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Consequences of Climate Change for Ecosystems and Ecosystem Services in the Tropical Andes

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The tropical Andes[1] harbor extraordinary biological and cultural diversity, contained in a mosaic of ecosystems (Josse et al. 2009). The region's complex topography, coupled with elevational and latitudinal gradients, results in varied physical conditions that create unique habitats and barriers for species movement. Temporal variability of climatic conditions, such as temperature, wind, and precipitation, also occurs across the tropical Andes over inter-annual and decadal time scales, as driven by the interplay between the tropical Pacific and Atlantic Oceans, and Amazonian influences (Marengo et al. 2004). Both humans and biota have adapted to the heterogeneity of the tropical Andean landscape and fluctuations in climatic conditions. An estimated 45,000 plant and 3400 vertebrate species (excluding fishes) have been documented from tropical Andean ecosystems, representing approximately 15% and 12% of species known globally, respectively. Nearly half of these species are endemic (Myers et al. 2000). The well-being of human populations has been linked to the functioning of tropical Andean ecosystems over a history that extends more than 10,000 years. Today, millions of people depend on these ecosystems as a source of fresh water, food, cultural importance, and many other ecosystem goods and services (Josse et al. 2009).

Recently, the range of natural climatic variability in the tropical Andes has started to exceed historically documented thresholds. Of particular concern is the general warming trend and its implications for the integrity of ecosystems and the human populations that depend on them. In this chapter, we explore current knowledge of the effects of climate change on tropical Andean ecosystems and ecosystem services. At present, other than unambiguous indications of a pronounced warming trend, the overall picture of the climatic future of the tropical Andes remains uncertain, making predictions about the fate of ecosystems difficult. Some studies on recent climate variability have been published, but much information remains observational or

[1] Many studies use 800 meters elevation as the lower limit of the tropical Andes. For central and southern Bolivia, this limit often extends to 600 meters. For Colombia 500 meters is often considered the lower limit.

anecdotal. The information presented here was gathered from discussions among climatologists, ecologists, anthropologists, and natural resource managers with expertise in the tropical Andes during a weeklong workshop designed to facilitate transfer of knowledge on climate change and tropical Andean biodiversity, together with a review of literature and other available information.

Climate Change Patterns in the Tropical Andes

Climate change in high elevation tropical locales, such as the tropical Andes, is not well simulated in current global General Circulation Models (GCMs), in part because of the models' coarse spatial resolution and the rugged topography of the long, relatively narrow Andean mountain chains (Marengo 2007; Urrutia and Vuille 2009). Climate projections from regional models show increased warming with elevation in the tropical Andes, with more pronounced warming at higher elevations (above 4000 m) on both eastern and western Andean slopes (Solman et al. 2008; Marengo et al. 2009; Urrutia and Vuille 2009). The magnitude of warming projected at high elevations in the tropical Andes is similar to that predicted for polar regions (Bradley et al. 2004; 2006). The consequences of climate change in the tropical Andes are of special concern because of the diverse nature of their ecosystems and the effects that changes in these ecosystems will have on a large human population directly dependent on the services they provide (Vuille et al. 2008). The combined population of the countries of Colombia, Ecuador, Peru, and Bolivia was close to 100 million people in 2009. Of these, Josse et al. (2009) estimate that 40 million depend directly on Andean ecosystems.

While recognizing uncertainties in climate change projections, we suggest that the climatic fate of ecosystems and ecosystem services in the tropical Andean region will be largely related to a few key trends. First, there is widespread evidence of increasing air temperature across the region (+0.11°C / decade over the past 60 years), a trend that has intensified in the past 25 years (+0.34°C / decade; Vuille and Bradley 2000; see Marengo et al., Chapter 7 this volume). Recent studies have suggested that warming across the region is more evident in the minimum than maximum temperature time series (Vuille et al. 2008; see Marengo et al., Chapter 7 this volume). Second, there is some evidence of change in patterns of precipitation, but these changes vary between eastern and western slopes of the Andes and inter-Andean valleys. Third, changes in cloud cover may also be significant for ecosystems, both in terms of rising cloud levels (Foster 2001; Ruiz et al. 2008; 2009) and in terms of the sunshine to cloud ratio. Some evidence suggests a decrease in occurrence of cloudy weather in the northern Andes, a trend that leads to more hours of sun exposure (Ruiz et al. 2008; 2009; Chapter 12, this volume).

