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Tropical ecosystems vulnerability to climate change in southern Ecuador

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Abstract

Tropical ecosystems are among the most vulnerable to climate change. Understanding climate impacts on these ecosystems is a primary challenge for policy makers, ecologists, and conservationists today. We analyzed the vulnerability of ecosystems in a very heterogeneous tropical region in southern Ecuador, selected because of its exceptional biodiversity and its ecosystem services provided to people of southern Ecuador and northern Peru. The vulnerability assessment focused on three components: exposure, sensitivity, and adaptive capacity. For the first two components, we identified stressors or drivers of change that negatively influence ecosystems. For the third component, we identified existing and potential buffers that reduce impacts. This process was developed in workshops and by expert elicitation. Representative Concentration Pathway (RCP) scenarios were used, considering RCP 2.6 and RCP 8.5 for a time horizon to 2050. Under the RCP 2.6 scenario, the components of overall vulnerability in the southern region of Ecuador showed very low to moderate vulnerability for most areas, particularly in semi-deciduous forest ecosystems, Amazon semi-deciduous forest, Amazon rainforest, and mangrove forests. These areas had high vulnerability under the RCP 8.5 scenario. A variety of conservation strategies (e.g., protected areas) were shown to increase the adaptive capacity of ecosystems and reduce their vulnerability. We therefore recommend improving these conservation initiatives in ecosystems like dry forests, where the greatest vulnerability is evident.

Keywords

biodiversity, drivers of change, exposure, sensitivity, adaptive capacity

Introduction

Climate change entails many challenges for future decades, especially potential impacts on people, crop production (IPCC, 2014; Thornton, Ericksen, Herrero, & Challinor, 2014; Wheeler & Von-Braun, 2013), and species conservation (Dawson, Jackson, House, Prentice, & Mace, 2011; McCarty, 2001). All climate models project a rise in temperature in South America, while the precipitation projections disagree and show either an increase or a decrease in coming decades (IPCC, 2016). For the Southern Region of Ecuador (SRE), most projections show an increase in precipitation and all show increases in temperature, suggesting increased climatic variation that would impact ecosystems and their services (Colwell, Brehm, Cardelús, Gilman, & John, 2008; Foster, 2001; Furniss et al., 2013; Glick, Stein, & Edelson, 2011; Pearson, 2006; Thornton et al., 2014; Thuiller et al., 2008). This problem could be exacerbated by population growth (Jiang & Hardee, 2011; Nagendra, Sudhira, Katti, & Schewenius, 2013) and increasing pressure on natural resources by land-use change, deforestation, fragmentation (Lewis, Malhi, & Phillips, 2004), and other stressors that increase vulnerability.

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Climate change will impact both human and natural systems (IPCC, 2001; Thornton et al., 2014). Ecosystems might suffer effects such as migration and extinction of species, changes in biodiversity, species composition and phenology, and reduced growth rates (Bellard, Bertelsmeier, Leadley, Thuiller, & Courchamp, 2012; Clark & Clark, 2010; Colwell et al., 2008; Feeley, Wright, Supardi, Rahman, & Davie, 2007; IPCC, 2001; Thomas et al., 2004; Williams, Jacksn, & Kutzbach, 2007). Ecosystems can have high levels of vulnerability due to habitat decline, vegetation loss (Glick et al., 2011), or changes in their altitudinal gradients (Cuesta, Bustamante, Becerra, Postigo, & Peralvo, 2012; Gómez-Mendoza, Galicia, & Aguilar-Santelises, 2008; Marquet et al., 2010). Ecosystems with a limited altitudinal range, such as páramo, can be highly vulnerable to incremental climate changes, causing páramo species to migrate towards upper elevations in order to find better environmental conditions (Young, Young, & Josse, 2011); however, these type of ecosystems can have less possibilities to migrate because their altitudinal restrictions.

SRE is located along an altitudinal gradient between the coast and the Amazon region (0 m a.s.l. – 3,800 m a.s.l.) of Ecuador (Barthlott et al., 2007; Brummitt & Lughadha, 2003). Throughout this gradient we can find complex ecosystems with dry and wet characteristics over short distances (Beck, Bendix, Kottke, Makeschin, & Mosandl, 2008), creating an important biodiversity hotspot (Brehm et al., 2008; Myers, Mittermeier, Mittermeier, Fonseca, & Kent, 2000; Richter, Diertl, Emck, Peters, & Beck, 2009), as a result of a high speciation rate, Andean depression (Huancabamba), topography conditions, microclimatic influences, and human intervention (Barthlott et al., 2007; Keating, 2008; Richter & Moreira-Muñoz, 2005; Richter et al., 2009). Throughout the SRE are 45% of the 91 described ecosystems of Ecuador (MAE, 2013), within which there are 7048 species of flora (Lozano, 2002), and a high percentage of endemic plants (29%) (Lozano, Delgado, & Aguirre, 2003). El Oro has 228 endemic plant species, Loja has 639, and Zamora Chinchipe has 568 (Lozano, 2002).

The varied ecosystems in the SRE provide many greatly valued goods and services to communities in the region (MAE, 2001), but despite the environmental and social importance of these ecosystems, currently there is little scientific information on their vulnerability to climate change or other environmental effects. Environmental impacts and climate vulnerability differ from place to place and between ecosystems, due to their differing structural, topographical, and environmental characteristics.

A vulnerability assessment of ecosystems in the SRE is needed in order to estimate impacts on ecological integrity and function, as well as on human livelihoods; additionally, these type of studies help to set priorities for conservation actions. This article is a baseline on the SRE ecosystems most vulnerable to climate change and those more able to adapt to adverse climatic conditions. Our results will help to design and implement strategies for climate change adaptation (Fussel & Klein, 2007) and mitigation, which will improve conservation programs not only in the SRE, but also in other tropical ecosystems.

Methods

Study area

The research was conducted in the Southern Region of Ecuador (SRE), which has an area of 27,535 km^2 (11% of Ecuador) (IGM, 2010). SRE includes El Oro with 600,659 inhabitants and a population growth rate of 1.5 %, Loja with 448,966 inhabitants and a population growth rate of 1.1 %, and Zamora Chinchipe with 91,376 inhabitants and a population growth rate of 2.0 % (INEC, 2010) (Figure 1). The average annual temperature ranges from 3°C to 26°C, and the annual precipitation is between 37 mm to 6,000 mm (Herbario-Loja, 2001; INAMHI, 2013; Richter & Moreira-Muñoz, 2005). Changes in ecosystems over the past three decades in Ecuador and in the SRE are mainly due to land-use changes, human settlements, mining, roads, and deforestation (Sierra, 2013; Wasserstrom & Southgate, 2013). These are the principal drivers of change and have often seriously degraded ecological systems (Sierra, 2013; Tarras-Wahlberg, Flachier, Lane, & Sangfors, 2001; Wasserstrom & Southgate, 2013), impacting biodiversity (Hautier et al., 2015) and ecosystem services.

