Understanding how GCC is affecting the biological diversity of the Andes is of utmost importance and timeliness given the relevance of the region for biological conservation. Our research questions were (1) what is the spatial (country-level) and temporal distribution of the scientific research exploring links between GCC and biodiversity in the Andean region? (2) What are the methodological approximations, areas of research and subjects of study most commonly considered? And (3) What are the trends in biodiversity responses most commonly found under different GCC stressors? We found that the first paper on GCC and biodiversity in the Andes was published in 2001. Since then the annual rate of publications, as well as the variety of areas of research, has risen steeply. The 65 published articles we found are likely to represent 1% of the scientific literature dealing with tropical ecology. Of those, more than half of the studies were conducted in a single country, used mostly observation rather than modelling or experimental methodological approaches, and focused mainly on plants. Studies dealing with birds, mammals and reptiles were notoriously underrepresented. The high number of GCC stressors and the great variety of responses found in this synthesis makes it difficult to draw general conclusions. However, we found that observational, modelling and experimental studies report negative GCC impacts on the biological diversity of the region. Most generally, observation and modelling studies report contractions of the distribution ranges of Andean species, and negative effects on species population densities and individual performance. We conclude our review suggesting that networking, recovering historic field data and conducting large-scale ecosystem experimental studies are critical to improve our knowledge on the effects of GCC on Andean biodiversity.

**Keywords:** Andean countries; biological response; experimental; observation and modelling studies; global climate change stressors

**Introduction**

Global climate change (GCC) comprises environmental and ecological changes that affect ecological systems, including human populations worldwide.[1] Although global warming is by far the most widely recognized GCC stressor, increases of the atmospheric concentrations of CO2, nitrogen deposition and land-use land-cover change (LULCC), also have strong effects on biological diversity and ecosystem functioning at global scales.[1] GCC stressors do not act in isolation, but interactively, making their overall impacts on biological diversity and ecosystem functioning difficult to disentangle.

The Andes mountain chain is critical for biodiversity conservation at the global scale.[2] Indeed, the Tropical Andes are considered the most important of all biodiversity hotspots, as it holds the highest variety of species of plants, amphibians, birds and mammals.[2] The great diversity of plants and animals supply medicines, food, fibres, construction materials and decorative and cultural crafts to local human populations.[3–6] It is estimated that people in an Andean country use at least 25% of the plant species recorded for the country.[7] The natural vegetation of the Andes is home to the wild relatives of plants that are global staple foods, including potatoes, tomatoes and quinoa.[8] This region also delivers key ecosystem services (i.e., water provision, carbon sequestration) to more than 50 million people living in or near the Andean mountain chain.[9] Thus, understanding how ongoing GCC is affecting the biological diversity of the Andes is of the utmost importance and timeliness.[10]

Across the globe, mountain regions are particularly vulnerable to GCC. Mountain habitats are reduced in size, experience a high geographic isolation and their environmental conditions (i.e., temperature, humidity) change considerable across small distances due to steep slopes. Evidence of GCC impacts on mountain systems has started to accumulate. For example, plant communities across European mountains have shown signs of thermal migration that include the decline of populations of cold-adapted species, and the increase of warm-adapted ones.[11,12]

Andean ecosystems are also responding to GCC. For example, the Northern Andes, a critical area for the conservation of global biodiversity, is expected to lose as...
many as 2000 endemic species as a consequence of GCC.[13] Species of trees in the Andes are shrinking their areas of distribution,[14] migrating upwards,[15] or experiencing higher rates of mortality and possibly of biomass loss.[16] Thus, GCC will dramatically impact the biological diversity and ecosystem functioning of the whole region. Moreover, Andean ecosystems have experienced strong reductions of their original area due to historic and present human activities. GCC is shifting the environmental conditions of the Andes at an unprecedented rate. The North and Central regions of the Andean range will experience climatic departure (i.e. strong divergence from historic climatic conditions) as soon as 2020.[17] In this part of the Andes, near-surface temperatures are expected to increase up to 5 °C by the end of this century, and will generate spatially heterogeneous changes in precipitation.[18–20]

Monitoring the volume and geographic distribution of scientific production in the field of ecology is important to evaluate the efficiency of the funds allocated by government and non-government institutions interested in promoting research and conservation of tropical areas.[21] Indeed, previous research of this type indicates that the amount of biological research in the Andean region is extremely limited compared to that conducted in the Amazonia and Central America.[21] Thus, providing a general view of the type of research, geographical distribution, and general responses of biological diversity to GCC is helpful to identify general trends of biological research. Identifying gaps on the patterns and rates of scientific production in the Andes may help to guide the interest of scientists and funding agencies in the region. In this study, we summarize the temporal trends of published research investigating the effects of GCC on the biodiversity of the Andean region up to 2015. We know of no previous synthesis of published information on this topic for the region. As such we focus our review in basic patterns presented by the scientific literature. Our research questions are, (1) what is the spatial (country-level) and temporal distribution of the scientific research exploring links between GCC and biodiversity in the Andean region? (2) What are the methodological approximations, areas of research and subjects of study most commonly considered? And (3) what are the trends in biodiversity responses most commonly found under different GCC stressors? We provide a review of published literature on the effects of GCC in the region, and hope to motivate scientists to accelerate research on this topic.

**Methods**

We began our synthesis by first searching in the Science Citation Index Expanded (Web of Science) for the period between April 1975 (the earliest date in Web of Science we had access to) and December 2015 using the following quotation: (climate change OR global warming OR global change) AND Ande* AND (species OR species richness OR species diversity OR biodiversity). We then selected articles that specifically addressed GCC effects on species diversity or organismal performance; however, we did not consider studies dealing with paleo-biology. We extracted the following information from each article: geographic scope, year of publication, type of study according to the main method used to assess the effects of GCC on species biodiversity (i.e. observation, experimental or modelling), area of research (e.g. biodiversity, extinction, physiology), type of organism studied (e.g. plants, animals, diversity in general) and the GCC stressor(s) (e.g. temperature increase, land-use cover change, etc.) driving the biological response investigated. For each study, the biological responses were categorized as increase, decrease or no change.

We used this information to analyze geographic and temporal trends of research production. We also discuss what type of organisms was more frequently investigated. Finally, we discuss general patterns of biodiversity responses to GCC by type of study: observation, experimental or modelling.

**Results**

**Geographic and temporal distribution of studies**

We found 65 articles that investigated the effects of GCC on organismal performance or species diversity in the Andes (Table 1). Thirty-nine of these studies were conducted in a single country, mainly in Ecuador, Peru and Chile, whereas 26 studies spanned two or more countries (Figure 1). The countries with the highest total number of studies were Ecuador (n = 31) and Peru (n = 30), whereas Argentina, Venezuela and Bolivia had about half the studies (n = 13, 13 and 15, respectively). Only three articles focused in the Andean region as a whole.

The first study to investigate GCC in the Andes was published in 2001, and the publication rates rose steeply until 2015. Indeed, about half of the studies were published between 2010 and 2015. Thus, from 2001 to 2015 the mean number of articles published on the subject of interest of this study was about four articles per year.