Several factors influence these climate trends. Natural climatic variations have affected climatic conditions across much of the planet in the past, including the Andes, and will continue to be influential in the future. Examples are the great ice ages at millennial scales, multi-centennial shifts such as the AD 1500-1880 Little Ice Age, and decadal climate shifts around 1850 (Thompson et al. 2006) and in the 1910s, 1940s, 1970s and 2000 (Marengo et al. 2004). At inter-annual and decadal time scales, warming has been detected in the high Andean mountains, together with a decrease in rainfall in the southern tropical Andes (see Marengo et al. Chapter 7, this volume; and see Figure 1.1). Inter-annual and decadal variability of precipitation has traditionally been related to Pacific Ocean influences through the El Niño Southern Oscillation (ENSO) and ENSO-like decadal modes of variability. However, variability in the moisture transport and intensity of trade winds from the tropical Atlantic Ocean also affects the tropical

Andes (Marengo et al. 2004). On intra-annual time scales, coupled interactions between sea-surface temperature (SST) anomalies, wind patterns, and the latitudinal displacement of the Inter-Tropical Convergence Zone (ITCZ) drive variations in regional cloudiness (Vuille and Keimig 2004).

Climate change may increase extreme events, such as droughts, heat and cold waves, or intense rainfall. For instance, in the central inter-Andean valleys of Peru above 3500 meters elevation, the number of intense rainfall events and early freezes has recently increased (E. Jaimes, SENAMHI, unpublished data). Some evidence of an increased occurrence of unusually heavy rainfall events has also been reported locally in the central Colombian Andes region (Ruiz et al. 2008).

Effects of Climate Change on Andean Ecosystems

Josse et al. (2009) recognize 133 different ecosystem types for the northern and central Andes, classified into nine major groupings. Elevation ranges, temperature, and precipitation regimes are among the factors that distinguish these ecosystems (Table 1.1). Both direct (e.g., changes in climatic factors) and indirect (e.g., resultant ecosystem responses) effects of climate change have already been observed in the tropical Andes, and we can hypothesize about what may occur in the next 100 years in each of the nine major ecosystem groupings. Table 1.2 summarizes these observations and hypotheses.

Certain characteristics of each grouping of tropical Andean ecosystems make them uniquely vulnerable to climate change (see Young et al., Chapter 8, this volume). For example, the extent and future viability of high Andean superpáramo and Puna ecosystems is of concern because of their occurrence at high elevations. Here, a 3°C increase in temperature could result in a theoretical 600 meter upward movement of species, and the resulting loss of habitat area for species that would have to move to keep up with their current habitat optimum could significantly affect their viability. Major changes are predicted for páramo ecosystems, based in part on their island-like distribution and highly endemic biota. For northern Andean páramos, Cuesta Camacho (2007) estimates that around 35% of bird species (102 species) and 60% of plant species (125 species) would become extinct or critically endangered by 2080, based on A2 high emission scenarios (IPCC 2007). The vulnerability of cloud forest ecosystems relates to their dependence on the level of cloud bases, which is predicted to shift with climate change. Rising cloud bases and a reduction in horizontal precipitation could lead to decreased moisture, with consequences for diverse epiphytes and the animal communities they support. Many species in cloud forests are adapted to narrow elevational ranges on steep slopes. Spatial heterogeneity of climate change could lead to collapse of populations or increased vulnerability to extinction.

Several factors make aquatic systems vulnerable to climate change. Warming temperatures may cause increased evaporation in lakes and wetlands, with concomitant reduction of habitat and potential changes in water quality (e.g., temperature, salinity), particularly where precipitation declines are predicted. In areas where water bodies are fed by glacial runoff, water levels have been augmented while water reserves stored in glacial ice are released by accelerated melting, but will decline when glacial mass disappears (Vuille et al. 2008). Wetlands, in particular cushion bogs (e.g., *bofedales*, *turberas*, *vegas*) located along margins of rivers and springs in high mountain grasslands and deserts, function as archipelagos of diversity. Climate change could result in reduced water availability, salinization, area reduction, and increased carbon emissions (CO_2 in particular) in these ecosystems.