Assessing the Vulnerability to Climate Change

Our assessment is based on the definition of vulnerability (vulnerability = exposure + sensitivity–adaptive capacity) by the Intergovernmental Panel on Climate Change (Cinner et al., 2012; Eigenbrod, Gonzalez, Dash, & Steyl, 2015; Füssel, 2010; Fussel & Klein, 2007; IPCC, 2001, 2007; Liu, Wang, Peng, Braimoh, & Yin, 2013). It included four components: i) values; ii) exposure; iii) sensitivity; and iv) adaptive capacity. The values assessed were the tropical ecosystems of southern Ecuador, due to their importance in providing goods and services to local and regional communities. Ecosystems were identified from information generated by the ecosystem classification system by the Ministry of Environment of Ecuador (MAE, 2013a, 2013b). This information was conglomerated in eight ecosystems based on the similarity of vegetation cover and seasonality. We evaluated the following biological systems: i) páramo (129,579 ha) (High Andean ecosystem distributed along the mountains

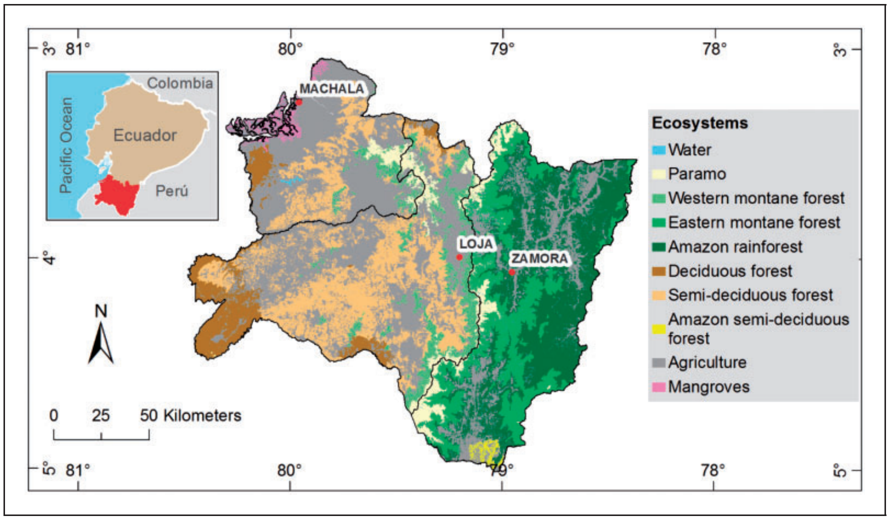


Figure 1. Ecosystems of the Southern Region of Ecuador.

above 3,000 m a.s.l. between closed forest and snow (Hofstede, Pool, & Mena, 2003)); ii) deciduous forest (138,990 ha); iii) semi-deciduous forest (482,164 ha); iv) western montane forest (138,951 ha); v) eastern montane forest (290,029 ha); vi) Amazon rainforest (463,259 ha); vii) Amazon semi-deciduous forest (9,663 ha); and viii) mangroves (23,026 ha). For each ecosystem we analyzed the exposure, sensitivity, adaptive capacity, and vulnerability to climate change (Figure 1).

Vulnerability is influenced by stressors that increase susceptibility (Cinner et al., 2012; Eigenbrod et al., 2015; Furniss et al., 2013; IPCC, 2001, 2007). We selected anthropogenic, natural or intrinsic, and climatic stressors as drivers of change in ecosystems. Management or conservation actions implemented at the SRE were considered to be buffers that could increase the adaptive capacity of ecosystems and reduce the effects of stressors (Dawson et al., 2011; Furniss et al., 2013; Fussel & Klein, 2007). We identified the main stressors of exposure and sensitivity as well as buffers for adaptive capacity through expert elicitation and three workshops (one per province) with the participation of researchers (universities and research centers from Ecuador), government representatives (Ministry of Environment, Ministry of Agriculture, Ministry of Water; and delegates of local governments from El Oro, Loja, and Zamora Chinchipe), community organizations, non-governmental organizations, and international experts (United States Forest Services and United States Agency for International Development). During this process around 40 experts provided information on what stressors or buffers have the most effect on ecosystems of the SRE. We based our final selection of the stressors and buffers on their importance and the available information. The variables used for this assessment are shown in Appendix 1.

Spatial analysis

Stressors and buffer variables were calculated using ArcGIS software, and the methodological process for each variable was based on its characteristics and the available information. Stressors and buffers were normalized on a scale of 0%–100% using normalization equations for categorical variables (Table 1, Eq. 4) or continuous variables (Table 1, Eq. 5). For each component (exposure, sensitivity, and adaptive capacity), we classified the level of influence of each stressor or buffer on ecosystems, establishing five categories (very low, low, moderate, high, and very high) through the method of natural breaks (Brewer & Pickle, 2002). For categorical stressors we assigned a weight based on the degree of impact on ecosystems, determined by workshops and the analytic hierarchy process developed by Saaty (1990, 2008).

Climatic exposure was calculated from eight general circulation models (GCMs) (BCC-CSM1-1, CCSM4, HadGEM2-AO, HadGEM2-ES, IPSL-CM5A-LR, MIROC5, MRI-CGCM3, NorESM1-M) of the Coupled Model Intercomparison Project Phase 5 (CMIP5), and two climate change scenarios to 2050 (RCP 2.6 and RCP 8.5) from WorldClim platform with a spatial resolution of 1 km^2. To reduce uncertainty associated with each model, we generated assemblies of scenarios of the climatic variables (IPCC, 2016), using a combination of a set of individual climate models. To this, we added eight models and took an average (Kharin & Zwiers, 2002; Knutti, Furrer, Tebaldi, Cermak, & Meehl, 2010) to reduce uncertainty and have a better representation than with individual models (Armenta, Dorado, Rodriguez, & Ruiz, 2014; Knutti et al., 2010; Lambert, & Boer, 2001). Assemblies were calculated for each of the climatic variables. Within the exposure assessment, we analyzed absolute changes in

Table 1. Assessing vulnerability to climate change of ecosystems: equations for the region south of Ecuador.

Equation	Description
Eq. 1 $E = \Delta Tave + \Delta Tmax + \Delta Tmin + \Delta Pp$	E: Exposure ΔTave: annual average temperature change ΔTmax. annual average maximum temperature change ΔTmin: annual average minimum temperature change ΔPp: Annual average precipitation change
Eq. 2 $S_{total} = S_{environmental} + S_{socioeconomic} + S_{intrinsic}$	S_{total}: Total sensitivity $S_{environmental}$: environmental sensitivity $S_{socioeconomic}$: socioeconomic sensitivity $S_{intrinsic}$: intrinsic sensitivity
Eq. 3 $AC = PAB + CSB + PDB$	AC: Adaptive capacity PAB: Protected areas buffer CSB: Conservation strategies buffer PDB: Population decrease buffer
Eq. 4 $N = \frac{VC}{Max \quad VC} \times 100$	N: Normalization (Categorical variable) VC: Value of the category Max VC: Maximum value of categories
Eq. 5 $N = \frac{(\text{"}raster\text{"} - \min(\text{"}raster\text{"}))}{(\max(\text{"}raster\text{"}) - \min(\text{"}raster\text{"}))} \times 100$	N: Normalization (continuous variable) min: Minimum value of the raster max: Maximum value of the raster

climatic variables (annual average temperature, annual average maximum and minimum temperature, and annual precipitation) between now and 2050 (Table 1, Eq. 1).

The total sensitivity (Table 1, Eq. 2) resulted from the analysis of the environmental, socio-economic and intrinsic sensitivity. Environmental stressors (land use, road density, deforestation, fragmentation and mining) were related to human activities that have caused changes in land cover, ecosystem structure and function. Socio-economic stressors (population density, population growth, basic needs, and water consumption) comprised factors like cultural and social conflicts, and living conditions that influence land use and natural resources. Finally, intrinsic stressors (mass movement, water deficit probability, flooding probability, and forest fires probability) were those with the potential to appear naturally within the ecosystem. The source of data for each stressor is shown in Appendix 2.

The stressors for each type of sensitivity (environmental, socio-economic, and intrinsic) were normalized and combined using map algebra. For categorical variables, we used a hierarchical process (Saaty, 1990, 2008) to weigh the importance of the relative effect of each of the categories of the variables; these weighs were established by experts during the workshops. This information was used to calculate the total sensitivity to both human and intrinsic stressors.

