Disrupted montane forest recovery hinders biodiversity conservation in the tropical Andes

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RESEARCH ARTICLE

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Disrupted montane forest recovery hinders biodiversity conservation in the tropical Andes

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Abstract

Aim: Andean montane forests are biodiversity hotspots and large carbon stores and they 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 that have experienced a forest transition between 2000 and 2005. Then, we use Landsat time series analysis of the normalized difference water index (NDWI) to classify four "realized recovery" trajectories ("ongoing", "arrested", "disrupted" and "no recovery") based on a sequential pattern of 5-yearly *Z*-score anomalies for 2005–2020. We compare these results against an analysis of change in tree cover to validate against other datasets.

Results: Across the tropical Andes, we detected a potential recovery area of 274 km^2 over the period. Despite increases in tree cover, most areas of the Andes remained in early successional 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 might 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 restoration, forest transition, Google Earth Engine, Landsat time series, natural regeneration, NDWI, tropical montane forest

1 | INTRODUCTION

Recovering degraded forest ecosystems is a global priority in this UN Decade on Restoration. Andean tropical montane forests (ATMFs) 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, owing 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.

ATMFs 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). Furthermore, fires in ATMFs release substantial carbon emissions from burning biomass (Oliveras, Anderson, et al., 2014; Oliveras, Malhi, et al., 2014).

Andean countries have pledged restoration commitments in the last decade and have started national restoration programmes in order 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. In this study, we use satellite remote sensing to identify areas of potential forest recovery in the tropical Andes and monitor subsequent forest recovery over a 15-year period to detect recovery trajectories and areas presenting restoration opportunities.

The factors driving tropical montane forest (TMF) decline in specific areas of the Andes are well explored, from smallholder 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 after degradation of TMF are not well understood to date (Christmann & Oliveras Menor, 2021).

In the last two decades, large areas of land have been abandoned in the Andes owing to rural- to-urban migration, an increase in the remittance economy, 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), in addition to creating opportunities for active forest restoration and afforestation (Knoke et al., 2014).

In areas where anthropogenic land use has decreased, forest recovery can 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., 2010; Chazdon, 2003; Holl, 2002). Forest recovery trajectories, in our study defined as the sequential pattern of forest recovery through time, are often nonlinear 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 geographical locations and 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 progresses steadily towards secondary forests (Figure 1a) either through active restoration (Günter et al., 2009) or through passive recovery (Davies et al., 2020; Palomeque et al., 2017); (2) "disrupted recovery" (Figure 1b), in which 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, such as wind throws or landslides; (3) "arrested recovery", owing to ecological inhibitors (Figure 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", owing to harsh abiotic conditions or biological constraints limiting recruitment and establishment or later occurring land-use changes (Figures 1d).

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-elevation 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 & Aide, 2011). In the right ecological and social conditions, it can create resilient ecosystems that store large amounts of carbon (Cook-Patton et al., 2020).

However, natural regeneration is not always possible because it is strongly influenced by land-use legacies, ecological conditions on

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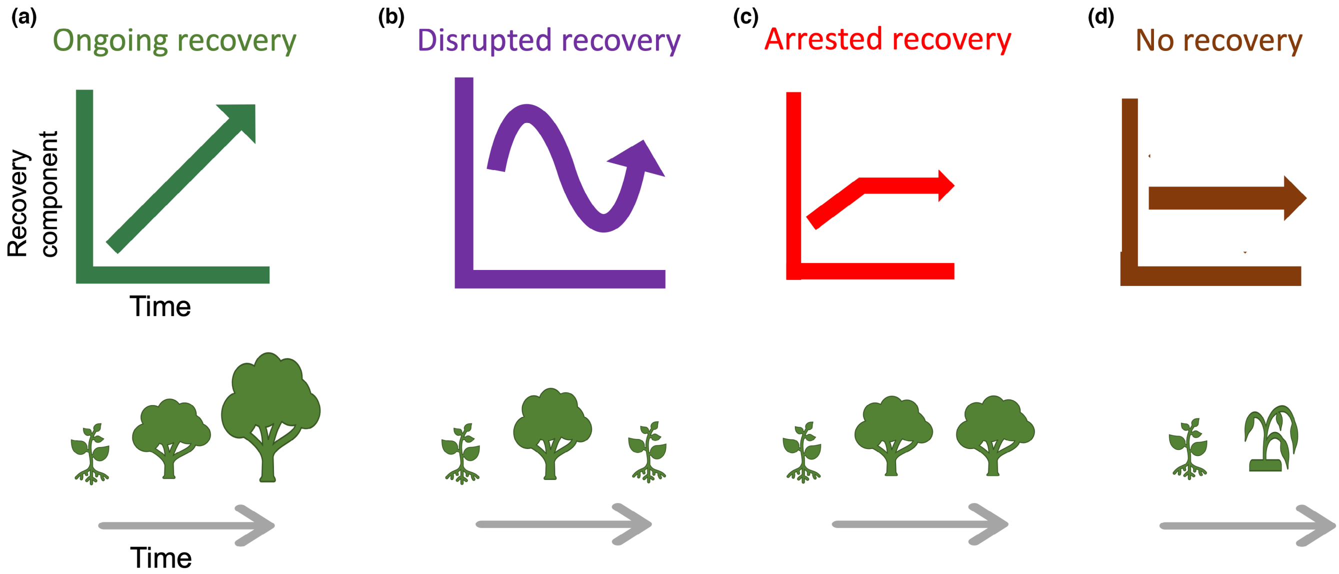