Beyond expected changes or vulnerabilities by ecosystem grouping, some general predictions about the effects of climate change on the tropical Andean landscape mosaic can also be made. First, contractions or expansions of ecosystems in terms of geographic area (e.g., contractions predicted for páramo and superpáramo), and a changing physical environment, will likely result in species disappearance or migration (see Larsen et al., Chapter 3, this volume). For example, in the Peruvian Andes, recent studies have already documented the disappearance of six threatened frog species from their historical ranges (von May et al. 2008), and three frog species have expanded their ranges upwards following recent deglaciation (T.A. Seimon et al. 2007). These kinds of species movements have implications for ecosystem structure (e.g., in terms of community dynamics) as well as ecosystem function (e.g., the role of different species in maintaining ecosystem processes).

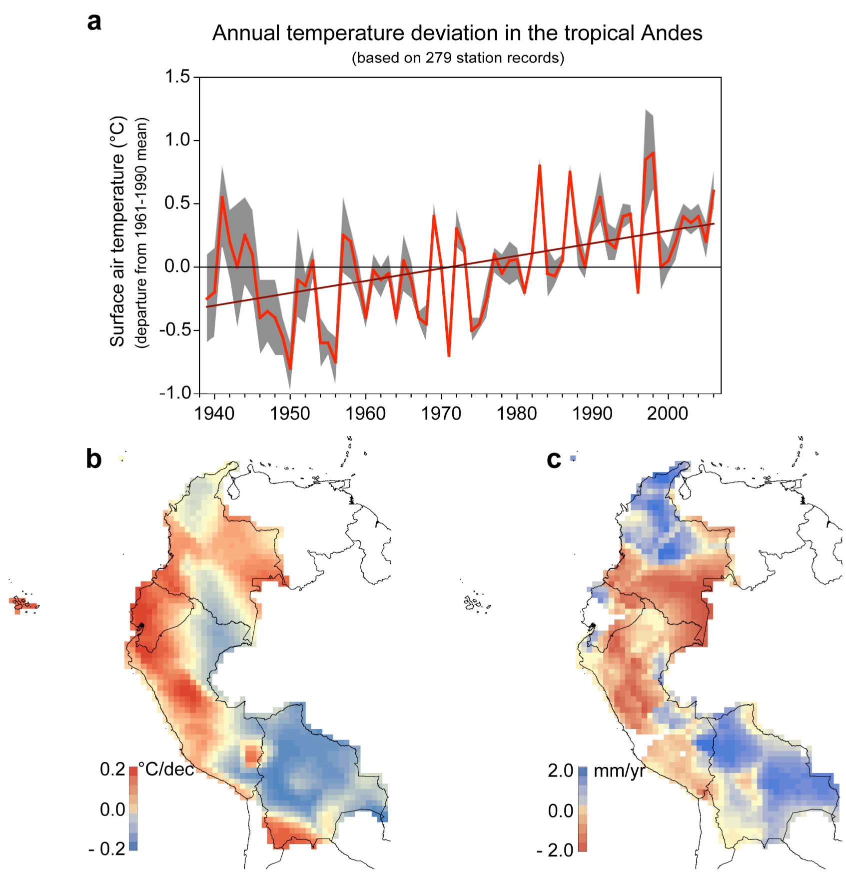

Figure 1.1. Temporal and spatial changes in mean temperature and precipitation in the tropical Andes. (a) Annual temperature anomaly with respect to 1961-90 average in the tropical Andes (1°N-23°S) from 1939 and 2006. Gray shading indicates ±2standard errors of the mean. The long-term warming trend (0.10°C/decade) is also indicated (from Vuille et al., 2008). (b) Mean decadal temperature trends across the tropical Andes of Colombia, Ecuador, Peru and Bolivia estimated over the interval 1951-2001. (c) Total annual precipitation trends across the tropical Andes of Colombia, Ecuador, Peru and Bolivia estimated over the interval 1951-2001.(b) and (c) from ClimateWizard (www.climatewizard.org). Figure prepared by R. Villalba.