Buffers such as protected areas, conservation tools, and population decrease were used to determine adaptive capacity (Table 1, Eq. 3). Buffers, as categorical variables, were normalized through each internal category. We assigned a weight depending on the degree of contribution to the adaptive capacity of ecosystems. A hierarchical method (Saaty, 1990, 2008) and expert elicitation process were used for assigning weights to the categories (Appendix 3).

Finally, we produced maps of exposure, sensitivity, adaptive capacity, and vulnerability, with a resolution of 30 m × 30 m.

Results

Exposure

Both scenarios (RCP 2.6 and RCP 8.5) projected an increase in annual precipitation, primarily in the deciduous ecosystems and the Amazon rainforest. The greatest increases in annual average temperature, annual average maximum temperature, and annual average minimum temperature were in the Amazon basin, particularly in the eastern montane forest, Amazon rainforest, and Amazon semi-deciduous forest. In the RCP 2.6 scenario, exposures from the inter-Andean ecosystems to the coastal region were very low to moderate, while those located in the Amazon basin had moderate exposure (Figure 2). The high emissions scenario (RCP 8.5) showed the eastern montane forest and Amazon semi-deciduous forest with high exposure (53% and 80% of its area respectively), and the Amazon rainforest

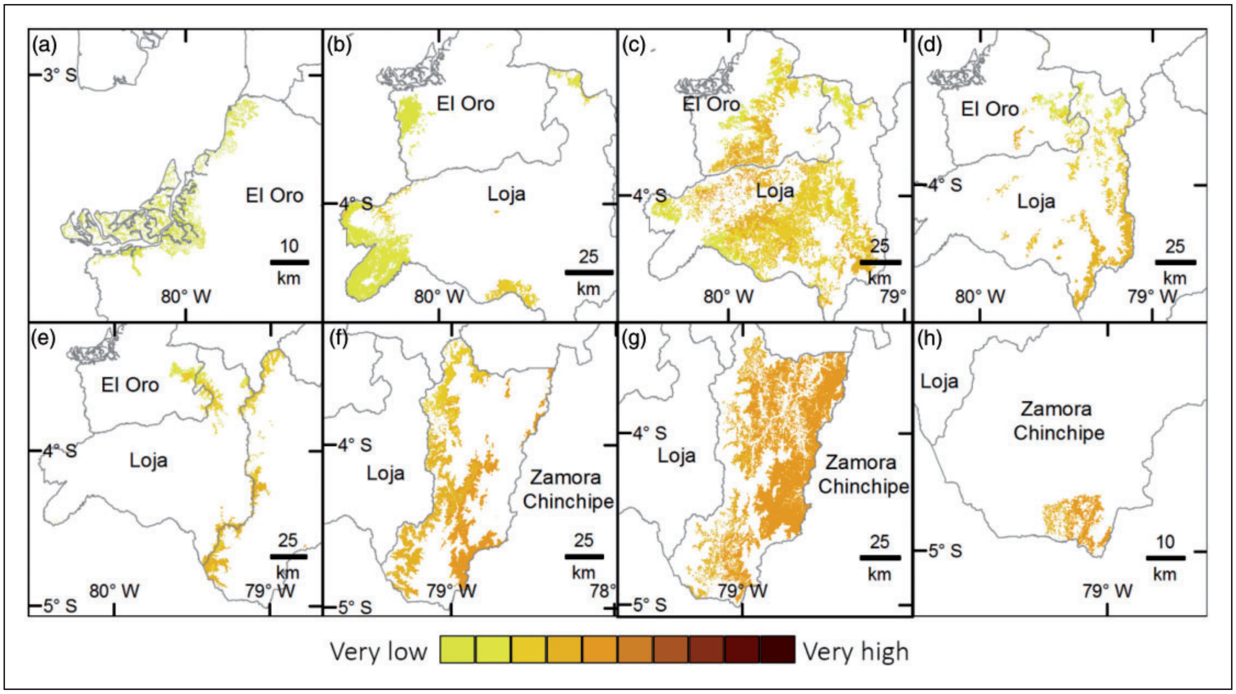


Figure 2. Exposure to climate change under a RCP 2.6 scenario. (a) Mangroves; (b) deciduous forest; (c) semi-deciduous forest; (d) western montane forest; (e) páramo; (f) eastern montane forest; (g) Amazon rainforest; (h) Amazon semi-deciduous forest.

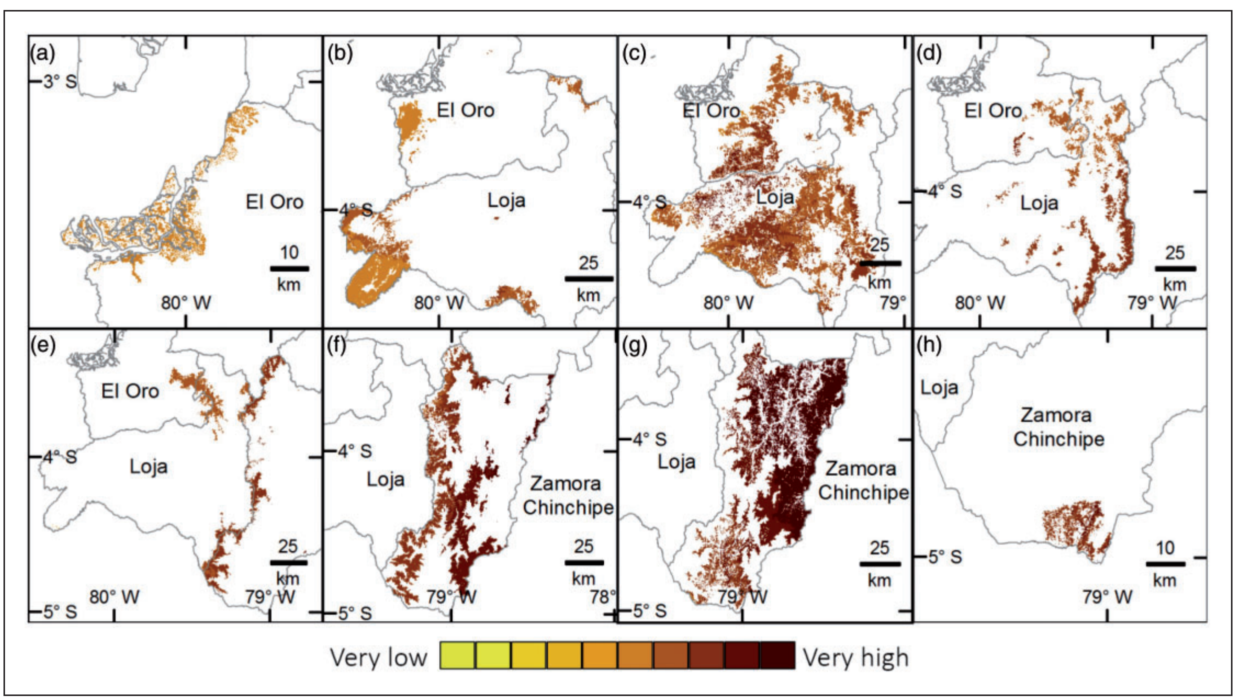


Figure 3. Exposure to climate change under a RCP 8.5 scenario. (a) Mangroves; (b) deciduous forest; (c) semi-deciduous forest; (d) western montane forest; (e) páramo; (f) eastern montane forest; (g) Amazon rainforest; (h) Amazon semi-deciduous forest.

(88% of its area) had very high exposure (Figure 3, Appendix 4).

