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Assessment of Potential Climate Change Impacts on Montane Forests in the Peruvian Andes: Implications for Conservation Prioritization

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Abstract: Future climate change will result in profound shifts in the distribution and abundance of biodiversity in the Tropical Andes, and poses a challenge to contemporary conservation planning in the region. However, currently it is not well understood where the impacts of climate disruption will be most severe and how conservation policy should respond. This study examines climate change impacts in the Peruvian Andes, with a specific focus on tropical montane forest ecosystems, which are particularly susceptible to climate change. Using an ensemble of classification models coupled with different climate change scenarios, we estimate high and low potential impacts on montane forest, by projecting which areas will become climatically unsuitable to support montane forest ecosystems by 2070. These projections are subsequently used to examine potential impacts on protected areas containing montane forest. The modeling output indicates that climate change will have a high potential impact on 58% of all montane forests, particularly in the elevation range between 800 and 1200 m.a.s.l. Furthermore, about 64% of montane forests located in protected areas will be exposed to high potential impact. These results highlight the need for Peru's conservation institutions to incorporate climate change considerations into prevailing conservation plans and adaptation strategies. To adjust to climate change, the adaptive capacity of forest ecosystems in the Peruvian Andes should be enhanced through restorative and preventive conservation measures such as improving forest functions and mitigating deforestation and forest degradation pressures.

Keywords: conservation planning; protected areas; cloud forests; species extinction; climate impact; ecological niche modeling



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1. Introduction

A growing body of literature points out that changing climate conditions will become a major threat to global biodiversity within the next 100 years [1–3]. Shifts in temperature and precipitation regimes at global and regional scales are expected to have profound impacts on the composition and stability of terrestrial ecosystems [4]. Climate-induced changes in the spatial distribution and extent of the world's major vegetation classes have already been observed [5]. As it appears, climate change is inevitable and increasing in magnitude over time [6]. Hence, its consideration in conservation planning is becoming critically important to ensure that long-term conservation goals can be achieved.

To improve conservation decision making, the discipline of Systematic Conservation Planning (SCP) has emerged, which aims to systematically identify representative, complementary and cost-effective priority areas for conservation to ensure the long-term

persistence of biodiversity [7]. Yet, there is uncertainty on how conservation planning should effectively anticipate the impacts of climate change. Thus far, only a limited number of studies have explicitly considered climate change in conservation prioritization assessments [8]. Most of them have accommodated the effects of climate change by prioritizing the future distribution of target species (e.g., [9,10]). Reserve selection algorithms are then used to design a comprehensive network of protected areas that safeguards the distribution of these species in the future. Albeit, range shift projections are surrounded by large uncertainties as they generally ignore species-specific traits that are linked to dispersal potential [11] and do not account for key biotic interactions such as predation and competition [12]. Additionally, location-specific dispersal barriers imposed by topographic gradients and landscape fragmentation are rarely addressed in biogeographic models [13]. These limitations of models to more accurately forecast where ecosystems and individual species will move as climate changes, poses a critical difficulty in conservation planning [14].

Alternatively, it could be argued that instead of projecting future ranges, it is more straightforward and robust to make predictions about where climate disruption could potentially lead to negative impacts within current distributional ranges [15]. In other words, it may be more straightforward to predict a change in climate suitability, rather than the impact thereof on the geographical distribution of biodiversity. This approach, however, may not enable conservation planners to prioritize cost-effective, representative and complementary protected area systems under future climate change. Nevertheless, it could advance our understanding as to where in the landscape the impact of climate change may be most severe, what its consequences for land use may be and where conservation actions may be necessary.

Assessing the impact of climate change is particularly important for regions where changing bioclimatic conditions will induce severe biodiversity loss and degradation, such as tropical mountain regions [16]. Particularly in these regions, many restricted range endemic species occur that may be unable to keep pace with rapidly changing climate conditions, which could ultimately lead to their extinction [17]. As noted by Jones, Watson, Possingham and Klein [8], research and investment prioritization should be allocated to species and ecosystems that are believed to be most vulnerable to climate change. This echoes the latest guidelines of the International Union for Conservation of Nature [18], which recommend the use of Species Distribution Models (SDMs) to define the Red List status of species highly vulnerable to climate change. Consequently, in areas severely threatened by climate change, where species and ecosystems with limited adaptive capacities occur, it might be necessary to look beyond traditional conservation planning principles as species representation, costs and complementarity, and prioritize conservation efforts in the long term for those species and ecosystems most likely to be affected by climate change.

Peru contains the fourth largest tropical forest coverage in the world, after Brazil, the Democratic Republic of Congo and Indonesia [19]. While much of the forest and deforestation-related research in Peru focuses on lowland Amazon ecosystems, some of the country's most important areas for biodiversity conservation are located within the Peruvian Andes forests [20]. These forests contain exceptional concentrations of endemic plants and vertebrate species, that are undergoing dramatic losses of native habitat [21]. A substantial portion of the Peruvian Andes forests is composed of tropical montane cloud forests [22], which are particularly rich in endemic flora and fauna [23]. Cloud forests are recognized as one of the world's terrestrial ecosystems most affected by climate change, due to their high sensitivity to rising temperatures and changes in precipitation and cloud distribution patterns [24,25]. Reductions in their spatial extent are already being observed [26,27], which emphasizes the significance of understanding climate-related forest change dynamics in the Peruvian Andes for conservation planning.