Table 1.1. Characteristics of major ecosystem groupings in the northern and central Andes. Based on Josse et al. 2009.

Ecosystem	**Altitudinal range**	**General characteristics of terrestrial components and distribution**	**Important species**
Páramo	>3000 m	High elevation humid shrublands occurring from Venezuela to northern Peru in relatively thin strips along the top of the northern Andes, fragmenting into small patches in the south to Argentina and harboring high levels of endemism.	*Espeletia* spp, *Chusquea, Jamesonia, Azorella biloba, Gynoxis*, Ericaceae, *Loricaria*, *Werneria*, many mosses, lichens and ferns
Humid Puna	2000-6000 m	Dominated by grasses, shrubs, and cacti, replacing páramo to the south where precipitation is lower, extending from northern Peru to Bolivia and Argentina	*Festuca, Calamagrostis, Stipa, Poa* spp. Liolaemus, llamas, alpacas, flamingos
Dry Puna	2000-6000 m	Almost desert-like vegetation in southern Peru through Bolivia to northern Argentina with low spiny shrubs	*Festuca, Stipa, Deyeuxiay, Parastrephia* spp. llamas
High Andean / Superpáramo	>4500 m	The very highest places on mountaintops or just below snow fields or glaciers with permanent vegetation, usually consisting of very small stature plants, lichens, and mosses. Occur throughout the tropical and temperate Andes.	*Azorella* spp. *Nototriche*, *Aschersoniodoxa*, *Menonvillea Attagis gayii*, Vicuña, high levels of endemism
Cloud Forest	1000-3500 m – to 600 m in southern Peru and Bolivia	Very humid forests receiving a significant amount of precipitation in the form of cloud-borne mist that is intercepted by trees, and have a highly endemic, closed canopy forest with high epiphyte loads. Occur throughout the tropical Andes.	*Ceroxylon, Dyctocaryum, Podocarpus, Calatola, Gustavia, Clusia* spp.
Seasonal Andean Forest	800-3100 m	Areas that experience 3-5 month dry seasons and reduced precipitation, with medium stature forests made up in part by deciduous trees. Occur throughout the tropical Andes, but more extensive in Peru and Bolivia.	*Roupala, pseudocordata, Psidium caudatum, Tipuana tipu, Calycophyllum multiflorum*
Dry Andean Forest	800-4100 m	Forests that typically have low stature trees with thick stems and leaves for water storage and abundant spines and chemical defenses. Occur primarily in Inter-Andean valleys in Ecuador, Peru, and Bolivia.	*Schinopsis haenkeana, Prosopis alba, Bursera* spp., *Plumeria* spp, *Jacaranda* spp.
Inter-Andean Valleys	1900-3500 m	Landscapes that have been heavily altered by humans for many millennia and are characterized by shrublands with seasonal herbs with adaptations to dry periods. Occur throughout the tropical Andes.	*Acacia feddeana, Caracidium andicola, Jatropha* spp, *Croton* spp, *Salvia* spp, *Tecoma arequipensis.* numerous Cactaceae species
Aquatic Habitats	>800 m	Lakes, wetlands, cushion bogs, streams, rivers. Occur throughout the tropical Andes.	*Orestias* spp, *Astroblepus* spp., *Chaetostoma* spp., *Phoenicoparrus* spp, *Theristicus* spp. *Telmatobius, Isoetes,* Ephemeroptera

Table 1.2. Observed and hypothesized ecosystem responses to changes in climatic factors in the tropical Andes. Information presented is based on discussions with climate scientists and ecologists with knowledge of the Andes and select references. Degrees of confidence in changes to climatic factors are indicated as: +low ++medium +++high