Exposure analysis trends reflected moderate to very high levels of exposure for both scenarios in the Amazon basin (Zamora Chinchipe), mainly in the Amazon rainforest, eastern montane forest, and Amazon semi-deciduous forest (Figures 2 and 3). However, the biggest absolute changes in climatic variables (annual precipitation, annual average temperature, annual average maximum temperature, and annual average minimum temperature) were for RCP 8.5. This suggests that climatic variables will have the greatest impact on ecosystems located in the eastern part of Ecuador.

Sensitivity

Ecosystems such as mangroves, deciduous forest, western montane forest, the Amazon rainforest, páramo, and eastern montane forest had mainly moderate to very low levels of sensitivity in large proportions of the territory, although the first four also have between 5% and 13% surface with high or very high sensitivity. Ecosystems that have a greater area in high sensitivity were the semi-deciduous forest and Amazon semi-deciduous forest, with 25% and 41% of their areas respectively (Figure 4, Appendix 5). These areas will be most affected in the future due to environmental stressors (land use, deforestation, mining, and road density) imposed historically by human pressure and degradation.

Adaptive capacity

SRE had an overall low adaptive capacity, ranging from very low (34% of the area) to low (29% of the area). Ecosystems that had very low adaptive capacity were the mangroves (79% of its area), the semi-deciduous forest (40% of its area), and western montane forest (36% of its area) (Figure 5, Appendix 6). The deciduous forest had a moderate adaptive capacity in 50% of its territory. Ecosystems located in the Amazon basin, such as the Amazon rainforest and the Amazon semi-deciduous forest, despite including major conservation areas (protected areas or conservation programs), had large areas with low adaptive capacity (41% and 84% respectively).

Páramo and the western montane forest have larger areas with very high levels of adaptive capacity (36% and 33% respectively). This is primarily because those ecosystems are located within protected areas (eg: Podocarpus National Park) and other conservation programs (*e.g.,* Biosphere Reserve Podocarpus–The Condor). These conservation measures are a buffer against impacts of climate change and anthropogenic activities, reducing ecosystem vulnerability.

Vulnerability to climate change

SRE under RCP 2.6 had moderate vulnerability, a trend reflected in most ecosystems. According to the assessment, 94% of the Amazon semi-deciduous forest, 74% of semi-deciduous forest, 70% of the mangrove, and 62% of the Amazon rain forest have moderate vulnerability (Figure 6, Appendix 7). However, the deciduous forest (57%), páramo (35%), and eastern montane forest (58%) had low vulnerability. For the RCP 8.5 scenario, all ecosystems show high levels of vulnerability, because the changes in climatic variables are more extreme.

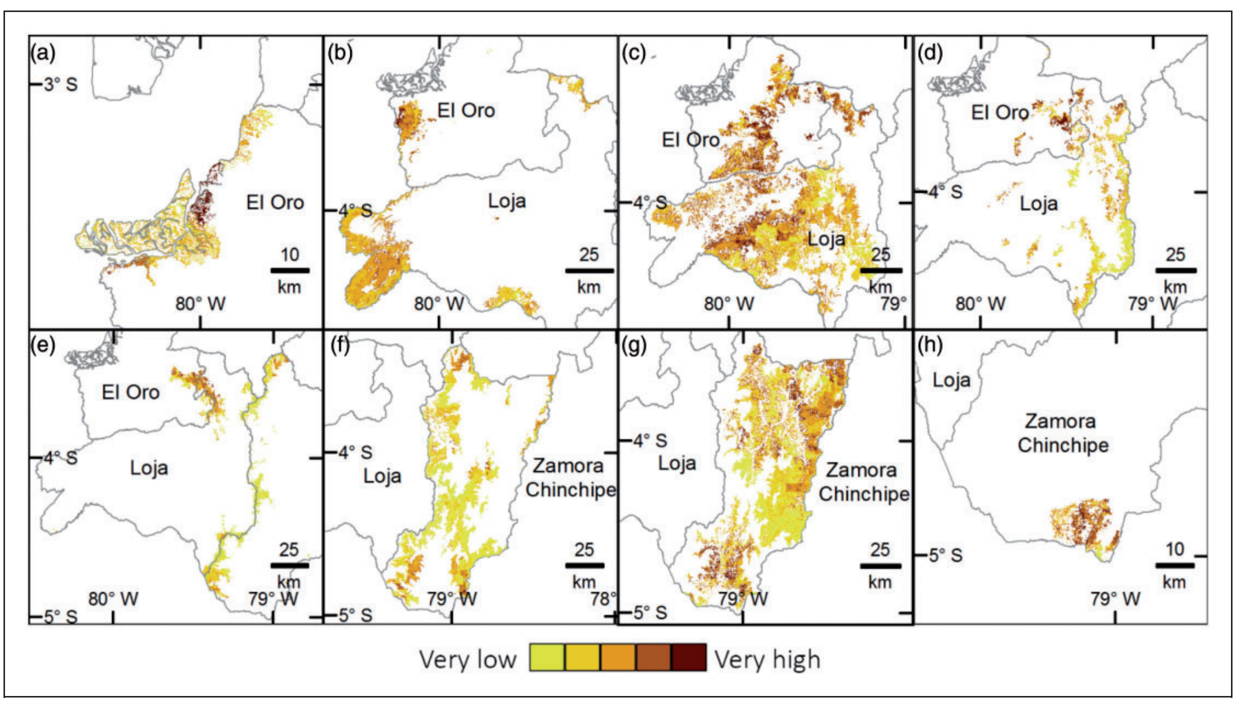


Figure 4. Sensitivity (a) Mangroves; (b) deciduous forest; (c) semi-deciduous forest; (d) western montane forest; (e) páramo; (f) eastern montane forest; (g) Amazon rainforest; (h) Amazon semi-deciduous forest.

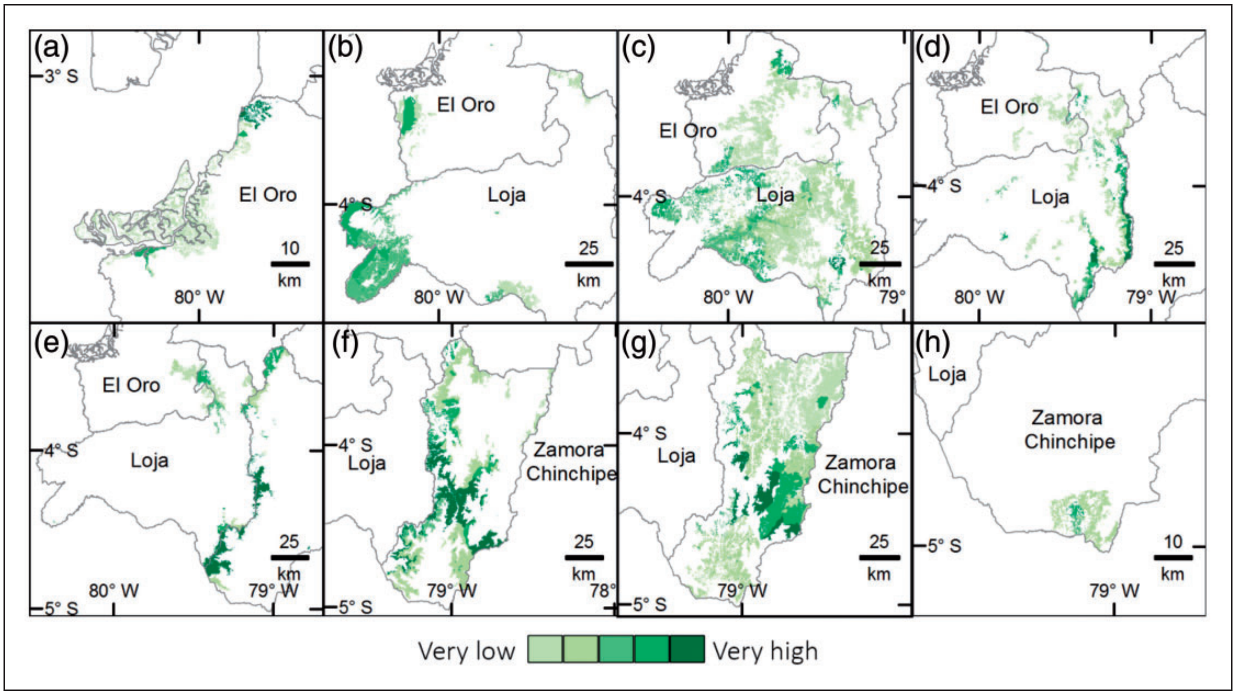


Figure 5. Adaptive capacity (a) Mangroves; (b) deciduous forest; (c) semi-deciduous forest; (d) western montane forest; (e) páramo; (f) eastern montane forest; (g) Amazon rainforest; (h) Amazon semi-deciduous forest.