FIGURE 1 Conceptual framework for four possible forest recovery trajectories in the Andes. The *x*-axis represents time and the *y*-axis a recovery component (e.g., vegetation structure, biodiversity and ecosystem function). a) represents the trajectory of 'ongoing recovery', b) 'disrupted recovery', c) 'arrested recovery' and d) 'no recovery'.

site and the landscape context (Aide et al., 2010; 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 cleared recently 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 used heavily and where microclimate, soil or topographical conditions are unfavourable. In these conditions, forests can experience "arrested succession" (Rojas-Botero et al., 2020; Sarmiento, 1997; Sarmiento et al., 2015), whereby an ecosystem is trapped in a resilient degraded state and does not progress to mature forest stages (Aide et al., 2010).

For restoration to be effective, it is crucial to identify areas where forests can recover naturally and where they cannot, in order to inform restoration planning strategically. This practical knowledge can elucidate how to allocate management and resources optimally to maximize 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 time-scale 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 protection of regenerating trees and woody species from disturbance, planting seedlings, direct seeding, soil improvements, enrichment planting, and management of invasive and competitor species (Christmann & 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 ATMFs, 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; Liu, 2016; Liu et al., 2019; Van Leeuwen, 2008).

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 (Sanchez-Cuervo & Aide, 2013; Sánchez-Cuervo et al., 2012). 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 means to monitor forest recovery trajectories over several decades (Decuyper et al., 2022; Meroni et al., 2017), which is the period within which ATMF recovery usually occurs (Aragón et al., 2021; Oliveras et al., 2018). The high spatial resolution (30 m) of Landsat enables us to capture adequately the recovery trends of the heterogeneous and mosaicked ATMFs, 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 (Van 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 Andean scale.

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 based to monitor forest recovery trajectories for 15 years. This information will help to 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 change in tree cover, forest recovery trajectory classes and normalized difference water index (NDWI)] manifest in the potential recovery areas for the period 2005–2020?
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)?

2 | METHODS

2.1 | 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 3500 m a.s.l. (Figure 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 <30%, because the accuracy of remotely sensed products and indices is drastically reduced on steep slopes owing to geometric distortions and shadows (Weiss & Walsh, 2009). Hence, our estimates are likely to be 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) (Figure 2 and Supplementary 1). These sites have distinct histories of degradation and land abandonment, such as a combination of agricultural, pastoral or fire legacies. They span various subtypes of ATMF (Supporting Information Supplementary S1) and have all been studied previously (Aguilar-Garavito et al., 2021; Oliveras et al., 2018; Wilson & Coomes, 2019; Wilson & Rhemtulla, 2016). We consulted local ecologists, conservation managers and the authors of previous studies to evaluate whether our recovery trajectory method provide an accurate represention of the forest recovery patterns in these landscapes.

2.2 | Detecting potential recovery areas

We identified potential areas for forest recovery (hereafter "potential recovery areas") as areas that had undergone an initial tree cover transition between 2000 and 2005, before monitoring "realized forest recovery" for the subsequent period, 2005–2020 (Figure 3a). We identified these using the "Tree Cover Multi-Year Global" (Table 1) dataset from Global Forest Cover Change (hereafter "GFCC") as pixels that had <10% tree cover in 2000 (i.e., <10% tree cover in an area is commonly considered to be unforested; Putz & Redford, 2010), which had increased by 2005 to >20% tree cover (i.e., early succession) and thus showed a substantial initial forest transition, such as that following land abandonment. We chose 20% as a threshold to ensure that the change was substantial and not within the variability and uncertainty of the dataset. Furthermore, the pixel had to remain >20% in 2010 and 2015, in order to exclude pixels that were under a fallow agriculture regime and continuously re-cleared for agriculture or other anthropic purposes. Potential recovery areas therefore include any kind of forest transitions following non-forest land uses, such as pasture, logging and agricultural field abandonment, in addition to abandonment of settlements, urban and industrial, or mining/extraction areas. Potential recovery areas do not include abandoned plantations or agroforestry systems because 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 v.1.2.1335.