Previous studies from the Andes have examined species-specific responses to climate change based on species-based ecological niche modeling (SDMs). For instance, Mavárez

et al. [28] modeled the current ecological niche of 28 species of Espeletiinae (Asteraceae) in the Venezuelan Andes and estimated the future distributions of potential climatically suitable habitats for these species. While species-based approaches provide important insights for the long-term conservation of specific species, it is argued that ecosystem and biome-based modeling could be more informative for the identification and prioritization of areas where a broad range of ecological communities and habitats can be preserved in the anticipation of climate change [29]. For the Tropical Andes, a region-wide biome-based assessment was provided by Tovar et al. [30], showing to what extent climate could affect biome distribution and where conservation actions would be appropriate in the future.

Here, we develop an ecosystem-based modeling approach to examine where and to what extent a change in climatic conditions could impact montane forest ecosystems. Given their biodiversity significance and high sensitivity to climate change, we specifically focus on Peruvian Andes forest ecosystems. First, the distribution of potential climate change impacts on montane forest is examined, by projecting which areas will become climatically unsuitable to support this type of ecosystem by 2070. This is done, using an ensemble of climate change scenarios. This information is then used to examine potential impacts of climate change on montane forests within current protected areas. Finally, we explore the implications of our results for conservation planning in the Peruvian Andes, by linking our climate change projections to land use change scenarios.

2. Methods

A nationwide land cover layer produced by Peru's Ministry of the Environment [22] was used to identify high jungle humid/perhumid forests (in Spanish: bosque húmedo/perhúmedo -semisaturado) in the Peruvian Andes (hereafter montane forests) see Table 1 and Figure 1. The MINAM layer consists of 75 different land cover types and was produced based on Landsat 5 TM satellite imagery from 2011 at 30 m resolution, and complemented with high resolution RapidEye and Google Earth imagery. Eight land cover types correspond to montane forests, located between 800 and 3600 m.a.s.l., with a total extent of about 117,000 km², covering approximately 9.1% of Peru's national territory (Table 1). Using ArcGIS 10.1 [31], we aggregated Peru's ecosystems into four distinct land cover classes for later modeling purposes: (1) montane forest ecosystems, (2) anthropogenically disturbed areas, (3) water bodies, and (4) all other ecosystems.

Table 1. Montane forest ecosystems.

Spanish Name	English Name	Altitude (m.a.s.l.)	Area (km ²)	Area (%)
Bosque de terraza baja basimontano	Lower terrace forest	800–2000	31	0.002
Bosque de terraza alta basimontano	Upper terrace forest	800–2000	4	0.0003
Bosque inundable de palmeras basimontano	Floodplain palm forest	800–2000	49	0.004
Bosque de montaña basimontano	Lower montane forest	800–2000	76,503	5.95
Bosque de montaña basimontano con paca	Lower montane forest with bamboo	800–2000	1364	0.11
Bosque de montaña montano	Mid-montane forest	2000–3000	30,724	2.39
Bosque de palmeras de montaña montano	Mid-montane palm forest	2000–3000	137	0.01
Bosque de montaña altimontano	Upper montane forest	3000–3600	8318	0.65

Peruvian montane forest ecosystems are distributed along the eastern slopes and valleys of the Andean mountain range, located between coordinates 3°5'10 South, 79°1'15 West, 14°29'24 South and 68°49'37 West, and elevations ranging from 800 up to 3600 m.a.s.l. This natural region is locally known as the yungas or the selva alta [22].

2.1. Current Montane Forest Distribution Modeling

The WorldClim version 2.0 bioclimate dataset [32] at 30 arc second spatial resolution (equivalent to about 1 km² at the equator) for the period 1970–2000 was obtained to model the distribution of montane forests under current climate conditions. This dataset consists of 19 bioclimatic raster variables commonly used in species distribution modeling (see Supplementary Materials, Table S1). Furthermore, using the WorldClim along with

solar radiation data [33,34] and the “Envirem” R-package [35], we generated an additional dataset consisting of 16 alternative climate variables (hereafter referred to as the Envirem variables, see Supplementary Materials, Table S2). The use of these variables has proven to significantly improve ecological distribution modeling performance [35]. All 35 rasters were cropped to Peru’s national territory. Using a Pearson’s correlation matrix, we discarded highly correlated variables ($r > 0.8$). This resulted in a dataset of three WorldClim variables (mean annual temperature, isothermality and precipitation seasonality) and three Envirem variables (continentality, potential evapotranspiration seasonality and potential evapotranspiration of the wettest quarter of the year). These variables were used to train an ensemble of different classification models.