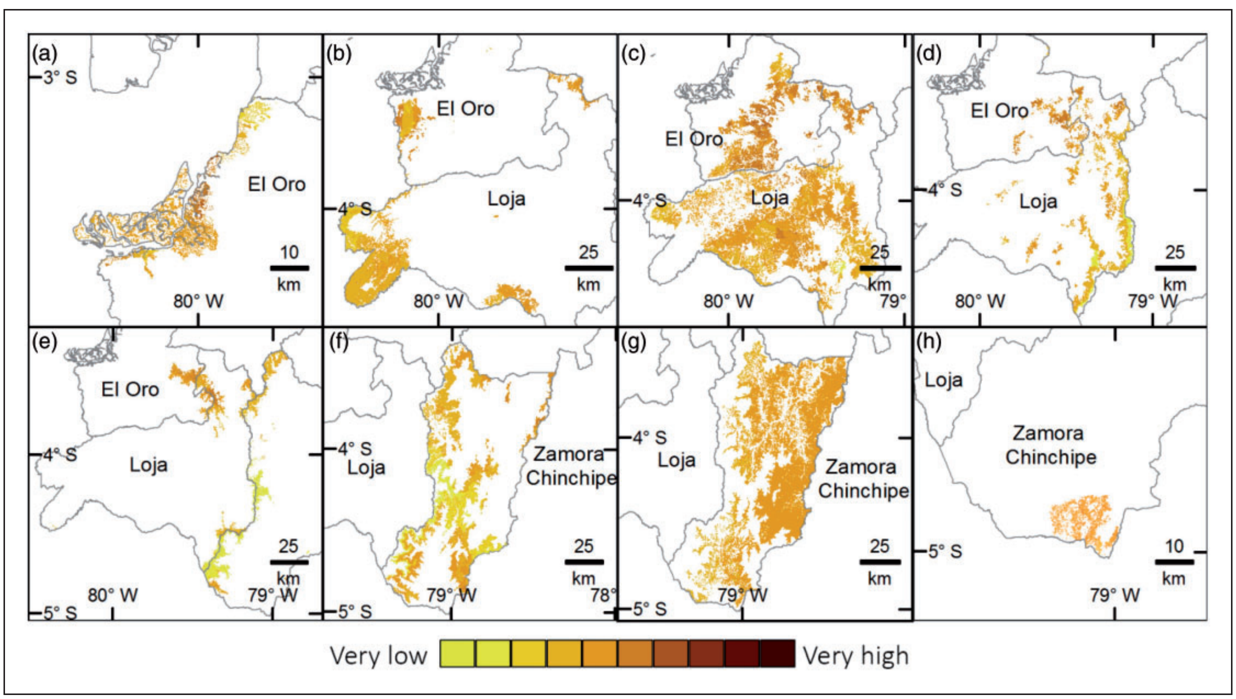


Figure 6. Vulnerability to climate change. RCP 2.6 scenario. (a) Mangroves; (b) deciduous forest; (c) semi-deciduous forest; (d) western montane forest; (e) páramo; (f) eastern montane forest; (g) Amazon rainforest; (h) Amazon semi-deciduous forest.

Ecosystems with the largest areas of high vulnerability are the Amazon semi-deciduous forest (98% of its territory), semi-deciduous forest (85%), mangroves (74%), and Amazon rain forest (69%) (Figure 7).

Discussion

By 2050, the annual average temperature would be expected to increase 1.46°C in the RCP 2.6 scenario; and 2.37°C in

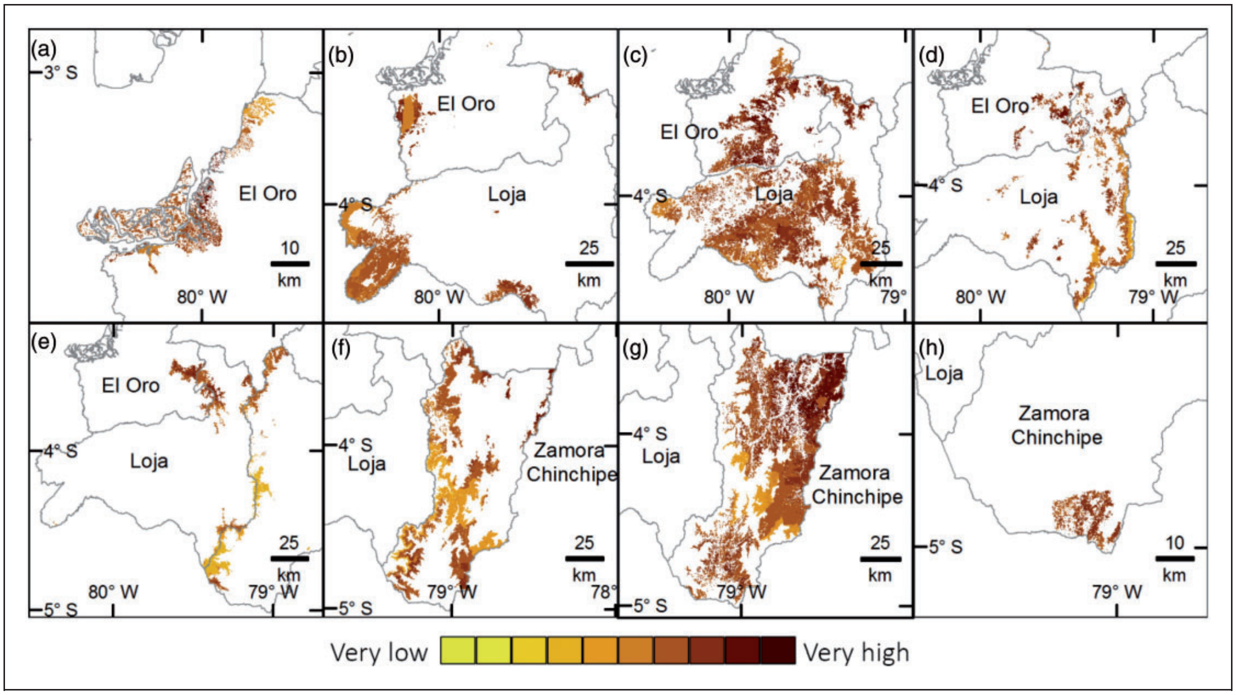


Figure 7. Vulnerability to climate change. RCP 8.5 scenario. (a) mangroves; (b) deciduous forest; (c) semi-deciduous forest; (d) western montane forest; (e) páramo; (f) eastern montane forest; (g) Amazon rainforest; (h) Amazon semi-deciduous forest.