**Methods, areas of research and subjects of study**

Observation studies were by far the most commonly used approach to investigate the effects of GCC in species diversity. Most of the studies (n = 37) used methods based on field observations. About a quarter of the articles (n = 19) used modelling techniques, and the rest (n = 10) used an experimental approach (Figure 2).
Table 1. Studies exploring the effects of global climate change on biodiversity in the Andes between 2001 and 2015.

| Number | Year | Title [reference] | Organism | Topic | Approach | Country |
|--------|------|-------------------|----------|-------|----------|---------|
| 1      | 2001 | Population declines and priorities for amphibian conservation in Latin America [38] | Animals (amphibians) | Population decline | Observation | Colombia, Ecuador, Peru, Chile |
| 2      | 2003 | Population decline of the Jambato toad *Atelopus ignescens* (Anura: Bufonidae) in the Andes of Ecuador [39] | Animals (amphibians) | Population decline | Observation | Ecuador |
| 3      | 2004 | Spatiotemporal influences of climate on altitudinal treeline in northern Patagonia [40] | Plants | Growth | Observation | Chile, Argentina |
| 4      | 2004 | Mountain biodiversity patterns at low and high latitudes [41] | Plants | Biodiversity | Observation | Ecuador, Peru, Bolivia |
| 5      | 2005 | Cambios en la Diversidad en Siete Comunidades de Anuros en los Andes el Ecuador [42] | Animals (amphibians) | Extinction | Observation | Ecuador |
| 6      | 2005 | Spatial and temporal variation in *Nothofagus pumilio* growth at treeline along its latitudinal range (35°40'–55° S) in the Chilean Andes [43] | Plants | Growth | Observation | Chile, Argentina |
| 7      | 2006 | Global warming and extinctions of endemic species from biodiversity hotspots [13] | Animals–Plants | Biodiversity | Modelling | Venezuela, Colombia, Ecuador, Peru, Bolivia |
| 8      | 2006 | A chytridiomycosis epidemic and severe dry season precede the disappearance of *Atelopus* species from the Venezuelan Andes [44] | Animals (amphibians–fungi) | Extinction | Observation | Venezuela |
| 9      | 2007 | High solar radiation hinders tree regeneration above the alpine treeline in Northern Ecuador [45] | Plants | Migration | Experimental | Ecuador |
| 10     | 2007 | Upward range extension of Andean anurans and chytridiomycosis to extreme elevations in response to tropical deglaciation [46] | Animals (amphibians–fungi) | Extinction | Observation | Peru |
| 11     | 2007 | A field experiment on climatic and herbivore impacts on post-fire tree regeneration in north-western Patagonia [47] | Plants | Regeneration, species interactions | Experimental | Argentina |
| 12     | 2007 | Consecuencias de las variaciones microclimáticas sobre la visita de insectos polinizadores en dos especies de Chaetanthera (Asteraceae) en los Andes de Chile central [48] | Plants–Animals | Species interactions | Experimental | Chile |
| 13     | 2008 | Temperature as a key driver of ecological sorting among invasive pest species in the tropical Andes [49] | Animals (insects) | Disease | Empirical | Ecuador |
| 14     | 2008 | Conservation strategies to mitigate impacts from climate change in Amazonia [50] | Biodiversity | Biodiversity conservation | Observation | Venezuela, Colombia, Ecuador, Peru |
| 15     | 2008 | Riding the wave: reconciling the roles of disease and climate change in amphibian [51] | Animals (amphibians–fungi) | Extinction | Observation | Venezuela, Colombia, Ecuador, Peru |
| 16     | 2009 | Long-term drivers of change in *Polylepis* woodland distribution in the central Andes [52] | Plants | Spatial distribution | Observation | Peru, Bolivia |
| 17     | 2009 | Projected climate-induced faunal change in the Western Hemisphere [53] | Animals (amphibians, birds, mammals) | Biodiversity | Modelling | Venezuela, Colombia, Ecuador |
| 18     | 2010 | Projected climate impacts for the amphibians of the Western Hemisphere [54] | Animals (Amphibians) | Spatial distribution | Modelling | Venezuela, Colombia, Ecuador, Peru, Bolivia, Chile, Argentina |

