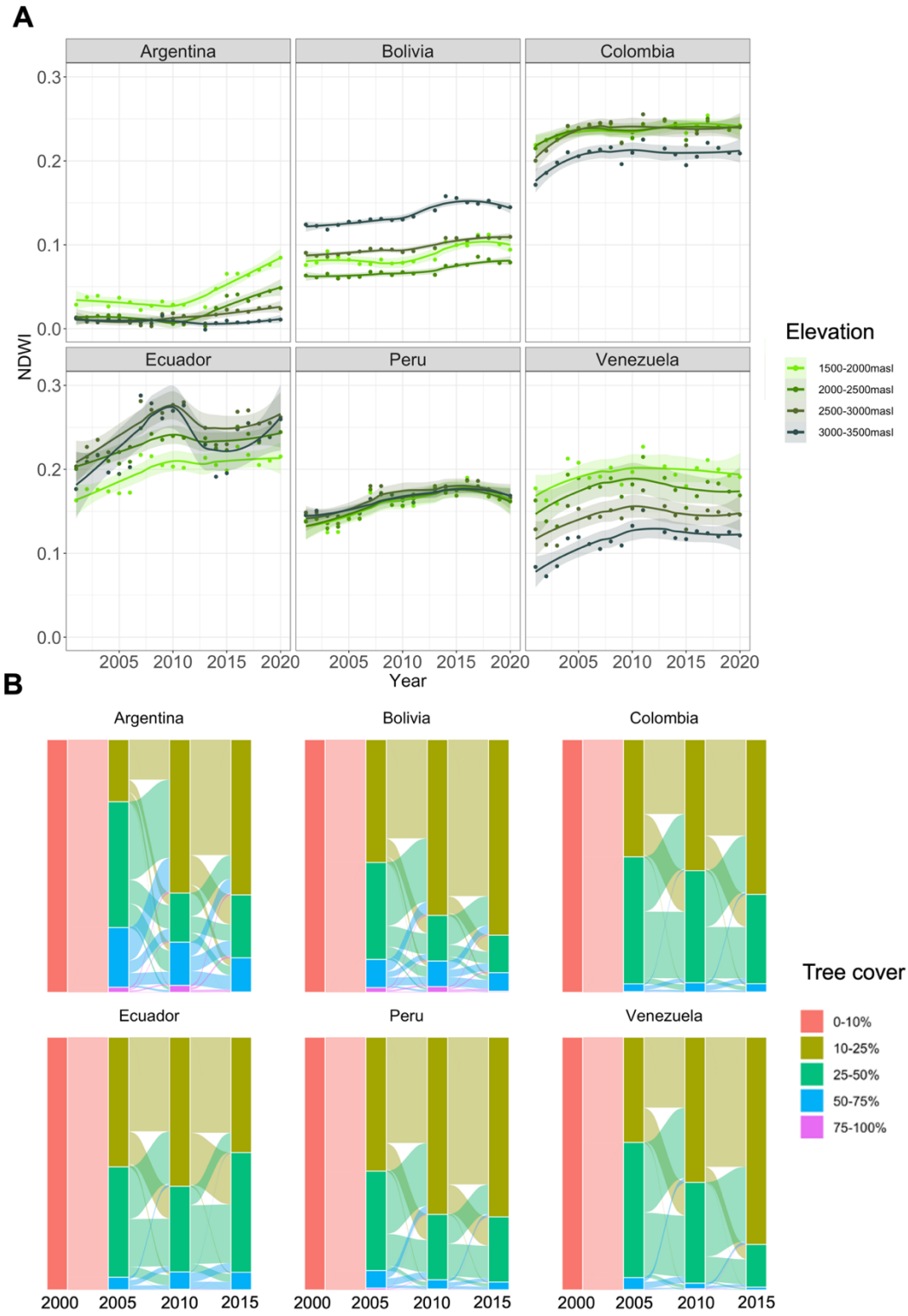
Supplementary 2. 6: Random Forest classification of forest successional stages for the Intag case study landscape. A) Final classification of four classes, overlaid with the 894 training points. B) Example of a mid-succession stage and mature forest stage, C) Example of an early forest succession and pasture /bare site.



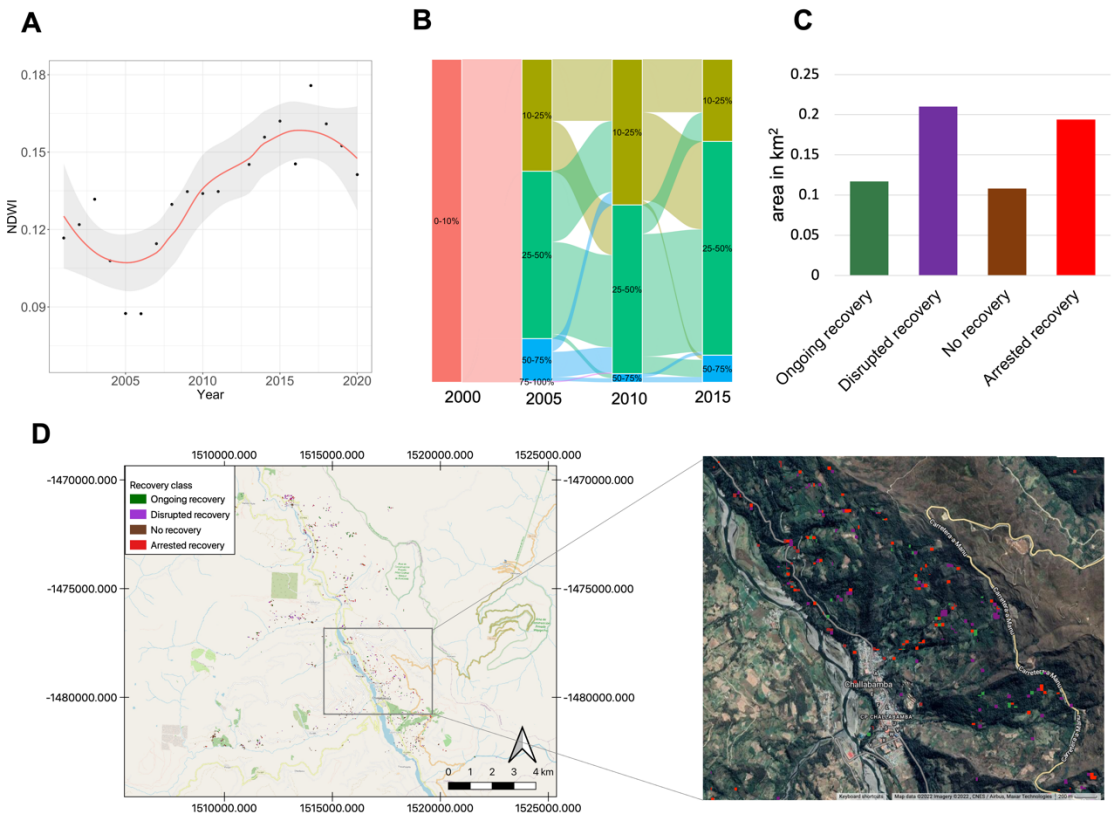
Supplementary 2. 7: Correlation of successional classes from supervised classification with Sentinel vegetation indices. A) GAM models for relationship between nine Sentinel vegetation indices or bands with successional classes, B) Spearman correlation for these relationships. C) PCA for position of the successional classes in the multivariate space of the nice indices & bands.



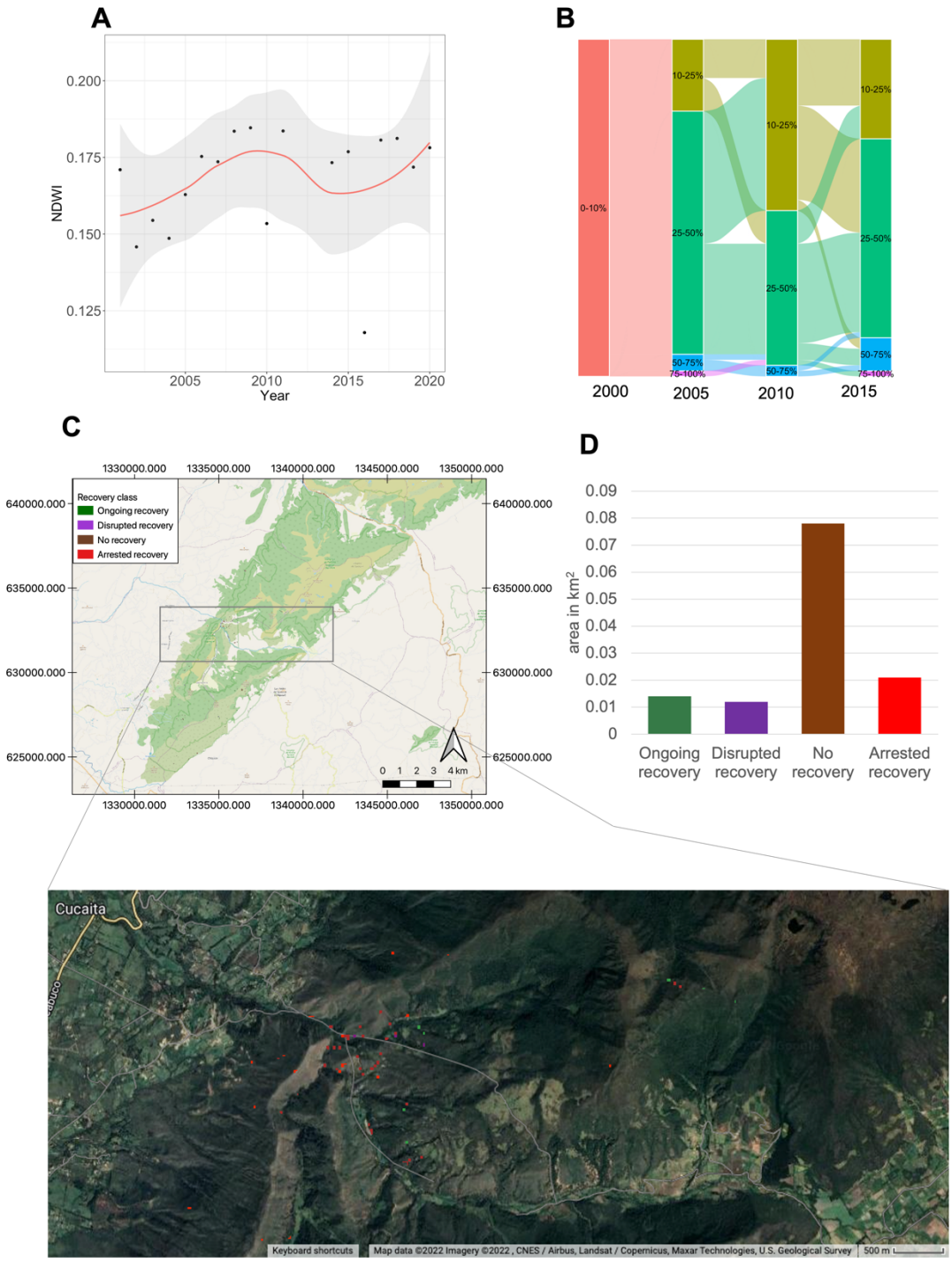
Supplementary 2. 8: Validation of Landsat data for 2021 against Sentinel data of 2021. Displayed are the Spearman coefficients.



Supplementary 2. 9: A) NDWI mean time series at different elevations for the six countries. B) Forest cover change in the six countries.



Supplementary 2. 10: Forest recovery trajectories in Challabamba, department of Cusco (Peru). A) NDWI time series in potential recovery classes, B) Tree cover change in potential recovery areas, C) Area in each recovery trajectory classes and D) Map of recovery trajectories across the valley and for a mountain side.



Supplementary 2. 11: Forest recovery trajectories in Iguaque National Park (Colombia). A) NDWI time series in potential recovery classes, B) Tree cover change in potential recovery areas, C) Map of recovery trajectories across the valley and D) Bar charts for proportions of recovery trajectories.

Preface to Chapter 4 (Paper III):

Chapter 2 (Paper 1) found a lack of socio-ecological restoration studies, as well as a specific lack of social goals and objectives in restoration science (Figure 2.8: green rectangle); a shortcoming that the Chapter 4 seeks to address through a socio-ecological qualitative approach to evaluating and studying restoration.

I also identified the limiting and enabling factors for TME restoration through a systematic review of academic literature. Key limiting factors include abiotic habitat constraints, dispersal limitation, biotic interactions, and land use legacy effects. It stood out how social, economic, and institutional factors were rarely mentioned as either barriers or promoting factors. In Chapter 3 (Paper II) I identified that across the Andes, and particularly in Peru, vast areas of abandoned land are not undergoing expected forest recovery. This trend of disrupted forest recovery at large is particularly visible in Peru. These disrupted, arrested and no-recovery areas are the areas where restoration interventions could be targeted to help overcome barriers to regeneration and to recreate thriving and biodiverse forest ecosystems. However, forest restoration success is highly dependent on the socio-economic and institutional context of a place and of practical feasibility (Aguiar et al., 2021; Löfqvist et al., 2022; Ota et al., 2020).

In Peru restoration interventions in Andean Forests do exist but these have to my knowledge not been systematically studied involving all relevant stakeholders and following a structured methodology. With restoration projects being a very recent endeavour in the Andes, it is not well-established what methods work best to restore Andean Forests in a way that benefits both nature and people. The government of the megadiverse Andean country of Peru has pledged to restore 3.2 million hectare of degraded land under the Bonn Challenge. While many of these efforts currently focus on the Peruvian Amazon, there is a need to also target recovery and establish recovery schemes in Peruvian montane forests, which albeit smaller in extent, host a multitude of endemic

and threatened plant species and harbour large carbon stores (Aragón et al., 2021; Zador et al., 2015). In Chapter 4 (Paper III), I use multi-stakeholder interviews at a restoration project level. I conduct 75 interviews with numerous stakeholders involved in restoration planning to find out how to do best-practice restoration. This complements the conclusions of Chapter 2, where I state that once a restoration priority site is identified working with local stakeholders is crucial to select the most appropriate restoration strategy.

The paper addresses several research priorities from the framework by Mathez-Stiefel et al (2017), namely Priority 2 of studying the interactions between social and environmental dynamics, Research Priority 3 of investigating impacts of governance and management practices on livelihoods and ecosystem services, Priority 4 of Setting sustainable foals for Andean forest management through inclusive, equitable and multistakeholder processes and Priority 5 of creating robust and place based governance models. In doing so it seeks to generate systems knowledge, target knowledge and transformation knowledge to aid in the research and practice of Andean forest restoration.

This manuscript has been submitted for publication to *People and Nature*. As per the journal guidelines the abstract follows a numbered structure. I conceived the initial idea for the study with inputs from Imma, Sarah and Aida. Isaias and Mayte assisted with interviews and logistics in the field and helped with transcription. Several local co-authors from the key institutions facilitated fieldwork, interviews, logistics and contacts. I conducted the data analysis myself and wrote the initial draft with inputs from Aida, Imma, Yadvinder and Sarah. Local co-authors helped with reviewing and editing. All co-authors provided comments on the final draft which I assembled.

Chapter 4 (Paper III)

‘Sowing and harvesting water’ – revisiting forest restoration in the Peruvian Andes through a multi-stakeholder analysis.

T. Christmann, I. Cjuno-Turpo, M. Lopez-Aranda, S. J. Wilson, A. Cuni-Sanchez V. Rondán, A. Ramirez, M. Arenas, F. Medina Castro, M. Mamani, C. Aucca Chutas, J. Recharte, O.A. Carrión-Moreno, F.B. Gonzalez Cabello, Y. Malhi, I. Oliveras-Menor

In collaboration with:

"We must give the topic of water more importance. […] There are institutions who care about many other things, but not about water, they are very much neglecting water."
– High Andean farmer



Figure 4. 0: Aerial view of the mosaicked high Andean landscape and of a forest restoration site at 3200m asl surrounding a lagoon. On the perimeter of the lagoon native *Polylepis spp*. was planted, while further outside exotic *Pinus radiata* was planted.

Abstract

1. Efforts to restore Peru's megadiverse Andean Forests are proliferating rapidly. While ecological determinants for restoration success are relatively well known, knowledge on the socio-economic and governance conditions that determine success of ecological restoration using native species are scarce.
2. Using a multi-stakeholder approach this paper analyses the motivations, objectives, enabling and limiting factors and preferences for effective ecological restoration of Andean Forests, through 75 semi-structured interviews with local community members, NGOs, and government actors in 11 restoration sites in Peru.
3. We find that across sites and stakeholder groups, the primary motivations for Andean Forest restoration were instrumental, especially to restore and improve water resources. In all stakeholder groups Andean Forests were mostly valued for their provisioning ecosystem services - with water provision valued by all stakeholders and firewood provision predominantly by communities - followed by regulating services (water retention and climate regulation).
4. Restoration success – the degree of perceived achievement of projects objectives - was high at all sites and scored between 2.4-3/3. Enabling factors for the restoration success were mostly social and institutional. There was no 'silver bullet' to successful restoration; rather, enabling factors were often social and included high levels of resource dependence of communities, support, and facilitation by NGOs, participatory management and governance structures, and creation of communal conservation agreements. Communities emphasized primarily social and institutional limiting factors, while government stakeholders emphasized technical challenges. We further identified three typologies of how projects engage and compensate communities: a 'payment model', a 'capacity model'

and a ‘mixed model’ which differ in their rentability, longevity, and social and economic benefits provided.

5. All stakeholder groups favoured active forest restoration and community members identified desirable native plant species with local use and hydrological value. Interviewees also highlighted that restoration needs to go beyond forests, and involve a mix of native tree planting, agroforestry, and restoration of mountain grasslands and peatlands to holistically improve water resources and long-term economic benefits at a landscape scale.

Synthesis and applications: According to the social, ecological, and economic priorities identified by the stakeholders we develop a ‘Mountain Landscape Restoration Approach’ recommending landscape-scale restoration interventions.

Key words

Andean Forest, community participation, ecological restoration, ecosystem services, forest governance, local livelihoods, *Polylepis*, water provision

Introduction

To achieve equitable and successful outcomes, implementers need to understand and integrate social dimensions when planning and executing restoration, as most restoration priority areas fall into regions with a low human development index (Löfqvist et al., 2022). One such global restoration priority area is the exceptionally species- and endemic-rich Tropical Andes Biodiversity Hotspots (Myers et al., 2000). Andean Forests have been extensively deforested and degraded for agriculture for many thousands of years (Valencia et al., 2018). Fire, overexploitation, and deforestation continue to have negative impacts on ecosystem structure, biodiversity, and local livelihoods today (Armenteras et al., 2011; Aucca & Ramsay, 2005; Lippok et al., 2013; Oliver et al., 2017; Oliveras et al., 2014). Nowadays, native Andean Forests occupy a fraction of their potential range (Ministerio del Ambiente, 2015). In the rural Andes, land-dependent subsistence farming is a vital source of livelihood and economy, and communities are highly dependent on the ecosystem services provided by the remaining forests (Programa Bosques Andinos, 2021). Andean forests are part of a complex socio-ecological system yet remain critically understudied (Mathez-Stiefel et al., 2017). To achieve sustainability in the Andean region, scholars have previously set out an agenda with 'Research priorities for the Conservation and Sustainable Governance of Andean Forest Landscape' which highlighted a series of research priorities related to investigating interactions between social and environmental dynamics, impacts of land governance and management practices on livelihoods, sustainability goals across scales and stakeholders, as well as landscape restoration practices (Mathez-Stiefel et al., 2017).

Restoring Andean Forests by planting native tree species (hereafter referred to as 'Andean Forest restoration') is one central strategy to recreate thriving Andean Forests. Ecological restoration is defined as the 'recovery of an ecosystem that has been degraded, damaged, or destroyed' (Society for Ecological Restoration, 2002). Andean forest restoration can also be conceptualised as a Forest

Landscape Restoration (FLR) strategy which aims to improve both forest ecosystem function and local livelihoods, well-being and resilience (Erbaugh & Oldekop, 2018). Alongside conservation policies, environmental education and empowering community participation, ecological restoration can help to sustainably manage Andean Forests for current and future generations (Pinos, 2020). Andean Forest restoration can improve agricultural productivity and thus benefit local livelihoods by improving water regulation and preventing soil erosion (Báez et al., 2010). It can also stimulate community economy by creating employment and enabling alternative practices such as tourism (Aucca & Ramsay, 2005). As such, the outcomes of Andean forest restoration are multi-dimensional and interlinked and can be conceptualized according to the framework by Erbaugh & Oldekop (2018). This framework links FLR to both ecological (ecosystem functions) and social (livelihoods, well-being and resilience outcomes) and distinguishes three distinct pathways: A direct pathway of an FLR project benefitting ecological functions, a second direct pathway of FLR directly benefitting livelihoods, well-being and resilience, and a thirds indirect pathway of interactions between social and ecological outcomes (Erbaugh & Oldekop, 2018). However, such multidimensional FLR outcomes have rarely been explored in depth and there is not such study for the Andean forest restoration yet.

While it is well established what biophysical and technical conditions enable and limit forest restoration in tropical mountain environments (Christmann & Oliveras Menor, 2021; Guariguata, 2005; Holl et al., 2000), the social side of Andean Forest restoration is little explored (Báez et al., 2010; Christmann & Oliveras Menor, 2021; Mathez-Stiefel et al., 2017). Little is known about what motivates actors to restore Andean Forests, whether restoration goals are achieved, which socio-economic and institutional factors enable and limit restoration, as well as what type of restoration is preferred by local communities and stakeholders. Investigating the motivations of different stakeholders to participate in restoration is key to designing future strategies that meet their needs and to ensure project sustainability. Motivations can be intrinsic, relational or instrumental (IPBES,

n.d.). In the Ecuadorian Andes, motivations to restore forests on farmland were shown to be largely instrumental and are described by a perceived 'ecosystem scarcity' and a desire to restore forest to enhance the provision of declined ecosystem services, such as the availability of water resources (Wilson & Coomes, 2019). In Peru it was found that families' economic reliance on subsistence products decreased intentions to restore High Andean *Polylepis* forests due to perceived competition with agricultural activity, while higher technological knowledge and a better understanding of ecosystem services increased restoration intentions (Joseph et al., 2021). Similarly, an Ecuadorian Andean case study found that a higher socioeconomic status increased interest in forest restoration and that motivations to restore were driven by species' utility in conserving water and soil and protecting from wind (Báez et al., 2010).