Table 2. Absolute changes in climatic variables of exposure scenarios RCP 2.6 and 8.5.

Variable	Scenario RCP 2.6 (absolute changes)	Scenario RCP 8.5 (absolute changes)
Annual precipitation (Pp–mm)	22–210	49–370
Annual average temperature (Tave–°C)	1.21–1.46	2.01–2.37
Annual average maximum temperature (Tmax–°C)	1.18–1.40	1.90–2.27
Annual average minimum temperature (Tmin–°C)	1.27–1.42	2.10–2.33

the RCP 8.5 scenario (Table 2). These changes could cause variations of current temperatures at specific locations and produce climatic conditions typical at lower altitudes (Peters et al., 2013). The Amazon basin had a high level of exposure, and ecosystems located between the Andes and the Amazon region would have high impacts. High levels of exposure could cause: changes in population dynamics, structure, and species composition, as well as migration, extinction or adaptation (Colwell et al., 2008; Dawson et al., 2011; McCarty, 2001; Pearson, 2006; Thomas et al., 2004; Thuiller et al., 2008). Distribution changes of tropical species could occur throughout the altitudinal gradient. In this case, lowland species will be more able to adapt to new climatic conditions along this gradient, but it will be difficult for species to populate these lowland areas, which would lead to biotic attrition (Colwell et al., 2008). On the other hand, páramo species may face increased isolation due to restricted geographical ranges, which could cause major extinctions of species that cannot adapt quickly (Tarras-Wahlberg et al., 2001; Wasserstrom & Southgate, 2013). Furthermore, some studies have estimated a change in the area of Andean biomes in the future. Ecosystems could face geographic expansion or reduction due to changes in environmental conditions, causing the extinction or migration of species (Anderson et al., 2011; Cuesta et al., 2012; Larsen et al., 2011).

Other studies in tropical rain forests suggest impacts to growth rates of trees, negatively correlated with increases in annual average temperature, annual average maximum temperature, and intensity of the dry season (Clark, Clark, & Oberbauerz, 2010; Clark, Piper, Keeling, & Clark, 2003; Feeley et al., 2007). These effects may be reflected in the ecosystems of the SRE as coming decades bring strong increases in temperatures, potentially beyond thermal optima for plant growth. This will result in stress and reduced net primary production and growth (Lambers, Chapin, & Pons, 2008; Schuur, 2003), causing impacts on ecosystem structure (Clark, Clark, & Oberbauerz, 2010).

The effects of increasing climatic exposure may deepen for sensitive ecosystems with anthropogenic or intrinsic stressors. Anthropogenic stressors such as land-use change, open roads, and deforestation usually cause significant impacts on natural systems (Fischlin & Midgley, 2007; Hautier et al., 2015; Laurance, Goosem, & Laurance, 2009; Liu et al., 2008; Wasserstrom & Southgate, 2013) and may alter the way that our ecosystems respond to climate change (Burkett, Wilcox, Stottlemyer, Barrow, & Fagre, 2005).

Within the SRE, semi-deciduous forest had higher levels of sensitivity because of deforestation, land use, mining, and roads, which are the main drivers of change. Although in our study the deciduous and semi-deciduous forest had some areas with high sensitivity, they had better conservation than those located in northern Ecuador or northern Peru (Aguirre & Kvist, 2014). In addition, the Amazon rainforest and the Amazon semi-deciduous forest also show sensitivity to stressors such as the opening of roads (Freitas, Hawbaker, & Metzger, 2010; Laurance et al., 2009; Liu et al., 2008), which facilitate access to resources, colonization, and inevitable land-use changes, increasing forest loss in the Amazon basin (Wasserstrom & Southgate, 2013). Intrinsic stressors such as mass movement, water deficit, and wildfire also affect our ecosystems. The study area has an irregular surface with moderate slopes in the valleys and steeper slopes as it approaches the Andean mountains (Bendix et al., 2013). The region's topography, geography, vegetation, and high rainfall, especially in the páramo, have impacts mainly on the western flanks of the Andes (Lozano, Busmann, Kupers, & Lozano, 2008).

Páramo and eastern montane forest ecosystems are better able to adapt to climate changes, mainly because much of the area is within protected areas. Additionally, the health of forests in southern Ecuador is better than those in the central and western region (Mena & Hofstede, 2006). Although the páramo has good adaptive capacity, we must not forget that these environments can be geographically isolated, making some species highly vulnerable in the future (Buytaert et al., 2011). On the other hand, there are ecosystems that have very low adaptive capacity, especially those located from the valleys to the coastal region (semi-deciduous forest, deciduous forest and mangrove), with clear and significant gaps in conservation. In addition to habitat loss, climate change will greatly increase the vulnerability of ecosystems (Eigenbrod et al., 2015). In this regard, the strengthening or the creation of conservation corridors could facilitate the connection between the lowlands and the Andes mountains, reducing the impacts of climate change on species (Killeen & Solórzano, 2008; Larsen et al., 2011).

We found that human activities are important drivers of change and climate vulnerability, and that certain strategies to adapt to climate change should be maintained and implemented. Conservation programs can reduce the degradation of natural resources and ecosystem services, as well as improve community development in the SRE. Although we used the RCP 2.6 and RCP 8.5 scenarios as optimistic and pessimistic respectively, is essential to realize that even if we improve strategies to address climate change (in the case of RCP 2.6), ecosystems will experience residual impacts. We therefore must address all environmental impact mechanisms and take steps to increase their adaptive capacity.

Implications for conservation

Assessment of vulnerability to climate change is a valuable tool to predict which ecosystems could be most affected by climate change and where major impacts may occur. Our results could be useful for policy makers in developing adaptation strategies and natural resource management plans, in order to improve ecosystems and species conservation. From the eight ecosystems assessed, we identified four ecosystems that continuously appeared with high levels of exposure and sensitivity as well as low adaptive capacity and could be prioritized for the development of conservation strategies; those ecosystems are: i) mangroves, ii) semi-deciduous forests, iii) Amazon semi-deciduous forest and iv) Amazon rainforest. Consequently, we will analyze in more detail which will be the conservation implications of our results with respect to these four systems.

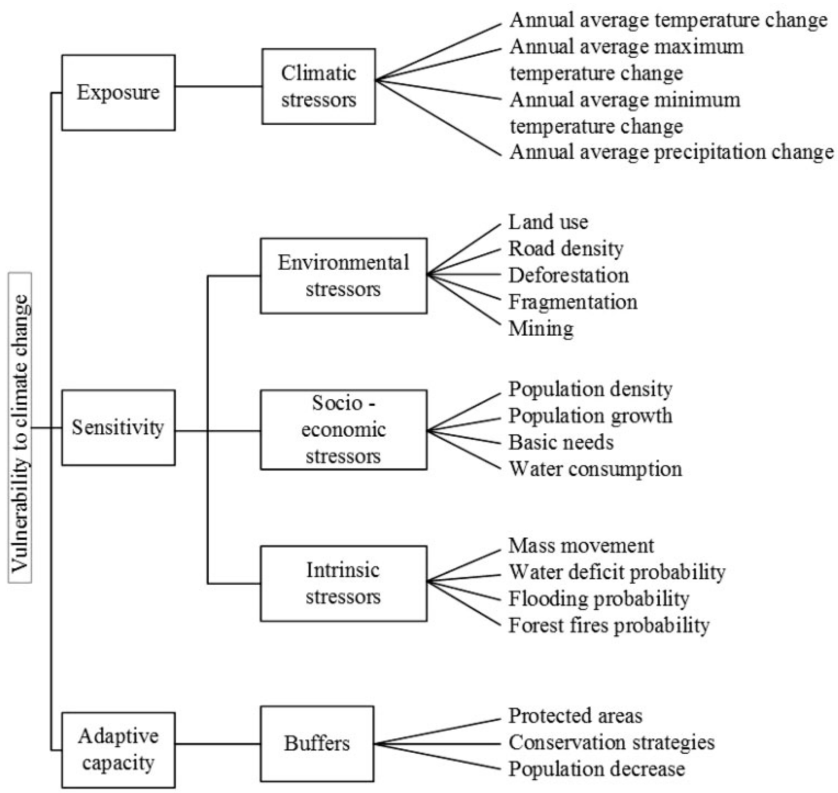
In the case of mangroves, land use is a big threat, mainly due to the establishment of commercial shrimp farms that historically have been affecting rural livelihoods (Beitl, 2012; Hamilton & Lovette, 2015). Moreover, the lack of conservation strategies to reduce climate change impacts and human influences on mangroves has attracted the development of unsustainable activities. There is an urgent need to strengthen existing laws and land-use plans that require conservation and rehabilitation programs but are not currently enforced or implemented. The regulation of shrimp farms is a good start, but cannot keep up with the destruction of mangroves. It is necessary to reduce human intervention and facilitate mangrove regeneration, but these actions must include productive alternatives for local people whose livelihoods are based on the mangrove.