(Continued)
| Number | Year | Title [reference]                                                                 | Organism                  | Topic                          | Approach       | Country                                |
|--------|------|-----------------------------------------------------------------------------------|----------------------------|-------------------------------|----------------|----------------------------------------|
| 19     | 2009 | Species dynamics in a montane cloud forest: Identifying factors involved in changes in tree diversity and functional characteristics [55] | Plants                     | Biodiversity and functional groups | Observation    | Peru                                    |
| 20     | 2009 | Does global warming induce segregation among alien and native beetle species in a mountaintop? [56] | Animals (insects)          | Invasive species               | Observation    | Chile                                   |
| 21     | 2009 | Ain’t no mountain high enough: plant invasions reaching new elevations [57]        | Plants                     | Species invasions              | Observation    | Chile                                   |
| 22     | 2009 | Epiphytic plants in a changing world-global: change effects on vascular and non-vascular epiphytes [58] | Plants                     | Species distributions, physiology, extinction | Observation    | Ecuador, Peru, Bolivia                 |
| 23     | 2010 | Woody species diversity in temperate Andean forests: the need for new conservation strategies [59] | Plants                     | Biodiversity conservation      | Modelling      | Chile                                   |
| 24     | 2010 | Functional biodiversity and climate change along an altitudinal gradient in a tropical mountain rainforest [60] | Plants–Animals             | Biodiversity and functional groups | Modelling      | Ecuador                                 |
| 25     | 2010 | Land-use and climate change effects on population size and extinction risk of Andean plants [61] | Plants                     | Population size, extinction    | Modelling      | Colombia, Ecuador, Peru and Bolivia    |
| 26     | 2010 | Changes in species interactions across a 2.5 km elevation gradient: effects on plant migration in response to climate change [25] | Plants                     | Species interactions           | Observation    | Peru                                    |
| 27     | 2010 | Effects of climate change on subtropical forests of South America [62]             | Plants                     | Biodiversity                   | Modelling      | Bolivia, Argentina                      |
| 28     | 2011 | Dendroecological analysis of defoliator outbreaks on Nothofagus pumilio and their relation to climate variability in the Patagonian Andes [63] | Plants–Animals             | Herbivory                      | Observation    | Argentina                               |
| 29     | 2011 | Summer freezing resistance decreased in high-elevation plants exposed to experimental warming in the central Chilean Andes [64] | Plants                     | Plant physiology               | Observation    | Chile                                   |
| 30     | 2011 | Projected changes in elevational distribution and flight performance on montane Neotropical hummingbirds in response to climate change [65] | Animals (Birds)            | Spatial distribution           | Modelling      | Venezuela, Colombia, Ecuador           |
| 31     | 2011 | Upslope migration of Andean trees [15]                                           | Plants (Birds)             | Migration                      | Observation    | Peru                                    |
| 32     | 2011 | Elevational ranges of birds on a tropical montane gradient lag behind warming temperatures [66] | Animals (Birds)            | Spatial distribution           | Observation    | Peru                                    |
| 33     | 2011 | Additive threats from pathogens, climate and land-use change for global amphibian diversity [67] | Animals (Amphibians)       | Extinction                     | Modelling      | Venezuela, Colombia, Ecuador, Peru, Bolivia |
| 34     | 2011 | Climate-induced input of turbid glacial meltwater affects vertical distribution and community composition of phyto and zooplankton [68] | Phyto and Zooplankton      | Community composition          | Observation    | Argentina                               |
| 35     | 2011 | Patterns and magnitude of temporal change in avian communities in the Ecuadorian Andes [69] | Animals (Birds)            | Biodiversity                   | Observation    | Ecuador                                 |
| 36     | 2011 | New highland distribution records of multiple Anopheles species in the Ecuadorian Andes [70] | Animals (Insects)          | Disease                        | Observation    | Ecuador                                 |
| 37     | 2012 | Neotropical C3/C4 grass distribution – present, past and future [71]              | Plants                     | Spatial distribution           | Modelling      | Colombia, Ecuador, Peru, Bolivia        |
| 38     | 2012 | Facilitative interactions do not wane with warming at high elevations in the Andes [72] | Plants                     | Species interactions           | Experimental   | Chile                                   |
| 39     | 2012 | Intra- and interspecific tree growth across a long altitudinal gradient in the Peruvian Andes [73] | Plants                     | Growth                         | Observation    | Peru                                    |
| 40     | 2012 | Efecto del aumento de la temperatura en la fotosíntesis de una especie alto-andina en dos altitudes [74] | Plants                     | Spatial distribution, physiology | Experimental   | Chile                                   |
| 41     | 2013 | Temperature-driven flower longevity in a high alpine species of Oxalis influences reproductive assurance [75] | Plants                     | Plant phenology                | Experimental   | Chile                                   |
| Year | Title                                                                 | Authors                          | Methodology | Location          |
|------|----------------------------------------------------------------------|----------------------------------|-------------|-------------------|
| 2013 | Temperature-dependent shifts in herbivore performance and interactions drive nonlinear changes in crop damages [76] | Plants–Animals Herbivory         | Experimental | Ecuador           |
| 2013 | Tree growth responses across environmental gradients in subtropical Argentinean forests [77] | Plants Growth                   | Observation  | Argentina         |
| 2013 | The relationship of tropical bird communities to tree species composition and vegetation structure along an Andean elevational gradient [78] | Animals Spatial distribution     | Observation  | Peru              |
| 2013 | Predicting climate change caused changes in global temperature on potato tuber moth Phthorimaea operculella (Zeller) distribution and abundance using phenology modelling and GIS mapping [79] | Animals Spatial distribution     | Modelling    | Ecuador, Peru, Colombia |
| 2013 | Four decades of Andean timberline migration and implications of biodiversity loss with climate change [80] | Plants Migration                | Observation  | Peru              |
| 2013 | Simulated warming does not impair seedling survival and growth of *Nothofagus pumilio* in the southern Andes [81] | Plants Growth, germination       | Experimental | Chile             |
| 2013 | Forest patches and the upward migration of the timberline in the southern Pervian Andes [82] | Plants Migration                | Observation  | Peru              |
| 2013 | Effects of climate change on species distribution, community structure, and conservation of birds in protected areas in Colombia [83] | Birds–Plants Species distribution, community structure, biodiversity conservation | Modelling    | Colombia          |
| 2014 | Biodiversity patterns and continental insularity in the tropical high Andes [84] | Plants–Animals Species distribution, biodiversity conservation | Observation  | Venezuela, Colombia, Ecuador, Peru, Bolivia, Chile, Argentina, Colombia |
| 2014 | Predicted altitudinal shifts and reduced spatial distribution of *Leishmania infantum* vector species under climate change scenarios in Colombia [85] | Animals Spatial distribution     | Modelling    | Venezuela, Colombia, Ecuador, Peru, Bolivia, Chile, Argentina, Colombia |
| 2014 | Using species distributions models for designing conservation strategies of tropical Andean biodiversity under climate change [86] | Plants–Animals Biodiversity      | Biodiversity | Venezuela, Colombia, Ecuador, Peru and Bolivia |
| 2015 | Relationships between climate variability and radial growth of *Nothofagus pumilio* near altitudinal treeline in the Andes of northern Patagonia, Chile [87] | Plants Growth                  | Observation  | Chile             |
| 2015 | Projected distribution shifts and protected area coverage of range-restricted Andean birds under climate change [88] | Animals Spatial Distribution    | Modelling    | Peru, Bolivia     |
| 2015 | Large-scale patterns of turnover and basin area change in Andean forests [16] | Species Diversity Conservation  | Observation  | Colombia, Ecuador, Peru, Argentina, Ecuador |
| 2015 | Invertebrate metacommunity structure and dynamics in an Andean glacial stream network facing climate change [89] | Animals Spatial distribution     | Modelling    | Colombia, Ecuador, Peru, Bolivia, Chile |
| 2015 | Changes in the distribution of multispecies pest assemblages affect levels of crop damage in warming tropical Andes [90] | Animal Species Invasion         | Observation  | Colombia, Ecuador, Peru, Bolivia, Chile |
| 2015 | Thermophilization of adult and juvenile tree communities in the northern tropical Andes [14] | Plants (Trees) Spatial distribution | Observation  | Colombia, Ecuador, Peru, Bolivia, Chile |
| 2015 | Future habitat loss and extinctions driven by land-use change in biodiversity hotspots under four scenarios of climate-change mitigation [91] | Plants Biodiversity conservation | Modelling    | Colombia, Ecuador, Peru, Bolivia, Chile |
| 2015 | The impact of climate change on the geographical distribution of two vectors of Chagas disease: implications for the force of infection [92] | Animals Spatial Distribution-Animal Physiology | Modelling    | Venezuela, Argentina |

(Continued)
| Number | Year  | Title [reference] | Organism      | Topic                | Approach       | Country          |
|--------|-------|-------------------|---------------|----------------------|----------------|------------------|
| 61     | 2015  | Climate change forces new ecological states in tropical Andean lakes [93] | Phytoplankton | Biodiversity          | Observation    | Ecuador          |
| 62     | 2015  | Strong upslope shifts in Chimborazo’s vegetation over two centuries since Humboldt [22] | Plants        | Biodiversity          | Observation    | Ecuador          |
| 63     | 2015  | Ecological and geographical analysis of the distribution of the mountain tapir (Tapirus pinchaque) in Ecuador [94] | Animals       | Spatial distribution  | Modelling      | Ecuador          |
| 64     | 2015  | The inability of tropical cloud forest species to invade grasslands above treeline during climate change: potential explanations and consequences [95] | Plants (Trees) | Migration             | Observation    | Venezuela, Colombia, Ecuador, Peru, Bolivia, Chile, Argentina |
| 65     | 2015  | Freezing temperatures as a limit to forest recruitment above tropical Andean treelines [96] | Plants (Trees) | Migration             | Experimental   | Peru             |