To maximize restoration success (here success is defined as the extent to which a given restoration objective is achieved), we need to look at a set of factors that enable and hinder project success – which can be classified into five categories: biophysical, technical, institutional/legal, social, and economic (as previously used in frameworks by Cerrón Macha et al., 2018; Le et al., 2014). In the Andes, the factors that facilitate and hinder land restoration are critically understudied (Hartman & Cleveland, 2018). Globally, social factors have often been found to trump biophysical factors in driving forest restoration success; hence an understanding of the social circumstances is key (Elias et al., 2021; Löfqvist et al., 2022; Ota et al., 2020; Stanturf et al., 2014; Wilson & Coomes, 2019).

At a continental South American scale, barriers for forest landscape restoration were found to be largely social and institutional, such as (1) the high dependence of local communities and countries' economies on natural resources; (2) conflicts over land tenure and access; (3) divergence in perceptions and values between social actors with contrasting worldviews, knowledge and power; and (4) the fragility of public institutions and policies (Aguiar et al., 2021). National-scale reports including several Peruvian biomes have broadly alluded to lessons learnt at a national scale (Cerrón Macha et al., 2018) and highlighted a range of legal, technical, ecological, social, and economic

challenges for restoration of montane forests. They emphasised the importance of socio-economic factors, and found that land ownership, environmental education, political boundaries, conservation agreements and community organization are key to restoration success. Another study on communal wetland restoration in Bolivia found that restoration was successful when restoration goals were aligned with instrumental community motivations related to perceived livelihood benefits such as water and soil conservation, food and fibre production and enhanced development (Hartman & Cleveland, 2018). Financial incentives helped ensure participation at initial stages while conflicts over land tenure and resource use, and outmigration distracted from restoration work (Hartman & Cleveland, 2018). In the Ecuadorian Andes, forest restoration was motivated by a need for water, and its success facilitated by communal land tenure of restoration sites as this enabled a participatory low risk approach and by the engagement of trusted leaders (Wilson et al., 2019; Wilson & Coomes, 2019).

So far, most socio-economic studies of Andean Forest restoration have focused on single landscapes and only focused on few stakeholders (e.g., either expert interviews with NGOs or community members) (Báez et al., 2010; Durand & Sevillano, 2017; Joseph et al., 2021), thereby not allowing to obtain an encompassing multi-stakeholder perspective of perceptions, values, and preferences. This hinders upscaling of restoration from the local to the regional and national scale – two research priorities stated for the conservation and governance of Andean Forests (Mathez-Stiefel et al., 2017). Another key priority for Andean Forest research is to analyse the costs and benefits of conservation and restoration interventions (Pinos, 2020). To successfully restore the highly degraded montane forest biome a holistic understanding is needed to learn why, where, and how to best implement restoration in a way that improves ecosystem services, biodiversity, and livelihoods of mountain communities. By using meta-analyses of local case studies, a pluralistic understanding of the restoration settings and the best approaches to create successful and equitable contextually effective restoration can be attained (Löfqvist et al., 2022).

Peru holds the largest extent of the tropical Andean Forest zone (229,140km^2 in Peru, vs. 147,159 km2 in Colombia and 39,968 km^2 in Ecuador) and 27.8% of Peru's national forest area is classified as Andean Forest (Programa Bosques Andinos, 2021). Peru has recently pledged to restore 3.2 million hectares of degraded land under the Bonn Challenge and was part of the Latin American restoration Initiative 20x20 (20 million hectare by 2020 across Latin America). However, so far experiences and knowledge sharing of Andean Forest restoration are limited. Further, ecological restoration is a relatively recent endeavour in Peru compared to other Andean countries such as Ecuador and Colombia (Murcia et al., 2017). The activity of ecological restoration has only been defined and formalized in 2011 in the New Forest and Wildlife Law (Ley No 29763), which describes ecological restoration as a "Human-induced process which seeks to help restore a degraded, damaged or destroyed ecosystem. Restoration tries to return an ecosystem to its historical trajectory." Most Andean Forest restoration projects are less than 10 years old, small-scale, and are implemented on small budgets (Murcia et al., 2017). The restoration work that does exist - some of it dating back to the 1980s - is not well studied or well-known and housed mainly in NGO-reports or government announcements.

This study seeks to draw a comprehensive picture of motivations, enabling and limiting factors, impacts and future directions for Andean Forest restoration. Specifically, our study aims to answer the following questions:

(1) What are motivations and objectives for forest restoration with native species in the Peruvian Andes across different stakeholder groups?
(2) Which social, economic, biophysical, institutional/legal, and technical factors affect restoration success according to different stakeholder groups?
(3) How do restoration projects impact community livelihoods?
(4) Through what models do restoration projects achieve community benefits, project sustainability, and restoration success?
(5) What type of restoration interventions are preferred by different stakeholders for the future?

Methods

Study system: Peruvian Andean Forests

Peruvian Andean Forests cover only 3% of Peru's territory (Ministerio del Ambiente, 2015) and can be classified into Andean montane forests (2000-3000m asl, extent of 3 072 387ha = 2.39% of Peru's area) and High Andean Forests between (above 3000m asl, 831 825ha = only 0.65% of Peru's area). Large areas in this elevation belt consist of pastures, plantations and agriculture, and rural communities depend heavily on the ecosystem services provided by the Andean Forests for their livelihoods (Baca, 2018). Peruvian Andean Forest experience a pronounced dry season between May and September. Mean annual precipitation ranges from 1000 to 3000mm and varies greatly according to location and topography (Arias et al., 2021; Malizia et al., 2020).

Andean montane forests include seasonal montane forests and tropical montane cloud forests which are permanently cloud-immersed. Canopy height ranges from 10-25m height, there is a high diversity of epiphytes, and they harbour a mix of evergreen and deciduous montane tree species, including from the Podocarpaceae, Lauraceae, Rubiaceae, Juglandaceae, Meliaceae, Moraceae, Clusiaceae, Cunoniaceae (Ministerio del Ambiente, 2015). Non-native timber species occur at a large scale in this elevation belt due to large-scale reforestation campaigns with *Eucalyptus* spp. and *Pinus patula* promoted by the World Bank and the Forestry Law ('*Ley Forestal de 1963'*) in the 1960s mainly aimed at preventing erosion (Guariguata et al., 2017).

High Andean Forests are functionally and compositionally distinct from the montane forests due to functional and morphological adaptations to extreme conditions of frost and drought (Montalvo et al., 2018). They feature distinct species of the families Rosaceae, Myrsinaceae, Clusiaceae, Myrtaceae, Bignoniaceae and Scrophulariaceae. Above 4000m asl High Andean Forests occur mostly as small forest relicts with few tree species of the genera *Polylepis* (Rosaceae, local name '*queñua*') growing up to 5000m asl, as well as *Buddleja*, (Scrophulariaceae, '*kishuar*') and *Gynoxys*

(Asteraceae, local name '*toqacho*', '*yuraq kishuar'*) and *Escallonia* (Escalloniaceae, '*t´asta'*) (Ministerio del Ambiente, 2015). *Polylepis* forests only cover 2-3% of their potential range in Peru due to a long history of exploitation for firewood and timber and degradation by escaped fires and livestock farming (Aucca & Ramsay, 2005; Fjeldså et al., 1996; Quispe-Melgar et al., 2020).

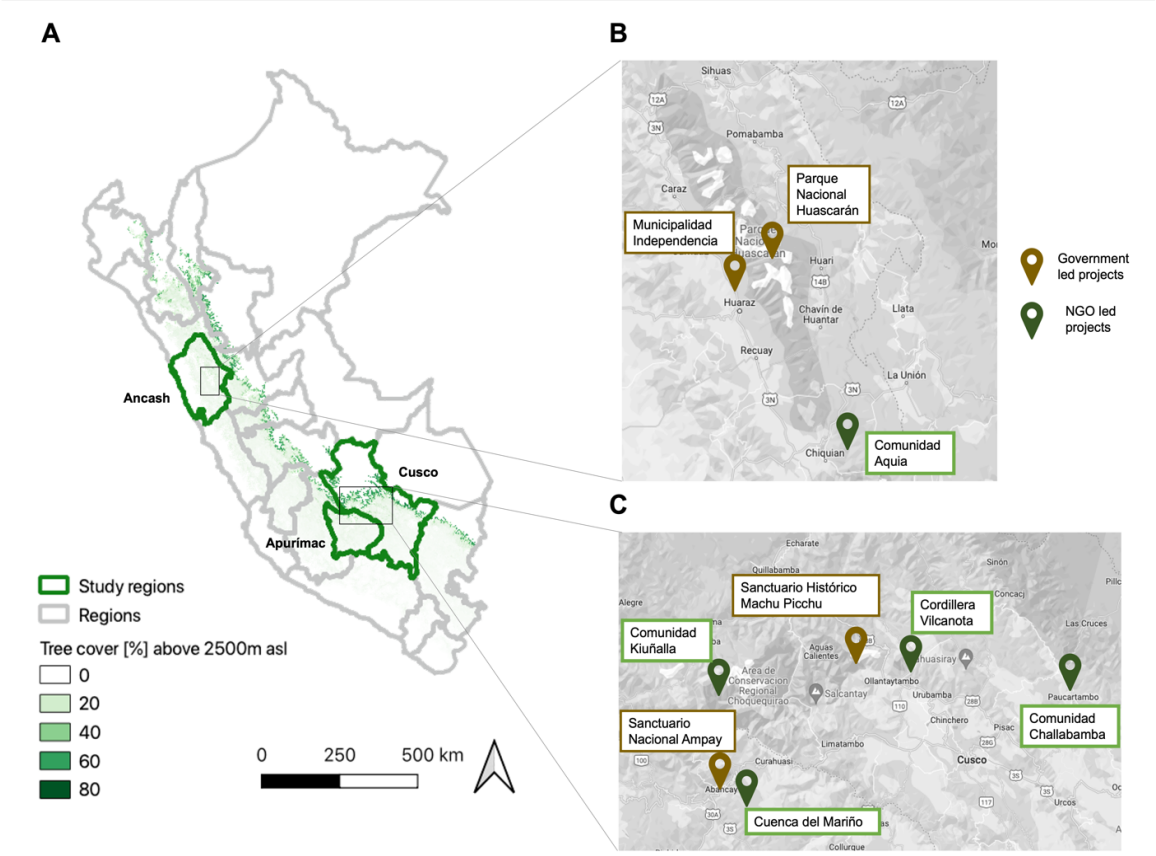


Figure 4. 1: Location of study sites. A) Map of Peru with the three case study regions overlaid over a map of forest cover percentages from GFCC above 2500m asl B) Study sites in Ancash and C) Study sites in Apurimac and Cusco

Description of stakeholders

In Peru, Andean Forest restoration is implemented by both the private and public sector on mainly community-owned land and is a complex endeavour and involves various stakeholders in the planning and implementation process (Cerrón Macha et al., 2018):

1) Government agencies at a national, regional, and local level. National-level agencies include the forestry service (SERFOR – *Servicio Nacional Forestal y de Fauna Silvestre*) embedded within the

Agricultural Ministry (MIDAGRI - *Ministerio de Desarollo Agrario y de Riego*), and the National Water Authority (ANA - *Authoridad Nacional de Agua*) embedded within MIDAGRI, and the Protected Area Authority (SERNANP – *Servicio Nacional Áreas Protegídas por el Estado*) embedded within the Ministry of the Environment (MINAM - *Ministerio del Ambiente*), as well as decentralized public organizations (OPD - *organismos públicos decentralizados*) such as AGRORURAL . At a sub-national level, regional and local governments also commission, fund and execute forest restoration. 2) Non-governmental organizations with a focus on development work and nature conservation; 3) Private enterprises involved with restoration through company commitments, compensation schemes or payment for ecosystem services such as mining, water resource management or tourism businesses; and 4) Local farming communities '*Comunidades campesinas'* who inhabit the Andean Forests biome and hold communal land titles of degraded land at high altitudes (2000-4500m asl). Since the Agrarian reform in 1968 communities have owned and farmed most of the High Andean land either as individuals, agrarian cooperatives, farming groups or communities (Fonseca Martel & Mayer, 1978; MIDAGRI, n.d.)., and as such restoration directly involves these communal agricultural cooperatives, the communal governing bodies ('*junta directiva*'), individual farmers and herders and the conservation managers (public, private or non-governmental). Communities range from 'modern' with access to many contemporary amenities and services to more 'rural' communities pursuing traditional agriculture by farming native tubers, legumes, maize, or squash, and/or herding sheep, horses, cows, and camelids in the Puna (Fonseca Martel & Mayer, 1978). Traditional rural farming communities have often relatively poor health and nutrition and low levels of education (Pinos, 2020). Farming communities have a long history of engaging with development agencies in the private, governmental, and non-governmental sector.



Figure 4. 2: Field visits. A) A 15-year-old mixed native forest restoration in Machu Picchu Sanctuary. Trees measure between 2-6m. B) 18-year-old Reforestation with *Polylepis racemosa* on a mountain slope at 4500m asl in the community of Aquia C) A fenced site with reforestation using *Polylepis* near a lagoon in Huascarán National Park. D) A greenhouse with 80,000 bare roots planted *Polylepis* seedlings in the Cordillera de Vilcanota, E) Women from the community sorting *Polylepis* stakes at the greenhouse near Challabamba and F) A practical fire prevention workshop run by ECOAN In the Cordillera de Vilcanota

Interviews and fieldwork

Fieldwork took place in August and October 2022 during the dry season through semi-structured interviews in the departments of Cusco, Apurímac, and Ancash (Fig. 4.1). We visited seven ecological restoration projects where only native species were used (run by NGOs or the government protected area authority), and four projects (run by other government agencies) which incorporated both ecological restoration with native species and interventions which we do not consider as restoration (e.g., exotic plantations). The focus in the interviews was exclusively on the project experience regarding ecological restoration. Projects ranged in age from two years old back to restoration initiated in the 1980s, with most projects being 5-10 years old. Restoration sites were situated at an altitude of 2800-4500m asl and hence covered both types of Andean Forests (Table. 4.1).

We conducted 75 interviews with key stakeholders involved with the planning, implementation, or maintenance of the restoration, such as community members, community leaders, government officials, NGO managers and technicians, private and academic actors. For each project site, the number of interviews ranged from 2 to 15 interviews depending on the size and actors involved. Seven were focus sites (Kiuñalla, Challabamba, Cuenca del Mariño, Vilcanota, Huascarán, Independencia and Aquia) with more than five interviews each for more in-depth analysis. Two interviews were conducted via video conference. We identified interviewees through initial key informant sampling with community leaders or project managers, who then recommended further participants. Interviewees and potential candidates were given a participant information leaflet (Supplementary 3.10) which explained the project and conditions of the interview. We conducted interviews with community members during sunset or sunrise to not inconvenience their farming work. 15% of interviews were carried out in Quechua by co-author Isaías Cjuno and translated into Spanish during the transcription, while interviews in Spanish were carried out by Tina Christmann, Isaías Cjuno and Mayte Aranda López.

Of all interviewees, 86.5% were male and 13.5% female (Supplementary 3.1). The proportion of female interviewees was low amongst community stakeholders due to a lack of females in leadership roles, however we endeavoured to interview as many women as possible who had participated in restoration activities. 59% of Interviewees were community members ('*comuneros*'), 14.9% NGO members, and 19% government officials from municipalities, regions or the state, and a minority were private or academic actors. Due to low sample sizes of private and academic actors, these are excluded in between-stakeholder comparisons. More than half of interviewees were above the age of 50, likely because of rural-to-urban migration of young people leaving farming communities (Aide & Grau, 2004).

Interviews were semi-structured, voluntary, and conducted using a 15-question template with a median time of 24min (min 10min, max 70min) (Supplementary 3.2). Respondents received no compensation for their time. After receiving a briefing of the conditions and scopes of the research project and the interview written or oral consent, interviewees were asked about several aspects of the ecological restoration: 1) motivations and preferences, 2) values of forests for their livelihoods, 3) the restoration objectives of the project, 4) perception of degree of success in reaching the objectives (scored between 1-3), 5) enabling and limiting factors, 6) impacts and benefits, 7) recommendations for other communities, 8) restoration preferences and 9) Visions for the future. Finally, interviewees could express any additional thoughts related to the restoration. We further conducted four technical interviews with the project managers of some focus restoration sites for in-depth information on project planning, implementation, maintenance, and monitoring (Supplementary 3.3). These interviews were treated as the same case as the general interview by the same interviewee. Methodology of the study was approved by the ethics board of the University of Oxford (CUREC: SOGE1A2021-215).

At each focus study site interviews were complemented with field visits of restoration sites, greenhouses, and capacity building workshops to familiarize ourselves with the challenges and success factors in the field and to learn about species selection and propagation.

Analysis

Data was analysed thematically at the stakeholder level using a mixture of inductive and deductive coding in NVivo, starting with general categories and subcategories, and iteratively filling and refining these with each interview. For restoration motivations we used a categorization into intrinsic, relational, and instrumental motivations (IPBES, n.d.). To categorize values and use of forests we applied the ecosystem service framework (Millennium Ecosystem Assessment., 2005), while to categorize enabling and limiting factors we used five categories: biophysical, technical, institutional/governance, social and economic inspired by a categorization previously used in restoration contexts (Cerrón Macha et al., 2018; Le et al., 2014). To identify social and ecological restoration outcomes we use the framework by Erbaugh & Oldekop (2018) on Pathways linking FLR to local livelihoods, well-being and resilience. In this framework direct and indirect pathways between FLR and social and ecological outcomes are distinguished. Interview codes were analysed by frequency of interviewees and frequency of occurrence of coding references.

Table 4. 1: Specification of the 11 study sites. * = featuring in a case study box in discussion. Bold indicates that the site was a focal site with more than 5 interviews conducted. Success level represents the average score of an interview question on perceived success and was only coded if answered by more than 5 respondents (with 1=low success, 2-medium success, 3-high success).

		Elevation [m asl] and forest type	Stakeholder groups interviewed	Planning start/ Restoration start	Size of restoration intervention	Ecological restoration	Type of intervention	# Interviews	Success level (max = 3)
1	**Community of Kiuñalla**	3000- 4414 (Andean montane forest)	NGOs: CEDES, Programa Bosques Andinos. Community	2014|2018	1 community, 100 ha total intervention area 30 ha restoration	Yes	Ecological restoration with mixed native species and conservation of native forests alongside livelihood improvements	11	2.6
2	**Watershed Cuenca del Mariño***	2500-4200 (High Andean Forest)	NGO: CEDES, Private: EMUSAP (water company) Community	2013|2016	3 communities, 70 ha	Partly	Ecological restoration with *Polylepis*, Grassland restoration, blue infrastructure (dams and reservoirs) Exotic Pine plantation	8	2.83
3	National sanctuary Ampay	2,900 to 5,235 (Andean montane forest)	Government: SERNANP	1990s|2002	120 ha,	Yes	Tree planting with native *Podocarpus Glomerata*	4	NA
4	Department of Apurímac	2000-4000 (High Andean Forest)	Regional government (GORE)	266 communities	Planned: 30 Million trees of which 20% native. 20 Million ha	Partly	Some ecological restoration with *Polylepis spp, Escallonia spp, Salix spp and Alnus spp.* Large-scale exotic Pine plantation	2	NA
5	**Community of Challabamba***	2820-4000 (Andean montane forest and	NGO: ACCA Community	2021|2021	78,000 seedlings, 40 ha	Yes	Ecological restoration with mixed native species and conservation of native forests	9	2.8

		cloud forests)							
6	**Mountain range Vilcanota**	3000-4500 (High Andean Forest)	NGO: ECOAN Community	1998|2000	20 communities, 6 Million seedlings	Yes	Ecological restoration with 7 species of *Polylepis* and conservation of native forests	13	2.4
7	Historic Sanctuary Machu Picchu*	2800-3000 (Andean montane forest)	Government: SERNANP	2002	20 ha/year 20,000seedlings/year	Yes	Ecological restoration with mixed native species and with productive native species	2	NA
8	**National Park Huascaran***	3400-6000 (High Andean Forest)	Government: SERNANP Community	Start in 1980	NA	Yes	Ecological restoration with *Polylepis*	7	NA
9	**Municipality Independencia**	3000-3900 (High Andean Forest)	Government: Municipality Community	2005	NA	Partly	Ecological restoration with *Polylepis*, but also large-scale plantation with exotic Pine	5	NA
10	**Community of Aquia***	3300-4500 (High Andean Forest)	NGOs: Instituto de Montana (IdM), ECOAN (since 2021) Community	IdM: 2004-2008 ECOAN: 2021	IdM: 20 ha during project and 20 ha goal post project ECOAN: 100,000 trees/year in 2022, 200,000trees/year in 2023	Yes	Ecological restoration with 2 species of *Polylepis* and protection of native forests alongside agricultural and livelihood improvements	12	3
11	Department of Ancash	2000-4000 (High Andean Forest)	Government: Agrorural Regional government	Early 2000s	NA	Partly	Ecological restoration with *Polylepis*, but also large-scale plantation with exotic Pine	2	NA

Results

What are the motivations and objectives for forest restoration using native species in the Peruvian Andes of key stakeholders?

All stakeholders stated they engaged in forest restoration primarily for instrumental reasons, i.e., to achieve something particular for people (Fig 4.3 A-C). This was especially true for community members (Fig 4.3 A). In particular, 70% of community members and 67% of NGO stakeholders cited maintaining and improving water resources for agriculture. As one community leader explained: *"You have to reforest [...] for sowing and harvesting water you have to work well with the planting, [choose] which plants attract [water] well, in the case of Queñua [Polylepis spp.], the paja [Stipa Icchu] also traps the mist"* (Community leader). Community members were further motivated by direct economic reasons (18% of community members), by a desire to improve their agriculture and livestock farming (14%) and to promote useful plants (11%). 50% of community members further said they were motivated to improve livelihoods for future generations, and 27% of community members also mentioned the wellbeing of their community.