OBSERVED CHANGES			HYPOTHESIZED CHANGES	
Climatic factors	**Ecosystem responses**	**References**	**Climatic factors**	**Ecosystem responses**
ANDEAN LAKES AND WETLANDS				
Increased temperature +++ Changes in water balance ++ Rise of lower limit of solid precipitation +++	Decreasing lake levels and drying of cushion bogs across the altiplano Rising elevation of highest lakes Upward movement of species (e.g., amphibians, nesting flamingos) Decline in populations of certain species (e.g., amphibians) and extinctions of local endemics (e.g., *Isoetes*)	Halloy 1983; A. Seimon et al. 2007	Increased temperatures, on the order of 2-4ºC +++ Increased number of extreme events ++ Changes in water balance +++	Altered hydrologic regimes and sediment loads Increased chance of eutrophication, decreased oxygen, and increased salinity in lakes Decreased carbon storage in cushion bogs Declines in species diversity and abundance, especially among endemics
HIGH ANDEAN / SUPERPARAMO				
Increased temperature +++ Changes in water balance ++ Rise of lower limit of solid precipitation +++ Increased insolation +	Upward migration of species and colonization by new species (e.g., *Pleurodema*, *Telmatobius*, *Liolaemus, Diuca speculifera*) Epidermis burning of vegetation (e.g., *Loricaria colombiana,* Cactaceae spp.) Shifts in species occurrence and responses (birds, mammals, plants) Upward shift of cultivation and grazing activities	T. A. Seimon et al. 2007; Hardy and Hardy 2008 Daniel Ruiz, unpublished data; Halloy 1981 Halloy 1985; Halloy 2002 Halloy et al. 2005a; Halloy et al. 2005b	Increased temperature, on the order of 3-4ºC +++ Slight increase in precipitation, but variable across region + Increased number of extreme events + Changes in water balance +++ Increased insolation + Increased wind + Changes in seasonality, particularly onset of conditions+ Increasing partial pressure of carbon dioxide +++	Glaciers virtually disappear Decrease in habitat area, with consequences for species interactions Declines in species diversity and abundance, increase in endangerment (e.g., *Polylepis*) and extinctions, and disappearance of indicator species CO_2 fertilization of landscape, with effects on water, soil and vegetation
PUNA				
Increased temperature +++ Changes in water balance ++ Rise of lower limit of solid precipitation +++	Increased dryness and salinity Burning of vegetation from		Increased temperature, on the order of 3-4ºC +++ Decrease in water balance ++	Extinction rates high among locally-adapted species

Increasing insolation + Changes in onset of seasons +	increased insolation (e.g. Cactaceae) Increased reports of sunburn, eye problems in human populations	Ulloa and Yager 2008; Yager et al. 2009)	Increase in extreme events + Increase in insolation + Increase in wind + Changes in onset of seasons + Changes in horizontal precipitation and cloudiness +	Colonization by species previously characteristic of lower elevations Increased human inhabitation of the landscape, adding further stress to climate induced changes
PARAMO				
Increased temperature +++ Rising lower limit of solid precipitation +++ Increasing insolation + More frequent and intense rainfall events, interrupted by longer dry periods +	Effects on soils: water saturation, nutrient lixiviation, erosion Increased sediment loads in streams Upward rise of species, pests, and diseases from lower altitudes Vegetation stress from alternation of heavy rains and dry periods		Increased temperature, on the order of 3-4ºC +++ Decrease in water balance ++ Increase in extreme events + Rise of lower limit of solid precipitation +++ Increasing insolation / decreasing cloud cover ++	Severe loss of habitat (up to 60%; F. Cuesta, pers. comm..) and high extinction risks Upward migration of species from lower altitude areas, and increased human influence on landscape Changing fire regime Reduction in water retention and filtration Reduction in carbon retention and sequestration
CLOUD FOREST				
Changing precipitation regimes, with increases or decreases in different areas ++ Upward movement of the condensation belt + Reduction in cloud cover in the northern Andes + Increased insolation + Changing seasonality, including shifts from two pluvial peaks to one during rainy season in the Northern Andes +	Extreme events like drought linked to tree die-offs (e.g., 2005 drought event) Increasing erosion and landslides on steep slopes Flooding events Upward migration of agriculture and human settlements	Ken Young, pers. comm. (Colwell et al., 2008; Svenning and Condit, 2008; Tewksbury et al., 2008)	Increased temperature ++ Changes in precipitation, with variability across the region + Change in ratio of horizontal to vertical rainfall, with decreased mist and clouds + Upward displacement of condensation belt, therefore less fog + Increased insolation +	Decrease or endangerment of heat and drought sensitive species (e.g., amphibians, epiphytes), and endemic species Reduced slope stability Increased human settlement, expansion of agriculture and grazing Increased risk of fire
DRY AND SEASONAL ANDEAN FORESTS				
Changing precipitation regimes, with increases or decreases in different areas +	Upward migration of pioneering species (e.g., *Cecropia* in Colombia) Landslides and erosion in areas	Gustavo Kattan, pers. comm. Rodney Martinez,	Increased temperature, on the order of 2-3ºC ++ Increase in annual precipitation, on the order of 400-500 mm	Increase in landslides and soil erosion in areas of increased annual precipitation Increase in growth rate of trees in