1. Young, BE, et al. Conserv Biol. 2001;15:1213–1223. 2. Ron SR, et al. J Herpetol. 2003;37:116–126. 3. Daniels LD, Veblen TT. Ecology. 2004;85:1284–1296. 4. Molau U. Ambio. 2004;13:24–28. 5. Bustamante MR, et al. Biotropica. 2005;37:180–189. 6. Lara A, et al. J Biogeogr. 2005;32:879–893. 7. Malcolm JR, et al. Conserv Biol. 2006;20:538–548. 8. Lampo M, et al. Herpetol J. 2006;16:395–402. 9. Bader MY, et al. Plant Ecol. 2007;191:33–45. 10. Seimon TA, et al. Global Change Biol. 2007;13:288–299. 11. Tercero-Bucardo N, et al. J Ecol. 2007;95:771–779. 12. Torres-Díaz C, et al. Revista Chilena de Historia Natural. 2007;80:455–548. 13. Dangles O, et al. Ecol Appl. 2008;18:1795–1809. 14. Killeen TJ, Solórzano LA. Philos Trans R Soc Lond B Biol Sci. 2008;363:1881–1888. 15. Lips KR, et al. PLoS Biol. 2008;6:e67. 16. Gosling WD, et al. J Veg Sci. 2009;20:1041–1052. 17. Lawler JJ, et al. Ecol Appl. 2009;19:588–597. 18. Lawler JJ, et al. Conserv Biol. 2010;24:38–50. 19. Ledo A, et al. For Ecol Manag. 2009;258(Suppl 1):S75–S84. 20. Molina-Montenegro M, et al. Ecol Res. 2009;24:31–36. 21. Pauchard A, et al. Front Ecol Environ. 2009;7:479–486. 22. Zotz G, et al. Progress in botany. Vol. 70. Berlin: Springer; 2009. p. 147–170. 23. Altamirano A, et al. Biol Conserv. 2010;143:2080–2091. 24. Bendix J, H, et al. Tropical rain-forests and agroforests under global change. 2010. p. 239–268. 25. Feeley KJ, Silman MR. Global Change Biol. 2010;16:3215–3222. 26. Hiltyer R, Silman MR. Global Change Biol. 2010;16:3205–3214. 27. Pacheco S, et al. Trop Conserv Sci. 2010;3:423–437. 28. Partiss J, Veblen TT. Global Change Biol. 2011;17:239–253. 29. Sierra-Almeida A, Cavieres LA. Oecologia. 2010;163:267–276. 30. Buemann W, et al. Global Change Biol. 2011;17:1671–1680. 31. Feeley KJ, et al. J Biogeogr. 2011;38:783–791. 32. Foreo-Medina G, et al. PloS One. 2011;6:e28535. 33. Hoj C, et al. Nature. 2011;480:516–519. 34. Hylander S, et al. J Plankton Res. 2011. 35. Latta SC, et al. Condor. 2011;113:24–40. 36. Pinault L, Hunter F, Malar J. 2011;10:236. 37. Bremond L, Boom A, Favier C. Global Change Biol. 2011;12:3234–3243. 38. Cavieres LA, Sierra-Almeida A. Oecologia. 2012;170:575–584. 39. Rapp JM, et al. Ecology. 2012;93:2061–2072. 40. Sanfuentes C, et al. Gayana Bot. 2012;69:37–45. 41. Arroyo MTK, et al. New Phytol. 2012;200:1260–1268. 42. Dangles O, et al. Global Change Biol. 2013;19:1056–1063. 43. Ferrero ME, et al. Plant Ecol. 2013;214:1321–1334. 44. Jankowski JE, et al. J Biogeogr. 2013;40:950–962. 45. Kroschel J, et al. Agric For Meteorol. 2013;170:228–241. 46. Lutz DA, et al. PLoS One. 2013;8:e74946. 47. Piper FI, et al. Perspect Plant Ecol Ecol Evol Syst. 2013;15:97–105. 48. Rehm EM, Feeley KJ. For Ecol Manag. 2013;305:204–211. 49. Velásquez-Tibatá A, et al. Reg Environ Change. 2013;13:235–248. 50. Anhelme F, et al. Arct Antarct Alp Res. 2014;46:811–828. 51. González C, Paz A, Ferro C. Acta Trop. 2014;139:30–39. 52. Ramirez-Villegas J, et al. J Nat Conserv. 2014;121:112–121. 53. Álvarez C, et al. For Ecol Manag. 2015;342:112–131. 54. Avalos VdR, Hernández J. Global Ecol Conserv. 2015;3:459–469. 55. Báez S, et al. PLoS One. 2015;10:e0126594. 56. Caudy-Fraunié S, et al. PLoS One. 2015;10:e0136793. 57. Crespo-Pérez V, et al. Global Change Biol. 2015;21:82–96. 58. Duque A, et al. Proc Natl Acad Sci. 2015;112:10744–10749. 59. Jantz SM, et al. Conserv Biol. 2015;29:1122–1131. 60. Medone P, et al. Philos Trans R Soc Lond B Biol Sci. 2015;370. 61. Michelutti N, et al. PLoS One. 2015;10:e015338. 62. Morueta-Holme N, et al. Proc Natl Acad Sci. 2015;112:12741–12745. 63. Ortega-Andrade HM, et al. PloS One. 2015;10:e0121137. 64. Rehm EM, Feeley KJ. Ecography. 2015;38:1167–1175. 65. Rehm EM, Feeley KJ. Ecology. 2015;96:1856.
We identified five main areas of research; the areas of ‘Biodiversity’ and ‘Spatial distributions of species’ were the focus of most studies, with 15 and 25 papers, respectively (Table 2). It is noteworthy that the representation of the areas of research has changed through time (Figure 1). The early research on GCC and diversity in the Andes focused on general aspects of species distribution, biodiversity conservation and species extinction, mainly amphibian’s species loss due to fungal infections (Figures 2 and 3, Table 2). Later on, the areas of study became more diverse, and had an increased representation of studies exploring physiology and forest dynamics.

With regard to the focus of the studies on different types of organisms, we found that most frequently research investigated the effects of GCC in species of plants (32 studies) compared to studies that considered species of animals or both types of organisms simultaneously (Figure 3(a)). Amphibians represented the most studied group of vertebrates, followed by insects and aquatic invertebrates (Figure 3(b)), whereas other groups of vertebrates, including birds, mammals and reptiles, were virtually excluded.

### Study types and trends of biodiversity response to GCC stressors

Observation studies explored the variation of 10 GCC stressors on more than 50 types of responses of biological diversity (Figure 4). Most of the papers explored how biodiversity or organismal biology was affected by higher environmental temperature \( (n = 16) \) and GCC variables considered simultaneously \( (n = 13) \). The GCC stressors studied generally affected biological diversity or organismal performance in one way or another, very few studies reported no effects. The studies often reported changes in the spatial distribution of the species, decreases of the population growth rates and altered rates of plant growth and seedling establishment (Figure 5).

Of the 19 modelling studies, 18 addressed the effects of all GCC stressors simultaneously on biodiversity (Figure 5). These studies focused on predicting how GCC will affect the spatial distribution of plant species, and the species diversity in general. Most of the studies predicted upward shifts and range contractions of species distributions, and decreased spatial ranges of species occupancy. Further, various studies predicted decreased species diversity under GCC.

The experimental studies largely focused on the effects of higher environmental temperatures (Figure 6). These studies explored the effects of higher environmental temperature or higher altitudinal distribution of species on plants or plant–animal interactions, and on plant physiological responses. It is interesting to note that these studies found decreased plant performance under experimental evaluations of GCC, but some studies reported no responses or changes in physiological activity or plant performance.
Discussion

Our findings indicate an uneven distribution of studies among Andean countries, where Ecuador and Peru (and to a lesser extent Chile) have a high volume of publications compared to other countries that remain virtually unexplored, mainly Bolivia (Figure 1). Indeed, other studies point out that much biological research is being conducted in Ecuador and Colombia compared to other countries, and that Ecuador occupies the best studied country of South America, including the Andean region, once research production is standardized by area.\[21\]

A study exploring the extent of ecological research in the Andes and Amazon between 1995 and 2008 in two prominent ecological journals found that only 77 of 373 studies focused in the Andean region during this period, and estimated that the total biological publications for both regions were of 1540 scientific articles.\[21\] According to our search, 13 studies were produced between 2001 and 2008 (Figure 2); therefore, roughly 1% of the ecological research conducted during that time period explored the effects of GCC and

---

Table 2. Breakdown of effects of GCC according to the areas of study.

| Major themes                        | Areas of research                                                                 |
|------------------------------------|----------------------------------------------------------------------------------|
| Biodiversity (n = 15)              | Biodiversity [4,7,17,27,35,52,62]
|                                    | Biodiversity and functional groups [19,24,61]
|                                    | Biodiversity conservation [14,23,59]
|                                    | Community composition [34,56]
| Species interactions (n = 8)       | Disease [13,36]
|                                    | Herbivory [28,42]
|                                    | Regeneration, species interactions [11]
|                                    | Species interactions [12,26,38]
| Extinction (n = 8)                 | Extinction [5,8,10,15,33]
|                                    | Population decline [1,2]
|                                    | Population size, extinction [25]
| Physiology and forest dynamics (n = 9) | Germination [47]
|                                    | Growth [3,6,39,43,53]
|                                    | Plant phenology [41]
|                                    | Forest dynamics [55]
|                                    | Plant physiology [29]
| Spatial distribution of species (n = 25) | Invasive species [20]
|                                    | Migration [9,31,46,48,64,65]
|                                    | Spatial distribution [16,18,30,32,37,44,45,51,54,58,63]
|                                    | Spatial distribution, animal physiology [40,60]
|                                    | Species distribution, community structure, biodiversity conservation [49,50]
|                                    | Species distribution, physiology, extinction [22]
|                                    | Species invasions [21,57]

Note: The numbers in parenthesis indicate the articles references according to Table 1.