All stakeholder groups mentioned intrinsic motivations to restore forests, due to an inherent value of nature, including to revert deforestation or degradation (21-33%), importance for biodiversity (17-27%), or for general environmental protection (7-20%).

Relational motivations, which reflect a symbolic relationship with nature through identity, were mentioned particularly by NGO and government stakeholders, with comments mostly related to professional duty of 'caring for nature' (Fig 4.3 B and C).

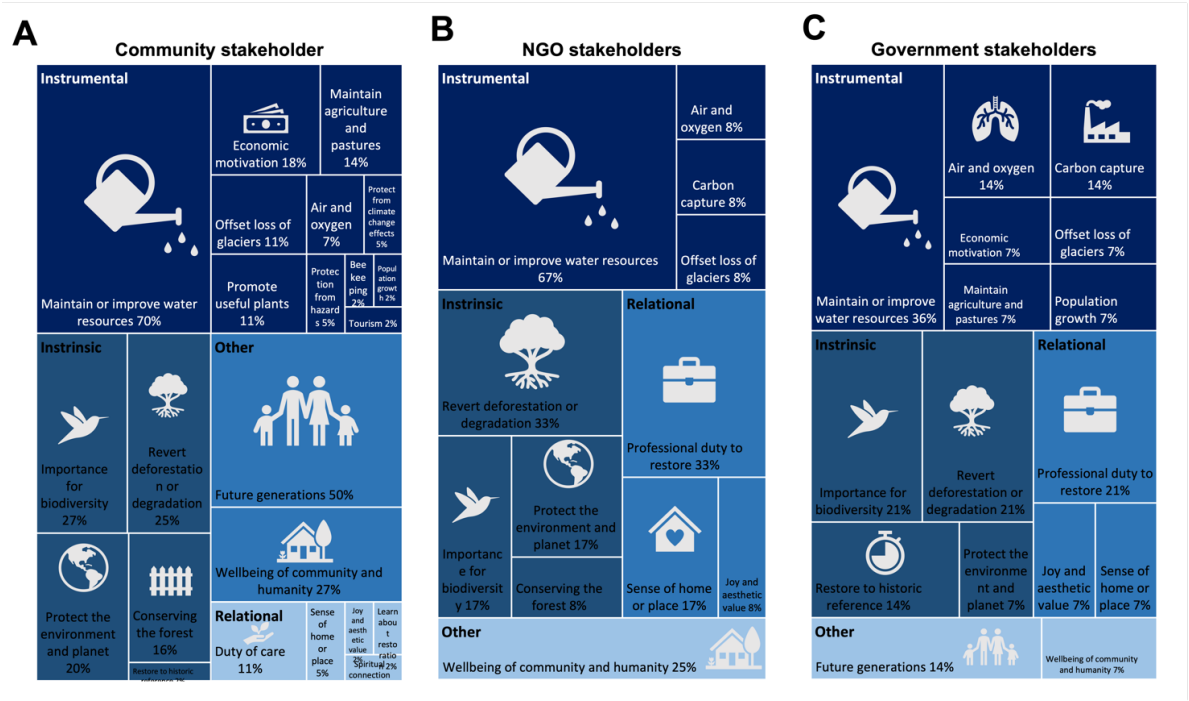


Figure 4. 3: Motivations for Andean Forest restoration for each stakeholder group shown as percentage of interviewees within the stakeholder group A) Community stakeholder (44 respondents), B) NGO stakeholder (14 respondents) and C) Government stakeholder (12 respondents). Blue represents instrumental motivations, light-green intrinsic motivations, pink relational motivations, and dark green other motivations.

The largely instrumental motivations aligned with the predominantly provisioning ecosystem services mentioned when interviewees were asked how native Andean Forests contribute to their wellbeing and to livelihoods of communities (Fig. 4.4). Provisioning ecosystem services (mentioned by 84% of interviewees) were most prominent in all stakeholder groups (Fig. 4.4 A). Water provision dominated as the key ecosystem service (mentioned by 61% of community members, 50% of NGO and 36% of government stakeholders), followed by provision of wood for fuel and construction (mentioned by 41% of community members, 25% of NGO and 29% of government stakeholders). Regulating services (Fig. 4.4 C) were mentioned by 41% of all interviewees with water retention as the most frequent regulating service (23% of community members, 33% of NGO and 14% of government stakeholders), followed by climate regulation (14%, 8% and 7% respectively). All stakeholders also referred to supporting ecosystem services (Fig 4.4 B), such as a biodiversity and habitat value, however this was more pronounced in for

community stakeholders (34%) than NGO (16%) and government stakeholders (6%). The Andean Forests act as refugia for birds and mammals of high conservation value, as an academic researcher put it: *"There is obviously biodiversity - the forest is a refuge for the Andean bear, there are quetzals in Huanipaca."* 23% of all interviewees further mentioned cultural services (Fig 4.4 D), such as aesthetic values, tourism, and recreation.

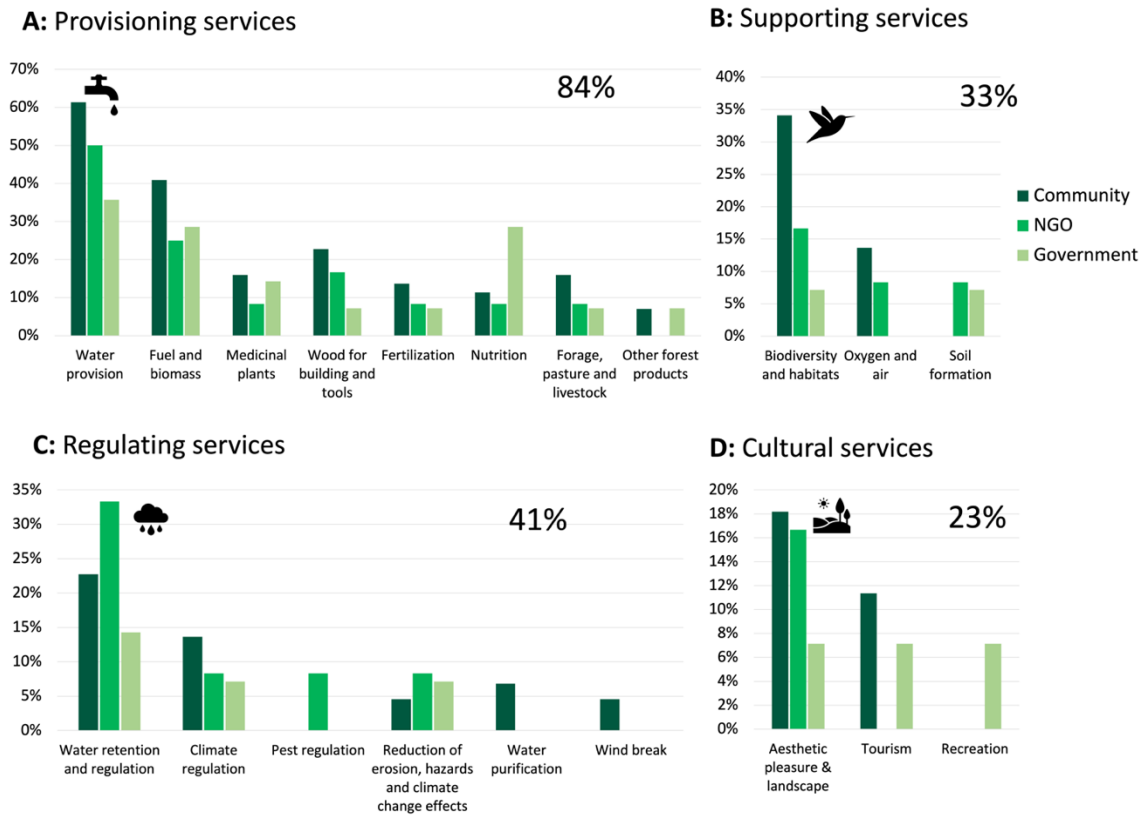


Figure 4. 4: Ecosystem services of Andean Forests for each stakeholder group. % represents the percentage of interviewees within each stakeholder group. For grouped results see Supplementary 3.3.

When asked about the perceived objectives of the restoration projects (Supplementary 3.5), 85% of all interviewees referred to social restoration objectives mainly improving water resources for their livelihoods (65% of interviewees), as described by a government official taking about restoration with *Polylepis*: *"The main objective has been to improve ecosystem services in the areas where*

water is used, especially in the micro-watershed [] because population growth there generates greater demand for water for human consumption. And with climate change […] water is diminishing." (Government official). Other social objectives were community education/capacity building (18% of interviewees), erosion protection (12% of interviewees) and protection from climate change impacts (12%).

Ecological objectives were cited by 55% of interviewees (Supplementary 3.5), and most prominently by NGO stakeholders (67% of NGO vs 52% of community and 57% of government). These included restoring forest cover (32% of all interviewees) and protecting existing biodiversity and ecosystems (32% of all interviewees). Economic objectives were mentioned by 49% of all interviewees and included generating income and employment for communities (29%), as well as creating alternative livelihood activities (15%).

How do social, economic, biophysical, institutional/legal, and technical factors affect perceived restoration success?

Participants were asked about their perception on whether restoration objectives were reached using a simple scale of one to three (with 1= no success, no objectives reached, 2= medium success, some but not all objectives reached and 3= high success, all objectives reached). All focal projects with enough respondents had average success scores between 2.44 and 3 (Tab. 4.1) and were considered successful by participants. Participants perceived a project successful for a variety of reasons, such as seedling survival, achievement of biodiversity benefits or improved water resources, as highlighted by a community leader describing project success: *"the planted seedlings are young […], beautiful and already harbour plenty of birds, there is humidity, and it looks nice"* (Community leader). After reflecting on restoration success, interviewees were asked what they perceived enabled and limited restoration project success, and this was then categorized into five classes: social, institutional/legal, economic, technical, and biophysical.

Enabling factors

Of the five categories, both NGO stakeholders and community interviewees cited social factors most frequently (Fig 4.5 A & D), while government stakeholders cited social factors less, likely because many government-led projects were in established conservation areas. Communal interest in restoration (43% of all interviewees), participatory management and governance (35% of interviewees) were key for long-term success of forest restoration. Specifically, the dependence of the communities on natural resources and a communal realization of the need to restore was pointed out to by an NGO actor to be a key success factor: *"Success begins with the decision of the community. The community identified that the water flow was decreasing due to their crops, so they made the decision to restore their forests because they realized that the degradation of the forests caused reductions in water flow"* (NGO actor).

Institutional/legal (Fig. 4.5 C) enabling factors made up 20-30% of coding references across all stakeholder groups. Support from NGOs (48% of interviewees), formal conservation commitments and agreements with communities (41%), strategic alliances (40%) and clearly defined land tenure were the most mentioned institutional enabling factors. A community member highlighted good collaboration with an NGO as a success factor:" The *institutions, the NGOs, help us, but we put the manual labour, we make the holes, the plantations."* (Community member)

An economic key factor for success (Fig. 4.5 B)– mentioned by 35% of all interviewees- was creating economic incentives for community participation. As a community leader said: "*Economically [the project is successful] because there is work. People worked earning their minimum salary, as an incentive"* (Community leader).

Government actors cited technical factors (Fig 4.5 A & E) more than NGOs and communities, including physically protecting restoration sites from livestock and encroachment, as emphasised by a government official *"If you want a short-term guarantee, you have to fence it."* This physical

site protection was also linked to legal site protection and community buy-in to reduce encroachment. Further species knowledge and selection (39% of interviewees), as well as the creating technical capacity to restore (29%) were key technical enabling factors mentioned by all stakeholder groups, such as species-site matching: *"In areas which have to be recovered from fires, degraded areas, and eroded soils we basically have produced more Polylepis racemosa, because it has its advantages, it is stronger, it spreads faster than the others and it adapted better in the area"* (government actor).

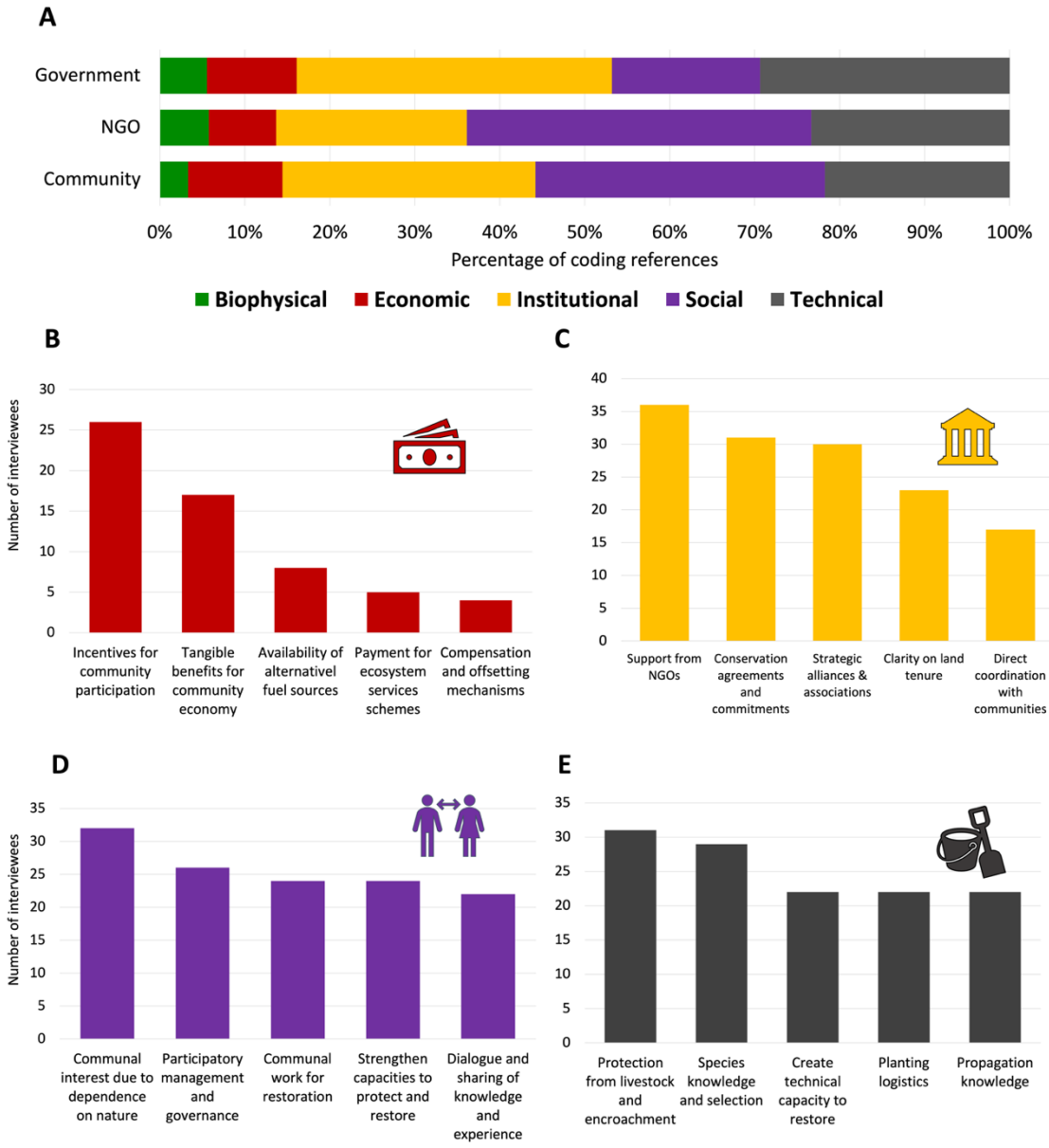


Figure 4. 5: Enabling factors for successful Andean Forest restoration by stakeholder group (A). Top 5 economic (B), institutional (C), social (D) and technical (E) enabling factors.

Limiting factors

NGO and community stakeholders cited social factors that limited restoration first and foremost, while government stakeholders focused more evenly on biophysical, institutional, and economic factors (Supplementary 3.7 A). These include the uncontrolled use of fire by communities (45% of

all interviewees), as well as a low environmental education and awareness of community members (24%), and a prevalent fear of land grabbing (21%) (Supplementary 3.7 D). A community leader concerned with wildfires said: *"I have always been focused on telling [the community] they should not do the fires, some burning garbage, some near the forests. Sometimes […] I have seen next to the ravine, that more than 200 ha have caught fire"* (Community leader).

All stakeholder groups highlighted biophysical limitations, including livestock encroachment (35% of interviewees), water limitations (33%) and slow growth of native species (16%) as main barriers to restoration success, as exemplified by a government actor: *"but how long will a Queñua [Polylepis spp] forest take us, sometimes 200 years. It is a very slow growth […] you would have to have a lot of heart [patience] that they grow for my children. [The community] already wants to see something sooner than that at least."* (Government actor).

Government actors centred more uniformly on biophysical, economic, and institutional factors. Institutional barriers (Supplementary 3.7 A) included a lack of commitment and continuity of leaders at both local and regional level, and conflicts arising due to agricultural land tenure of potential restoration sites (25% of all interviewees). With the way communities are governed by short-term committees ('*juntas directivas'*), community members also saw a risk in this lack of continuity: "*the president [of the community] only lasts 2 years, and suddenly another comes and is not interested [in the restoration]. So, I would say that the institutions need to come and train the community, the president that leaves and [the one who] enters so that this will be done continuously*." (Community member).

All actors mentioned a series of technical limitations, such as a lack of monitoring and maintenance of sites (28% of interviewees). An academic actor reflects on this shortcoming: *"There is no maintenance in the first months, years. […] It is not enough to simply plant, you must accompany this process. […] But there is still a long way to go to have evidence of interventions."* (Academic actor). Further, challenging site conditions and accessibility for planting (23% of interviewees) are

a key issue in the high Andean rugged territory such as highlighted by a community member: "*to Huamanhuece we go on horseback. Walking we would get tired – this is far away.*" (Community member).

How do forest restoration projects impact community livelihoods?

Forest restoration projects had numerous positive and negative impacts for communities (Supplementary 3.6). Positive impacts (mentioned by 100% of interviewees) were classified into economic and non-economic benefits. Economic benefits were further classified into direct (mentioned by 71% of interviewees) and indirect (mentioned by 77% of interviewees) economic benefit. These outcomes largely correspond to Pathway 2 and 3 of direct and indirect benefits of FLR for local livelihoods according to Erbaugh & Oldekop's 2018) framework.

Positive economic impacts

Direct economic benefits (Pathway 2) mainly consisted of paying the community or individual workers for their labour (60% of all interviewees) or payments towards a community fund, e.g., for production of seedlings. Direct payments were prominent in government-led restoration projects (e.g., Ancash, Machu Picchu) which often aimed at creating labour: *"[A benefit was to] […] provide massive labour to the communities, because the community members rarely have a job. […] It was a substantial contribution to the social and economic part of the project, beyond the environmental part."* (Government actor). Payments varied from smaller token payments (9.25$ in Challabamba) to locally adjusted daily wages for unqualified labour (18.5$ in Machu Picchu).

77% of interviewees mentioned indirect economic benefits (Pathway 2), including providing the community with tools and materials for agricultural and infrastructural activity (31% of interviewees), and creation of alternative livelihoods (through tourism, artisan activity, pisciculture etc) (20%). Further, support with seeds for improved pastures was another benefit (19% of

interviewees), as highlighted by a community member "The NGO office *supports us with seedlings, hoses, pea seeds, vegetables"*. Other indirect economic benefits included the provision of cooking fuel (gas or Eucalyptus wood), support with community infrastructure (15%) and nutrition (12%) and improved livestock breeds (7%). In the case of restoration in protected areas where farming families hold ancient land rights, high Andean livestock farmers participate in Andean Forest restoration in return for using state-owned grazing land within the protected areas.

Positive non-economic impacts

The most prominent non-economic benefit was capacity building and environmental education of communities (Pathway 2), a benefit mentioned by 91% of community members and 67% of NGO members, and less so by government actors. An NGO actor describes this in the following statement: "*We have just started training on forest fire prevention. This Sunday […] we will [do a training on] managing sprinkler irrigation and then [the community] will come for training in tourism, training on nutrition with their own products to improve food security"* (NGO actor). Moreover, projects fostered education and participation of school kids (17% of interviewees) and increased environmental awareness of the community (13% of interviewees). A quarter of NGO actors also highlighted the improvement of communal governance and communal identity and pride. Additional benefits included field visits (9% of interviewees), aesthetic landscape benefits (4%) and increased interest for the area (4%).

Negative impacts

Most projects had initial negative impacts due to an opportunity cost (Pathway 3) for agriculture and livestock (29% of interviewees) because land was fenced and closed off for the restoration activities. However, these were outweighed by the resulting benefits for agriculture and community wellbeing, such as emphasized by a community leader: "*The people surrounding the reforestation*

were uncomfortable saying that they are fencing the path of my animals, but later they became aware and now they no longer say anything." (Community leader).

Opportunity costs for timber and wood use were also mentioned by community members and government actors, but again in most cases the restoration institution had provided fuel alternatives: *"Before they cut down indiscriminately everywhere [...]. The NGO arrives there and tells us not to cut any more, better instead we give firewood {eucalyptus} to each family 100 cuttings. If the NGO had not intervened right now, the hill would already be bare."* (Community leader). 17% of interviewees reported no negative impact of the project.

Models of community engagement

We identified three typologies of how participants engaged in restoration and were compensated: the 'payment model', the 'mixed model' and the 'capacity model' (Figure 4.6).

The 'payment model' - often applied by governmental institutions such as municipalities or regional governments – pays participants directly for their work (Fig 4.6 - see Independencia and Ancash) paying individual people or households for contractual labour or providing other direct economic benefits. It has immediate short-term economic benefits, while non-economic benefits are considered secondary. In sites with the 'payment model' we find that interviewees from stakeholder groups other than the government had a less intrinsic and more economic motivation to restore: *"We are now 310 community members […] And we helped [with the restoration] because the money helped us."* (Community member).