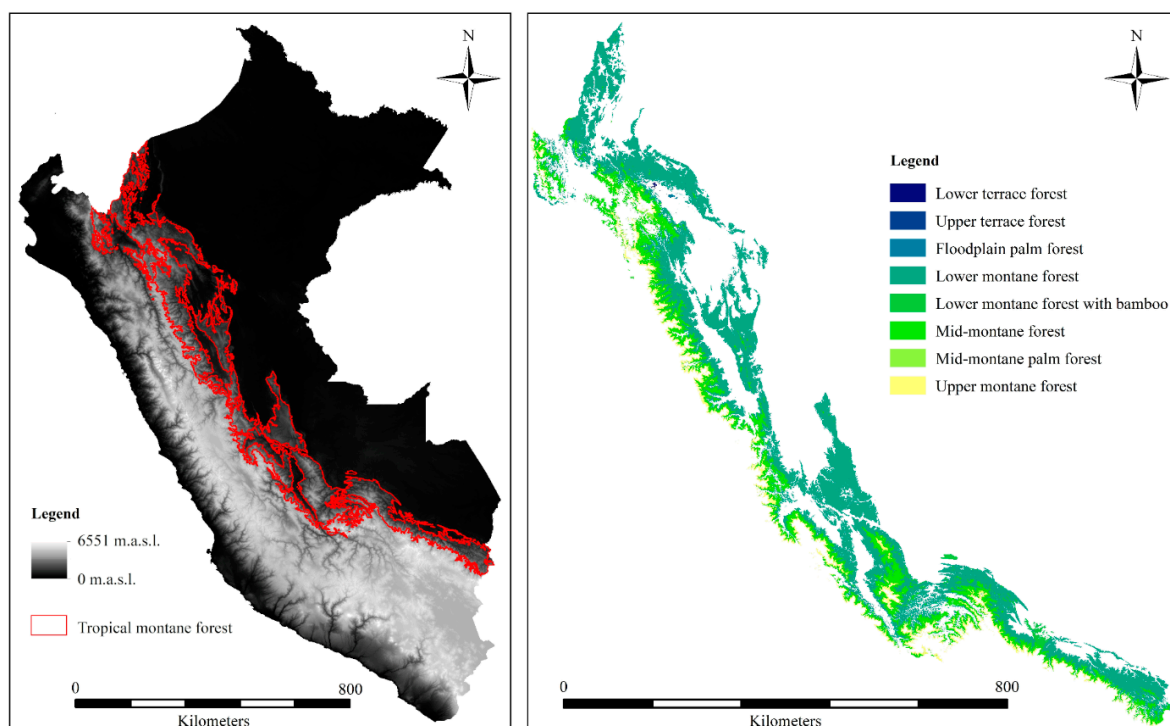


Figure 1. Left: Digital Elevation Model (DEM) with the distribution of tropical montane forests in Peru. Right: Distribution of the eight different forest types that correspond to tropical montane forest.

Ensemble forecasting has shown to reduce the uncertainties associated with individual statistical modeling procedures, by combining projections from multiple models into a single consensus forecast [36,37]. For this study, we selected five modeling techniques commonly applied in species distribution modeling: (1) Artificial Neural Networks (ANN; Ripley [38]), (2) Generalized Linear Models (GLM; McCullagh and Nelder [39]), (3) Boosted Regression Trees (BRT; Elith et al. [40]), (4) Random Forests (RF, Breiman [41]), and (5) Multivariate Adaptive Regression Splines (MARS, Friedman [42]). Training data was extracted based on Peru’s aggregated land cover layer, using a random sample of 10,000 data points corresponding to land cover class 1 (montane forest ecosystems) and 10,000 data points corresponding to land cover class 4 (other ecosystems) as the dependent variable, and corresponding climate data as the independent variables. The performance of each model was evaluated by means of a 10-fold cross validation using 30% of the training data [43]. We calculated the area under the curve (AUC) of the receiver operating characteristic (ROC) to estimate model accuracy. AUC ranges from 0 to 1, with values >0.9 indicating very good, values >0.8 indicating good and values >0.7 indicating acceptable modeling performance [44].

2.2. Potential Climate Change Impacts on Montane Forests in 2070

The fitted models were used to extrapolate the potential distribution of montane forests under projected climate change conditions to the year 2070. Following Ponce-Reyes et al. [45], we only examined which areas within the present distribution of montane forests remain climatically suitable to support montane forests in the future. This means that the potential formation of montane forest beyond its present distribution is not examined here, as this is a process that could potentially take several centuries [45,46] and is therefore considered beyond the temporal scope of this study. Moreover, it is assumed that tropical montane cloud forests are unable to expand their range beyond the tree line towards higher elevations [47].

We obtained spatial climate datasets for 2070 from WorldClim version 1.4 [48], and generated the Envirem variables for 2070 following the procedure described above. WorldClim provides downscaled and calibrated output from a range of General Circulation Models (GCMs) that have simulated the change in climate under four different greenhouse gas emission scenarios (referred to as representative concentration pathways; RCPs). These climate simulations were developed through the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. [49]), whose results were used in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change [50]. In this study we considered RCP8.5, which is believed to be the most realistic scenario for the middle-long term [6]. RCP8.5 assumes a business as usual scenario, where high population growth, low income growth and modest rates of technological innovation induce a prolonged increase of energy demands and greenhouse gas emissions [51]. To account for uncertainties and variability associated with climate simulations, we adopted a consensus approach. That is, we used future climate data from 17 GCMs available via WorldClim that correspond to RCP8.5 to predict the potential distribution of montane forests under climatic conditions in 2070. Consequently, based on the 5 classification models we fitted earlier and the climate data provided by the 17 GCMs, we generated 85 predictions of future montane forest distribution.