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 seven bands (Table 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 Tropical rainfall measuring mission (TRMM) data (NASA, 2021) by creating a mosaic for the driest month across the

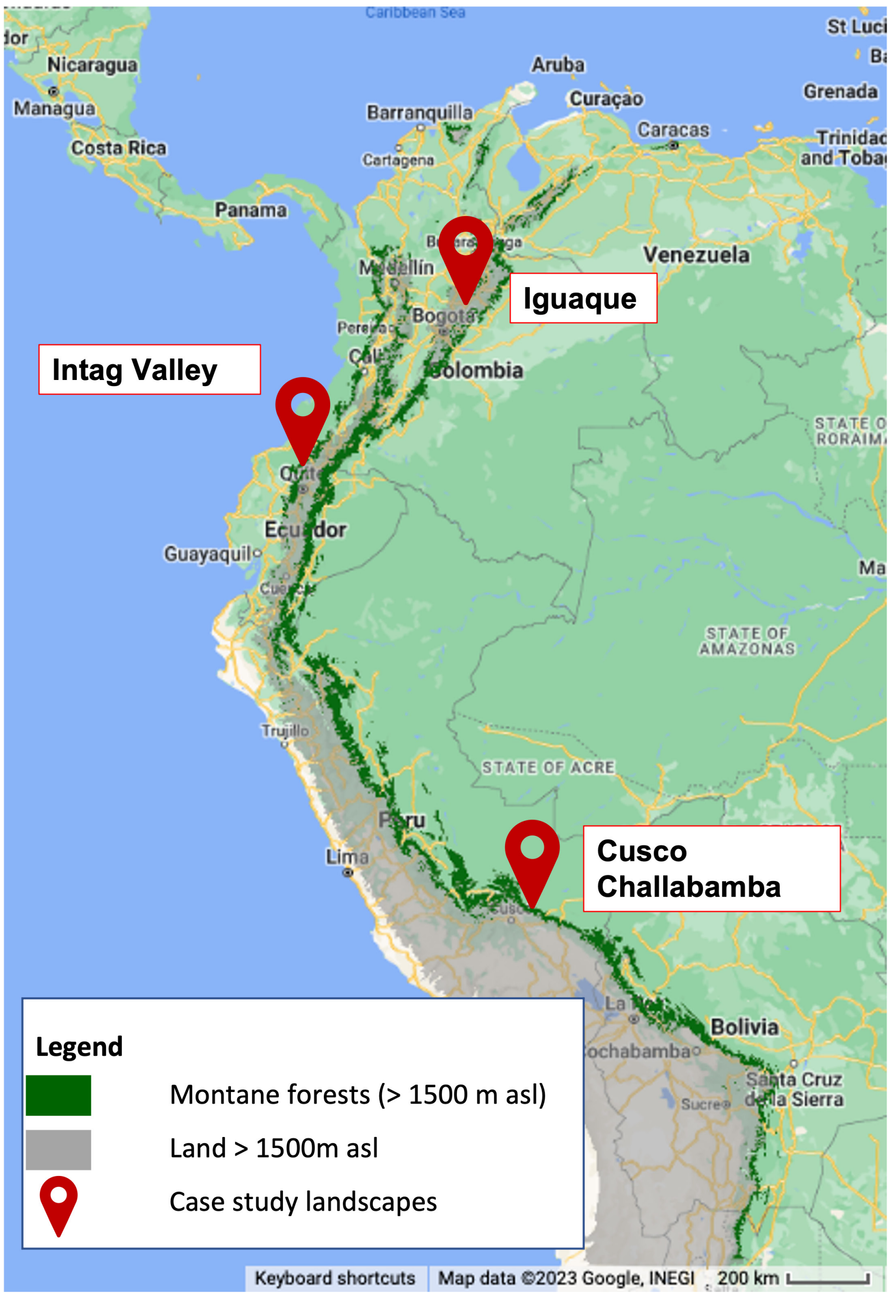

FIGURE 2 Extent of study and location of case study landscapes.

period 2000–2020 for each pixel (Figure 3b). In this way, we generated one image of the most cloud-free month per year and obtained an image collection with a total of 20 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 (Enhanced Vegetation Index - EVI, Normalized Difference Vegetation Index - NDVI, Difference vegetation index - DVI, Relative vegetation index - RVI, Modified Soil Adjusted Vegetation Index 2 - MSAVI2 and Normalized Difference Water Index - NDWI; Xue & Su, 2017). Information of the use of these indices for forest recovery monitoring can be found in the Supporting Information (Supplementary S2).

2.3.1 | 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 (Supporting Information Supplementary S4–S7); and (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 (Supporting Information Supplementary S8).