---

Figure 3. Distribution of the studies according to (a) type of organism and (b) type of animal studied.
biodiversity in the Andes. These numbers illustrate a large knowledge limitation on how biological diversity of the Andes, an already poorly investigated region, is responding to GCC.

Our results also revealed that much of the knowledge we have about biodiversity and GCC in the Andes focuses on plants. It has been developed using observation or modelling approaches using information available on large repositories of biological data, mainly botanical databases; therefore many of these studies include two or more countries (Figures 1–5). Moreover, much of the early research exploring biodiversity and GCC at the scale of the whole Andean region explored amphibian’s extinction and their links to fungal infection and higher environmental temperatures (Figure 3). Surprisingly, research on insect responses to GCC represented almost half of the studies. The insects are likely receiving attention from scientists because they are amenable to field studies over small spatial and short temporal scales. These patterns, however, make it clear that certain organisms, including birds and mammals are virtually ignored of biological studies of GCC.

The high number of GCC stressors and the great variety of responses found in this synthesis makes it difficult to draw general conclusions (Figures 4–6). However, we found that observational, modelling and experimental studies report negative GCC impacts on the biological diversity of the region. Most generally, observation and modelling studies report contractions of the distribution ranges of Andean species, and negative effects on species population densities and individual performance (Figures 5 and 6). Further, interspecific

| Stressor | Increase | Decrease | No response |
|----------|----------|----------|-------------|
| Temperature (n=16) | Physiological changes (22) p | Ecosystem productivity (39) p | Alitudinal distribution (3, 6) p |
| | Competition for pollinators (21) p | Freezing resistance (29) p | |
| | Desiccation damage (22) p | Germination rates (22) p | |
| | Displacement of native species (21) p | Growth rates (43) p | |
| | Plant growth rates (3, 6, 43, 55) p | Population densities (16) p | |
| | Tree growth of certain species (39) p | Tree growth of certain species (39) p | |
| | Tree turnover (55) p | Range size (59) p | |
| | Alitudinal shift. (63) p | Native species (20) a | |
| | Disease rates (28) a, p (10) a, f | | |
| | Alitudinal distribution (3, 5, 22) a | | |
| | Amphibian densities (10) a | | |
| | Introduced species (20) a | | |
| | Shifts in species abundance (61) pl | | |
| Global Climate Change (n=13) | Alitudinal distribution (31) p (32, 36) a | Diversity of species (4) a | Disease (15) a f |
| | Extinction rates (1, 2, 5) a | Population density (1, 5) a | Extinction (15) a |
| | Population densities (5) a (19) p | Population densities (19) p | Population density (5) a |
| | Widespread expansion (36) a | Species diversity (35) p | Timberline stability (46, 64) p |
| | Disease rates (28) a p | Species richness (19) p | |
| | Genetic diversity within species (4) p | | |
| | Non linear growth (53) p | | |
| | Disease rates (28) a p | Leaf production (22) p | |
| | Changes in species composition (22) p | Leaf longevity (22) p | |
| | Extinction (22) p | Population densities (16) p | |
| | Leaf mortality (22) p | | |
| | Epidemic expansion (8) a | | |
| Higher altitudinal distribution (n=3) | Alitudinal distribution (birds) (44) a-p | Snowfall abundance (48) p | |
| | Extinction (50) a-p | Seed dispersal (48) p | |
| | Isolation (30) a-p | Species richness (birds) (44) a | |
| | Microclimate severity (44) p | | |
| Higher incidence of Diseases (n=2) | Extinction (8, 15) a-f | Population densities (15) a-f | |
| | Glacial reduction (n=2) | Changes in species abundance (34, 56) pl | Regional diversity (56) pl |
| | Extinction (56) pl | | |
| Higher atmospheric CO2 (n=1) | Photosynthetic capacity (22) p | | |
| | Growth rates (23) p | | |
| Higher availability of soil nutrients (n=1) | Plant invasions (21) p | | |
| Lower landscape connectivity (n=1) | Capacity of species to migrate (14) a | | |

Figure 4. Summary of GCC stressors addressed and the responses found in 37 observation studies exploring the effects of GCC on Andean biodiversity between 2001 and 2015.

Notes: The numbers in parenthesis indicate the article according to Table 1; letters indicate organisms (a = animals, p = plants, f = fungi). Colours unify factors and responses.
interactions (e.g. disease) altered by GCC have already resulted in widespread extinction of amphibians in the Andes. However, it is worth noting that the responses of biodiversity were highly variable, particularly when environmental factors were isolated in experimental studies (Figure 6).

Andean species are responding to GCC by migrating to higher altitudinal ranges.\cite{14,15,22} Differences on the rates of species upslope migration are likely to affect species diversity, interspecific interactions and the ecosystem persistence per se. Recent research indicates that even highly mobile Andean species have narrow environmental envelopes;\cite{23} thus even moderate changes in environmental conditions may threaten the persistence of less mobile high-altitude species. Differences in the tempo of migration may also disrupt interspecific interactions, which may threaten the persistence of the species (e.g. if a species lacks a critical mutualism in its reproductive cycle), or alter their relative densities in the community (e.g. if a species experiences higher or lower predation rates).\cite{24,25} Thus, differences in migration rates and their resulting effects on species interactions are likely to result in hybrid and novel ecosystems in the Andes.\cite{26} A critical aspect of research will be to determine the areas where these changes will take place, and what actions can be taken to enhance species migration considering landscape permeability that include urban development, agriculture, land abandonment and ecosystem restoration, LULUCC.

**Directions for future research**

Pitman et al.\cite{21} present a list of insightful recommendations to improve the scientific production in the Andes and Amazon. In this section, we focus on specific approaches that can be adopted to improve substantially

---

### Table 5

| Stressor | Increase | Decrease | No response |
|----------|----------|----------|-------------|
| GCC (n=14) | Extinction due to habitat loss (69) p.a. | Range shifts, climatic niche (48, 52) p.a. (54, 63) a | Altitudinal distribution (79) p.a. |
| Higher land use change (n=1) | Extinction (7, 52) p.a. | Species diversity (48, 52) p.a. (23, 24, 59) p (15, 33, 20) a | |
| Higher temperature (n=1) | Shifts in spatial distribution (49, 57) p.a. (37, 45) a | Human incidence of disease (51, 60) a | |
| Higher altitudinal distribution (n=1) | Species turnover (52) p.a. | | |
| Higher altitudinal distribution (n=1) | Altitudinal distribution (24*, 30, 52) a (24*, 27) p.a. | | |
| Higher altitudinal distribution | Pest damage (65, 57) a | | |
| Higher solar radiation | Evapotranspiration (24) p | | |
| Lower nighttime temperature (n=1) | Species range movements (18) p | | |
| Lower precipitation (n=1) | Risk of extinction for species (20) p | | |
| Freezing events (n=1) | Shifts of species altitudinal distributions (55) p | | |

* Higher altitudinal distribution would depend on precipitation regimes.