For the areas classified as montane forest in less than 50% of the predictions, we assumed a high potential impact of future climate change. Hence, the majority of the predictions indicate that these areas will become climatically unsuitable to support montane forest ecosystems by 2070. These areas were aggregated into a layer that defines where the impacts of future climate change on montane forests are projected to be high. On the other hand, low potential impacts were assumed for areas classified as montane forest in more than 50% of the predictions. The breaking point at 50% was based upon the “majority vote criterion” proposed by Araújo, et al. [52]. To explore the variability between the classification models and climate datasets used, we overlaid all predictions and mapped to what degree the distribution of montane forest was predicted consistently. All distribution modeling procedures were carried out using the R statistical software [53]. The approach followed to estimate the potential impact of climate change on montane forest and current protected areas (see following section) is displayed in Figure 2. An overview of the datasets used in this study is provided in the Supplementary Materials (Table S3).

2.3. Potential Climate Change Impacts on Montane Forests within Current Protected Areas

The layer that was developed to identify high potential impacts of future climate change on montane forests was subsequently used to examine the impact on montane forests within current protected areas. We considered national, regional and private protected areas, as they constitute Peru’s principal conservation areas, both in terms of surface area and biodiversity conservation [54]. Using spatial datasets of protected areas obtained from Peru’s Ministry of the Environment [55], we first calculated the current coverage of montane forests within protected areas. Subsequently, we calculated the extent of high potential impact within protected areas for 2070 (see Figure 2) and examined differences between protected area categories.

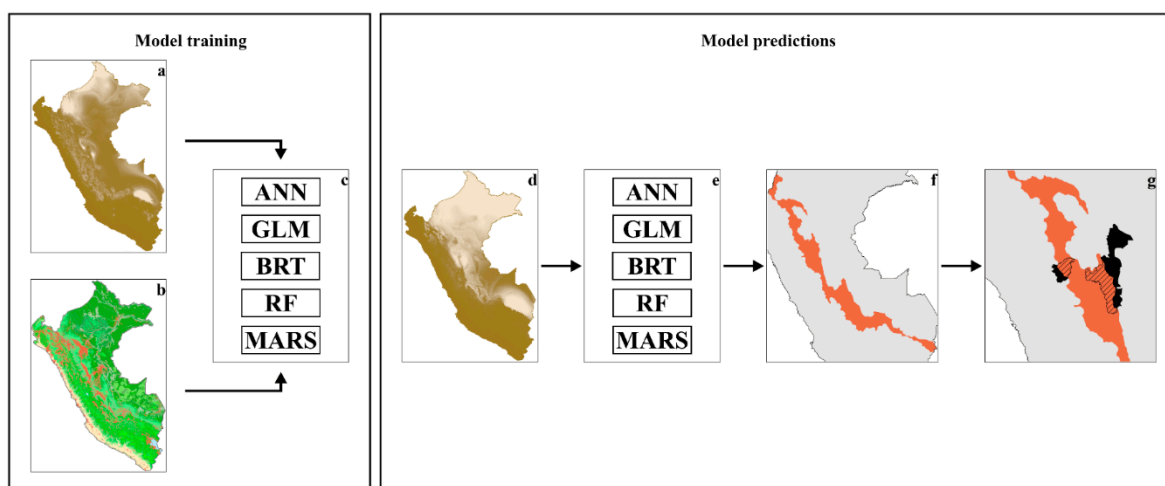


Figure 2. Flow diagram of the methodology employed to examine potential impacts of climate change on montane forests and protected areas. **Left:** Model training. Training data is extracted from current climate (a) and land cover datasets (b) to fit an ensemble of five classification models (c). **Right:** Model predictions. Future climate datasets derived from 17 GCMs (d) are used as input for the fitted classification models (e) to generate a consensus forecast of high potential climate change impact on montane forests in 2070 (indicated by the red area; (f)). Impacts on montane forests in protected areas (indicated by black polygons; (g)) are estimated by calculating the extent of high climate change impact within their current distribution (indicated by the shaded areas).

3. Results

3.1. Projected Climate Change Impacts on Montane Forest in 2070

The five classification models that were fitted to define the relation between the current distribution of montane forests and current climate conditions yielded AUC-values >0.70 , of which three models yielded AUC-values >0.85 (see Supplementary Materials, Table S4). This indicates good modeling performance and confirms the applicability of these models for projecting the distribution of climate suitability for montane forest ecosystems in future scenarios.