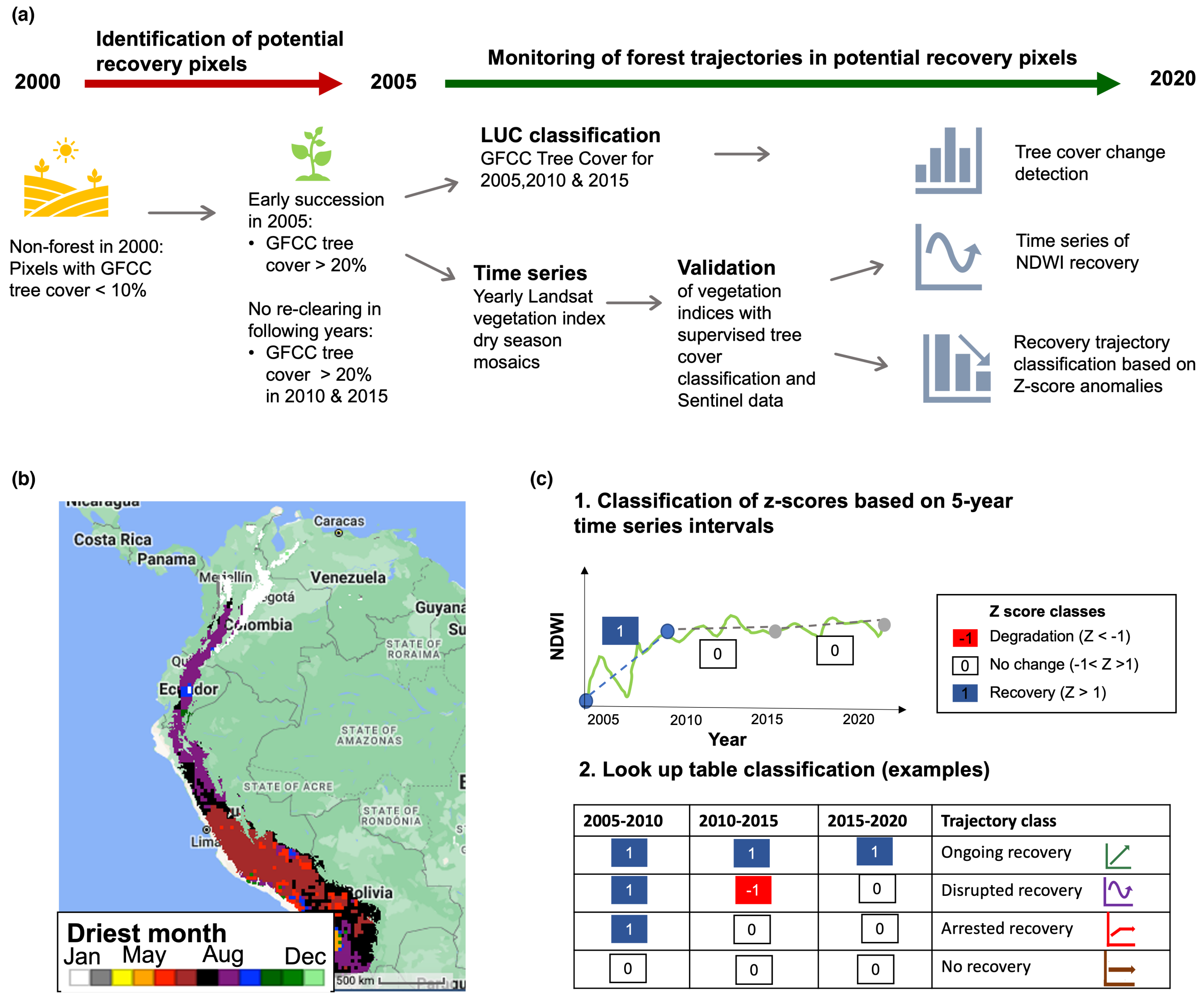

FIGURE 3 Specification of methods for forest trajectory analysis. (a) Workflow to identify potential recovery areas and monitor forest trajectories using tree cover classifications and vegetation indices (Supplementary 2). (b) Driest months in each pixel based on Tropical rainfall measuring mission (TRMM) data. This is the month used for creation of driest month mosaics of Landsat data. (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 the sequence of *Z*-scores. The complete look-up table can be found in the Supporting Information (Supplementary S3).

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's ρ in capturing the successional stages (Supporting Information Supplementary S7); (2) it showed a good fit with the higher-resolution Sentinel data (Supporting Information Supplementary S8); (3) NDWI is sensitive to water absorption and canopy structure and therefore a good index to track structural changes during vegetation recovery owing to the inclusion of SWIR bands (Liu, 2016); and (4) although NDWI is correlated with NDVI, NDWI does not saturate as quickly and allows us to track more variation in environments with denser vegetation 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) and to map drought effects on temperate forest (Wang et al., 2007).

NDWI is calculated as follows:

$$\mathrm{NDWI} = \frac{\mathrm{NIR} - \mathrm{SWIR}}{\mathrm{NIR} + \mathrm{SWIR}} \quad (1)$$

Our validation was done using supervised classification based on 894 points visually classified using Google Earth high-resolution images in one case study landscape (Supporting Information Supplementary S6). 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 validate our method directly 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

TABLE 1 Specification of data sources and sensors.

Sensor or product	Spatial resolution	Specification	Years	Bands
Landsat 7 ETM surface reflectance	30m	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	30m	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	30m	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	30m	Landsat vegetation continuous fields	2000, 2005, 2010, 2015	Tree canopy cover percentage (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	27,830m	Monthly precipitation estimates	For each month between 2000 and 2020	Precipitation (in millimetres per hour)

in the last decade and often lack regular and long-term monitoring (Murcia et al., 2017).

2.3.2 | 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, because forest recovery tends to show nonlinear temporal patterns (Decuyper et al., 2022). We computed aggregated mean time series for the six tropical Andean countries and for five elevation belts of 500 m width between 1500 and 3500 m a.s.l.