	with increased precipitation (e.g, western Ecuador) Variations in water temperature of aquatic environments	pers. comm. Ricardo Villalba, unpublished data	(Urrutia and Vuille 2009), and intensity of precipitation++	previously dry areas Declines or endangerment of sensitive species (e.g, certain rodents, nectarivorous bats, amphibians, fishes) Increased human settlement, expansion of agriculture and grazing Increased risk of fire
INTERANDEAN VALLEYS				
Changing precipitation regimes, with increases or decreases in different areas + Changes in seasonality, especially onset of seasons + Increased heterogeneity of climatic conditions between geographical areas +	Increased threat from human activities Reduced agricultural productivity Increased incidence of vector-borne diseases (e.g., malaria, dengue fever)	(López and Zambrana-Torrelio, 2006) Daniel Ruiz, unpublished data	Increased temperature, on the order of 3-4.5ºC + Moderate increase in precipitation in lower elevation valleys +	Changes in water balance, with increased water deficit, leading to reduced agricultural production and increased dependence on irrigation water and expanding infrastructural developments Changing fire regime Increased threat to slow-growing and long-lived vegetation

The expansion of geographic ranges is in some ways analogous to the introduction of exotic species into new landscapes, where newly colonizing species can alter the identity and strength of direct and indirect biotic interactions (Levine et al. 2004; White et al. 2006), as well as change the physical structure of ecosystems (Crooks 2002) and alter the strength of disturbance regimes (Brooks et al. 2004). Formation of no-analog communities (e.g., species assemblages that are currently unknown to occur) is also a potential outcome of climate change (Fox 2007; le Roux and McGeoch 2008). As community structures shift, an important question is whether or not the functional roles of disappearing species will be replaced by new migrants to ecosystems (Vos et al. 2008).

Second, the changes in climatic factors are also likely to influence abiotic functional processes of ecosystems. Increased erosion and landslides could accompany changes in precipitation regimes, particularly in ecosystems that span steep slopes, like montane or cloud forests. An increase in the ratio of vertical (rain) to horizontal (wind-blown mist) precipitation has been predicted for some ecosystems traditionally dominated by mist, such as the páramo; this change could affect the water retention and filtration capacity of the páramo. Also important is a rise in the elevational level of solid (snow, graupel) precipitation. For areas with vegetation and geomorphology in equilibrium with solid precipitation (which infiltrates slowly as it melts), a shift to liquid precipitation leads to increases in runoff, siltation, and erosion. Effects of climate change on nutrient cycling are uncertain. In aquatic systems, rising temperatures may lead to a decrease in dissolved oxygen and an increased potential for eutrophication. Wetlands and the páramo could shift from being sinks to sources of carbon in the short term with warming and drying.

Finally, the synergistic, interactive effects of climate change with other stressors to tropical Andean ecosystems—such as habitat modification, exotic species, and water pollution—may be severe and unexpected. For example, previous studies have shown that, at a species level, pesticide exposure at sublethal concentration in the presence of predation risk can cause massive mortality in amphibian larvae (Sih et al. 2004). Although these studies were not conducted on tropical Andean species, they do provide a window into the possible fates of species in landscapes with multiple stressors. It remains to be seen if and how changing climatic factors will interact with biotic (predation, disease, poor food supply) and abiotic (suboptimal habitat conditions) stressors to affect tropical Andean species. Beyond the species level, páramos provide an example of the potential for interactive effects of climate change with human-induced stressors at a larger scale. As climate warms, their lower margins may become more suitable to agriculture and thus more threatened by human activities. A combination of climate change and increased human influence on the páramo may also increase the spread of anthropogenic fires, considered a serious threat to integrity of this ecosystem (see Ruiz et al., Chapter 12, this volume).