The outcomes of the modeling procedures to examine future climate suitability and potential climate change impacts are displayed in Figure 3. The areas highlighted in dark grey indicate climate conditions that are projected to remain suitable for montane forests in 2070 which, in turn, points to low potential climate change impact. In contrast, the areas highlighted in red indicate climate conditions that are projected to become unsuitable for montane forests, which in turn, points to high potential climate change impact. Consequently, the modeling outcomes point to an area of about 68,000 km² (which corresponds to 58% of all current montane forest areas), where the impacts of climate change are projected to be high. Out of this, 66,000 km² (~97%) corresponds to lower montane forests in the elevation range between 800 and 2000 m.a.s.l. These forests are mainly distributed along the eastern flank of the Peruvian Andes. For these areas, variability among modeling results is generally low (see Supplementary Materials, Figure S1), indicating a relatively high certainty of the predictions. Further, the model projections point to 900 km² (~3%) of mid-montane forest and 1300 km² (~16%) of upper montane forest areas, where climate conditions are projected to be no longer suitable to support these types of ecosystems in 2070. This implies that at mid to higher elevations, the impact of climate change on montane forests could be expected to be limited.

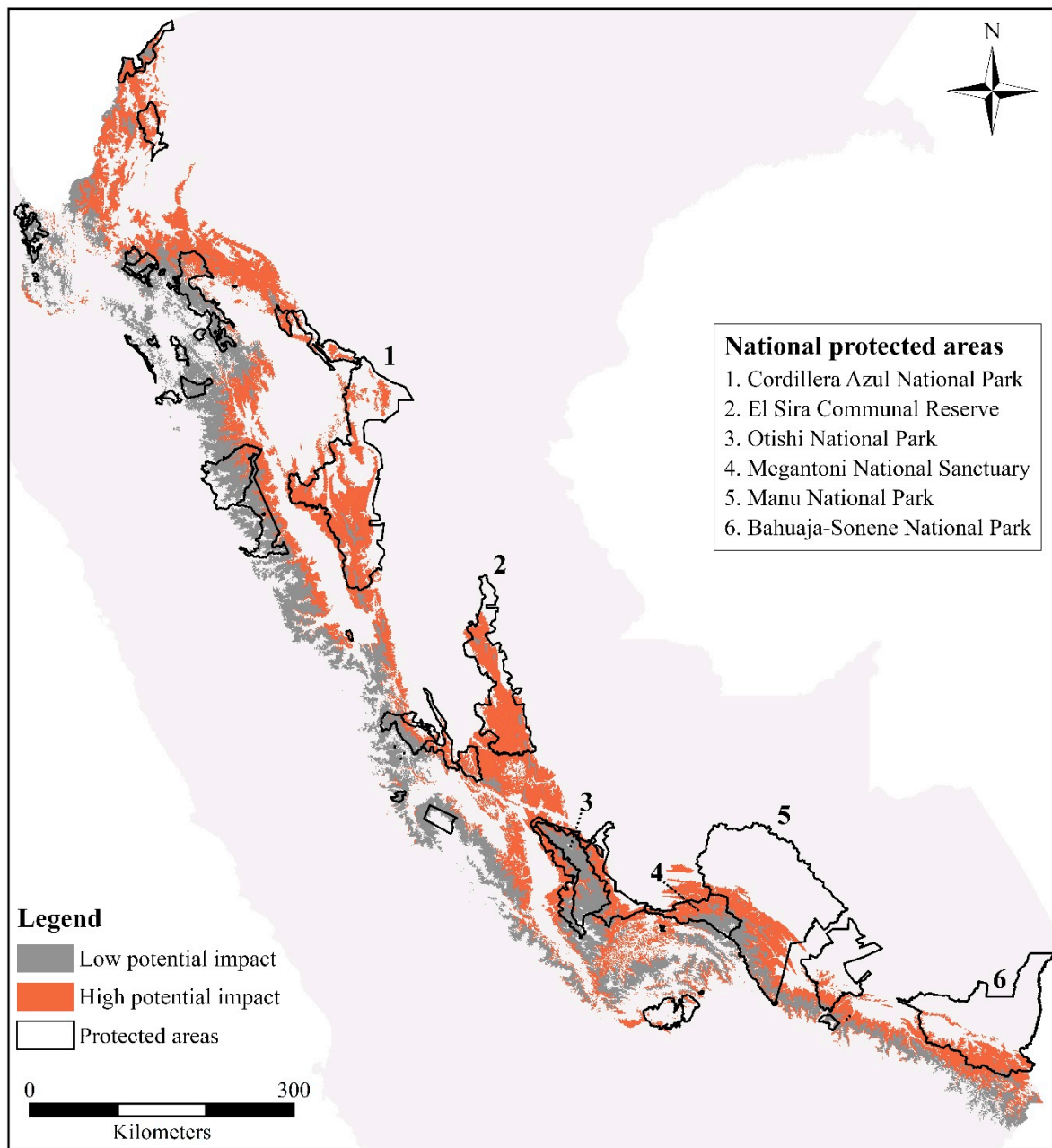


Figure 3. Potential climate change impact on Peruvian Andes forests in 2070, as a function of projected climate suitability. Projections were based upon a majority vote criterion, using the aggregated outcomes of 85 different models. Polygons in the figure indicate current national, regional and private protected areas. Numbers in the figure correspond to six national protected areas that in conjunction contain 62% of all currently protected montane forests in Peru.