We extracted tree cover values from the GFCC dataset for the time steps 2005, 2010 and 2015 for all pixels in the potential recovery classes (the dataset terminates in 2015). We grouped the tree cover into five tree cover classes (0–10, 10–25, 25–50, 50–75 and 75–100%) and assessed changes in tree cover 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 the beginning of forest recovery (Figure 3a,c). *Z*-scores are useful for this purpose because they provide a standardized and relative measure of change accounting for variability and noise of a given pixel and can help to 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 the *Z*-score as the difference between the NDWI value of the last and first image of the 5-year time interval and dividing it by the standard deviation of the residuals for each year of the given time interval (for calculation of the *Z*-score for an exemplary period of 2005–2010, see Equation 2).

$$Z - \text{score}_{2005-2010} = \frac{X_{2010} - X_{2005}}{\text{SD}_{(\text{res2006},\text{res2007},\text{res2008},\text{res2009},\text{res2010})}} \tag{2}$$

Residuals for each year were calculated as the difference between the observed and predicted NDWI value (Equation 3, example for residuals for the year 2007).

$$\text{res}_{2007} = X_{2007} - \left(X_{2005} + 2 \times \frac{X_{2010} - X_{2005}}{5} \right) \tag{3}$$

We reclassified *Z*-scores for each time interval in three *Z*-score classes. A *Z*-score of greater than one or smaller than minus one 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; and 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 (Figure 3c; Supporting Information Supplementary S3). 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 that 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, because 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 showed either stagnation or negative *Z*-scores during all time steps) were classified as "no recovery". The class "no recovery" therefore includes cases of ongoing or repeated degradation and instances of no change (Supporting Information Supplementary S3).

3 | RESULTS

3.1 | 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 and 2020, forest recovery was slow and did not progress quickly to higher tree cover stages or high NDWI values (Figure 5a,b). NDWI increased steadily until 2010 before plateauing, a trend observed across different elevations and countries (Supporting Information Figure S9b, Supplementary S9). Lower elevations did not show higher NDWI values homogeneously across the Andes (Figure 6b; Supporting Information Supplementary S9a). For instance, in Ecuador and Bolivia the highest values were found in the potential recovery areas at 2500–3500 m a.s.l. (Supporting Information Supplementary S9a).

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), Ecuador 10% (29 km^2) and Venezuela 7% (20.1 km^2) and Argentina 2.3% (6.4 km^2) of all potential recovery areas (Figure 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% (Figure 5). Colombia, despite having the second largest extent of Andean forests, had the largest potential recovery area of 1% in relationship to its national Andean forest area. Peru had 0.5%, Ecuador 0.5%, Bolivia 0.3%, Venezuela 1.2% and Argentina and 0.6%.

About 71% of all potential recovery areas did not show "ongoing recovery" (Figure 4a). In all countries, "disrupted recovery" was the most frequent forest recovery trajectory, and the partitioning of recovery trajectories was broadly similar (Figure 4b–g). Colombia had one-quarter 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,

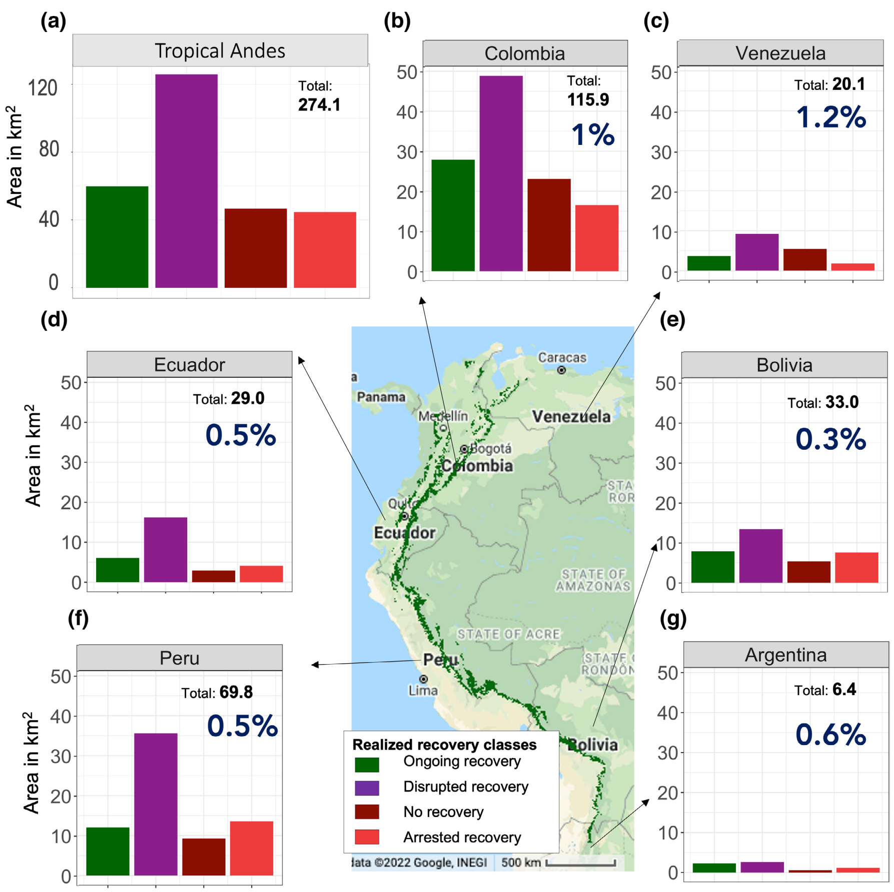

FIGURE 4 Realized recovery trajectories in abandoned land across the Andes (a) for the entire mountain range, and (b–g) by country. Percentages show the potential recovery area in relationship to Tropical Andean Forest area in each country. The central map shows the extent of Andean forests >1500 m a.s.l. 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.