Changing Ecosystem Services in the Andes

In the tropical Andes and elsewhere, the well-being and progress of human populations depend on the integrity of ecosystems (Table 1.3). The benefits people receive from ecosystems are known as ecosystem services, grouped by the Millennium Ecosystem Assessment (2005) into four general categories: *provisioning services* (e.g., water, food, timber, fiber), *regulating services* (e.g., climate regulation, flood control, down-slope safety, water purification), *supporting services* (e.g., soil formation, photosynthesis, nutrient cycling, pollination, waste disposal), and *cultural services* (e.g., recreation, aesthetics, spiritual values). The ability of ecosystems to provide these services to humans depends on a typically high degree of integrity or health of ecosystems. Nevertheless, as human demands on ecosystems increase with growth of population and consumption, and increased technology, there is greater potential for ecosystem degradation and intensification of trade offs related to ecosystem services. Climate change adds another dimension, as an additional driver of ecosystem change and a cause of shifts in human resource use. Although refuges and protected areas are seen as one way to buffer these services against threats (Dudley and Stolton 2003), climate change could jeopardize tropical Andean ecosystems' capacity to provide ecosystem services, as discussed below.

Vast changes are expected to water-related ecosystem services. Human populations in the Andes and adjacent lowland areas have long relied on Andean ecosystems for water-related services, in particular water supply, flow regulation, energy, and waste assimilation (Bradley et al. 2006; Buytaert et al. 2006; Vuille et al. 2008; also see Anderson et al., Chapter 23, this volume). These services fall into categories of *provisioning* and *regulating* services (Millennium Ecosystem Assessment 2005), and the ability of Andean ecosystems to provide these services in the future will be affected by climate change. Of specific concern in the region are the effects of warming on glaciers and degradation of vegetative cover. Mountain glaciers, Andean wetlands (including peat bogs), and the spongy páramo act as buffers of highly seasonal precipitation, providing water even during periods of little rainfall (Vuille et al. 2008). At present, páramo streams supply the majority of water to several of the region's largest cities, including Bogotá (~8 million inhabitants) and Quito (~2 million inhabitants; Bradley et al. 2006; Buytaert et al. 2006; Vuille et al. 2008). Andean rivers (both glacier- and páramo-fed) provide most irrigation water for croplands (FAO 2003; Buytaert et al. 2006), and through hydropower plants, generate ~50% of regional electricity (see Anderson et al., Chapter 23, this volume). Wastewater from most human settlements in the Andes is also discharged directly into rivers without prior treatment; reduced flow would mean reduced capacity of these systems for waste dilution and assimilation. Glacier retreat and drying of wetland and páramo areas are processes that could substantially alter stream flow patterns, presenting threats to water supply and energy generation. The density and size of human populations that depend on tropical Andean ecosystems for water and energy create a critical, urgent need to develop adaptation strategies to climate change (Bradley et al. 2006; Vergara et al. 2007).

Shifts in services related to agricultural production could occur as a consequence of climate change and changing patterns of human settlement. Tropical Andean ecosystems impart benefits that facilitate crop cultivation, livestock grazing, and timber production, among other agricultural activities. These benefits fall into categories of *provisioning* and *supporting* services (Millennium Ecosystem Assessment 2005). Over millennia, tropical Andean populations have developed highly diverse agricultural systems, and shaped landscapes (Erickson 2000; Mann 2000). In fact, the tropical Andean region is considered an important global center of agricultural biodiversity, containing a large number of the wild relatives of some of the world's most important food and fiber crops (e.g., potato, tomato, corn, peanuts; Halloy et al. 2005a).