3.2. Projected Climate Change Impacts on Protected Areas

We identified twenty-three national, five regional and thirty private protected areas that in conjunction provide coverage to 39,093 km² of montane forests, which corresponds to 33% of the total montane forest area (Figure 3). According to the model projections, about 25,042 km² (~64%) of all protected montane forests will be highly impacted by the future change in climate suitability. Striking differences in the projected impact of climate change can be observed between protected area categories. That is, the change in climate suitability and its associated impacts on montane forests are projected to be most extensive in national protected areas (~69%) and notably less extensive in regional (~33%) and private protected areas (~2%).

Nearly two-thirds (~62%) of all protected forests are contained within 6 large national protected areas, each of which contains more than 2000 km² of montane forests (Figure 3). The expected impacts of climate change will vary considerably among these areas. For instance, high projected impacts on montane forests within the Cordillera Azul National Park and the El Sira Communal Reserve correspond to about 95% of the area (6448 km² and 4026 km², respectively), while high projected impacts in the Otishi National Park correspond to <20% of the current area.

4. Discussion

This study has projected the climatic suitability for Peruvian Andes forest ecosystems under future climate change. The projected shift in suitable climatic conditions for these ecosystems implies a range of changes that may directly or indirectly impact montane forest biodiversity within the coming decades, including changes in rainfall patterns, reduced cloud formation, temperature increases and associated drought stress, compositional changes in current species assemblages and rising incidence of pests and plagues [56–58]. Our results suggest that in some places of the Peruvian Andes, future climate conditions will no longer be suitable to support rare montane forest ecosystems such as terrace forests and floodplain palm forests. The loss of floodplain palm forests would for instance imply that characteristic plant species such as those from the genus *Alchornea* would go locally extinct [22]. In more general terms, the ecological consequences of a changing climate will potentially be most severe along the Andean foothills. The disruption of climatic conditions, particularly those at elevations between 800 and 1500 m.a.s.l., tends to concur with high concentrations of threatened and endemic vascular plants and vertebrate species [59].

Biodiversity conservation in the Andes largely depends on national protected areas, with estimates indicating that between 70 and 80% of protected species are covered by protected areas at the national level [60]. The results of our models highlight potential impact of climate change on montane forest biodiversity within national protected areas in the Peruvian Andes. Most notable is that nearly all (~95%) of the montane forest ecosystems within Peru's Cordillera Azul National Park and El Sira Communal Reserve are projected to undergo severe climate-induced change. Rising temperatures will cause species with limited climate-adaptive capacities to migrate upslope towards higher elevations, where generally less land is available due to the natural geometric shape of mountains [61]. For instance, in the specific case of the El Sira Communal Reserve, empirical findings from Forero-Medina et al. [62] point to an upward shift in the range of Andean bird species due to gradual changes in temperature, habitat conditions and the availability of food resources. Given that climate conditions are becoming increasingly unsuitable to support species' montane forest habitats, and montane species have nowhere else to go but upwards, it will become more and more difficult for these species to find patches of suitable habitat that respond to their needs. Eventually this implies that several species in the El Sira Communal Reserve and the Cordillera Azul National Park could go extinct, unless they are able to adapt quickly enough to the change in climate and habitat conditions. These so-called "mountaintop extinctions" are becoming more common in the Peruvian Andes [63] and as a future environmental crisis, it is a subject that deserves greater attention in present conservation planning.

Beyond addressing the threat of species extinction, a pragmatic approach to achieve long-term conservation outcomes might be to focus on identifying and protecting biodiversity in those areas that have good chances to withstand climate-induced changes [15]. Our results show that climate change-resilient forests are predominantly located at higher elevations, as a consequence of the upward shift of climate suitability. These forests are, at the same time, increasingly threatened by human intervention. Peru's high altitude grasslands located above the tree-line (above approximately 3000–3500 m.a.s.l.) are extensively used for farming and other productive activities, which hinders the forest to naturally migrate towards higher areas through colonization and succession processes [47]. Furthermore, anthropogenic activities in these places may be causing the Peruvian Andes

tree-line to retreat downwards [25], with potentially detrimental effects on the underlying cloud forest ecosystems. On the other hand, the shift in climatic conditions as highlighted in our study is likely to displace forest extractive practices from low-lying areas towards higher locations. Ovalle-Rivera et al. [64] argue, for example, that temperature changes will push deforestation associated with the cultivation of coffee further upwards, as farmers will be forced to move their plantations to higher elevations. These synergistic changes in climate and land use point to a parallel up and downslope contraction of the already narrow distributional limits of montane forest ecosystems, which poses an evident challenge for their conservation in the future. Hence, under the dual threat of climate change and deforestation, conservation planners should take actions in areas that are resilient in terms of climate stressors but also vulnerable in the face human activities [65].

Unlike most conservation planning assessments, the aim of this study was not to propose a comprehensive protected area network for the Peruvian Andes. As shown by other studies [66–68], the development of cost-effective, representative and complementary protected area networks requires the incorporation of arguably infeasible amounts of land area, which emphasizes the need for prioritization [20]. Systematic conservation planning that includes future climate change scenarios brings along additional challenges, because it remains rather difficult to accurately forecast how species and ecosystems will respond to a changing climate. Alternatively, in this study we proposed an ecosystem-based modeling approach to identify areas where a change in the bioclimatic envelope could potentially affect montane forest. The outcomes presented here are intended to inform Peru's conservation policies and help prioritize conservation efforts and resources in the Peruvian Andes in the long run.