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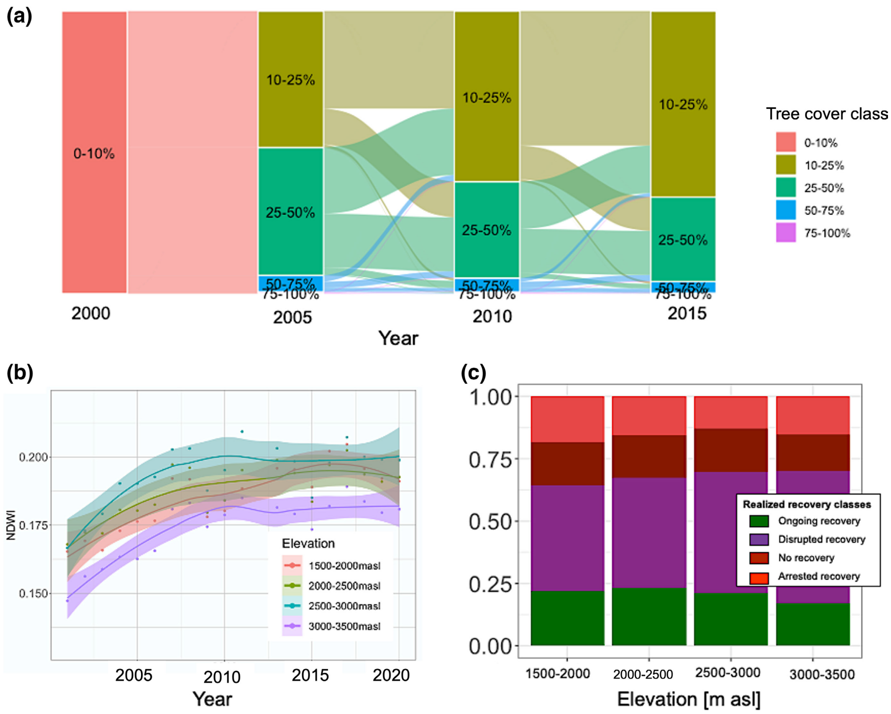

FIGURE 5 Forest recovery in potential recovery areas of 2000–2005 across the Andes. (a) Tree cover change from 2000 to 2015 (the dataset terminates in 2015). (b) Normalized difference water index (NDWI) mean time series in different elevation zones. (c) Realized recovery trajectories in different elevation zones.

but 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 >3000 m a.s.l. along with a decrease in "ongoing recovery" (Figure 5c).

The GFCC tree cover change analysis also corroborated these findings (Figure 5a). In 2005, half of all recovery pixels had advanced to medium tree cover classes of 25–50%, but by 2010 and 2015 much of this area reverted to low tree cover stages, with two-thirds of the potential recovery areas showing 10–25% tree cover.

In Ecuador, >50% of the potential recovery areas progressed to tree cover classes >25% by 2015, and only small proportions reverted to lower tree cover. In all other countries, most potential recovery areas stayed at <25% tree cover by 2005, and between 2010 and 2015 most of the 25–50% tree cover areas reverted to 10–25% tree cover (Supporting Information Supplementary S9b).

3.2 | Validation in three forest recovery landscapes

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

3.2.1 | Intag valley

In the Intag valley (Ecuador), mean NDWI increased over 20 years (Figure 6a). Ongoing forest recovery was the dominant trajectory (Figure 6c,d). Likewise, the tree cover analysis showed a steady increase towards higher successional classes in each time step, such that by 2020, 90% of areas were in either mid (25%–50%) or later succession (>50) stages (Figure 6b). Areas of ongoing recovery were distributed across the case study landscape, and watershed areas that had undergone community tree planting showed instances of successful ongoing recovery, such as the core area of the watershed reserve, El Paraíso (Figure 6d).

3.2.2 | Cusco—Challabamba

Surrounding Challabamba, north of Cusco (Peru), NDWI time series showed an initial decrease followed by a logistic increase, with highest NDWI values after 10–15 years since abandonment (Supporting Information Supplementary S10a). Tree cover trajectories showed an initial progression to early succession stages by 2005, followed by a reduction in mid succession classes and a reversion towards 10–25% tree cover in 2010 and 2015 (Supporting Information Supplementary S10b). Most areas showed "disrupted recovery" (Supporting Information Supplementary S10c), such as near forest clearings and quarries, or "arrested recovery" in pastures (Supporting Information Supplementary S10d).