The 'capacity model' involves whole community groups, generates multiple non-economic benefits, and creates indirect economic benefits outlast project time scales (Fig 4.6 B – Aquia, Kiuñalla, Ampay and Huascarán). The 'capacity model' promotes improved agricultural practices and provides alternative livelihood activities (e.g., by sowing higher productivity grasses, better livestock breeds, value added production) that align with restoration goals. Under this model

implementers also provided material resources to improve land management (tools, fences, irrigation infrastructure) and households (gas cookers, Eucalyptus firewood). This model integrates environmental education and long-term capacity building, and the impacts of the project are designed for long-term sustainability. The case study of Aquia exemplifies this model as community members received a suite of benefits and had a high degree of environmental awareness and project appreciation even 15 years after the end of the project (Box 2 case study Aquia).

Between these two contrasting models lies a spectrum of mixed approaches, the 'mixed model' which use aspects of both the payment and the capacity model, such in Vilcanota, Challabamba and Cuenca del Mariño, Machu Picchu and Apurímac (Fig. 4.6 B). In Challabamba, community members are paid to work in the greenhouse, but trees are planted during communal workdays *'faenas'* without compensation. The NGO also provided workshops based on the community's needs and helped improve irrigation infrastructure (see Box 2 case study Challabamba).

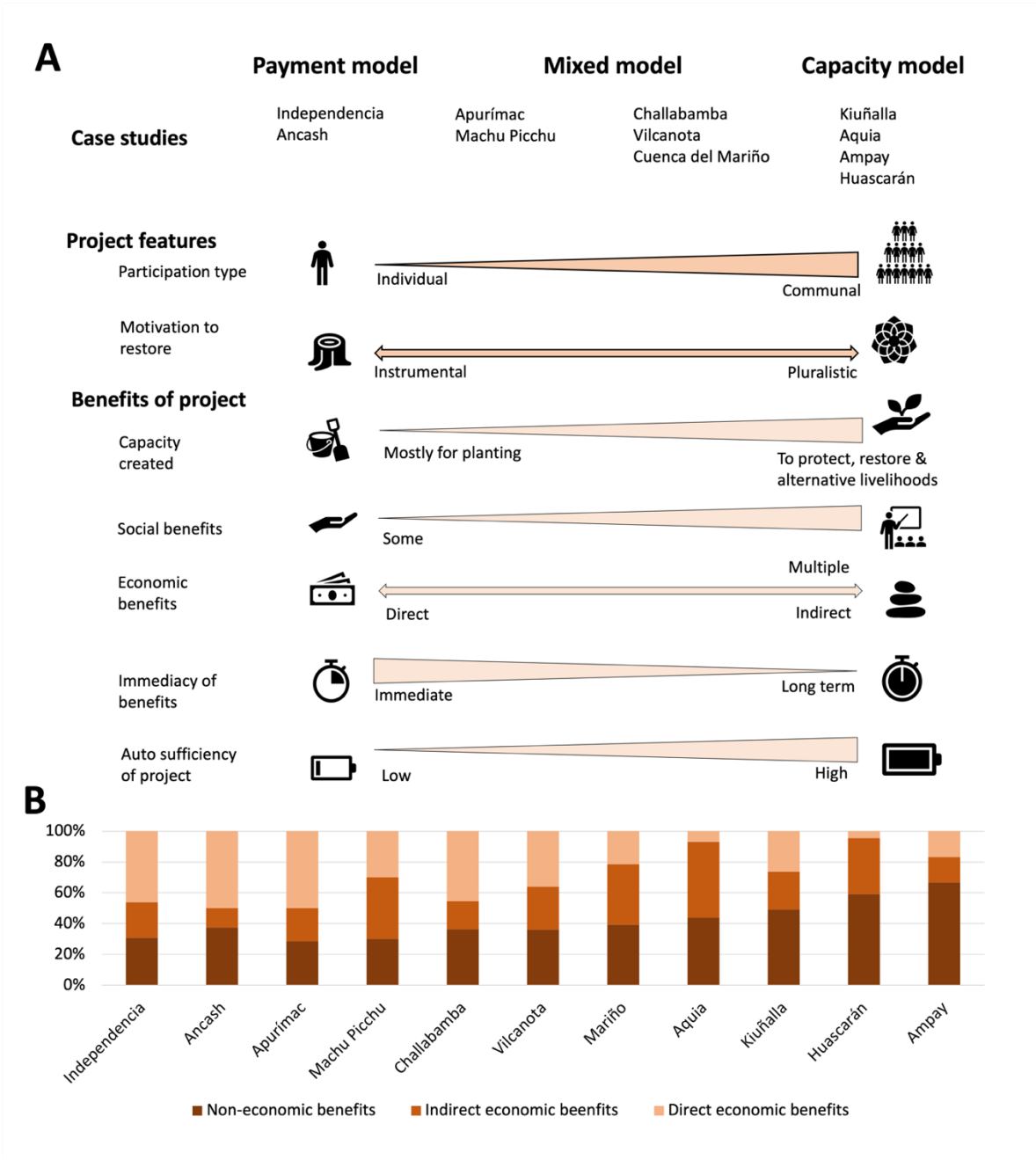


Figure 4. 6: Three governance models identified and assigned to each case study area. A) Classification of the three models according to project features and benefits of project B) Types of benefits between the 11 project sites, classified as in Table 3 and sorted by quantity of respondents who mentioned non-economic benefits.

What type of restoration interventions are preferred by different stakeholders?

Interviewees were asked what kind of restoration interventions they preferred in their local area, or in the case of project managers of NGO/governments in their intervention area. 55 % of community members and 92% of NGO stakeholders expressed a preference for active reforestation (Fig 4.7 A), i.e., tree planting, mostly with exclusively native species (Fig 4.7 B, Supplementary 3.8). 50% of NGO stakeholders frequently mentioned protection and conservation of native ecosystems as a complementary strategy, while government actors more frequently referred to the restoration of non-forest ecosystems (79% of government stakeholders) such as Puna grasslands, wetlands and shrublands: "*I am particularly a friend of making it a combination. […] All forest restoration should combine tree, shrub, and herbaceous species. And within this even the pastures.*" (Government official).

Agroforestry was frequently cited by all stakeholder groups (15% of community, 42% NGO and 15% of government) and for this community members preferred tree species with a direct market or use value: *"And more part could be fruit trees. And it could also be in an intermediate part with Elderflower – next to the plots. Elderflower is normally used for marmalades"* (Community leader) or trees that provided fertilizer and forage: *"what we must plant around these fields is basul [Erythrina falcata], pisonay [Erythrina edulis] because the leaves are going to feed the plants.* […] *Pisonay can serve as fodder for guinea pigs and cows*" (*Community member*).

Interviewees largely preferred native trees in future restoration projects (Fig. 4.7 B) and mentioned over 40 desirable species for forest restoration (Supplementary 3.8). Species preferences varied between our focus project sites (i.e., the sites with more than 5 interviews) – in the NGO-led project sites (Kiuñalla, Marino, Challabamba, Aquia and Vilcanota) the preference for exclusively native species was considerably higher, than in the municipality-led site Independencia where 80% of interviewees preferred a mix of native and exotic species. In the National Park Huascarán all

interviewees preferred native species only. Most opinions on exotic species were negative (62% negative references), due to undesirable effects of prominent exotics like Eucalyptus and Pine on water resources: *"If there is eucalyptus near the water springs, this sucks all the water*." (Community leader) or pointed out deterioration of farmland: "*The leaves, the roots of the Eucalyptus ruin the ground for us. […], it doesn't even serve us as fertilizer"* (Community member).

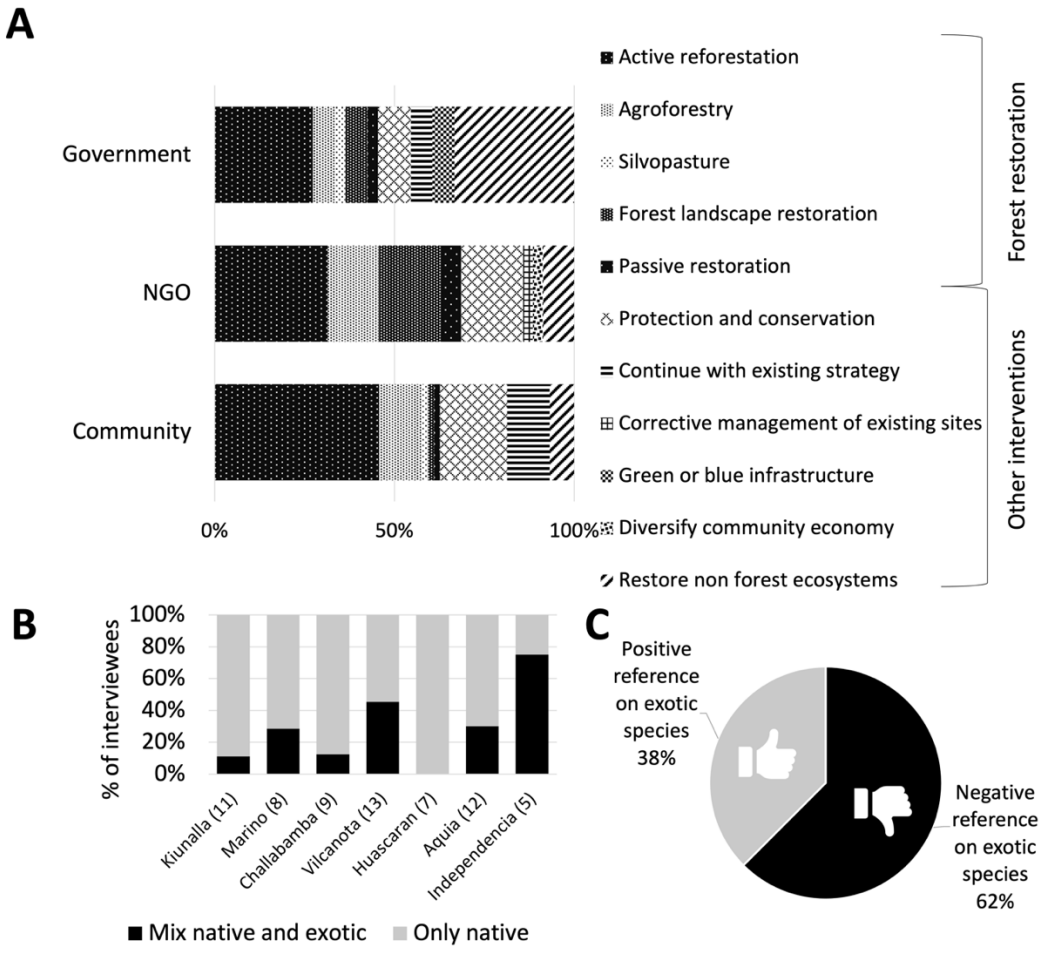


Figure 4. 7: Restoration preferences of the three key stakeholder groups for the future. A) Preferred interventions in the three main stakeholder groups, B) Species mix preferred in the 7 focus study sites. The other five sites did not have enough interviewees to calculate percentages C) Opinion on exotic species as % of coding references.

Discussion

'Sowing and harvesting water' – a water-centred approach to restoration of Andean Forests using native species.

At the global level, restoration initiatives often aim to restore forests to conserve biodiversity and sequester carbon. However, our results clearly indicate that people restore Andean Forests for the local benefits they provide; improving water resources is the primary motivation for all stakeholders and seen as the lifeline of communities for their agricultural practices. The desire to restore forests for the direct, local benefits they provide has been found across the Andes (Báez et al., 2010; Durand & Sevillano, 2017; Joseph et al., 2021; Ota et al., 2020; Wilson et al., 2019; Wilson & Coomes, 2019). Restoring Andean Forest using native species for local and regional water benefits was often linked to the concept of 'Sowing and harvesting water' (*'Siembra y cosecha de agua'*), a term originating two decades ago in Ayacucho (ABA - Ayacucho, n.d.). 'Sowing and harvesting water' combines a variety of activities that intercept and retain water in a landscape, including activities that improve water recharge in the subsoil and aquifers and increase humidity through fog collection by trees and *in situ* water recharge (e.g., conservation and restoration ofwetland and grassland and reforestation with native water-conserving species).

Our findings on motivations for restoration being linked to water services align with the 'Ecosystem service scarcity path' theory reported in other Andean countries (Wilson et al., 2019): in the Ecuadorian Andes the main motivation for communal tree planting was to restore water resources, and 4-7 years post restoration community members reported improved water quality and quantity. Farmers in our study frequently mentioned the direct importance of forest restoration in improving water availability for their agricultural livelihoods: *"The forest in this zone is giving us water and it is capturing water and, given the dry season, this is quite a lot of support. Because if we didn't have water, how would we do what we need to do?"* (Community member). This 'water motivation

path' is particularly timely given the recent prolongation of dry seasons, deglaciation, and water scarcity in the Peruvian Andes (Giráldez et al., 2020; Motschmann et al., 2020). On the other hand, government and NGOs shared a range of more conservation-driven motivations such as reversing deforestation, and a sense of moral or professional duties to restore. This difference in restoration motivations between stakeholders has been found in various forest ecosystem contexts (Ota et al., 2020).

To date the effects of forest restoration with native species on the water balance of tropical montane forest systems remains largely understudied (but see Bonnesoeur et al., 2019; Bruijnzeel, Mulligan, et al., 2011; Bruijnzeel, Scatena, et al., 2011). Interviewees mentioned a variety of anecdotal pathways through which forests and reforestation contributed to improved water quality and quantity. Andean Forests were related to aquifer recharge and water retention: *"[Andean Forests] contribute to regulation of water flow and act like great sponges. The soil is full of mosses and leaves, they capture the humidity and infiltrate it little by little into the soil"* (NGO technician) and *"The forests retain water during the wet periods, and this allows us to be able to count on our water reservoirs during the dry season. We witnessed that Queñua [Polylepis] is a tree that traps water"* (Private actor). Native species were believed by community members to "*retain water through their roots", "catch cloud water"* and increase local humidity *("the forest creates humidity"*). This in line with emerging knowledge on the 'forest sponge-effect' whereby tropical forest intercept cloud water droplets from fog, retain moisture in the soil and extend water availability into the dry season (Ogden et al., 2013). Hydrological studies in tropical forests in Panama have shown that mature and secondary native forests show high vertical water flow during storm events and recharge the ground water (Birch et al., 2021). Apart from regulating water quantity, our study respondents highlighted that Andean Forests also control water quality (*"the [forested] catchment is like a filter, like a big sponge" – community member)*. The role of secondary tropical forests in regulating water quality has also been reported before in tropical watersheds in Panama (Chavarria et al., 2021).

Many references on hydrological effects were anecdotally derived from local field observations, as highlighted by an NGO official: "*the local people have understood that the Queñua [Polylepis] contributes to water recharge. Still, we can't tell this [water flow effect] quantitatively, but qualitatively yes"*. Consequently, some stakeholders highlighted the need to conduct systematic studies on hydrological effects of forest restoration: *"There hasn't been a methodological scientific process [to water flow monitoring] such as that in the first year we do [construction of the] lake, second year we do reforestation, to see the response of the micro basin. You can't say 'okay now it doesn't dry out because we have reforested." (*Academic actor). To date, hydrological effects of forest restoration with native species in the Andes are largely unknown, and more studies have looked at the effect of afforestation with exotic trees and found a detrimental effect on downstream water supply (Bonnesoeur et al., 2019). Thus, we call for more research on the hydrological effects of forest restoration with native species, especially by monitoring the hydrological effects over time, as canopy closes, and root depth of plants increases.

Restoring water resources was integrated into the design of most restoration projects (see example case, Box 1). Communities and NGOs prioritized reforestation with native species adjacent to headwaters, springs, and streams, and preferred native tree species considered as water 'savers': *"You must plant enough Queñua [Polylepis] to retain water. This will increase the water" (NGO actor)* and *"We must reforest, to sow and harvest water. We must work with the plants that attract water well, like the Queñua [Polylepis] and the Icchu grass [Stipa Icchu]"* (Community member). Exotic species were often seen as 'water suckers', and many interviewees underlined that exotic species need to be far away from water resources: "*We cannot plant pine above, they know that pine and eucalyptus are the ones that dry up the water, therefore, they cannot be planted at the headwaters."* (NGO actor).

Communities are willing to restore and steward the land to counteract the loss of water due to rapid deglaciation, landscape degradation and changing rainfall patterns (Zimmer et al., 2022). This

presents an opportunity to capitalize on global support to undertake restoration that also provides local benefits. While restoration of montane forests might in the future yield some opportunities for carbon markets, there is a scalar difference between prominent global restoration goals that attract global funding, especially through carbon offsetting schemes, and the landscape-level goals identified in this study that directly benefit local people, mostly through improved water services. A funding mechanism that incorporates local water-related restoration are national and regional hydrological payment schemes: The case study 'Cuenca del Mariño' financed the restoration and conservation of High Andean ecosystems using payment for hydrological services (MERESEH – *mecanismo de retribución de servicios hídricos*) and international development funding (Box 4.1). Such payment mechanisms are also used by SERNANP to finance and implement restoration in government protected areas (Box 4.1).

Box 4. 1: Case study: Cuenca del Mariño

Strategic multi-actor collaboration and financing to improve water provision.

The case of communal restoration in Cuenca del Mariño

The city of Abancay (63.100 inhabitants, in Apurímac) and its rural areas experienced severe water scarcity following exacerbated dry seasons and gradual glacier loss in the last decades. This led to the creation of projects to recover and conserve upstream ecosystems managed by a consortium of institutions: HELVETAS, SUNASS, EPS EMUSAP and the NGO CEDES Apurímac. The main goal was to improve the supply of water resources at the headwaters of the Mariño river. The project was financed by international funding programs and development agencies and by a payment mechanism for water ecosystem services (MERESEH).



Community members build a fence during a communal work day.

A series of water conservation and montane forest restoration projects were implemented on communally owned land in the upper river basin. Activities included constructing dams and natural reservoirs for water retention, protecting montane forest relicts and wetlands, and planting *Polylepis spp*. and the Puna grass *Stipa Icchu*. Three local communities participated through traditional communal workdays *'faenas'*. Materials and capacity building sessions were provided by the local NGO CEDES. Tensions initially arose with upland herders of alpaca and sheep forced to reduce or relocate their livestock, but the project design dealt with this by providing alternative livelihoods to disadvantaged community members. The NGO served as a successful mediator in organizing

interventions and had an ethos of horizontal governance. Committed community leaders helped to inspire their communities to participate in the projects. The payment for hydrological ecosystem services mechanism gives financial stability and longevity to the project and is a replicable multi-actor, multi-level model to involve consumers of natural resources – in this case the water works (downstream users) and agricultural irrigation committees (upstream users)- in Andean Forest restoration.

The case of state protected areas in Nor Yauyos Cochas

To improve water regulation and availability to communities in and near the protected reserve Nor Yauyos Cochas, SERNANP carries out ecological restoration by re-introducing several native species to degraded montane areas (*Polylepis* spp., *Kagenekia lanceolata, Escallonia resinosa, Escallonia myrtilloides, Caesalpinea spinoza*, '*Queñua*', '*Lloque'*, *'Chachacomo'*, *'Karkar*' and *'Tara'* respectively). With a long-term vision, nurseries were built very close to the degradation sites to facilitate future plantings. In 2023 the planting of 100,000 seedlings is planned in alliance with local governments, community authorities, private companies (EPS Emapa Cañete) and the support of the NGO ECOAN. As this project greatly benefits water regulation and provision it was also executed through a MERESE payment for ecosystem services scheme, to generate a direct positive ecological impact on the Andean ecosystems in 30% of the reserve's area.



Greenhouse with *Polylepis* seedlings in Nor Yauyos Cochas

Leveraging social, economic, and institutional factors to make restoration succeed.

We found that direct economic incentives were not necessarily the most effective at motivating restoration. Rather, projects that provided tangible social and economic benefits and instilled an intrinsic desire of local communities to restore forests seemed to have higher restoration success, longevity and higher community engagement and valuing of restoration activities. These findings concur with the literature in that providing incentives and socio-economic benefits through the restoration project is key (Ota et al., 2020), such as in this study benefits for community development, improved agriculture, alternative livelihoods, or direct monetary payments. This

seems to be particularly important in the Andes where developing health infrastructure, improving nutrition and education are thought to be the foundations for a community's engagement in restoration (Pinos, 2020). Almost all projects provided benefits to community economy, as highlighted by a community leader *"The NGO did not only have the objective to help with reforestation but also with artisanal work, solar panels and greenhouses."* (Community leader). Nonetheless, communities wanted to see benefits on short time scales, likely because they are weighing up the opportunity cost of engaging in restoration activities against the provided benefits. Projects with a pure 'Payment approach' did not generate long-term social benefits such as building capacity beyond technical planting and instilling an intrinsic desire in the communities to restore, as previously found in Ecuador (Wilson & Coomes, 2019). In one project site where community members had no advanced understanding of the benefits of the restoration for water or biodiversity but commented that they did restoration because they were told to: *"The government told us that we had to reforest with Queñua"* (Community member). In government protected areas, people engaged in restoration in retribution for grazing rights and were described as well-organized and environmentally conscious: likely because of their intricate connection with the natural world *"The pasture users are organized, and because they live in the conservation area, they assume this responsibility and contribute"* (Government actor).

We found that a higher degree of dependence on natural resources - which is typical of areas of subsistence farming in Latin America (Aguiar et al., 2021) - led to a high level of communal interest for engaging in forest restoration. Communal interest to participate in restoration due to resource dependence was a key success factor, as pointed out by a community member: "*We are delighted to work with the reforestation, especially when it is about water"*. Restoration was not seen to compete with agriculture or livestock farming, but to benefit it through 'sowing and harvesting water'. This is contrary to findings that reliance on subsistence products decreased intentions to restore forests (Joseph et al., 2021). However, our findings concur with work elsewhere in the

Andes, where communities with a higher degree of natural resource reliance were more engaged in forest restoration (Wilson & Coomes, 2019).