In semi-deciduous forests, widespread throughout El Oro and Loja provinces, fragmentation and deforestation are the biggest problems. These forests need biological corridors connecting protected areas, biosphere reserves, Ramsar areas, agroforestry systems dominated by pastures or monocultures (like the central region of El Oro and the central and western part of Loja), and restoration projects in areas such as the western part of El Oro and southwestern part of Loja, where there is great demand for water.

Amazon semi-deciduous forests comprise a small portion of the SRE in southern Zamora Chinchipe and extending toward the northern part of Perú. This ecosystem is highly affected by environmental stressors, primarily mining concessions, road construction, fragmentation, and deforestation. This ecosystem is outside important conservation areas, such as Podocarpus National Park or Yacuri National Park, where anthropogenic pressures have been reduced. Biological corridors between such conservation areas and the remnants of Amazon semi-deciduous forests could improve these forests' adaptive capacity.

The Amazon rainforest concentrated in Zamora Chinchipe, suffers the same stressors as the Amazon semi-deciduous forest. Because of the rainforest's potential for carbon storage and its role in climate change mitigation, conservation strategies should be focused on increasing forest cover through restoration projects that will contribute to carbon sequestration.

Appendix 1. Stressor and buffers variables used for the vulnerability assessment



Appendix 2. Source of data of each stressor and buffers.

	Variable	Source	Spatial resolution
Exposure	Annual average temperature	Worlclim – Global Climate Date	~1 km
	Annual average maximum temperature	Worlclim – Global Climate Date	~1 km
	Annual average minimum temperature	Worlclim – Global Climate Date	~1 km
	Annual precipitation	Worlclim – Global Climate Date	~1 km
Sensivity	Land Use	Ministerio del Ambiente del Ecuador (2013)	30 m/1:100,000
	Road Density	Secretaria Nacional de Planificación y Desarrollo 2012	1:50,000

(continued)

Appendix 2. Continued

	Variable	Source	Spatial resolution
	Fragmentation	Calculated by us	30 m/1:100,000
	Deforestation	Ministerio del Ambiente del Ecuador (2013)	30 m/1:100,000
	Mining	Agencia de Regulación y Control Minero del Ecuador 2014	1:50,000
	Population density	Instituto Nacional de Estadísticas y Censos del Ecuador 2010	1:50,000
	Basic needs	Instituto Nacional de Estadísticas y Censos del Ecuador 2010	1:50,000
	Population growth	Instituto Nacional de Estadísticas y Censos del Ecuador 2010	1:50,000
	Water consumption	Calculated by us	1:50,000
	Mass movement	Secretaria de Gestión de Riesgos del Ecuador 2010	30 m/1:100,000
	Water deficit probability	Ministerio de Agricultura, Ganadería, Acuacultura y Pesca & Instituto Nacional de Meteorología e Hidrología 2002	30 m/1:100,000
	Flooding probability	Secretaria de Gestión de Riesgos del Ecuador 2013	30 m/1:100,000
	Forest fires probability	Secretaria de Gestión de Riesgos del Ecuador 2013	30 m/1:100,000
Adaptive capacity	Protected areas	Ministerio del Ambiente del Ecuador (2013)	1:50,000
	Conservation Strategies	Ministerio del Ambiente del Ecuador (2013)	1:50,000
	Population decrease	Instituto Nacional de Estadísticas y Censos del Ecuador 2010	1:50,000

Appendix 3. Weights for adaptive capacity buffers.

Buffer	Category	Weight (Saaty Matrix)	Normalization
Protected areas	State natural areas (PANE)	0,52	100,0
	Municipality reserve	0,23	43,9
	Protected Forest	0,14	27,6
	Socio bosque	0,08	14,9
	Restricted zone	0,04	7,4
Conservation strategies	Biosphere reserve		50,0
	Ramsar		50,0

Appendix 4. Exposure results.

Exposure (scenario)	Ecosystem	Level of exposure	Percentage
RCP 2.6	Mangroves	Very low	100,0
RCP 2.6	Deciduous forest	Very low	80,2
RCP 2.6	Deciduous forest	Low	19,8
RCP 2.6	Semi-deciduous forest	Very low	15,9
RCP 2.6	Semi-deciduous forest	Low	81,5
RCP 2.6	Semi-deciduous forest	Moderate	2,6
RCP 2.6	Western montane forest	Very low	18,2
RCP 2.6	Western montane forest	Low	80,8
RCP 2.6	Western montane forest	Moderate	1,0
RCP 2.6	Páramo	Very low	14,4

(continued)

Appendix 4. Continued

Exposure (scenario)	Ecosystem	Level of exposure	Percentage
RCP 2.6	Páramo	Low	85,3
RCP 2.6	Páramo	Moderate	0,3
RCP 2.6	Eastern montane forest	Very low	0,0
RCP 2.6	Eastern montane forest	Low	63,9
RCP 2.6	Eastern montane forest	Moderate	36,1
RCP 2.6	Amazon rainforest	Low	16,2
RCP 2.6	Amazon rainforest	Moderate	83,8
RCP 2.6	Amazon semi-deciduous forest	Low	22,9
RCP 2.6	Amazon semi-deciduous forest	Moderate	77,1
RCP 8.5	Mangroves	Moderate	100,0
RCP 8.5	Deciduous forest	Moderate	58,0
RCP 8.5	Deciduous forest	High	42,0
RCP 8.5	Semi-deciduous forest	Moderate	1,9
RCP 8.5	Semi-deciduous forest	High	93,6
RCP 8.5	Semi-deciduous forest	Very jigh	4,5
RCP 8.5	Western montane forest	Moderate	0,1
RCP 8.5	Western montane forest	High	98,7
RCP 8.5	Western montane forest	Very jigh	1,1
RCP 8.5	Páramo	Moderate	0,2
RCP 8.5	Páramo	High	99,5
RCP 8.5	Páramo	Very jigh	0,4
RCP 8.5	Eastern montane forest	High	52,9
RCP 8.5	Eastern montane forest	Very jigh	47,1
RCP 8.5	Amazon rainforest	High	12,0
RCP 8.5	Amazon rainforest	Very jigh	88,0
RCP 8.5	Amazon semi-deciduous forest	High	80,0
RCP 8.5	Amazon semi-deciduous forest	Very jigh	20,0

Appendix 5. Sensitivity results.