To explore the relevance of our results to inform conservation decisions, it is needed to reflect on some of the methodological limitations and uncertainties associated with climate change models such as the ones developed in our study. First, to fit our models we used downscaled WorldClim datasets, which are based on interpolated climate data from weather stations. It has been argued that WorldClim data may not reflect well the climate conditions in places where sparse weather station networks exist, as in the Andean forest region [69]. However, other authors have shown that WorldClim data concur closely with climate data from weather stations located near cloud forest ecosystems [70], which suggests these datasets are suitable for modeling Andean forest distributions. Second, to reduce uncertainties associated with future projections, we adopted a consensus approach using climate data from 17 GCMs available via WorldClim that correspond to RCP8.5. Some of the GCMs we used may not adequately represent future climatic conditions in our study area and it has been proposed to employ selection procedures through which the incorporation of the least plausible GCMs can be avoided [71]. Nevertheless, we decided to use all GCMs available to rule out any form of model selection bias and ensure we capture the maximum possible range of changes in future climate conditions. Finally, it should be noted that possible spatial autocorrelation in our data may have affected the performance of our models. Following the approach by Tovar, Arnillas, Cuesta and Buytaert [30] we randomly drew a data sample with an Euclidean distance of 3 km between individual data points, but it proved impossible to completely remove spatial autocorrelation. Meanwhile, we did our very best to decrease modeling uncertainty more generally, by using five different modeling techniques and by generating an additional set of climate variables to reduce the possibility of omitting relevant predictor variables, which is also known to be an important cause of spatial autocorrelation [72].

Scenarios for Conservation Prioritization under Future Climate Change

Here, we describe some the practical implications of our study for conservation planning in the Peruvian Andes. Our results point to an extensive area where future changes in climatic conditions could severely affect montane forests. The question remains how current and future conservation actions could adequately respond to these changing conditions. First, it is important to note that a shift in climatic conditions will not result in an

impact on forest cover per se. The capacity of trees and forest ecosystems to adjust to new climatic conditions has been associated with a range of evolutionary adaptive mechanisms at different hierarchical levels (from the individual to the species and community level), including acclimation and epigenetic responses, natural selection and local adaptation, succession and colonization and biotic interactions [73,74]. To what extent these processes take place depends on overall ecosystem functioning and, in turn, the degree of anthropogenic disturbance [75,76]. Consequently, to estimate climate-induced forest change scenarios and prioritize for conservation, understanding local human-forest interactions over the course of time is also required. With respect to the Peruvian Andes, the rapid development of economic activities in the last few decades has caused severe loss and degradation of natural forest ecosystems [77]. Changes in land use have primarily occurred at elevations below 1500 m.a.s.l., which is also where our model results show the most prominent changes in climate conditions. These destructive land use practices under a rapidly changing climate constitute a major threat to the fragile montane forest ecosystems within these places.

Peru's conservationists will thus be facing the challenge to identify and take actions in areas where we could expect changes in climate and land use to reinforce each other within the coming decades. To support conservation decision-making in light of future climate change in Peru's montane forest region and elsewhere, we operationalize two scenarios to illustrate when and what type of conservation measures are needed to improve forest ecosystem functioning and, in turn, better allow these ecosystems to adapt to changes in climatic conditions (Figure 4). For clarity, each scenario is presented and discussed separately, but in reality, a combination of the two scenarios is likely to exist. This will have implications for the design and implementation of conservation measures.

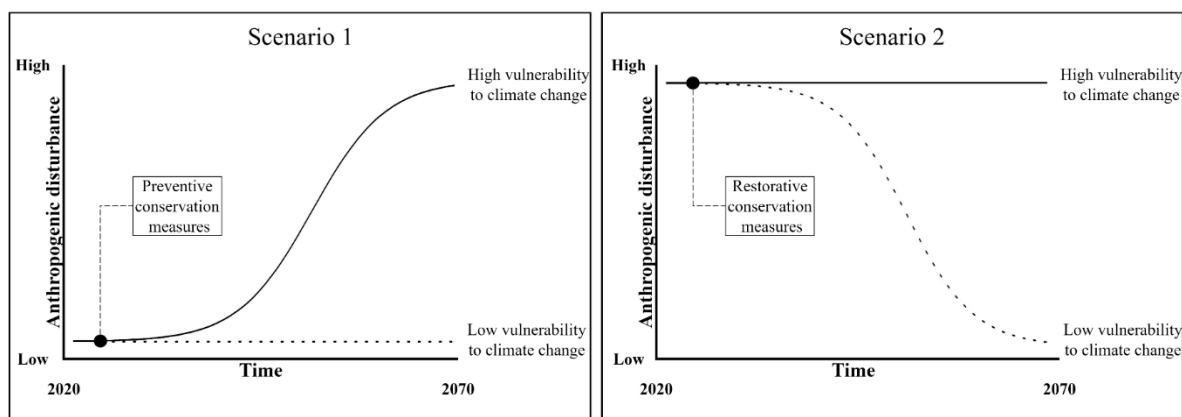


Figure 4. Two conceptual scenarios to describe when and what type of conservation measures are needed to increase the resilience of forest to changes in climatic conditions. **Left:** Scenario 1. Without conservation measures, anthropogenic disturbance of forest will increase over time, leading to a higher vulnerability to climate change in the future (displayed by the solid line). When preventive conservation measures are implemented, currently low levels of anthropogenic disturbance could be maintained, leading to enhanced forest functioning and a lower vulnerability of forest to climate change (displayed by the dashed line). **Right:** Scenario 2. Without conservation measures, anthropogenic disturbance of forest will remain high over time, leading to a higher vulnerability to climate change in the future (displayed by the solid line). When restorative conservation measures are implemented, currently high levels of anthropogenic disturbance could be reduced, leading to a lower vulnerability of forest to climate change (displayed by the dashed line).