Our results show that participatory management was a key success factor in all project stages: from selecting restoration sites, deciding which species to plant, to choosing a locally appropriate way of implementation and compensation. Working closely with local communities to develop social and economic benefits is key for achieving restoration outcomes (Aucca & Ramsay, 2005; Hartman & Cleveland, 2018) as without considering people's values and social outcomes most restoration projects will fail (Rosa et al., 2020). Hence, restoration planning should be conducted with the community committee and decisions given approval by the community assembly, for instance through participative workshops and planning days. Implementation can be done through community tasks *'faenas'* which were described by NGO-stakeholders as *'very powerful'* and help implementing restoration with the community through its established structures whilst providing a social space and intra-communal dialogue and sharing: *"Every year when we do the planting the community gets together, we dress ourselves [in traditional dresses], prepare food, and pay tribute to Pachamama, then we dance [...] These are the reasons why the community willingly takes part."* (Community member)

We found that a lack of environmental education and awareness of forest benefits in the rural Andes hindered restoration work, as explained by a community leader: *"We are still not well educated [on environmental conservation]. Some of my colleagues are cutting the Intimpas [Podocarpus glomerata], while others are protecting the mature Intimpas which are more than 500 years old."* Hence, a key to long term success of restoration projects is to promote education and strengthen capacities of local communities to protect and restore Andean Forests. Capacity building needs to meaningfully involve local communities in all stages of the restoration project. In the context of this study capacity building in the communities included a suite of interventions and goals to empower communities in forest protection and improved livelihiods: creating an understanding of

the value and the services of Andean forests (e.g. workshops of forest ecosystem services in Kiuñalla), creating mechanisms for long lasting forest protection (e.g. fire prevention workshops by ECOAN in Vilcanota), and creating capacity for alternative agricultural livelihoods (e.g. improved livestock and grazing management in Aquia).

Creating long lasting is especially important to make restoration sustainable beyond the project timeline – as when the facilitating institutions leave restoration needs to be self-sufficient and community-run. Hence, capacity building must go beyond creating technical skills for restoration, and instead promote a sustainable way of land management which includes protection of forests from major antropogenic disturbances. Meaningful capacity building often incorporated traditional ecological knowledge (TEK). In the restoration site in Kiuñalla for example the NGOs worked closely with elders and women of the community to establish biodiversity baselines in interactive workshops: *"we did workshops to recover knowledge [on tree biodiversity in the forest], we also did competitions where many of the women took part. The competitions aimed to see who could retrieve the most diversity from the forest, who knew most species" (Academic actor).* Involving knowledgeable community members and their TEK in restoration projects is crucial to 1) create a baseline of species in the native forest, 2) identify which plants are most valued by local communities and 3) learn how to best propagate and maintain these plants.

Incorporating TEK into restoration project stages is a foundation for successful and equitable forest restoration (Reyes-García et al., 2019; Robinson et al., 2021). Many of the communities we visited had an intricate traditional ecological knowledge of Andean Forests, which in workshops was interwoven with restoration planning, such as informing restoration baselines and species selection. Especially, elders referred to over 80 species with medicinal value, such as a female community member who had promoted the medicinal plants of her community at a national level: *"I went to Lima, a fieldtrip […]. We displayed medicinal plants. […]. Sometimes on the coast they do not know these plants, what they are for, [we displayed] more than 80 varieties." (*female community

member). It is key to consider power dynamics and to ensure that the integration of TEK is not tokenistic, in order to achieve procedural, recognitional and distributional equity (Löfqvist et al., 2022).

Threats from uncontrolled human-induced fires were a key difficulty mentioned by all stakeholders. Fires have been used for centuries by Andean communities in the Puna grasslands to manage grazing resources, as well as for traditional and religious reasons (Manta et. al., 2018). As a result, many Puna plant species show adaptations to fire such as vigorous resprouting and high allocation of biomass to underground (Oliveras et al., 2014). However, recent changes in climate and land use are causing a disequilibrium and increasing incidence and area of fires (Manta et. al., 2018) which spread into lower elevations to the less fire adapted Andean Forests and tropical montane cloud forests (Román-Cuesta et al., 2011). In the departments of Cusco and Apurímac where we conducted most of our interviews, incidence of fires increased in the last 50 years (Manta et. al., 2018). Restoration projects need to work with communities on fire management and adaptation strategies to ensure that future restoration sites, natural ecosystems and communities are safe. The NGO ECOAN for instance does fire prevention workshops with community leaders who are then meant to function as leaders of community fire brigades (Fig 4.3 F).

Conflicts around land tenure and opportunity costs for agriculture were frequently brought up as a limiting factor for restoration by communities, government and NGO stakeholders. All NGOs, governments and engaged community groups noted the need to be crystal clear about land tenure security, such as explained by a community leader: *"it is social work to explain to the community that they will keep owning the land, no one will grab it - they can still use it"*. Further, formalizing forest conservation agreements whereby the whole community retains ownership for the restoration sites was crucial to avoid informal appropriation of territories by subgroups because of investment of restoration labour. Fencing was then necessary as this physically protects restoration sites from disturbance by herbivory during key development stages (Aguirre et al., 2011).

We found that strategic alliances which are multi-layered and polycentric institutions were key to achieving restoration goals - these included alliances between local organizations such as farming cooperatives and community groups, and between actors involved in landscape management of different hierarchical levels, such as local NGOs, regional governments, government agriculture initiatives (AGRORURAL), national protected area authorities and private actors (e.g. water companies, tourism companies etc). Multi-level and polycentric structures are thought to work well due to their ability to flexibly respond to local scale problems, and to make level-dependent decisions in a way a centralized single-actor system cannot (Lebel et al., 2006). A key example of such a strategic multi-layer alliance are the cases of the Mariño river basin and Nor Yauyos Cochas (Box 4.1).

Recovering Andean Forests is a multi-decade endeavour (Aragón et al., 2021; Oliveras, Malhi, et al., 2014), and hence long-term continuity of projects is vital. However, we found that a lack of continuity of leaders - at the communal and government level - often impaired this, resulting in fluctuating support, funding, and community interest for restoration. On the other hand, having dedicated community leaders and community forestry groups, such as reforestation committees, helped achieve restoration outcomes, as previously found in forest landscape restoration initiatives across the tropics (Ota et al., 2020). Although all projects harnessed some form of communal participation and provided direct and indirect benefits, many social, institutional, and technical barriers still hinder effective restoration work. Hence, future research could elaborate guidelines to improve collaborative processes in Andean Forest restoration to guarantee project longevity and continued benefits to communities.

Box 4. 2: Case study Challabamba and Aquia

Different governance models for community engagement

Economic motivations in a young restoration project in Challabamba

Reforestation in Challabamba began in 2021 with a goal to recover areas degraded by wildfires and restore water resources in a strongly agricultural area. The Cusco-based NGO Conservación Amazonica (ACCA) encountered a community split into several remote sectors who have a generally low environmental awareness and initially distrusted the NGO fearing land grabbing. Further, communities demanded immediate rentability of the project. ACCA's approach is to work closely with the community assembly, agreeing to only plant native species up stream, beyond farmers' fields. To motivate farmers to participate, the NGO paid daily compensations of 35 soles (9.25$) per day for propagation work in the greenhouse which is particularly taken up by female community members who otherwise lack economic income. Further there were payments for restoration plantings of 0.6-0.7 soles (0.16$) per plant. To increase community, buy-in, the NGO helped with community development such as improving irrigation infrastructure on their farms. Thereafter the irrigation committee was empowered to incentivize people to participate in tree planting up-stream, otherwise they would not be allocated water from the irrigation. The project has now had two successful planting seasons with 40ha planted with mixed native species.

Restoration to improve livelihoods and agriculture in Aquia.

Aquia is a remote farming community in the department of Ancash focused on dairy farming and dairy production. In the early 2000s the NGO Instituto de Montaña started to restore *Polylepis* forests to improve water resources for livestock farming while increasing native forest cover. Initially the community was sceptical of the project so during workshops on forest awareness and participatory consultations the community assembly decided the project should be implemented with two of Aquia's agricultural associations who would directly benefit from an increase in forest cover.



Farmers in Aquia are receiving a training on improved livestock breeds. Photo: Instituto de Montaña

The associations were involved in all restoration stages, from choosing restoration sites to propagating and planting seedlings. As a compensation the NGO provided the associations with high productivity pasture grasses, improved sheep breeds, agricultural tools, and irrigation infrastructure. Members of the associations carried out the restoration work through communal *'faenas'* where all generations took part. School children were involved through a school campaign on the importance of Andean Forests. The project created long-term capacity – not only for restoration planting but also for higher efficiency farming, and taught farmers about value added dairy production. Positive impacts of the project were the improvement of environmental awareness, improved communal organization and an increased level of pride and self-esteem. Even though the project terminated in 2009, the community still recognize how valuable restoration is for their agricultural way of living. A new NGO in the area, ECOAN – who focuses on nationwide *Polylepis* restoration – has identified Aquia as a promising site to upscale *Polylepis* restoration and started reforestation work in 2021. Because the community has already seen restoration benefits in the past project and acquired capacities, there is high willingness to participate in larger-scale plantings of *Polylepis* and achieved record-breaking planting efforts of planting 200,000 seedlings in one day in February 2023.

Overcoming technical and biophysical barriers to restoration success

In addition to social limiting factors, many biophysical and technical limitations were highlighted by interviewees which can be overcome by consideration of traditional ecological knowledge, site-specific restoration techniques as well as planting logistics adapted to the mountain context.

Interviewees frequently mentioned biophysical challenge to growth of Andean tree species, which is in line with previous research on slow vegetative growth, harsh temperatures and conditions, livestock herbivory and high fragmentation level resulting in low seed supplies (Pinos, 2020; Vásquez et al., 2014; Wesche et al., 2008). Accordingly, technical factors were often cited as ways to overcome these biophysical limitations to improve scale of planting and planting success. *Polylepis spp*. have been found to regenerate well from vegetative cuttings of branches (Mindreau & Zúñiga, 2010). Two practices are established; collection of branches from mother trees for propagation in the greenhouse (*'propagación con esqueje'*) or by air layering trees (*'acodo aéreo'*) whereby little ring incisions are made around living tree branches and a bag of soil is attached at the incision point to promote root growth (Mindreau & Zúñiga, 2010). However, vegetative propagation could cause a decreased resilience of restored forests due to cloning an of donor forest due to encroachment, such as explained by an NGO actor: *"Every time we are producing more [stakes], there are more mutilated branches from the forests because I have to make cuttings."* (NGO actor). Hence, collection sites and mother trees need to be strategically selected to not overstrain healthy *Polylepis* populations. In Huascarán National Park SERNANP solved this challenge by setting up 'stake orchards' from which genetic material is used for reforestation (Supplementary 3.9). At the same time, using non-local *Polylepis* species must be avoided because of hybridization risks (Pinos, 2020), which is often done due to a lack of seedlings with local provenance. The use of other Andean high-altitude species such as Buddlejas ('*kishuar'* [*Buddleja*

incana] and *'Colle'* [*Buddleja coriaceae*], see Supplementary 3.8) should also be considered to ensure higher species diversity and resilience of restoration sites.

Restoration sites are largely located in remote, upstream areas, with difficult access, causing challenges for both planting and monitoring. Challenges related to weight of seedlings in transit can be solved through propagating and transporting seedlings with bare root, such as done by the NGO ECOAN who use this technique to plant up to 200,000 seedlings in one community per day. Decentralizing greenhouse infrastructure and placing greenhouses close to restoration sites also helps reduce logistic challenges and is a method pioneered by the Protected Area authority SERNANP (Supplementary 3.9). Further, aerial layering of *Polylepis* eliminate the need of a greenhouse as seedlings are grown in forest relicts close to restoration sites (Mindreau & Zúñiga, 2010). Drone monitoring of remote restoration sites is a promising future avenue in remote Andean Mountain locations (Robinson et al., 2022).

Beyond forest restoration – a mountain landscape restoration approach

In a mountain range so extensive and socio-economically diverse and complex as the Andes, many types of restoration are required. Even though our interviews were concentrated on forest restoration, all stakeholders mentioned the importance of also restoring non-forest ecosystems such as the high Andean grasslands ('*Puna*' or '*Pajonal*') and wetlands ('*bofedales*') to improve water resources: "*I wish that all institutions support the planting of Icchu in the highlands, wetlands, in the hills. So that [these ecosystems] can help with our water resources, because every day the planet is drying up more*." (Community member). Andean grasslands are key for water provision and regulation, soil fertility, provision of food, wool and fibre, microclimate regulation and several other ecosystem services, making them important sources of livelihoods (Rolando et al., 2017). Puna grasslands also show high belowground productivity storing similar amounts of carbon as tropical

cloud forests (Oliveras et al., 2014). Given the high degree of agricultural dependence on both forested and non-forested ecosystems, we call for a holistic mountain landscape restoration approach incorporating a spectrum of restorative action. Finding the right locations for restoration to maximize ecosystem services is key and different locations within landscapes need to be prioritised for different restoration interventions (Lamb, 2018). Further, the upscaling of locally effective landscape management solutions, such as forest restoration, considering multiple stakeholders is a key priority to achieve sustainability in Andean forest landscapes (Mathez-Stiefel et al, 2017). Hence, we suggest a mountain-landscape centred allocation and prioritization of restoration and conservation interventions which includes both considerations of watershed restoration and forest landscape restoration (Fig 4.8).

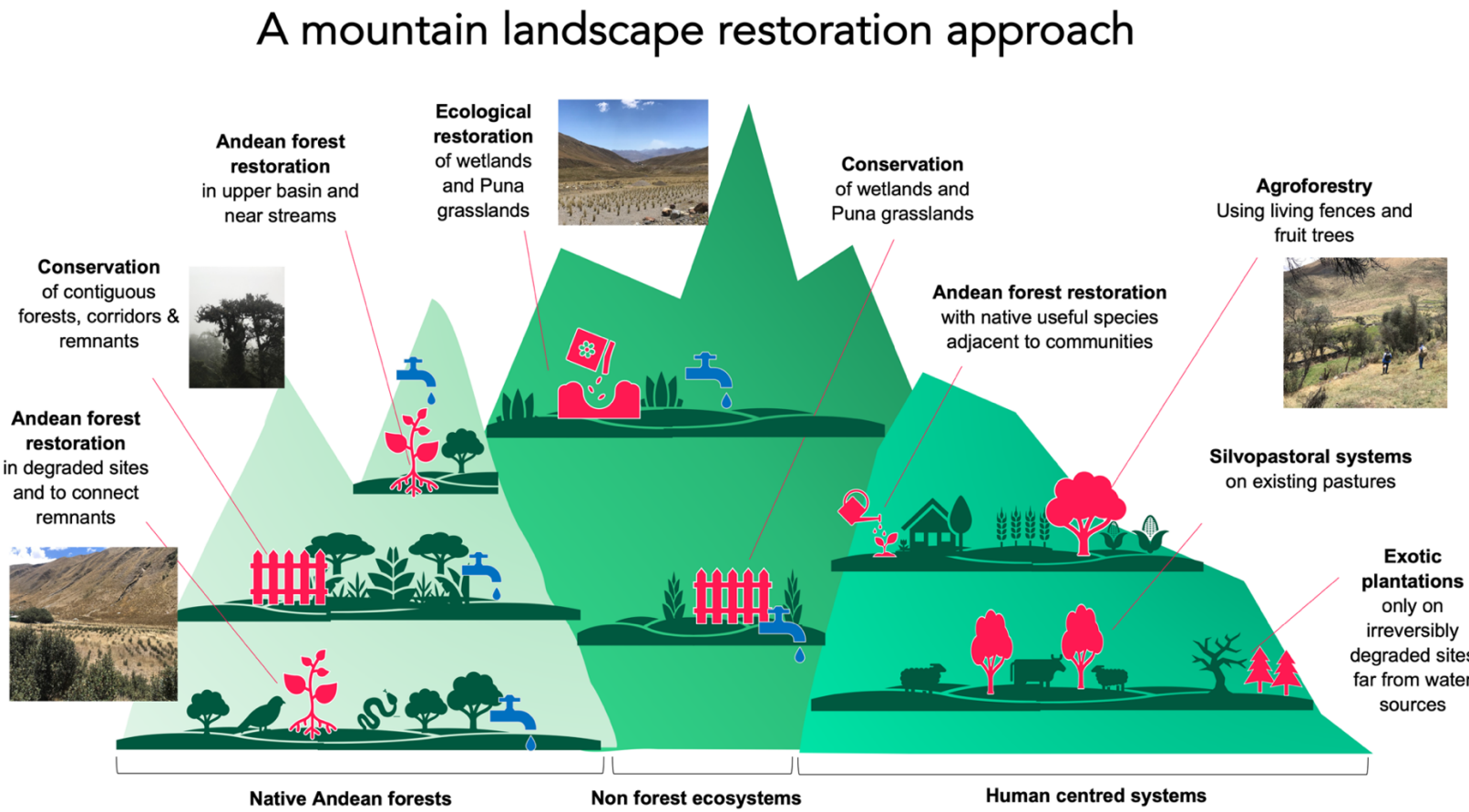


Figure 4. 8: A mountain landscape restoration approach, which goes beyond montane forest restoration to include other natural and human-centred ecosystems. Blue taps indicate interventions which according to our analysis have a high potential to restore water flow and provide water resources.

Specifically, we propose the adoption of the principles of forest landscape restoration (World Resources Institute, n.d.) which respect the ecological, topographic, economic, and socio-cultural complexity of the High Andean landscape:

1) Andean Forest restoration should be conducted using native species at a mountain landscape level considering all its natural and cultural ecosystems ranging from the lower montane forest to the high Andean Forests and the non-forested ecosystems. Zonation and species selection must consider elevation level, local provenance, biodiversity value, water retention effect and provision of direct benefits.

2) Andean Forest restoration is a complex multi-stakeholder endeavour which must provide pluralistic direct benefits to people. Hence, stakeholder engagement and participation of local communities and land users are key and can be achieved through strategic polycentric and multi-layered alliances and with an ethos of horizontal governance.

3) Andean Forest restoration needs a functional approach which considers the provision of ecosystem services and water resources, promotion of native biodiversity and direct benefits to communities. It should be designed with a multi-decadal vision to guarantee longevity and ongoing provision of ecosystem services.

4) Natural ecosystems need to be conserved and restored through community conservation agreements, payment for ecosystem service schemes and the creation of alternative livelihoods like eco-tourism. Together with international conservation payments the mechanisms of payment for hydrological ecosystem services are a useful tool to channel resources towards water-centred Andean Forest restoration.

5) Interventions need to be tailored to local contexts using a suite of locally designed interventions centred on provision of hydrological ecosystem services, biodiversity, and livelihoods (ranging from agroforestry, productive restoration to ecological restoration (Fig 4.8). This could be

done by creating a national Andean Forest restoration strategy which identifies restoration hotspots and creates subsequent regional and local prioritization studies.

6) Adaptive management and monitoring of interventions need to be conducted with a long-term project vision to ensure benefits and success across the slow restoration timeline of Andean Forests and to manage restoration according to changing needs of mountain communities.

Statements and declarations

Author Contributions

TC – Conceptualization - Lead, Methodology - Lead, Investigation - Lead, Transcription -Lead, Data curation - Lead, Formal analysis, Visualization, Writing - Original Draft - Lead, Writing - review & Editing - Lead, Funding.

IO - Conceptualization, Methodology, Planning and logistical support, Writing - review & Editing, Supervision – Lead.

SW - Conceptualization, Methodology, Writing - review & Editing, Supervision.

ACS - Conceptualization, Methodology, Writing - review & Editing.

YM - Conceptualization, Writing - review & Editing, Supervision.

MLA - Investigation, Transcription, Data curation, Writing - review & Editing.

IC - Investigation, Transcription, Data curation, Writing - review & Editing.

AR - Planning and logistical support, Writing - review & Editing.

MM - Planning and logistical support, Writing - review & Editing.

VR - Planning and logistical support, Writing - review & Editing.

MA - Planning and logistical support, Writing - review & Editing.

JR - Writing - review & Editing.

FMC - Planning and logistical support - review & Editing.

OACM - Planning and logistical support - review & Editing.

CA - Planning and logistical support.

Conflict of interest

The first author (TC), the advisors (IO, YM, ACS, SW) and ICT have no conflict of interest. The other authors (MLA, AR, MM, VR, JR, FMC, CA) were or are involved in institutions that implement forest restoration in the Andes.

Data accessibility statement

Upon acceptance the data will be published on the data repository Mendeley Data.

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Supplementary material

Supplementary 3. 1: Demographic characteristics of interviewees

Demographic characteristic	Categories	Number of interviewees [%]
Age	<= 30	9 [12.1%]
	30-50	25 [33.3%]
	>=50	41 [54.6%]
Gender	Male	64 [85.3%]
	Female	11 [14.7%]
Involvement in agriculture	Yes	46 [61.3%]
	No	29 [38.7%]
Education	School	43 [57.3%]
	University	32 [42.7%]
Stakeholder group	Community	44 [58.6%]
	Government	14 [18.6%]
	NGO	12 [16%]
	Private	3 [4%]
	Academia	2 [2.7%]
Residence of interviewee	Rural	49 [65.3%]
	Urban	26 [34.6 %]

Supplementary 3. 2: Interview guide for general interview

Part 1: General

1. What is your job/occupation? Do you have other additional jobs or sources of income? Do you produce anything for subsistence?
2. How were you involved with the restoration project? For how much time did you work with the project?
3. Why did you decide to restore or help with the restoration of Andean Forests?
4. Do you think the Andean Forests of the area help with community livelihoods? If yes, how?

Part 2: Objectives of project

5. In your opinion what were the main objectives of the restoration project?
6. Did the project have any other ecological, social of economic objectives?
7. Which ones were the two most important objectives?

Part 3: Success factors and barriers

8. How were the project objectives achieved by now?
9. On a scale from 1-3 how well have the project objectives been achieved [with 1 being no goals achieved and 3 being all goals achieved]?
10. If the objectives were achieved [goal achievement category 3]:
    a) What helped achieved these objectives? What made it successful?
    b) Were there any other management/institutional, ecological, economic, social or cultural factors that contributed to the success? [these factors were asked successively]
11. If the objectives were not achieved [goal achievement category 1 or 2]:
    a) Why were the objectives not achieved? What were the barriers that impeded to achieve these objectives?
    b) Were there any other barriers/limitations such as management/institutional, ecological, economic, social or cultural factors? [these factors were asked successively]
    c) What do you recommend as a solution?