Ecosystem	Level of Sensitivity	Percentage
Mangrove	Very Low	10,77
Mangrove	Low	46,31
Mangrove	Moderate	26,51
Mangrove	High	5,77
Mangrove	Very High	10,64
Deciduous Forest	Very Low	2,65
Deciduous Forest	Low	36,37
Deciduous Forest	Moderate	44,29
Deciduous Forest	High	13,90
Deciduous Forest	Very High	2,79
Semi-deciduous Forest	Very Low	7,39
Semi-deciduous Forest	Low	27,84
Semi-deciduous Forest	Moderate	31,21

(continued)

Appendix 5. Continued

Ecosystem	Level of Sensitivity	Percentage
Semi-deciduous Forest	High	25,38
Semi-deciduous Forest	Very High	8,18
Western Montane Forest	Very Low	28,47
Western Montane Forest	Low	32,30
Western Montane Forest	Moderate	20,30
Western Montane Forest	High	13,32
Western Montane Forest	Very High	5,61
Páramo	Very Low	45,44
Páramo	Low	28,55
Páramo	Moderate	18,38
Páramo	High	6,00
Páramo	Very High	1,63
Eastern Montane Forest	Very Low	42,08
Eastern Montane Forest	Low	40,06

(continued)

Appendix 5. Continued

Ecosystem	Level of Sensitivity	Percentage
Eastern Montane Forest	Moderate	13,97
Eastern Montane Forest	High	3,57
Eastern Montane Forest	Very High	0,32
Amazon Rainforest	Very Low	21,05
Amazon Rainforest	Low	35,89
Amazon Rainforest	Moderate	24,70
Amazon Rainforest	High	13,55
Amazon Rainforest	Very High	4,82
Amazon Semi-deciduous Forest	Very Low	4,96
Amazon Semi-deciduous Forest	Low	12,47
Amazon Semi-deciduous Forest	Moderate	30,38
Amazon Semi-deciduous Forest	High	41,38
Amazon Semi-deciduous Forest	Very High	10,80

Appendix 6. Adaptive Capacity results.

Ecosystem	Level of Adaptive Capacity	Percentage
Mangrove	Very Low	79,27
Mangrove	Low	4,73
Mangrove	High	6,70
Mangrove	Very High	9,30
Deciduous Forest	Very Low	22,25
Deciduous Forest	Low	0,30
Deciduous Forest	Moderate	49,50
Deciduous Forest	High	27,95
Deciduous Forest	Very High	0,00
Semideciduous Forest	Very Low	40,43
Semideciduous Forest	Low	27,94
Semideciduous Forest	Moderate	19,89
Semideciduous Forest	High	10,84
Semideciduous Forest	Very High	0,90
Western Montane Forest	Very Low	35,56
Western Montane Forest	Low	24,31
Western Montane Forest	Moderate	11,94
Western Montane Forest	High	16,18
Western Montane Forest	Very High	12,01
Páramo	Very Low	21,72
Páramo	Low	17,40
Páramo	Moderate	5,85
Páramo	High	19,16
Páramo	Very High	35,87
Eastern Montane Forest	Very Low	5,33

(continued)

Appendix 6. Continued

Ecosystem	Level of Adaptive Capacity	Percentage
Eastern Montane Forest	Low	42,05
Eastern Montane Forest	Moderate	4,91
Eastern Montane Forest	High	14,95
Eastern Montane Forest	Very High	32,76
Amazon Rainforest	Very Low	27,21
Amazon Rainforest	Low	40,75
Amazon Rainforest	Moderate	1,62
Amazon Rainforest	High	19,77
Amazon Rainforest	Very High	10,65
Amazon Semi-deciduous Forest	Very Low	0,10
Amazon Semi-deciduous Forest	Low	83,65
Amazon Semi-deciduous Forest	Moderate	8,29
Amazon Semi-deciduous Forest	High	7,96

Appendix 7. Vulnerability to climate change results.

Vulnerability (scenario)	Ecosystem	Level of Vulnerability	Percentage
RCP 2.6	Mangrove	Very Low	0,40
RCP 2.6	Mangrove	Low	25,89
RCP 2.6	Mangrove	Moderate	70,44
RCP 2.6	Mangrove	High	3,28
RCP 2.6	Deciduous Forest	Very Low	0,01
RCP 2.6	Deciduous Forest	Low	57,83
RCP 2.6	Deciduous Forest	Moderate	42,15
RCP 2.6	Deciduous Forest	High	0,02
RCP 2.6	Semi-deciduous Forest	Very Low	0,39
RCP 2.6	Semi-deciduous Forest	Low	24,15
RCP 2.6	Semi-deciduous Forest	Moderate	74,19
RCP 2.6	Semi-deciduous Forest	High	1,27
RCP 2.6	Western Montane Forest	Very Low	9,56
RCP 2.6	Western Montane Forest	Low	39,77
RCP 2.6	Western Montane Forest	Moderate	49,96
RCP 2.6	Western Montane Forest	High	0,72
RCP 2.6	Páramo	Very Low	34,50
RCP 2.6	Páramo	Low	35,25
RCP 2.6	Páramo	Moderate	30,20
RCP 2.6	Páramo	High	0,05
RCP 2.6	Eastern Montane Forest	Very Low	16,07
RCP 2.6	Eastern Montane Forest	Low	57,52
RCP 2.6	Eastern Montane Forest	Moderate	26,41
RCP 2.6	Eastern Montane Forest	High	0,00
RCP 2.6	Amazon Rainforest	Very Low	2,78
RCP 2.6	Amazon Rainforest	Low	33,69

(continued)

Appendix 7. Continued

Vulnerability (scenario)	Ecosystem	Level of Vulnerability	Percentage
RCP 2.6	Amazon Rainforest	Moderate	61,74
RCP 2.6	Amazon Rainforest	High	1,79
RCP 2.6	Amazon Semi-deciduous Forest	Low	6,13
RCP 2.6	Amazon Semi-deciduous Forest	Moderate	93,87
RCP 8.5	Mangrove	Low	0,00
RCP 8.5	Mangrove	Moderate	16,14
RCP 8.5	Mangrove	High	74,05
RCP 8.5	Mangrove	Very High	9,81
RCP 8.5	Deciduous Forest	Moderate	25,87
RCP 8.5	Deciduous Forest	High	73,22
RCP 8.5	Deciduous Forest	Very High	0,91
RCP 8.5	Semi-deciduous Forest	Low	0,00
RCP 8.5	Semi-deciduous Forest	Moderate	4,52
RCP 8.5	Semi-deciduous Forest	High	85,27
RCP 8.5	Semi-deciduous Forest	Very High	10,21
RCP 8.5	Western Montane Forest	Low	2,79
RCP 8.5	Western Montane Forest	Moderate	17,12
RCP 8.5	Western Montane Forest	High	72,20
RCP 8.5	Western Montane Forest	Very High	7,89
RCP 8.5	Páramo	Low	28,59
RCP 8.5	Páramo	Moderate	16,53
RCP 8.5	Páramo	High	53,13
RCP 8.5	Páramo	Very High	1,75
RCP 8.5	Eastern Montane Forest	Low	3,05
RCP 8.5	Eastern Montane Forest	Moderate	35,02
RCP 8.5	Eastern Montane Forest	High	60,37
RCP 8.5	Eastern Montane Forest	Very High	1,62
RCP 8.5	Amazon Rainforest	Low	0,01
RCP 8.5	Amazon Rainforest	Moderate	11,07
RCP 8.5	Amazon Rainforest	High	68,89
RCP 8.5	Amazon Rainforest	Very High	20,03
RCP 8.5	Amazon Semi-deciduous Forest	High	97,59
RCP 8.5	Amazon Semi-deciduous Forest	Very High	2,33

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