---

### Table 6

| Stressor | Increase | Decrease | No response |
|----------|----------|----------|-------------|
| Higher temperature (n=7) | Changes of species interactions (43) a-p | Flower longevity (41) p | Facilitation (38) p |
| Pest damage (42) a-p | Hydraulic capacity (40) p | Fertilization process (41) p | |
| Pollinator activity (13) a-p | Photosynthetic capacity (40) p | Growth rates (53) p | |
| Growth of seedlings (67) p | Photosynthetic rates (40) p | Seeding production (38) p | |
| Higher alitudinal distribution (n=1) | Colonization rates at higher elevations (26) p | Seed predation (26) p | Changes in physiology (30) a |
| Higher alitudinal distribution | Seedling establishment (9) p | | |
| Higher solar radiation | Basemats abundance (9) p | | |
| Lower nighttime temperature (n=1) | Seeding abundance (9) p | | |
| Lower precipitation (n=1) | Tree regeneration above treeline (9) p | | |
| Freezing events (n=1) | Growth of seedlings (47) p | | |
| | Treeline upward movement (65) p | | |

Notes: The numbers in parenthesis indicate the article according to Table 1; letters indicate organisms (a = animals, p = plants, f = fungi). Colours unify factors and responses.
and over a short-to mid-period of time our knowledge about the effects of GCC on Andean biodiversity. All the proposed directions of research and collaboration would certainly be more helpful if accompanied by strong efforts on human and institutional capacity building.

Networking
Recent networking initiatives have proven very powerful to move forward the field of ecology in the context of GCC globally.[27–30] In the Andean region, the Andean forest network [31] has brought together more than 40 scientists working in the region. Most researchers have contributed their invaluable field data to build a large data-set that is currently being used to conduct studies that explore Andean forests responses to GCC (e.g. [14,16]). In the same way, scientists associated to the GLORIA network are using a core methodology to monitor biodiversity and climate change in high Andean summits.[32,33] Hence, support to ecological networks in the Andes can greatly improve the scientific production of the region.

Recovering historic field data
The general lack of studies of GCC in the Andes may be explained in part by the young history of science in the region where long-term studies are mostly lacking. Thus, historic ecological data can serve as the base to conduct ecological surveys that may give us insights about the types and rates of change of Andean biodiversity and ecosystems. For example, a recent study examines patterns of species, vegetation and LULCC in the Chimborazo volcano using historic data collected by Humboldt in 1802.[22] More recent data, including biodiversity surveys [34] and permanent plots established in the Andes in the last decades can also be very valuable to assess midterm trends of change of the plant community, at least in terms of species dominance and stand structure.

Conducting large-scale ecosystem experimental studies
It is urgent to explore the interactions between nutrient availability and temperature on biodiversity in Andean ecosystems. The recent incorporation of stoichiometry concepts to the study of thermal adaptation [35] suggests complex responses to GCC, where species physiological responses to increases in temperature will also depend on the biogeography of nutrient limitation. We found no articles connecting biodiversity with ecosystem scale effects of GCC, with regard to higher atmospheric CO₂ concentrations and/or nutrient availability. Hence, our capacity to predict how these critical aspects of GCC will affect the diversity of the region is very limited; some evidence suggests that Andean forests can be highly responsive to higher availability of soil N and P.[24,36] Further, it is uncertain how soil nutrient limitation will change in highly heterogeneous tropical montane forests under GCC.[37] Experimental and modelling studies could provide some answers to these issues. Although database literature searches are far from providing a complete view of the existing literature on a subject, we think that this study provides a general overview of the effects of GCC on the biological diversity of the Andes.

Associate Editor: Veerle Vanacker

Disclosure statement
No potential conflict of interest was reported by the authors.

Funding
This work was supported by the Universidad Técnica Particular de Loja [PROY-CCNN-1034] and the Swiss Agency for Development and Cooperation (SDC).

ORCID
Selene Báez http://orcid.org/0000-0002-7236-6242
Liliana Jaramillo http://orcid.org/0000-0002-8611-8311
Francisco Cuesta http://orcid.org/0000-0002-5150-073X
David A. Donoso http://orcid.org/0000-0002-3408-1457

References
[1] Vitousek PM. Beyond global warming: ecology and global change. Ecology. 1994;75:1861–1876.
[2] Myers N, Mittermeier RA, Mittermeier CG, et al. Biodiversity hotspots for conservation priorities. Nature. 2000;403:853–858.
[3] Báez S, Borgtoft H, Fjeldså J, et al. People and Biological Diversity: Two Case Studies From the Andean Foothills of Ecuador. Diva Technical Report 3. Centre for Research on the Cultural and Biological Diversity of the Andean Rainforest (DIVA). The Danish Environmental Research Programme, Aarhus, Denmark. 2008. p. 1–142.
[4] Hofstede R, Ambrose K, Báez S, et al. Biodiversity-based livelihoods in the ceja andina forest zone of Northern Ecuador: multi-stakeholder learning processes for the sustainable use of cloud forest areas. In: Bruijnzeel LA, Scatena FN, Hamilton LS, editors. Tropical Montane Cloud Forests: Science for Conservation and Management. Cambridge: Cambridge University Press; 2010. p. 644–651.
[5] Báez S, Ambrose K, Hofstede R. Ecological and social bases for the restoration of a high Andean cloud forest: preliminary results and lessons from a case study in Northern Ecuador. In: Bruijnzeel LA, Scatena FN, Hamilton LS, editors. Tropical Montane Cloud Forests: Science for Conservation and Management. Cambridge: Cambridge University Press; 2010. p. 628–643.
[6] Thomas E, Douterlunge D, Vandebroek I, et al. Human impact on wild firewood species in the rural Andes community of Apillapampa, Bolivia. Environ Monit Assess. 2011;178:333–347.
[7] de la Torre L, Navarrete H, Muriel M, et al, editors. Encyclopedia of useful plants of Ecuador [Encyclopedia of useful plants of Ecuador]. Quito: Herbario QCA de la Escuela de Biología, Pontificia Universidad Católica del Ecuador; 2008.

[8] Pickersgill B. Domestication of plants in the Americas: insights from Mendelian and molecular genetics. Ann Bot. 2007;100:925–940.

[9] Cincotta RP, Wisnewski J, Engelman R. Human population in the biodiversity hotspots. Nature. 2000;404:990–992.

[10] Feeley K, Silman M, Duque A. Where are the tropical plants? A call for better inclusion of tropical plants in studies investigating and predicting the effects of climate change. Front Biogeogr. 2015;7:174–176.

[11] Gottfried M, Pauli H, Futschik A, et al. Continent-wide response of mountain vegetation to climate change. Nat Clim Change. 2012;2:111–115.

[12] Pauli H, Gottfried M, Reiter K, et al. Signals of range expansions and contractions of vascular plants in the high Alps: observations (1994–2004) at the GLORIA master site Schrankogel, Tyrol, Austria. Global Change Biol. 2007;13:147–156.

[13] Malcolm JR, Liu C, Neilson RP, et al. Global warming and extinctions of endemic species from biodiversity hotspots. Conserv Biol. 2006;20:538–548.

[14] Duque A, Stevenson PR, Feeley KJ. Thermophilization of adult and juvenile tree communities in the northern tropical Andes. Proc Natl Acad Sci. 2015;112:10744–10749.

[15] Feeley KJ, Silman MR, Bush M, et al. Upslope migration of Andean tree communities. J Biogeogr. 2011;38:783–791.

[16] Báez S, Malizia A, Carilla J, et al. Continental-scale patterns of turnover and basal area change in Andean forests. PloS One. 2015;10:e0126594.

[17] Mora C, Frazier AG, Longman RJ, et al. The projected timing of climate departure from recent variability. Nature. 2013;502:183–187.

[18] Vuille M, Bradley RS, Werner M, et al. 20th century climate change in the tropical Andes: observations and model results. Clim Change. 2003;59:75–99.

[19] Vuille M, Francou B, Wagnon P, et al. Climate change and tropical Andean glaciers: past, present and future. Earth-Sci Rev. 2008;89:79–96.

[20] Urrutia R, Vuille M. Climate change projections for the tropical Andes using a regional climate model: temperature and precipitation simulations for the end of the 21st century. J Geophys Res Atmos. 2009;114:D02108.

[21] Pitman N, Widmer J, Jerkins CN, et al. Volume and geographical distribution of ecological research in the Andes and the Amazon, 1995–2008. Trop Conserv Sci. 2011;4:64–81.