Part 4: General questions

12. Did the project affect community livelihoods? If so, how did the restoration project affect the community livelihoods?
13. Did the project provide any economic benefits for the communities? If yes, what economic benefits did the project provide?
14. Did the project provide any non-economic benefits for communities? If yes, what benefits did it provide?
15. What are the main lessons learnt from the project which could help improve other restoration projects in Andean Forests?
16. When thinking about forest restoration in your local area: what restoration interventions do you favour? Why do you favour these interventions?
17. Based on your experiences in the project, do you have recommendations for other communities or projects who want to restore their Andean Forests?
18. Is there anything else you like to mention?

Supplementary 3. 3: Interview guide for technical interview with project managers

General

1. What were your responsibilities in the project?
2. When did the project start and how long has it lasted?

The site

3. Who owns the land of the project?
4. What is the designation or conservation status of the site?
5. Was the ecosystem degraded before the project? If it was degraded, what were the causes of project site degradation?
6. Before the project began, did the forests on the site naturally regenerate?
7. How was the land used before the project?

Financing

8. Who funded the project?
9. What was the total budget of the project?
10. How was the budget distributed during the different stages of the project? (Planning, implementation, monitoring and management)

Community

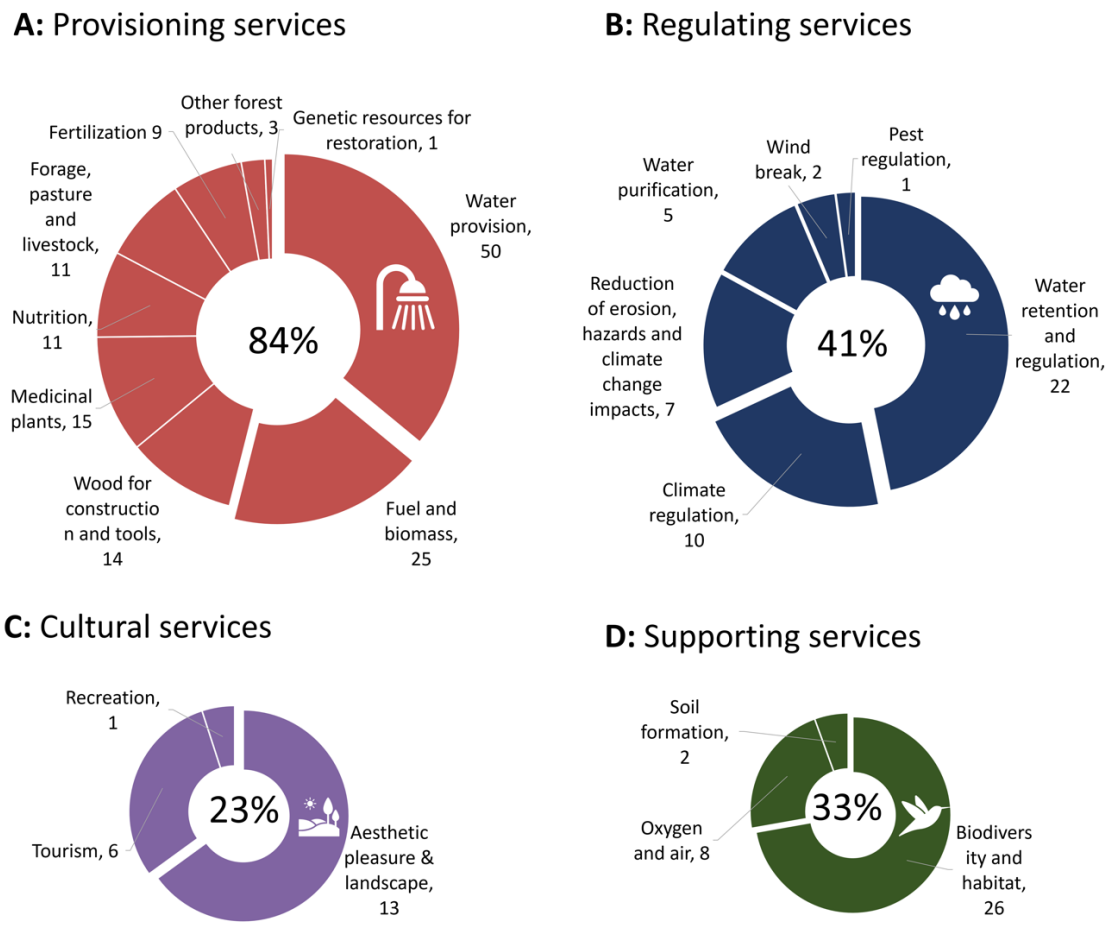
11. How were local communities involved in the project?
12. What role did communities play in the project? (E.g., active or passive role)
13. How many families/individuals participated in the project?
14. In what capacity did community members participate? (E.g., as assemblies, as agricultural cooperatives, households, individuals etc.)
15. At what stage of the project were the communities involved? (Planning, implementation, monitoring and management)
16. How long were communities involved? (E.g., how many hours/full-time, sporadically etc.)
17. Were community members paid? If so, what work were they paid for?
18. Were there differences between the involvement of women and men?

Restoration

19. What restoration methods were used? (Planting native trees, planting exotic trees, agroforestry, natural regeneration, other methods)
20. Why did they select this method?
21. If there was species planting: Which species were planted and why? Were the species native? Where did they get the seeds? What was the method of propagation?
22. Did you do other interventions to restore the site? (e.g., fences, fire breaks, soil amendments, invasive species control, weeding/clearing etc.)?

Maintenance and monitoring

23. Was/is there ongoing maintenance and management on site? If so, what kind of maintenance and handling? (Irrigation, weeding etc.). How long were the restoration areas maintained?
24. Are restored areas monitored? If so, what is included in monitoring (e.g., plant survival, water flow, benefits to communities, other services...)? If so, how long have you monitored/will you monitor? If there is/has been no monitoring – why not?
25. Did you partner with someone to monitor? E.g., university, NGOs etc.
26. Does the project depend on external support? (Labour, money etc.), or is it already self-sufficient?



Supplementary 3. 4: Ecosystem services of Andean Forests aggregated for all stakeholder groups.

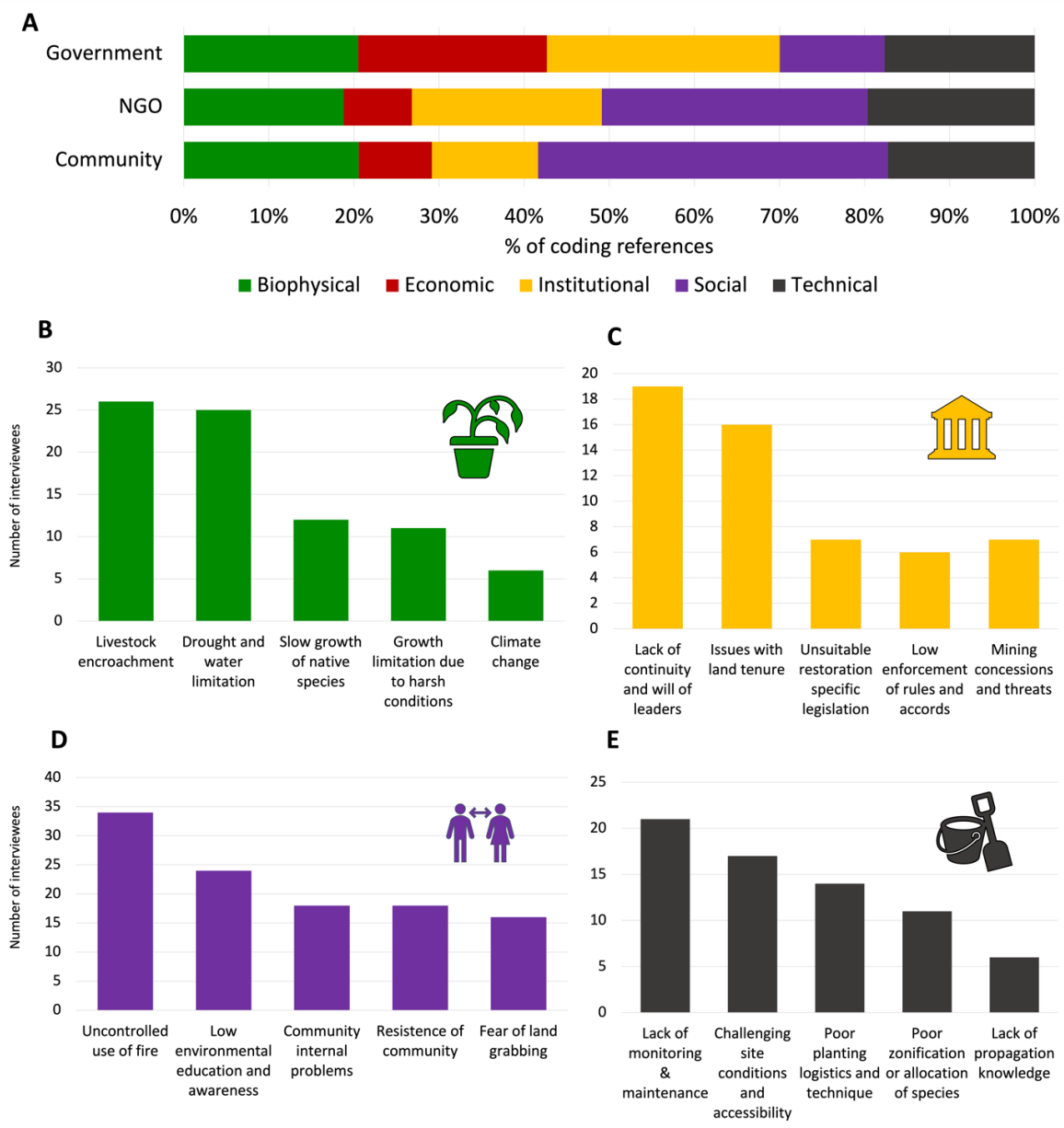
Supplementary 3. 5: Perceived objectives of the projects by the three main stakeholder groups and for all interviewees. Only most frequent objectives are listed.

Perceived objectives of project	% of Community (n=44)		% of NGO (n=12)		% of Government (n=14)		% of all interviewees (n=75)	
	#	%	#	%	#	%	#	%
Ecological objectives	23	52%	8	67%	8	57%	41	55%
· Restore forest cover	13	30%	5	42%	6	43%	26	35%
· Conserve biodiversity and ecosystems	20	45%	4	33%	1	7%	25	33%
Economic objectives	21	48%	7	58%	7	50%	37	49%
· Generate income for communities	13	30%	5	42%	4	29%	22	29%
· Creation of alternative livelihoods activities	6	14%	4	33%	1	7%	11	15%
· Creation of labour	0	0%	1	8%	5	36%	7	9%
· Promote tourism	3	7%	1	8%	0	0%	5	7%
Social objectives	37	84%	11	92%	10	71%	64	85%
· Water resources and regulations	27	61%	9	75%	7	50%	49	65%
· Generate social benefits for communities	5	11%	2	17%	3	21%	13	17%
· Build capacity	4	9%	5	42%	0	0%	9	12%
· Protect from climate change impacts	4	9%	1	8%	3	21%	9	12%
· Sensibilization, awareness and education	4	9%	1	8%	3	21%	9	12%
· Soil and erosion protection	6	14%	0	0%	2	14%	9	12%

Supplementary 3. 6: Benefits of restoration projects mentioned by stakeholder groups.

Type of impact		Description	% of community (n=44)	% of NGO (n=12)	% of government (n=14)	% of all interviewees (n=75)
Positive	**Direct economic benefit (71%)**	Daily wages for restoration work	68%	67%	60%	60%
		Payments to community fund	32%	8%	23%	23%
	Indirect economic benefit (77%)	Provision of tools and materials (hose pipes, irrigation tools, work tools, fences)	32%	50%	31%	31%
		Promotion of alternative livelihoods (horticulture, artisanal work, apiculture, pisciculture, tourism etc)	23%	33%	20%	20%
		Provision of improved forage and grasses	16%	25%	19%	19%
		Infrastructure improvements (roads and paths, irrigation canals, water reservoirs, greenhouses etc)	14%	17%	15%	15%
		Increased agricultural productivity due to higher water availability	9%	17%	15%	15%
		Nutrition support	16%	8%	12%	12%
		Improved livestock (high productivity breeds, small animals like guineapigs)	5%	17%	7%	7%
		Provision of alternative fuel and energy sources (gas, eucalyptus wood, solar panels)	7%	0%	5%	5%
		Non-timber goods from forest with market value (medicinal species, resins, dry wood)	0%	8%	5%	5%
		Potential for future carbon offsets	0%	0%	1%	1%
		Timber with economic value	5%	0%	1%	1%
		Reduction of uncontrolled fires	0%	0%	1%	1%
		Value added production	2%	0%	1%	1%
	Non-economic benefits (93%)	Capacity building and education of community	91%	67%	67%	67%
		Participaction and education of children	16%	17%	17%	17%
		Increased environmental awareness	16%	17%	13%	13%
		Improvement of communal governance (leadership, empowerment, creation of committees)	11%	25%	12%	12%
		Field visits and trips	9%	8%	14%	9%

		Identity, pride and self-esteem	5%	25%	0%	7%
		Aesthetic improvement of landscape	2%	0%	14%	4%
		Interest for area (international, research)	0%	8%	14%	4%
		Improved quality of life	5%	0%	7%	4%
		Cultural benefits	2%	8%	0%	3%
Negative	**Opportunity cost (37%)**	Restrictions on agriculture/livestock practices	30%	50%	21%	29%
		Forbidden to harvest timber	7%	0%	7%	5%
	Other	Water competition, loss of labour time, pest species	2%	8%	7%	4%
	None	No observed negative impact of the project	23%	17%	7%	17%



Supplementary 3. 7: Limiting factors for Andean Forest restoration by stakeholder group (A). Top 5 biophysical (B), institutional (C), social (D) and technical (E) enabling factors.

Supplementary 3. 8: Species mentioned by communities for future restoration interventions including their taxonomy and local uses, * indicates that the local use/value was taken from an ecotourism guide by (Baiker, 2011), NA indicates cases where taxonomy and/or local value was unclear.

	Species (local and scientific name)	**Family**	**Local use/value**
Native trees	*Polylepis racemosa*	Rosaceae	Water retention
	Queñua (Polylepis incana)	Rosaceae	Straight growth, water provision, biodiversity
	Kishuar [Buddleja incana]	Scrophulariaceae	Aesthetic, good construction wood/straight growth
	Colle, qolle [Buddleja coriacea]	Scrophulariaceae	Grows in areas above 3800m asl, flowers used to dye wool and alpaca fibre
	Aliso/Lambram [Alnus acuminata]	Betulaceae	Retains water, wood, fast growth, natural dye, nitrogen fertilizer for soils
	Cedro [Cedrela sp.]	Pinaceae	Wood
	Intimpa/Romerillo [Podocarpus glomerata]	Podocarpaceae	Biodiversity value, good wood, aesthetic value
	Yuruma [Morella pubescens]	Myriaceae	Water retention, fruits eaten by birds and Andean bear
	Chachacomo [Escallonia resinosa]	Escalloniaceae	Good wood, used for making tool handles
	Popa [Gaiadendron punctatum]	Loranthaceae	Fruits eaten by birds
	Unca [Myrcianthes oreophila]	Mrytaceae	Construction wood
	Pukap'isqay [Prunus huantensis]	Rosaceae	Good wood
	Panti [Viburnum cf reticulatum]	Viburnaceae	NA
	Toqachu [Gynoxys pillahuatensis]	Asteraceae	Wood for construction
	Arayan [Eugenia mirtomimeta]	Myrtaceae	Water retention, essential oils
	Molle/ Peruvian Pepper [Schinus molle]	Anacardiaceae	Edible fruits, leaves used for textile dye*, improves soils
	Cala cala	NA	Water retention
	Chinuela	NA	NA
	Tasta [Escallonia myrtilloides]	Escalloniaceae	Can grow in degraded areas, wood for tools
	Ollantay	NA	Wood
	Monte romero	NA	NA
	Kello halato	NA	Disinfectant
	Monte canelo. wayrasqa	NA	Tea, aromatic plant
	Pachatayancu [Baccharis spp.]	Asteraceae	Medicinal against cough
	Pacha muna [Clinopodium nubigenum]	Lamiaceae	Medicinal
	Chuyllur [Vallea stipularis]		Good wood, water retention, medicinal

	Tallanca, Tayanca [Baccharis spp]	Asteraceae	Medicinal, For Dyeing, good to recover soils
	Curuchu	NA	NA
	Lima Lima	NA	Good wood
	Nogal [Juglans neotropica]	Juglandaceae	Wood, walnuts
Agroforestry	*Manzana/Apple [Malus spp,]*	Rosaceae	Fruits
	Pera/Pear [Pyrus spp.]	Rosaceae	Fruits
	Ciruelo/Plum [Prunus spp.]	Rosaceae	Fruits
	La Tuna [Opuntia spp]	Cactaceae	Fruits
	Palta/avocado [Persea americana]	Lauraceae	Fruits
	Khari Khari [Rubus roseus]	Rosaceae	Fruits
	Sauco [Sambucus peruviana]	Adoxaceae	Fruits, fertilizer, living fence
	Guaba [Inga edulis]	Fabaceae	Fruits, fertilizer
	Tara [Caesalpinia spinosa]	Fabaceae	Nutrition: carob beans, market value, water retention, textile dye
	Pisonay/Basul [Erythrina falcata (a) y Erythrina edulis]	Fabaceae	Food for guinea pigs, fertilizer
Exotic trees	*Pino [Pinus globuli, Pinus patula]*	Pinaceae	Wood, pine mushroom
	Capuli [Prunus serotina]	Rosaceae	Fruits
Other growth forms	*Carrizo [Phragmites australis]*	Poaceae	Fertilizer
	Ichu [Stipa ichu]	Poaceae	Water retention, erosion control, pasture grass
	Ryegrass	Poaceae	Pasture grass

Supplementary 3. 9: Case study experiences of overcoming technical and biophysical challenges from government led restoration.

Seedling propagation techniques pioneered during 30 years of government experience:

The government protected area authority (SERNANP, formerly *Instituto Nacional de Recursos Naturales*) has worked on Andean Forest restoration since the 1990s and pioneered methods that tackle many of the technical challenges of restoration.

Machu Picchu's flying greenhouses:



The Machu Picchu historic sanctuary has experienced recurring wildfires, causing destabilization of slopes and loss of biodiversity. Since the early 2000s SERNANP has been on a mission to restore the montane forests to stabilize the soils and bring back native species. SERNANP uses a combination of ecological restoration with native species of high conservation value and native species valued for their local use by local settlers such as *Inga edulis* and *Alnus acuminata*. Access to sites is via hiking tracks meaning that restoration interventions are labour intensive and limited by how many seedlings people can manually carry. SERNANP solved this problem by creating 'flying greenhouses' [*viveros volantes*], i.e., small decentralized micro greenhouses right next to the restoration sites, which are also used in other Andean protected areas such as Nor Yauyos Cochas. This ensures plants are adapted to local climate and that transportation efforts of grown seedlings are minimized and allows to reforest at a larger scale. However, drought mortality is a problem in the greenhouse as irrigation cannot be done manually at these locations. Hence, small natural reservoirs were constructed next to each greenhouse (see photo) to overcome water limitations during propagation and to irrigate seedlings once planted out. Almost 20 years after the project began, the restoration site shows a closed canopy with *Alnus acuminata* measuring over 10m while slower growth species approach 2-3m.

Huascarán's stake orchards:



Strong biophysical limitations in the field mean that planted seedlings must be as 'fit' as possible to withstand harsh conditions. To ensure survival of *Polylepis* in the field, in the 1990s the former protected area authority in Huascarán National Park created *Polylepis* 'stake orchards' where trees are grown in selective densely planted conditions to create competitive trees from which to extract stakes for future restoration plantings. Pruning and good maintenance of these orchards ensure growth of plants with best possible traits. This is a promising practice for future restoration plantings as this reduces pressure on native forest relicts from which stakes are usually taken. While seed orchards are emerging worldwide as locations to propagate sought after native species for restoration, this was the only site where we encountered such a long-term method.

Supplementary 3. 10: Participant information and recruitment leaflet

Entrevista sobre la restauración de bosques Andinos

Los **Bosques Andinos** albergan una gran biodiversidad, además de proporcionar servicios ecosistémicos como la regulación del agua y la protección contra la erosión. Son de **importancia local y también global**.

En el Perú hay varios proyectos que aspiran a **restaurar bosques andinos degradados**. Estos proyectos pueden servir como ejemplos de **aprendizaje para futuros proyectos de restauración,** para asegurar que los proyectos creen las mayores oportunidades para la naturaleza y para las comunidades.

En mi doctorado, quiero averiguar qué impulsa el **éxito de la restauración de bosques Andinos**. Con este objetivo, estoy visitando varios proyectos y haciendo entrevistas con comunidades, ONG y gobiernos.

Los resultados van a **informar la ciencia y la práctica de la restauración en la región Andina,** ya que voy a presentarlos en conferencias internacionales y en revistas académicas.

Toda la **información será protegida y tratada confidencialmente**. Mi universidad ha aprobado los métodos y la ética del proyecto (CUREC: SOGE1A2021-215).

Me gustaría hacer una entrevista de 20-40 minutos con usted para escuchar y aprender de su experiencia y sus ideas. Su participación es totalmente voluntaria.

Tina Christmann, estudiante de doctorado en geographía y medioambiente, Universidad de Oxford (Reino Unido)
Whatsapp +51 993289735| e-mail tina.christmann@worc.ox.ac.uk
Mayté Alejandra López Aranda, Estudiante de Ingeniería Forestal, Universidad Nacional Agraria La Molina (Lima, Perú)
Whatsapp +51 934246505 | e-mail maytela4@gmail.com

Chapter 5

Synthesis

"A positive thing is that if you go with a good message, you will encounter response from the people." – Government conservation official



Figure 5. 1: In the Vilcanota mountain range community leaders receive a training on fire management and prevention.

This thesis provides key insights into the science and practice of restoration in TMEs and outlines several recommendations going forward (Fig. 5.2). In this UN Decade on Ecosystem Restoration, we must develop and implement restoration that is scalable, effective, sustainable in the long-term and provides benefits to people and nature. TME restoration requires an interdisciplinary multi-scalar approach whereby scientists, practitioners and decision makers work together to plan, implement and monitor restoration. In this thesis I used a multi-scalar and multi-actor approach,

conducting a synthesis of the disjunct scientific findings on TME restoration of the last two decades, harnessing technologies and big data opportunities to monitor forest recovery over large scales, and collaborating with actors on the ground who implement and interact with ecosystem restoration.