The first scenario describes a situation where anthropogenic disturbance of forest is currently low but likely to rise quickly over time. This corresponds, for example, to intact forest areas that represent high economic value due to their geographical location or physical properties [78]. To enhance forest resilience, it may be argued that an anticipated shift in climate suitability should be accompanied with adequate measures to prevent local deforestation and forest degradation pressure. This may increase forest functioning and heterogeneity, which allows for tropical forests to better respond to and recover from climatic

stressors over time [79,80]. With regard to the Peruvian Andes, Bax and Francesconi [81] developed land use models to identify areas where anthropogenic activities are likely to expand within the coming decades. The climate projections presented in our study, in conjunction with the land use change scenarios from Bax and Francesconi [81], provide a first glance of opportune forest locations for the expansion of protected areas as part of a precautionary forest management approach. These locations include, for instance, some of the largely in-tact forest areas to the west of the Otishi National Park (located in the Junín region), where both deforestation and climate change pressures are expected to intensify in the foreseeable future.

The second scenario describes a situation where large-scale anthropogenic disturbance of forest has already been taking place. In the case of already disturbed and degraded forest ecosystems, a better strategy to counter the impacts from climatic stressors will be to strengthen ecosystem functioning through restoration and reclamation efforts [82]. Implementing payments for ecosystem services schemes and agroforestry initiatives may also be an appropriate strategy to restore degraded tropical forest areas, while simultaneously addressing rural poverty and development needs within the Peruvian Andes. Candidate areas for restorative measures, taking into account current disturbance regimes, human presence and potential climate change exposure, are for instance located to the southeast of the Otishi National Park in the Cusco region.

5. Conclusions

The prospects of climate change illustrate a future in which major conservation challenges and uncertainties lie ahead. The outcomes of this study show that under a worst-case climate change scenario for the year 2070, more than half of all Peruvian Andes forests will no longer be climatically suitable to persist within their current distribution. Most striking is that by the year 2070, nearly all montane forest ecosystems within Peru's Cordillera Azul National Park and El Sira Communal Reserve will be subjected to climatic circumstances that are not adequate for the existence of these ecosystems.

Changes in climatic conditions are not isolated, but set in motion a myriad of mechanisms that, in one way or another, will be causing ecosystems to migrate, acclimatize, adapt or break apart and disappear. Resource managers and conservation specialists are now confronted with the exceptionally difficult task of developing approaches that incorporate climate uncertainties into prevailing conservation plans and planning principles. The modeling framework presented in this study provides a pragmatic method to guide conservation decision making in the Peruvian Andes, by assessing where a shift in suitable climatic conditions could translate into impacts on forest ecosystems. In addition, based on the outcomes of our study we present two scenarios applicable to the Peruvian context that could guide conservation planners to identify and take actions to reduce land-use change pressures and, in turn, enhance climatic resilience of montane forest ecosystems. More empirical research is, at the same time, needed to further our understanding of human-forest-climate interactions.

In the cases where no conservation or adaptation actions are taken for whatever reasons, as society, we need to face the threat that climate change poses to ecosystem degradation and large scale species extinction. As financial resources for conservation are scarce and apathy is plentiful, focusing efforts on areas that provide the biggest bang for buck, may be our best bet to safeguard rare and fragile ecosystems in a specific region, such as montane forest ecosystems in the Peruvian Andes. Conservation strategies that target potential climate change impacts on species and ecosystems, will need to integrate multiple stakeholders and implement diverse landscape conservation strategies to increase climate resilience. These principles are for instance embedded in the *Amazonía Resiliente* project, a UNDP conservation project that targets climate change impacts and other human induced pressures in the Peruvian Amazon and premontane Andes forests. The project aims at increasing the extent of protected areas, improving connectivity between conservation areas and remaining habitat, increasing the diversity of habitats within the conserved

ecosystems, and importantly, working with the communities and organizations that seek the proper management of natural resources. The climate change projections presented in this study provide knowledge-based support for conservation efforts such as *Amazonía Resiliente*, showing where conservation actions are feasible and most needed within a rapidly changing environment.

Supplementary Materials: The following supplementary materials are available online at <https://www.mdpi.com/1999-4907/12/3/375/s1>, Table S1: Bioclimatic variables, Table S2: Envirem variables, Table S3: Datasets used in this study, Table S4: Classification model performance, Figure S1: Variability (as a measure of uncertainty) between the outcomes of different combinations of classification models and climate datasets used to generate montane forest projections.

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