3.2.3 | Iguaque

In Iguaque National Park (Colombia), mean NDWI time series showed slow recovery trends over the period of 15 years (Supporting Information Supplementary S11a). The majority of pixels were classified as "arrested recovery" and "no recovery" (Supporting Information Supplementary S11c), which were mostly located at the outskirts of the park, adjacent to roads and in proximity to pastures, while

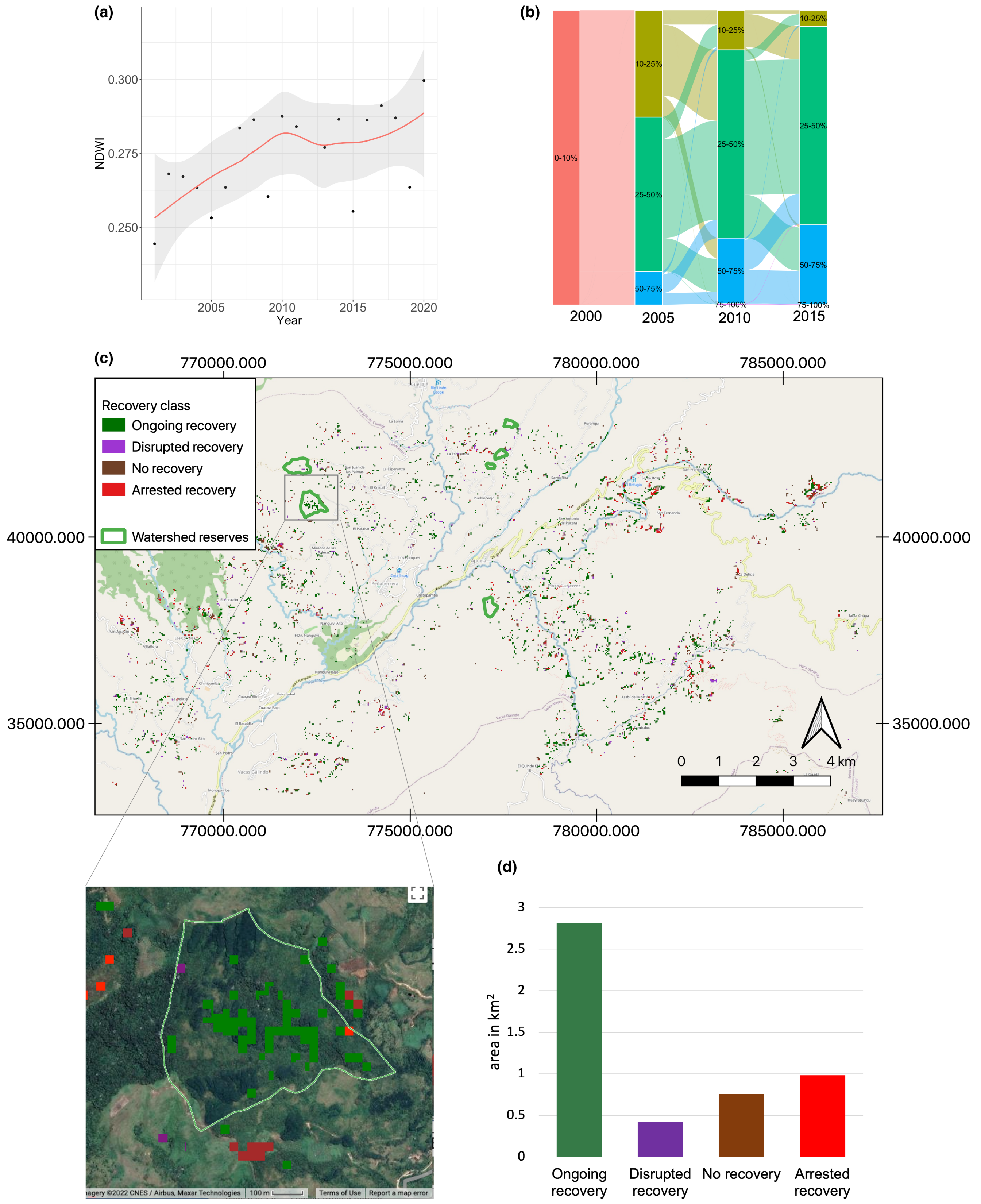

FIGURE 6 Forest recovery trajectories in the Intag valley (Ecuador). (a) Normalized difference water index (NDWI) time series in potential recovery classes. (b) Tree cover change in potential recovery areas. (c) Map of recovery trajectories across the landscape and zoom into the restored water shed reserve El Paraíso. (d) Area in each recovery trajectory class.

"ongoing recovery" areas were found nearby forests (Supporting Information Supplementary S11d). Areas that initially showed a rapid succession to 25–50% by 2005, often reverted later to lower succession classes (Supporting Information Supplementary S11b).

4 | 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 and 2020 and to corroborate findings from previous coarse-scale studies on Andean forest change dynamics (Aide et al., 2019; Graesser et al., 2015; Sanchez-Cuervo & Aide, 2013; Sánchez-Cuervo et al., 2012).

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.