To conclude this thesis, I provide: i) a synthesis of the main findings of the thesis, ii) a conclusion with reference to the theoretical frameworks with research priorities by Mathez-Stiefel et al (2017), and iii) a 10-point agenda with recommendations for the science and practice of Andean Forest restoration..

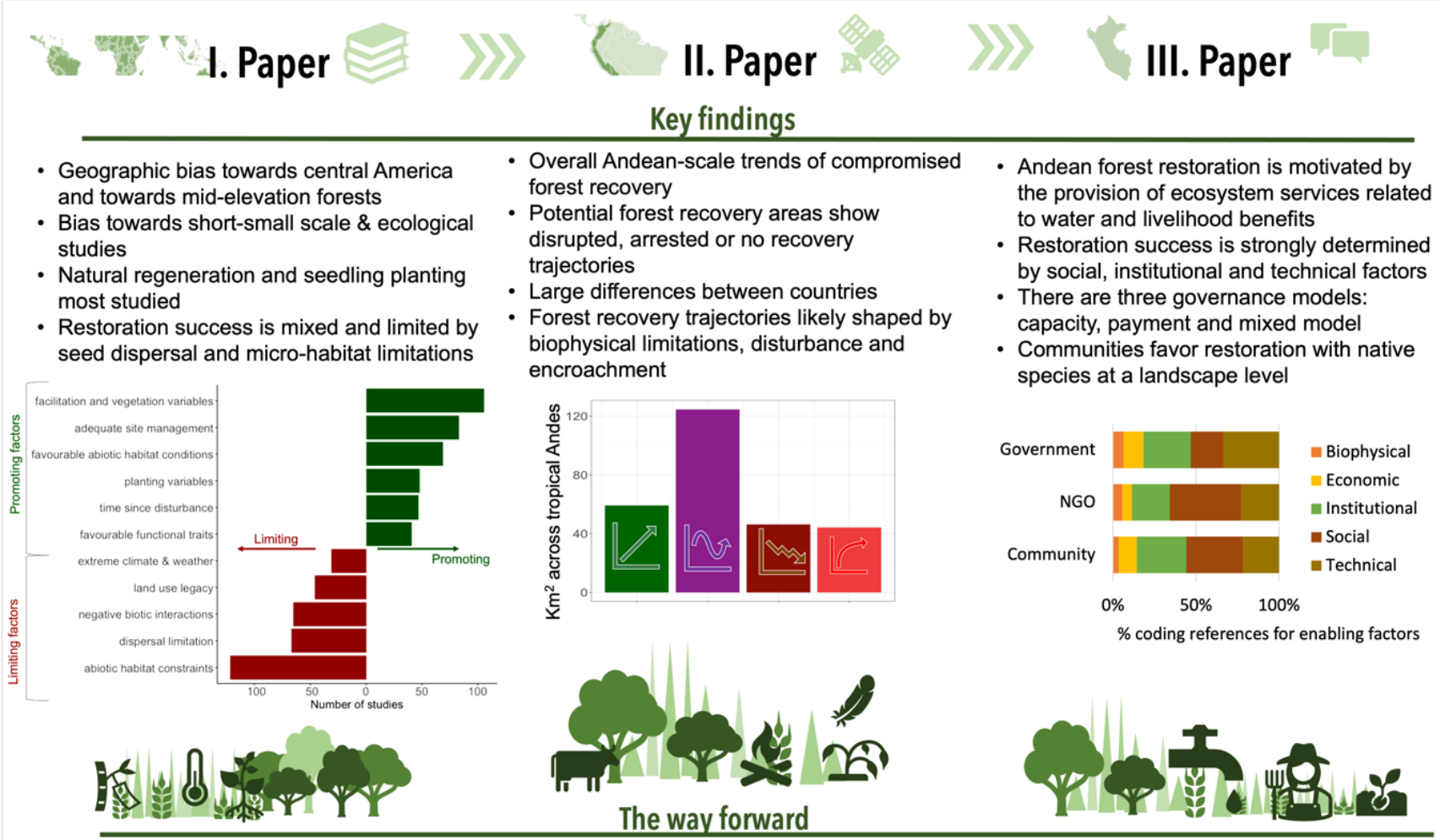


Figure 5. 2: Synthesis of DPhil chapters

Summary of the main findings

In Chapter 2 (Paper I), I synthesized the state of science of TME restoration and identified the main knowledge gaps for TME restoration. I then outlined a road map to direct future research towards understudied key geographic areas and research topics. Key gaps included studying the world's largest mountain ranges, like the Andes, and addressing underrepresentation of certain ecosystem types such as mountain grasslands. Most reviewed studies had a purely small-scale and short-term experimental set up and looked at site-level ecological and biophysical variables. Accordingly, the main barriers and limiting factors to restoration success were found to be biophysical site-factors including biotic and abiotic conditions for plant growth, landscape fragmentation and remnant vegetation. Most studies lacked a larger-scale socio-economic lens and did not involve assessments of people's perception, motivations, and values of restoration. There is a need to assess outcomes of TME restoration over large scales and long periods of time, especially by making use of remote sensing technologies for restoration planning and monitoring.

Chapter 3 (Paper II) then tackled these research gaps identified in Chapter 2 by applying a newly developed methodology to assess forest recovery in Andean montane forests over 15 years. I found an overwhelming trend of disrupted and arrested forest recovery across the biodiversity hotspot. As most of the potential recovery areas did not recover through natural regeneration, prioritizing restoration efforts in such sites can help optimize restoration planning, and allocation of resources. In this chapter I provided a simple methodological framework which can be adapted to various temporal and spatial contexts and datasets to both monitor restoration and prioritize interventions based on detailed recovery trajectories. This method can be used at regional or national scales to determine restoration hotspot regions. Importantly, local scale field-based site-assessments drawing on socio-economic information (community preferences and priorities, income status, land tenure, proximity to communities etc) and biophysical information (small scale topography, proximity to water sources etc) are required to plan definite restoration sites and final interventions.

Chapter 4 (Paper III) then zoomed specifically into the field scale to assess what motivates and drives the success of Andean Forest restoration at a local and national scale in Peru. Using a multi-stakeholder analysis, this research provides an overview and recommendations for the practice of forest restoration in Peru – a country which has only recently set out a national restoration agenda (Murcia et al., 2017). I find that motivations for restoration were largely instrumental and tied to water provision and derivation of direct benefits and align with the 'ecosystem-scarcity path theory' for restoration (Wilson & Coomes, 2019). I further identified the importance of considering several key socio-economic, institutional, biophysical, and technical conditions to improve restoration and noted that these vary substantially between stakeholder groups. In the chapter I presented three community engagement models and their advantages and disadvantages to help pick the most suitable model for future interventions and shed light on the functionality of capacity-centred vs payment-centred restoration. Finally, I presented a mountain landscape scale approach which incorporates social and ecological dimensions related to water provision, biodiversity and livelihoods benefits.

Critical reflection and conclusion

My thesis used the 'Research Priorities for the Conservation and Sustainable Governance of Andean Forest Landscapes' by Mathez-Stiefel et al (2017) as a conceptual framework, to structure the themes and knowledge gaps tackled and to tie in with an expert-validated contextually relevant agenda to Andean forest Landscapes and tropical mountain landscapes more generally. I also used a framework related to equity for restoration (Leach et al., 2018; Löfqvist et al., 2022) and a framework on pathways linking FLR with social and ecological outcomes (Erbaugh & Oldekop, 2018) .

Through empirical findings my thesis was able to address several research priorities across System, Target and Transformation knowledge expressed by Mathez-Stiefel et al (2017), first and foremost

Knowledge Priority 7 'Promote restoration in Andean forest landscapes'. As described in the synthesis these new empirical findings are the systematization and comparison of ecological restoration practices in TME (Paper I), the identification of forest recovery trajectories and land use change processes at large scales (Paper II) and the investigation of local stakeholder perceptions and priorities for Andean forest restoration (Paper III). However, several notable issues and limitations arose in my thesis papers which warrant critical reflection in connection to the Mathez-Stiefel et al (2017) framework, and to other key frameworks deployed in this thesis.

Priority 7.1 of the framework is to *'Identify the main potentials, bottlenecks, and enabling institutional conditions for restoration by critically reviewing, through a multistakeholder participatory process, existing initiatives in the region*.' While Paper I tackled the issue of systematization at a pantropical level, it missed out on crucial grey literature and papers which did not have an English abstract for the search string to be triggered. This means that e.g., literature by non-academic stakeholders was left out of the study. As I found in my literature search for Paper III in the Andes, large parts of the available literature, and especially those looking at socio-economic dimensions of restoration (Baca, 2018; Cerrón Macha et al., 2018; Murcia et al., 2017; Sabogal et al., 2020) are not within the academic domain but considered 'grey literature' situated in government, and non-governmental domains. This is partially why my systematic review might have concluded that restoration studies in certain key regions such as the Andes are rare. Not including grey literature which involves local stakeholders also meant that certain dimensions, especially socio-economic foci were underrepresented. My systematic review found that the academic literature on ecosystem restoration in tropical mountains, which mainly relies on quantitative methods, is heavily focused on measuring ecological drivers and outcomes of restoration. This contrasts strongly with Paper III, in which a qualitative multi-stakeholder approach brings many more socially and economically centred restoration dimensions to light. Future studies could explicitly incorporate grey literature in meta analyses, but they will also need to investigate

ways of systematically vetting grey literature and ensuring comprehensive search strings which consider academic and non-academic terminology. Along those lines, future studies could further include search strings that incorporate local names of specific ecosystem types (e.g. *'Bosques Andinos', 'Yungas'* etc) to tap into a broader, more complete base of research. In the end, trade-off between precision and research costs and labour will need to be considered in such meta-analyses, and likely such comprehensive studies will be most realistic at a national or ecosystem type level.

Priority 7.2 of Mathez-Stiefel's framework is to *'Compare active restoration approaches with the self- regeneration capacity of degraded forest (secondary succession pathways) after different forms and durations of use'*. In Paper I I did address this comparative issue through a meta-analysis of various intervention types and found mixed results between restoration interventions and following different degradation levels, yet generally higher success rates for active interventions. Thi matches several lines of research that have shown that natural regeneration in TME is generally inhibited by microclimatic factors, invasive vegetation and lack of dispersal sources (Guariguata, 2005c; Holl, 1999; Meli et al., 2017). However, my Paper I was very high-level and compared a multitude of interventions across different ecosystem types and with different end goal. Mapping out causes and effects for different restoration outcomes for instance through an effect-size approach (such as done by Crouzeilles et al., 2017) was impractical, and instead a broader meta-analytical approach was taken. Therefore, I was not able to come to absolute conclusion of effectiveness of active vs restoration interventions. Still, many restoration interventions generally showed mediocre success rates of most types of restoration assessed in Paper I, showing that the question of how to best restore TME is not finally resolved. Matching of restoration intervention with initial degradation stages is key for improving ecological restoration outcomes (Chazdon et al., 2021; Ghazoul & Chazdon, 2017; Shono et al., 2020). Hence, future studies could compare success rates of a prevalent intervention type (e.g., tree planting with native species) in a specific ecosystem type (e.g. cloud forest) across different stages of initial degradation (e.g. pasture site vs

agricultural fallow). This could provide a a quantitative understanding of the most effective suite of interventions for a given degradation scenario and help steer management interventions.

Priority 2 in Mathez-Stiefel's framework is to assess the *'Interactions between complex social and environmental dynamics in the Andean forest landscape'*. For this, an understanding of past and present landscape dynamics is needed and causes, drivers, and trajectories of forest ecosystem change across different spatial scales need to be investigated. In Paper II I attempted such a study of forest change dynamics across the tropical Andes with a specific focus on forest recovery trajectories. While previous studies have highlighted that structural complexity is a more appropriate metric than tree-cover related RS indices in measuring ecosystems functions (Camarretta et al., 2019), my Paper II was limited to tree-cover related datasets due to limited data availability and processing power. This led me to choosing a compromise solution combining tree cover data and the NDWI index. Many datasets on land cover or vegetation structure are not available pre 2010, or are at a low spatial and temporal resolution. Datasets that could be used to more holistically characterize forest recovery trajectories in future studies would be RADAR or LIDAR derived vegetation structure metrics (e.g. GEDI), hyperspectral data (e.g. Sentinel) and high resolution land cover datasets (e.g. WorldView).

Like Mathez-Stiefel et al (2017) mention in this priority point 2, understanding the drivers and causes of these changing forest dynamics is key and for this robust information on the spatial and temporal land use change and cover patterns is needed.. I hypothesized the likely causes of several forest recovery trajectories (such as encroachment for disrupted recovery, fires or agriculture for no recovery, and invasive species for arrested recovery), as it was merely impossible to do a causal study for these at the Andes-wide scale. Ideally, a casual study would have involved high resolution land cover datasets and fire datasets to detect preceding and surrounding land use patterns and disturbances, as well as socio-economic data to assess impacts of e.g. population density, migration patterns or human development index. Integrating datasets on these ecological and socio-economic

factrs could help identify where forest recovery is limited by biophysical or by man-made factors. Future studies could integrating remote sensing data wit in situ, but to date this has been mostly done on small spatial scales (Arasumani et al., 2020; Decuyper et al., 2022; Wilson & Coomes, 2019a).

Priority 6 is the *'Up- and out-scaling approaches for successful management practices from local to national and regional levels'*. My Paper II gives direction for large spatial prioritization of restoration opportunity hotspots, based on where historically different forest recovery trajectories have been observed. However, to ultimately allocate restoration interventions, many of the multidimensional considerations elucidates in Paper III need to be integrated. These include a clear understanding of the restoration motivations and objectives of the local stakeholders and a prioritization of restoration interventions according to these. For instance, if local communities are motivated by water scarcity, and aim to restore water provision and regulation, then spatial restoration prioritization needs to be done based on ctchment information and by considering local hydrology. Further, spatial prioritization needs to be interwoven with local scale data related to governance features, such as tenure structures, use right, resource management units and traditions. Ultimately integrating ecological and socio-economic metrics is key to determine trade-offs and locate restoration in a way to deliver restoration objectives (Budiharta et al., 2016). My data from Paper II can at best serve as a general assessment of the 'status quo' of forest recovery trajectories to date, and as an action call to act on these sobering trends of unsuccessful and disrupted forest recovery across the Andes. Mathez-Stiefel et al's (2017) action calls to *'conduct research on Andean Forest landscape that is scalable'* is still urgent, and the integration of different disciplines and data layers will be key to effectively plan and manage these landscapes sustainably.

Paper III targeted a range of research priorities across Systems, Target and Transformation knowledge defined by Mathez-Stiefel et al (2019), and in doing so presented a comprehensive picture of motivations, preferences, solutions and priorities for Andean Forest restoration.

One of the system knowledge priorities in the research agenda is to *'Characterize the relationship between the structure and functioning of Andean forest ecosystems and their contribution to hydrological and other key ecosystem services'*. Paper III gave an ecosystem service perspective of Andean forest restoration, where stakeholder motivations for forest restoration were found to be strongly linked to hydrological services, as previously observed in community forest restoration initiatives in Ecuador (Wilson et al., 2019). While all stakeholder groups unanimously agreed on the direct effect of Andean forest restoration on water provision and regulation, there are very few studies in the Andes establishing a clear empirical link between reforestation with native trees and downstream hydrological benefits. Some studies, largely derived from comparisons across different land use types (Bonnesoeur et al., 2019) hint at a potential benefit of native species reforestation for the water provision and regulation of water flows in the dry season, but no empirical studies in the High Andean context have compared pre and post restoration intervention. Often different sustainable management interventions were mixed with forest restoration so that it is different to disentangle the de facto effect of the forest restoration. So it is still unknown, how long it will take for hydrological services to be restored following reforestation with native species – likely it will be in the time frame of decades. My Paper III characterized the perceived effect of forest on ecosystem services in a qualitative manner through interviews. It was difficult to disentangle to what extent these relationships between forest restoration and water were actually directly experienced by the interviewees, or whether the perception of this relationship were influenced and modulated by capacity building workshops and trainings by the managing institutions. Future research could empirically and quantitatively investigate the latitudinal development of hydrological ecosystem through time. This will be especially useful for determining the extent and speed of ecosystem service restoration to feed into payment for ecosystem service mechanisms.

Priority 3 of Mathez-Stiefel's agenda highlights a need to understand the *"The relationships among ecosystem services, livelihoods, and the effectiveness of forestry and agroforestry practices"*. Paper

III provided some insights into this by characterizing direct and indirect livelihood benefits of the forest restoration. Many of the indirect benefits were mediated by a strong links between ecosystem services (especially water, fuel provision, erosion control) and livelihoods, in that long-term benefits resulted from an improvement of ecosystem services related to the project. I further qualitatively found that project with a 'capacity' approach tended to create more indirect and long-term benefits and to be more effective and self-sufficient over the time scale of decades. This resonates with findings by previous scholars that decentralized models of FLR tend to be more successful (Erbaugh & Oldekop, 2018). Erbaugh's and Oldekomp's framework provided a crucial guide to characterize different livelihood, well-being and resilience benefits. However, our results were strongly biased towards the mention of livelihood benefits, with only few participants speaking about negative consequences. This lack of focus on failures and trade-offs has previously been already acknowledged (Erbaugh & Oldekop, 2018). Negative outcomes of restoration (i.e. declines in livelihoods or negative impacts) are for instance employment security, loss of use/land rights, reduced income and consumption, violence, leakage such as displaced logging (Erbaugh & Oldekop, 2018). The main negative outcome mentioned by interviewees in Paper III was loss of agricultural land and opportunity costs. This may be due to the snow balling approach employed in our study meaning that we interviewed a chain of largely optimistic interviewees in favour of the restoration projects, and who enjoyed being involved in the process. To assess defacto outcomes of restoration future studies could include rigorous counterfactuals e.g., compare outcomes between areas with and without forest restoration and also include more contentious cases such as restoration following mining. Similarly, longitudinal studies could monitor households and communities before, during and after projects to assess the development of outcomes through time, as previously suggested (Erbaugh & Oldekop, 2018).

Target knowledge priority 4 states the *'need to develop, in conjunction with place- and non- place-based stakeholders, a joint vision that can guide policy, practices, and planning strategies in a*

rapidly changing context.' My Paper III addressed this priority in many ways, by including both place-based (local communities, conservation agents) and non-placed based (national government agencies) stakeholders and by identifying future preferences and visions together with them. The aggregated vision was framed in the mountain landscape approach and uses parallels to the principles of FLR, as well as the central findings of my own study. One key limitation however was a bias towards certain stakeholder groups, especially male stakeholders. While I was able to interview over 45 community members, and to organize interviews in the indigenous language, I was only able to interview few women and marginalize groups due to practical and cultural reasons. Their perspective on restoration visions and goals is hence underrepresented in my study, and future studies aiming to define sustainability goals will need to make special reference to the perspectives of women, and other marginalized groups (Mathez-Stiefel et al., 2017). Moreover, future studies could use the equity dimension framework by Löfqvist et al (2021) to structure qualitative research on the impacts of restoration interventions on equity, and on the role of equity for restoration success.

The results in Paper III presented a multitude of socio-economic, institutional and technical barriers for restoration success, which also addressed Priority 7 of *'Identifying the main potentials, bottlenecks, and enabling institutional conditions for restoration by critically reviewing, through a multistakeholder participatory process, existing initiatives in the region.'* Many of the bottlenecks identified, namely agree with previous studies in Latin America and the Andean countries (Aguiar et al., 2021; Hartman & Cleveland, 2018; Joseph et al., 2021; Lebel et al., 2006). These enabling and limiting factors are highly complex and interlinked and there are likely many feedbacks and loops defining where to best intervene to improve restoration success. My Paper III mainly provided a relative assessment of the importance of different enabling and limiting conditions but did not focus on the interlinkages and relationships between these factors. Future studies could conduct a

full mapping of the relationships e.g. through participatory mapping approaches. This could then help identify critical interventions and lever points to improve conditions for restoration.

Mathez-Stiefel et al (2017) based their Research priorities framework on the fact that Andean Forest Landscapes are complex socio-ecological systems whereby external social, economic and environmental settings and dynamics impact the AFL system in which different actors, governance systems and resource systems and units interact and set conditions for the creation of action situations that can improve livelihood systems. Central to this idea is the importance of different actors and stakeholders in shaping action situations. Like identified in my Paper III, these actors can have different perceptions on what motivates restoration, and what drives Andean forest restoration outcomes and success. Interdisciplinary approaches which focus on both knowledge production and creation of interventions are needed to fully disentangle the links and interactions between actors and create actionable, sustainable interventions (Mathez-Stiefel et al 2017). Different actions by the relevant stakeholders across science, policy and practice will be needed to drive positive change in Andean forest restoration practices.

Based on the empirical findings and the knowledge gaps identified in this thesis, I have developed a multi-disciplinary 10-point agenda for the science and practice of AF restoration. This agenda is meant to provide a set of recommendations more specifically targeted to Andean forest restoration, and to recommend interdisciplinary actions that go beyond the academic world.

A 10-point agenda with recommendations for the science and practice of Andean Forest restoration

Across the chapters I identified several overarching points for discussion on the science and practice of TME restoration. In Chapter 2 (Paper I) overall research priorities for the science of TME restoration were highlighted. In Chapter 3 and 4 (Paper II and III), a series of priorities and

directions for both the science and practice of restoration of Andean Forests emerged. I summarize these priorities into ten discussion points (Fig. 5.3) and design a 10-point agenda for restoration science and practice which is intended to direct the future restoration of Andean Forests towards an effective, holistic, science-led, long-term, and equitable endeavour. The agenda is based on the premise that Andean Forests are part of a complex socio-ecological system requiring interdisciplinary and people-centred solutions to catalyze change (Mathez-Stiefel et al 2017). The agenda items are linked with the equity dimensions according to Löfqvist et al (2021), as well as one immediate recommendation for restoration science (**RecS**) and one key recommendation for restoration practice or policy (**RecP**).