[22] Morueta-Holme N, Engemann K, Sandoval-Acuña P, et al. Strong upslope shifts in Chimborazo’s vegetation over two centuries since Humboldt. Proc Natl Acad Sci. 2015;112:12741–12745.

[23] Cárate-Tandalla D, Leuschner C, Homeier J. Performance of seedlings of a shade-tolerant tropical tree species after moderate addition of N and P. Front Earth Sci. 2015;3:75.

[24] Hillyer R, Silman MR. Changes in species interactions across a 2.5 km elevation gradient: effects on plant migration in response to climate change. Global Change Biol. 2010;16:3205–3214.

[25] Sheldon KS, Yang S, Tewksbury JJ. Climate change and community disassembly: impacts of warming on tropical and temperate montane community structure. Ecol Lett. 2011;14:1191–1200.

[26] Gibb H, Sanders NJ, Dunn RR, et al. Climate mediates the effects of disturbance on ant assemblage structure. Proc R Soc Lond B Biol Sci. 2015;282. Article ID 20150418.

[27] Basset Y, Barrios H, Segar S, et al. The butterflies of Barro Colorado Island, Panama: local extinction since the 1930s. PloS One. 2015;10:e0136623.

[28] Borer ET, Harpole WS, Adler PB, et al. Finding generality in ecology: a model for globally distributed experiments. Methods Ecol Evol. 2013;5:65–73.

[29] Anderson-Teixeira KJ, Davies SJ, Bennett AC, et al. CTFS-ForestGEO: a worldwide network monitoring forests in an era of global change. Global Change Biol. 2015;21:528–549.

[30] CONDESAN. Red de Bosques Andinos [Andean Forest Network]. 2016 [cited 2016 Aug 8]. Available from: http://www.condesan.org/redbosques

[31] Cuesta F, Muriel P, Beck S, et al. Biodiversidad y Cambio Climático en los Andes Tropicales – Conformación de una red de investigación para monitorear sus impactos y definir acciones de adaptación [Biodiversity and Climate Change in the Tropical Andes – Conformation of a research network to monitor its impacts and delineate adaptation actions]. Red Gloria-Andes. Condesan, Secretaría General de la Comunidad Andina, Red Gloria-Andes. Quito: CONDESAN, Secretaría General de la Comunidad Andina; 2012.

[32] Cuesta F, Muriel P, Llambi LD, et al. Latitudinal and altitudinal patterns of plant community diversity on mountain summits across the tropical Andes. Ecography. in review.

[33] Donoso DA. Long-term stable equilibrium of a tropical ant community. Funct Indic. in review.

[34] Kaspari M, Clay NA, Lucas J, et al. Thermal adaptation and phosphorus shape thermal performance in an assemblage of rainforest ants. Ecology. 2016;97:1038–1047.

[35] Homeier J, Hertel D, Camenzind T, et al. Tropical Andean forests are highly susceptible to nutrient inputs – rapid effects of experimental N and P addition to an Ecuadorian montane forest. PloS One. 2012;7:e47128.

[36] Dalling JW, Heinemann K, Gonzalez G, et al. Geographic, environmental and biotic sources of variation in the nutrient relations of tropical montane forests. J Trop Ecol. 2016;32:368–383.

[37] Young BE, Lips KR, Reaser JK, et al. Population declines and priorities for amphibian conservation in Latin America. Conserv Biol. 2001;15:1213–1223.

[38] Ron SR, Duellman WE, Coloma LA, et al. Population decline of the Jambato toad Anfro (Anura: Bufonidae) in the Andes of Ecuador. J Herpetol. 2003;37:116–122.

[39] Daniels LD, Veblen TT. Spatiotemporal influences of climate on altitudinal treeline in northern Patagonia. Ecology. 2004;85:1284–1296.

[40] Molau U. Mountain biodiversity patterns at low and high latitudes. Ambio. 2004;13:24–28.

[41] Büstamante MR, Ron SR, Coloma LA. Cambios en la diversidad en siete comunidades de Anuros en los Andes de Ecuador [Changes in the diversity of seven anuran communities in the Andes of Ecuador]. Biotropica. 2005;37:180–189.
[43] Lara A, Villalba R, Wolodarsky-Franke A, et al. Spatial and temporal variation in *Nothofagus pumilio* growth at tree line along its latitudinal range (35°40′–55°5′ S) in the Chilean Andes. J Biogeogr. 2005;32:879–893.

[44] Lampi M, Rodríguez-Contreras A, La Marca E, et al. A chytridiomycosis epidemic and a severe dry season preclude the disappearance of *Ateleopus* species from the Venezuelan Andes. Herpetol J. 2006;16:395–402.

[45] Bader MY, van Geloof I, Rietkerk M. High solar radiation hinders tree regeneration above the alpine treeline in northern Ecuador. Plant Ecol. 2007;191:33–45.

[46] Seimon TA, Seimon A, Daszak P, et al. Upward range extension of Andean anurans and chytridiomycosis to extreme elevations in response to tropical deglaciation. Global Change Biol. 2007;13:288–299.

[47] Tercero-Bucardo N, Kitzberger T, Veblen TT, et al. A field experiment on climatic and herbivore impacts on post-fire tree regeneration in north-western Patagonia. J Ecol. 2007;95:771–779.

[48] Torres-Díaz C, Cavieres LA, Muñoz-Ramírez C, et al. Consecuencias de las variaciones microclimáticas sobre la visita de insectos polinizadores en dos especies de *Chaetanthera* (Asteraceae) en los Andes de Chile central. [Consequences of microclimatic variations on pollinator insect visits to two species of Chaetanthera (Asteraceae) in the Andes of Central Chile]. Revista Chilena de Historia Natural. 2007;80:455–468.

[49] Dangles O, Carpio C, Barragan AR, et al. Temperature as a key driver of ecological sorting among invasive pest species in the Tropical Andes. Ecol Appl. 2008;18:1795–1809.

[50] Killeen TJ, Solórzano LA. Conservation strategies to mitigate impacts from climate change in Amazonia. Philos Trans R Soc Lond B Biol Sci. 2008;363:1881–1888.

[51] Lips KR, Diffendorfer J, Mendelson JR, et al. Riding the wave: reconciling the roles of disease and climate change in amphibian declines. PLoS Biol. 2008;6:e72.

[52] Gosling WD, Hanselman JA, Christopher K, et al. Long-term drivers of change in *Polylepis* woodland distribution in the central Andes. J Veg Sci. 2009;20:1041–1052.

[53] Lawler JJ, Shafer SL, Bancroft BA, et al. Projected climate-induced faunal change in the Western Hemisphere. Ecology. 2009;90:588–597.

[54] Lawler JJ, Shafer SL, White D, et al. Projected climate impacts for the amphibians of the Western Hemisphere. Conserv Biol. 2010;24:38–50.

[55] Ledo A, Montes F, Condes S. Species dynamics in a montane cloud forest: identifying factors involved in changes in tree diversity and functional characteristics. For Ecol Manag. 2009;258(Suppl 1):S75–S84.

[56] Molina-Montenegro M, Briones R, Cavieres L. Does global warming induce segregation among alien and native beetle species in a mountain-top? Ecol Res. 2009;24:31–36.

[57] Pauchard A, Kueffer C, Dietz H, et al. Ain’t no mountain high enough: plant invasions reaching new elevations. Front Ecol Environ. 2009;7:479–486.

[58] Zetz G, Bader MY. Epiphytic plants in a changing world-global: change effects on vascular and non-vascular epiphytes. In: Lüttge U, Bösschlag W, Büdel B, et al., editors. Progress in Botany. Berlin: Springer Berlin Heidelberg; 2009. p. 147–170.