4.1 | 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 to minimize cloud effects and geometric distortions, which are 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, in which early successional pioneer species should be superseded by later succession species, resulting in a mixed layer canopy with complex vegetation structure. Although tropical montane forests take several decades to recover biodiversity, biomass and vegetation structure fully following disturbances (Aragón et al., 2021; Oliveras, Malhi, et al., 2014; Trujillo-Miranda et al., 2018), yearly gaps in Landsat data coverage before 2000 did not allow us to extend this analysis reliably 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), whereas for areas 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 owing 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 practised 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). Furthermore, 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., 2010). In contrast, trajectories of "disrupted recovery" also occurred, probably owing to use and interaction of local inhabitants with the forest in the more accessible locations, 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 owing to use restrictions. "Ongoing recovery" areas are likely to be a cause of natural regeneration, because there were no reforestation efforts in Iguaque at the start of the century. We found mostly "arrested" or "no recovery" areas, 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 causing 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 probably inhibit forest recovery: invasive pasture grasses, such as 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). Furthermore, seed dispersal is limited owing 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 after wildfires and anthropogenic disturbance (Oliveras, Anderson, et al., 2014; Oliveras, Malhi, et al., 2014) and slow recovery of above-ground biomass after land abandonment of agroforestry systems (Aragón et al., 2021). It was concluded that Peruvian montane forests take >15 years to recover biomass after wildfires (Oliveras, Anderson, et al., 2014; Oliveras, Malhi, et al., 2014), a period extending beyond our study length.

4.2 | Recovery trends across the tropical Andes

Across the tropical Andes, an area of 274 km^2 made an initial forest transition between 2000 and 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 ATMFs 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 the initial vegetation gain manifests as "disrupted", "arrested" or "no recovery". This is probably attributable to the higher resolution of our study, better capturing smaller-scale patch dynamics compared with regional aggregation methods.

The disrupted recovery we observed is probably attributable to ecological factors interacting at different scales. At a continental level, forest recovery trajectories might be driven by extreme climate events, such as 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), which was a period that coincided with a low point of NDWI values in our time series.

Regionally, forest recovery depends strongly 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, Anderson, et al., 2014), changes in land use 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 attributable to recolonization of remote areas after 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 that 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 "no recovery" trajectory identified here (Holl et al., 2000; Scowcroft & Jeffrey, 1999). Also "disrupted recovery" could be caused by repeated disturbance in the system, such as fires set by pastoralists to manage grazing resources, which have been shown to have a significant impact on montane forests in Peru (Oliveras et al., 2018). Furthermore, low protection of recovering areas from livestock, owing to lack of fencing, is likely to cause "disrupted recovery" as regrowing seedlings are predated on. "Arrested recovery" of Andean forests has been detected extensively 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 owing to harsh edapho-climatic conditions (Guariguata, 2005) and competitive interactions with invasive species (Aide et al., 2010).

4.3 | 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 protection of 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 to 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 to identify reasons for low forest recovery and devise appropriate restoration methods.

Although 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 to be attributable 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 present 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 recovery (Chazdon et al., 2021). The first step is to determine which biophysical limitations and socio-economic 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 for natural regeneration (Chazdon et al., 2021), for instance, in topographically complex and fragmented mountain landscapes, where propagule sources are lacking owing 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 and shading seedlings from high solar radiation) and assisted natural regeneration techniques that blend active and passive approaches (fire protection, fencing from herbivores and 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 that 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 such as *Inga spp or Alnus acuminata* from the Fabaceae family can improve soil fertility and 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 introduction of agroforestry systems, creating incentives to allow forests to recover (payment for environmental service schemes and 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 crucial in potential areas for restoration.

4.4 | Avenues for further research

Further research could elucidate drivers and solutions for forest recovery. Owing 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 at a 10 m resolution could be used for this purpose. At present, however, this dataset dates only 7 years back and does not allow the construction of 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.

Although 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 such as tree-planting efforts need to be evaluated. Owing to the large extent of our study, we stuck to three 5-year time steps to provide a simple look-up table instead of deploying complicated methods, such as 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 (Cerrón Macha et al., 2018; Programa Bosques Andinos, 2021). Together with local- and regional-scale assessments of the biophysical and socio-economic factors limiting the success of forest restoration and comprehensive restoration feasibility studies, our analysis could help to steer efforts and tailor restoration strategies to areas where forest recovery is compromised.

5 | 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. Although 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 management 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 to locate priority regions for intervention. Many other highly biodiverse tropical mountain ranges, in addition to 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 codesigned with local mountain communities to deliver holistic restoration goals.

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AUTHOR CONTRIBUTIONS

T.C. and I.O.M. conceived the initial study design and developed methodology. Y.M. provided advice on calculations. T.C. led data analysis and wrote the first draft of the manuscript, with supervision by I.O.M. X.P., D.A. and S.W. provided local knowledge on recovery processes in the case study landscapes. All co-authors provided critical feedback at different stages of the analyses and contributed to manuscript writing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Mendeley Data at: 10.17632/4xr3b82689.1. https://data.mendeley.com/datasets/4xr3b82689/1

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