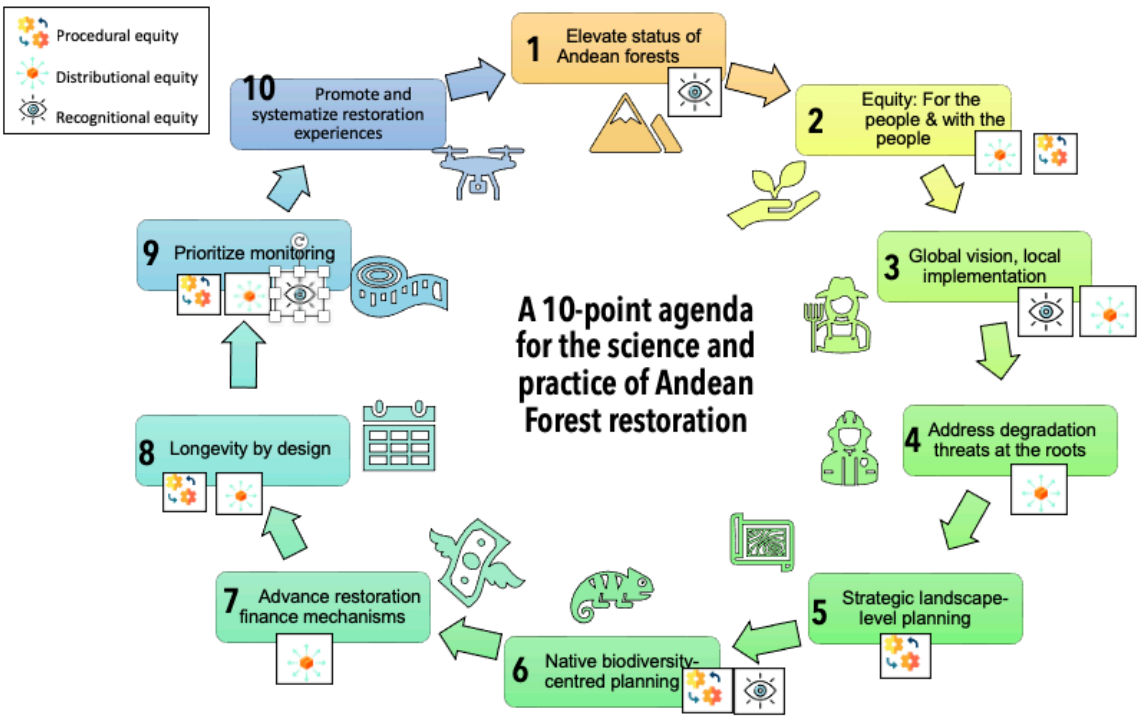


Figure 5. 3: A 10-point agenda for the science and practice of the restoration of Andean Forests including the relevance of the three equity dimensions for each agenda item.

1. Elevate the status of Andean Forests

So far there has been comparatively little international interest for the Andes as the restoration discourse in South America is still strongly focused on the lowland forests and on restoration

interventions that create large carbon gains. For instance, a simple google scholar search hit for 'forest restoration Andes' shows 48,000 research vs 107,000 hits for 'forest restoration Amazon'.

Relatively few scientists in Peru, for instance, specialize on the Andean Ecosystem. Andean Forests are rarely seen as a biome worth studying and investing in and as a result, to date disproportionately little resources – whether scientific, practical, or financial – are funnelled towards the science and practice of conservation and restoration of Andean Forest. The perception of there being relatively more international than national interest in Andean forest was highlighted by a by a government agent "*The climate resources are focused on the Amazon, but are not looking at the Andes. Because of the [high] forest cover and so on. In this Peruvian case, more researchers from abroad are studying [Andean forests] than from our own universities.*"

The lack of Andean forest research focus has also previously been lamented in the scientific community (Mathez-Stiefel et al., 2017). Andean Forests are valuable ecosystems in their own right – and valuable amongst other things for water, livelihoods and biodiversity. Elevating the status of Andean Forests is as much a scientific challenge as it is a societal one and will require ongoing emphasis on the importance of Andean Forests for the global and local community. Luckily, some Pan-Andean initiatives such as the terminated multi-national Programa Bosques Andinos have recently paved the path to more international interest for Andean forests, and emerging initiatives such as the NGO Acción Andina now aim to unleash the potential of Andean-wide Forest restoration by mobilizing resources and bringing relevant actors together. Still, there are some urgent recommendations to elevate the status of Andean forests nationally and internationally.

RecS 1.1: Make a concerted effort to systematize on the lessons learned on Andean Forest restoration across the mountain range and share restoration experience on an international stage.

RecP 1.2: Underline the importance of Andean Forests for livelihoods and ecosystem services across South America and on a national level.

2. Equity: for the people, with the people

Equity must be central to restoration planning and implementation (Elias et al., 2021; Leach et al., 2018; Löfqvist et al., 2022; Ota et al., 2020). My Paper III has shown the importance of social and institutional considerations related to recognitional, procedural and distributional equity for the long-term success of restoration.

In my fieldwork in the Andes, I found that stakeholders value Andean Forests for their provisioning and regulating services, that restoration objectives were largely social, and that restoration projects were considered successful when they achieved socio-economic outcomes besides ecological outcomes. This contrasted with what I found in Chapter 2 (Paper I) where I used a literature review. The literature review showed a prevalence of ecological objectives and ecological success factors. This showed that many of the established methods in restoration science (mainly experimental restoration set ups, greenhouse experiments and chrono-sequences) lack a comprehensive socio-ecological view and hence miss out on elucidating a variety of highly crucial non-biophysical factors which become relevant beyond the plot scale. Chapter 4 (Paper III) took a broader scale and multi-stakeholder approach and showed the prevalent focus of local stakeholders of restoring forests for instrumental reasons specially to provide invaluable hydrological services to communities. Common challenges identified in my Paper III were strongly people-centred align with barriers identified in previous forest restoration studies in Latin-America (Aguiar et al., 2021). The identified barriers and success factors were strongly tied to distributional and procedural equity, namely promoting environmental education and awareness, providing tangible benefits to communities, securing land tenure and conservation agreements, and creating stable leadership and governing institutions. Hence, any restoration intervention that strives to be successful in the long term needs to be done in a manner to benefit communities. To this end active engagement and

participation of communities in all planning and implementation phases is key and from the outset of a project procedural equity must be actively promoted. Wherever possible it is advisable to follow a 'capacity-model' which seeks to promote holistic capacity building through environmental education, forest stewardship and provide multi-dimensional long-term benefits to communities and key stakeholders. Restoration in the High Andes must balance different stakeholders' needs, be people-centric and particularly consider community motivations, preferences and perceptions. This resonates with the 10 people centred rules for ecosystem restoration which highlight the importance to make ecosystem restoration a people-centred endeavour where livelihoods and equity are at the forefront (Elias et al., 2021). To promote sustainable and equitable forest restoration in the Andes meaningfully involving all key actors is crucial. Only by recognizing and involving the voices of all involved actors, and especially marginalized groups affected by restoration, can recognitional and procedural equity be achieved and restoration success guaranteed (Elias et al., 2021; Ota et al., 2020; Robinson et al., 2021).

RecS 2.1: Carry out science which engages and involves local stakeholders to determine how to best enable people-centred restoration.

RecP 2.2: Design and implement Andean Forest restoration with a people-centric mindset and by involving, consulting and harnessing participation of local communities during key project stages.

3. Global vision, local implementation

While there is an overwhelming global policy drive to restore ecosystems for carbon and biodiversity in this UN Decade on Restoration, there is still a need to implement restoration according to very local and contextual requirements. A fine balance needs to be found which mobilizes and leverages the global support and enthusiasm for restoration, and associated funding mechanisms, while making restoration fit for local context to provide local benefits. This agenda point ties to both recognitional and procedural equity.

Chapter 2 (Paper I) found that the global science of TME restoration is prominently focused on ecological restoration objectives, namely restoring forest cover and structure and biodiversity, and using small scale ecological research design. Hence, it largely focuses on biophysical factors which enable and hinder restoration achieving these objectives. Prominent limiting factors were bioclimatic limitations and seed dispersal, while the most mentioned promoting factors were facilitation through vegetation and tailored site-management strategies. Globally, TME Restoration science is hence more concerned with investigating which species need to be planted and which restoration interventions provides the best ecological outcomes. Locally however, TME restoration needs to consider socio-economic and institutional factors to the same extent as biophysical factors. Despite many of the visited restoration projects from Paper III bearing fruits – both ecologically and socially – there are still some challenges to successful long-term restoration, related to land tenure, mistrust, creation of alternative livelihoods and longevity of projects. An elaboration of guidelines for participatory and inclusive local restoration of Andean Forests could help address these issues by laying out criteria for equitable and just restoration in an Andean context and presenting best-practices, such as some of the capacity-model projects identified in Paper III (See figure 5.3).

RecS 3.1: Study trade-offs between global restoration goals, local benefits , and design solutions and elaborate criteria for best-practice equitable restoration in the Andes.

RecP 3.2: Harness global funding and support while designing local restoration with contextual livelihoods foci.

4. Address threats and disturbances at the roots

Paper II showed that natural regeneration by itself is not sufficient at large to restore Andean Forests. Many disturbances, ranging from fire, grazing, selective logging and climate change, led to disruptive recovery trajectories in recovering forests, and deforestation and land clearing is ongoing (Armenteras et al., 2011). Hence, any kind of restoration project needs to simultaneously address the causes of forest conversion and disturbance right at the root, and for this needs to consider distributional equity.

There are a variety of approaches which detail how forest ecosystems can be conserved and how disturbances and deforestation can be avoided and minimized. These include the creation of communal or government protected areas and reserves, fire prevention and management workshops, provision of alternative fuel sources, improved agriculture and livestock methods requiring less land, helping communities adapt to global change and climate change, environmental education and capacity building to instil valuation of Andean Forests (Paper III). Going forward, addressing the root causes of Andean Forest destruction and degradation will ensure that local communities have the resources and the support to be stewards for intact and restored forests.

RecS 4.1: Investigate the most effective and socially just ways of minimizing threats to mature and regrowing Andean Forests.

RecP 4.2: Incentivize and promote the protection of Andean Forests through national policies and locally tailored approaches.

5. Strategic landscape-level planning

Andean Forest restoration needs to be strategically allocated, zoned and prioritized in the context of the diverse high Andean landscape mosaic. A national-level prioritization and opportunity assessment could be useful to spatially direct restoration interventions to check the multiple goals of water provision and biodiversity benefits, while also being achievable with limited resources. Such a prioritization study needs to consider procedural equity of all relevant stakeholders and could draw on some of the factors identified in this study.

These include allocating restoration where natural regeneration is unsuccessful (disrupted and arrested recovery areas from Paper II), prioritizing locations adjacent to headwaters in the uplands and streams, and creating a zonation based on existing ecosystems, local land tenure and proximity to communities. A basis for such a prioritization was sketched in the mountain-landscape restoration approach in Paper III. For instance, priority will need to be given to upstream areas of high hydrological value, as well as to areas that could connect biodiversity corridors. Such a prioritization could draw on a combination of forest recovery trajectories, satellite-derived high resolution land use maps, GIS maps of landscape features and cadastre data. Landscape level restoration planning will need to be done at a mountain landscape and regional scale, using data on topography, hydrology, current and past land use, land tenure and socio-economic variables. Moreover, a strategic prioritization exercise must be accompanied by ongoing stakeholder participation.

While this thesis strongly focuses on forested ecosystems – many of the other TME deserve stronger scientific attention and this also stands out in the Andes. In Paper I, I highlighted the need to research grassland and wetland restoration. The data from Paper III also showed that various stakeholders have a willingness to restore grasslands, however many informal discussions with conservation practitioners showed that, thus far, there are very few projects aiming at restoring non-forested high-altitude ecosystems, and that the socio-economic context of the High Andean

grassland ecosystems is distinct from that of montane forests. There are still many lessons to be learned for effective grassland restoration. A future avenue for research would be to elucidate the socio-economic processes by which grassland restoration can be improved and upscaled, as well as developing technologies to aid the planning, implementation of grassland restoration which to date are very scarce.

RecS 5.1: Assess the potential, cost and opportunity for Andean Forest restoration for key regions in the Tropical Andes.

RecP 5.2: Create a national prioritization for Andean Forest Restoration.

6. Native biodiversity-centred planning

Many high Andean tree species such as *Polylepis* spp. are threatened due to habitat loss, overexploitation, and climate change. At the same time, large governmental planting programs reaching up to 3500m asl focus on plantations of exotic species, such as *Pinus patula* and *P. radiata* to generate revenue, halt erosion, provide wood and associated pine derived products such as the Pine mushroom. As shown in previous literature (Bonnesoeur et al., 2019) and in the stakeholder interviews, these monoculture plantations have negative consequences for the hydrological cycle due to their high-water consumption, their low biodiversity value and detrimental effects for soil fertility. Exotic plantations do not provide the water provision benefits and direct benefits which were desired by local communities. The focus of Andean Forest restoration hence needs to be on native tree species and prioritize species which are of high habitat value for fauna and other associated flora, as well as species which help retain water in the uplands. Further native biodiversity centred planning needs to make use of native species which provide direct benefits to communities, such as medicinal components, fruits, and other uses.

Andean Forest restoration in the upper montane forest has a strong species-focus on *Polylepis spp* – the species with the highest elevational growth (Fig. 5.4). One main problem is that *Polylepis spp*.

are dominantly propagated asexually using vegetative cuttings and stakes resulting in genetic cloning of trees across the landscape and with potentially associated challenges of resilience. Sexual propagation of *Polylepis* spp. is so far unviable and more research will need to be done on making this method scalable. Further, many interviewees mentioned a range of other native tree species which could be grown at mid to high elevations (3000-4000m asl) such as highlighted in Paper III. However, to date, propagation protocols for these species are underdeveloped and role model projects which use these species do not exist.

Selecting and growing the right kind of species needs to involve procedural equity and recognitional equity dimensions, whereby stakeholders work together to identify the locally idela biodiversity resources.

RecS 6.1: Study the propagation of a range of threatened and understudied high Andean tree species and devise restoration protocols.

RecP 6.2: Incentivize the planting of native Andean species and disincentivize exotic plantations in areas of biological and hydrological importance.

7. Financing restoration in the Andes

Financial means for Andean Forest restoration are still low and the bulk of projects I visited relied on development funds or private donations managed by NGOs or on government funding allocated to protected areas. There are a variety of funding mechanisms which could provide finances to upscale Andean Forest restoration which were used by some restoration projects, and which are growing across the Andes. These include longer term conservation funds from international development programs which tend to be used by NGO actors (for instance the HELVETAS project CODESAN from the Swiss Development agency which led to the creation of the multi-national Programa Bosques Andinos), and payments for ecosystem services specifically hydrological services schemes which tend to be used in government-led restoration projects (MERESEH

schemes). Carbon offsets are, to date, used infrequently – likely due to the slow growth of montane tree species resulting in little carbon accumulation in the first 10 years. However, in the longer term, recovering Andean Forests do store substantial amounts of carbon, reaching almost half the carbon stocks of tropical forests after 30 years (Gilroy et al., 2014). Interviewees pointed out a potential for carbon markets in the future. Further, given the importance of Andean Forests for biodiversity and water provision, a hybrid offsetting and payment-for-ecosystem services scheme which integrates carbon, biodiversity and water goals could be a viable finance model going forward which needs to be explored. It is paramount that these financing schemes consider distributional equity of financial benefits.

RecS 7.1: Investigate a financing scheme that includes carbon, water and biodiversity and guarantees distributional equity.

RecP 7.2: Leverage payment for ecosystem services schemes and create strategic alliances to involve key actors of natural resource use in such schemes.

8. Longevity by design

With Andean Forests Restoration being a slow process due to biophysical limitations (Aragón et al., 2021), restoration projects and restoration science needs to be multi-decadal. Hence, project design needs to be long-term and have a socio-economic vision that extends beyond the planting phases, and to do so incorporating procedural and distributional equity concerns is key. Previous studies in the tropics have shown that a series of social and governance factors affect longevity and persistence of forest restoration (Nerfa et al., 2021). To achieve longevity, it is imperative to maintain ongoing engagement with local communities and create long-term governance institutions for stewardship and responsibility. Long-term governance structures include the creation of local forestry committees and the designation of restoration sites as community reserves or sustainable use reserves. Further, as shown in Paper III, concerted education efforts with schools and children

to increase awareness of Andean Forest ecosystem services are needed to ensure future generations have pluralistic motivations to engage in, maintain and promote restoration. In line with previous restoration research in the Andes on socio-economic factors that facilitate restoration management (Hartman & Cleveland, 2018), Paper III showed that the creation of long-term benefits and incentives which outlast the implementation stages are crucial, such as the instigation of improved agricultural practices and alternative income streams which reduce reliance on land and avoid re-clearance of restoration sites down the line.

RecS 8.1: Set up research projects with a long-term vision e.g., through research networks and collaboration and study the socio-economic factors that help achieve restoration longevity in an Andean Forest context.

RecP 8.2: Design restoration projects with mechanisms to outlast the project timeframe and create suitable institutions and governance mechanisms as well as compensation mechanisms that remain viable following project termination.

9. Monitoring

During both my fieldwork and my desk-based research (Paper I and II), I discovered that long-term monitoring of restoration in TME beyond the initial plant establishment phase of 2-5 years is rare. I further encountered this issue of lack of monitoring when searching for field validation sites for my Paper II. I reached out to various institutions and scientific networks who confirmed they had no long-term restoration sites with field measurements that would be useful for pixel-based validation. This difficulty was also confirmed during fieldwork for Paper III – there was no long-term, on-the ground monitoring of most projects (max 1 monitoring season 1-5 years post planting), and the projects were very small scale (often less than 1ha) in difficult and steep locations. Further, monitoring of socio-economic outcomes was scarce. However, this is necessary to determine to what extent procedural, recognitional and distributional equity was achieved, and socio-economic

indicators can be included in the monitoring of forest landscape restoration outcomes, along side forest ecosystem function indicators (Erbaugh & Oldekop, 2018).

Mostly, simple vegetation structure indicators such as plant survival and plant height are measured for 1-3 years post intervention, however growth success, biodiversity and ecosystem function at a decadal stage were never measured. Hence, it is not known whether key stone species, such as seed dispersing birds or mammals did return, and whether the restored ecosystem achieved a similar function to a reference system. The lack of regular and long-term monitoring inhibits the application of maintenance and corrective measurements, such as removal of weeds and invasive species at later stages of development. In some of the restoration sites, this lack of maintenance was particularly visible with restored seedlings overgrown by early succession shrubs. Scientists, NGOs, and government stakeholders uniformly lamented a lack of resources. Monitoring of hydrological flows following restoration with native species is even less studied (Bonnesoeur et al., 2019) and could yield interesting results for science and practice. For instance, investigating which native species best regulate water flows and ensure improved water provision is a key research priority.

Remote sensing technologies provide opportunities to facilitate monitoring and planning, but still come with many challenges associated with cost, spatial and temporal resolution, and need for thorough training for application. Often, simple methods such as visual monitoring using Google Earth observations or aerial imagery of restoration sites were used to monitor restoration progress in the sites I visited. Few of the restoration agencies make use of more sophisticated and automated technologies for planning and monitoring – mostly due to lack of technical capacity. Only in Aquia did the NGO ECOAN use drone flights to count survival of *Polylepis* seedlings. The potential for use of technologies for restoration monitoring is increasing especially with newer higher resolution datasets, products, and sensors (Camarretta et al., 2019; Robinson et al., 2022), e.g., cheaper drone technologies, Planet satellite data at a 5m resolution and WorldView land use datasets at a 10m

resolution, which can detect dynamics at a sub-stand level. The method to monitor forest recovery trajectories presented in Chapter 3 (Paper II) can be adapted and used at a project scale using more recent and higher scale remote sensing products.

RecS 9.1a: Investigate the most effective use and practicality of technologies and approaches for long-term and large-scale monitoring of Andean Forest restoration.

RecS 9.1b: Research which native species best contribute to local water availability and hydrological control during restoration interventions.

RecP 9.2: Allocate a substantial amount of project resources and focus to the monitoring stage.

10. Promote and systematize restoration experiences.

Restoration projects in the Andes often have little visibility and are conducted by several actors, often with competing interests (Cerrón Macha et al., 2018; Murcia et al., 2017). Hence, experiences of on the ground restoration projects are not organized in centralized databases, are not publicly shared and are subsequently hard to find. This scarcity of synthesis and organization of restoration projects hindered finding suitable validation sites for Paper II and finding project sites to visit for Paper III. Only once I was in the field, talking face to face to restoration practitioners and planners, did the world of Andean Forest Restoration open itself up to me. Via internet research I had only identified four suitable restoration projects to be visited in the region of interest, but during interviews and meetings I heard about many more restoration sites, particularly those run by government agencies which were not widely advertised and showcased. In the end I managed to visit eleven restoration projects and covered a broader range of restoration experiences and stakeholders which was only feasible due to 'project snowballing' in the field.

To tackle the challenges of disjunct and hard to locate restoration projects, there is a need for a concerted effort to systematize and gather restoration experiences. This could be done by creating a Pan-Andean database of Ecosystem restoration locations to be used for future research and to learn from existing experience. This database should include a range of restorative interventions along the restoration spectrum (including natural regeneration, active restoration, FLR, agroforestry etc) in all prominent Andean Ecosystems and as such also involve Andean grasslands and peatlands. Beyond geographic data and contacts, such a database could also include additional information of key motivations, preferences, outcomes, and success factors of each entered project as well as contact details and further readings. It is crucial to elevate case study knowledge along global approaches to bring to light some of the successful initiatives and share their stories, success factors and how challenges can be overcome (Löfqvist et al., 2022).

RecS 10.1: Create a Pan-Andean Forest restoration database and network.

RecP 10.2: Incentivize and motivate restoration stakeholders to share experiences and lessons learnt through a centralized approach.



Figure 5. 4: A Polylepis restoration site near the Aquia community in Ancash (Peru) where seedlings grown from vegetative cuttings on aerial layers were planted in 2007 on steep rocky slopes. The trees now form dense stands with heights between 2 and 4 m.

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