[59] Altamirano A, Field R, Cayuela L, et al. Woody species diversity in temperate Andean forests: the need for new conservation strategies. Biol Conserv. 2010;143:2080–2091.

[60] Bendix J, Behling H, Peters T, et al. Functional biodiversity and climate change along an altitudinal gradient in a tropical mountain rainforest. In: Tschakert P, Leuschner C, Veldkamp E, et al., editors. Tropical rainforests and agroforests under global change. Berlin: Springer Berlin Heidelberg; 2010. p. 239–268.

[61] Feeley KJ, Silman MR. Land-use and climate change effects on population size and extinction risk of Andean plants. Global Change Biol. 2010;16:3215–3222.

[62] Pacheco S, Malizia L, Cayuela L. Effects of climate change on subtropical forests of South America. Trop Conserv Sci. 2010;3:423–437.

[63] Parísis J, Veblen TT. Dendroecological analysis of defoliator outbreaks on *Nothofagus pumilio* and their relation to climate variability in the Patagonian Andes. Global Change Biol. 2011;17:239–252.

[64] Sierra-Almeida A, Cavieres LA. Summer freezing resistance decreased in high-elevation plants exposed to experimental warming in the central Chilean Andes. Oecologia. 2010;163:267–276.

[65] Buermann W, Chaves JA, Dudley R, et al. Projected changes in elevational distribution and flight performance of montane Neotropical hummingbirds in response to climate change. Global Change Biol. 2011;17:1671–1680.

[66] Forero-Medina G, Terborgh J, Socolar SJ, et al. Elevational ranges of birds on a tropical montane gradient lag behind warming temperatures. PloS One. 2011;6:e28535.

[67] Hof C, Araujo MB, Jetz W, et al. Additive threats from pathogens, climate and land-use change for global amphibian diversity. Nature. 2011;480:516–519.

[68] Hylander S, Jepson T, Lebret K, et al. Climate-induced input of turbid glacial meltwater affects vertical distribution and community composition of phyto- and zooplankton. J Plankton Res. 2011.

[69] Latta SC, Tinoco BA, Astudillo PX, et al. Patterns and magnitude of temporal change in avian communities in the Ecuadorian Andes. Condor. 2011;113:24–40.

[70] Pinault L, Hunter F. New highland distribution records of multiple *Anopheles* species in the Ecuadorian Andes. Malar J. 2011;10:236.

[71] Bremond L, Boom A, Favier C. Neotropical C3/C4 grass distributions – present, past and future. Global Change Biol. 2012;18:2324–2334.

[72] Cavieres LA, Sierra-Almeida A. Facilitative interactions do not wane with warming at high elevations in the Andes. Oecologia. 2012;170:575–584.

[73] Rapp JM, Silman MR, Clark JS, et al. Intra- and interspecific tree growth across a long altitudinal gradient in the Peruvian Andes. Ecology. 2012;93:2061–2072.

[74] Sanfuentes C, Sierra-Almeida A, Cavieres LA. Efecto del aumento de la temperatura en la fotosíntesis de una especie alto-andina en dos altitudes [Effects of the raise of temperature in the photosynthesis of a high-Andean species in two altitudes]. Gayana Bot. 2012;69:37–45.

[75] Arroyo MTK, Dudley LS, Jespersen G, et al. Temperature-driven flower longevity in a high-alpine species of *Oxalis* influences reproductive assurance. New Phytol. 2013;200:1260–1268.

[76] Dangles O, Herrera M, Mazoyer C, et al. Temperature-dependent shifts in herbivore performance and interactions drive nonlinear changes in crop damages. Global Change Biol. 2013;19:1056–1063.

[77] Ferrero ME, Villalba R, De Membriani M, et al. Tree-growth responses across environmental gradients in subtropical Argentinean forests. Plant Ecol. 2013;214:1321–1334.
[78] Jankowski JE, Merkord CL, Rios WF, et al. The relationship of tropical bird communities to tree species composition and vegetation structure along an Andean elevational gradient. J Biogeogr. 2013;40:950–962.

[79] Kroschel J, Sporleder M, Tonnang HEZ, et al. Predicting climate-change-caused changes in global temperature on potato tuber moth Phthorimaea operculella (Zeller) distribution and abundance using phenology modeling and GIS mapping. Agric For Meteorol. 2013;170:228–241.

[80] Lutz DA, Powell RL, Silman MR. Four decades of Andean timberline migration and implications for biodiversity loss with climate change. PloS One. 2013;8:e74496.

[81] Piper FI, Fajardo A, Cavieres LA. Simulated warming does not impair seedling survival and growth of Nothofagus pumilio in the southern Andes. Perspect Plant Ecol Evol Syst. 2013;15:97–105.

[82] Rehm EM, Feeley KJ. Forest patches and the upward migration of timberline in the southern Peruvian Andes. For Ecol Manag. 2013;305:204–211.

[83] Velásquez-Tibatá J, Salaman P, Graham CH. Effects of climate change on species distribution, community structure, and conservation of birds in protected areas in Colombia. Reg Environ Change. 2013;13:235–248.

[84] Anthelme F, Jacobsen D, Macek P, et al. Biodiversity patterns and continental insularity in the tropical high Andes. Arct Antarc Alp Res. 2014;46:811–828.

[85] González C, Paz A, Ferro C. Predicted altitudinal shifts and reduced spatial distribution of Leishmania infantum vector species under climate change scenarios in Colombia. Acta Trop. 2014;129:83–90.

[86] Ramírez-Villegas J, Cuesta F, Devenish C, et al. Using species distributions models for designing conservation strategies of tropical Andean biodiversity under climate change. J Nat Conserv. 2014;22:391–404.

[87] Álvarez C, Veblen TT, Christie DA, et al. Relationships between climate variability and radial growth of Nothofagus pumilio near altitudinal treeline in the Andes of northern Patagonia, Chile. For Ecol Manag. 2015;342:112–121.

[88] Avalos VdR, Hernández J. Projected distribution shifts and protected area coverage of range-restricted Andean birds under climate change. Global Ecol Conserv. 2015;4:459–469.

[89] Cauvy-Fraunié S, Espinosa R, Andino P, et al. Invertebrate metacommunity structure and dynamics in an Andean glacial stream network facing climate change. PloS One. 2015;10:e0136793.

[90] Crespo-Pérez V, Régnièr J, Chuiue I, et al. Changes in the distribution of multispecies pest assemblages affect levels of crop damage in warming tropical Andes. Global Change Biol. 2015;21:82–96.

[91] Jantz SM, Barker B, Brooks TM, et al. Future habitat loss and extinctions driven by land-use change in biodiversity hotspots under four scenarios of climate-change mitigation. Conserv Biol. 2015;29:1122–1131.

[92] Medone P, Ceccarelli S, Parham PE, et al. The impact of climate change on the geographical distribution of two vectors of Chagas disease: implications for the force of infection. Philos Trans R Soc Lond B Biol Sci. 2015;370.

[93] Michelutti N, Wolfe AP, Cooke CA, et al. Climate change forces new ecological states in tropical Andean lakes. PloS One. 2015;10:e0115338.

[94] Ortega-Andrade HM, Prieto-Torres DA, Gómez-Lora I, et al. Ecological and geographical analysis of the distribution of the mountain tapir (Tapirus pinchaque) in Ecuador: importance of protected areas in future scenarios of global warming. PloS One. 2015;10:e0121137.

[95] Rehm EM, Feeley KJ. The inability of tropical cloud forest species to invade grasslands above treeline during climate change: potential explanations and consequences. Ecolography. 2015;38:1167–1175.

[96] Rehm EM, Feeley KJ. Freezing temperatures as a limit to forest recruitment above tropical Andean treelines. Ecology. 2015;96:1856–1865.