Future changes in patterns of precipitation and temperature, as well as increased atmospheric CO_2, will affect agricultural production in the Andes. Consequences of these climatic changes might include intensification of agriculture in existing cropland or grazing areas, or expansion of the agricultural frontier both upwards to higher elevations (already being observed, as described in Chapter 2, this volume, and Halloy et al. 2005a) and downslope into

Table 1.3. Examples of ecosystem services provided by tropical Andean ecosystems.
Key: + Relevant ++ Important +++ Very important

Ecosystem	Provisioning services								Regulating services		Supporting services	Cultural services	
	Food			Fresh water	Fuel	Timber	Wild harvest medicinal plants	Hydro energy	Carbon storage	Down slope safety	Soil fertility	Recreation	Spiritual and sacred values*
	Agriculture	Grazing	Agro biodiversity										
Lakes and wetlands		++	+	+++	+			++	+++	+	++	+++	+++
High Andean / Superpáramo		+		+++			++	++	+	++	+	+++	+++
Puna	++	++	+++	+	++		++		+		+	+++	+
Páramo	+	++	+++	+++	++		++	++	+++	+++	+	+++	+
Cloud forest		+		+++	+++	+++	++	+++	+++	+++	+	+++	+
Interandean valleys	+++	+++	+++	+	++	+	+++	+	+	+	++	+++	++
Dry / seasonal Andean forest	+	+	++	+++	+++	+++	++	+++	+++	+++	+	+++	+

* Related to ancestral and spiritual traditions that do not have substitutes

lowland tropical forests. Crops may also be increasingly susceptible to damage by insect herbivores and pests under warmer conditions and rises in atmospheric CO_2 (Perez et al. 2010). Analyses of fossil leaves from 55.8 million years ago, when a sudden, transient elevation in temperature and atmospheric CO_2 occurred between the Paleocene and Eocene epochs, linked these climatic shifts to a significant rise in the percentage of damaged leaves and diversity of damage by insect herbivores (DeLucia et al. 2008). Additionally, many cultivated species are closely dependent on pollination from insects, birds, and bats. Climate change related effects on these species, or on other food species upon which they may depend for part of the year, could affect crop yields (see Buchmann and Nabhan 1996 for North American examples). Decreases in native agrobiodiversity could substantially increase risk of crop failure from extreme climatic events and increase crop vulnerability to disease (Garrett 2008). The combined pressure of climate change and anthropogenic degradation of agricultural landscapes may place many ecosystems at risk and affect future food security in the tropical Andes (Altieri and Merrick 1987; Nabhan 1989; FAO 1996; Brack 2005; Halloy et al. 2005a; Halloy et al. 2005b).

Decreased down-slope stability and safety is expected. In steep mountain landscapes, ecosystems, particularly forests, play an essential role in erosion control and slope stability. These services fall into the category of *regulating services* and depend on the presence and continuity of vegetative land cover, and also climatic variables like precipitation. Two projected effects of climate change in the tropical Andes are noteworthy here, as they could influence erosion and slope stability. Shifts from misty precipitation (horizontal rainfall and fog) to more liquid precipitation (vertical rainfall) in areas like the páramo and cloud forests could lead to greater erosion. At higher elevations, the shift from solid precipitation (snow and graupel, or *garrotillo*) to pluvial precipitation similarly leads to decreasing infiltration and increasing surface runoff and erosion. The more frequent occurrence of extreme events, such as heavy or prolonged rainfall, could have important implications for slope stability and consequently the safety of human settlements in downslope areas.

Ability of ecosystems to provide cultural services may be compromised by climate change. The cultural history and natural history of the tropical Andes are interwoven. Human cultures, knowledge systems, religions, and social interactions of Andean peoples all reflect a strong connection to the landscape and the importance of a sense of place. High mountains, lakes, certain trees and animals, and many other geographic and biological entities have sacred status in Andean cosmology (Bauer and Stanish 2001). These sacred sites and beliefs influence landscape management strategies. Tropical Andean ecosystems in good ecological condition also provide recreation areas and a basis for environment-based tourism, an important source of revenue for tropical Andean countries. Climate-related changes could influence ecosystems' ability to provide cultural services, and may degrade the identity of natural areas (e.g, visual, iconic biodiversity elements). The impact of loss of cultural services is difficult to measure but merits attention, as it relates to the overall well-being of human populations in the region.

Contribution of Andean ecosystems to climate regulation may change. Andean ecosystems, particularly Andean forests, the páramo, and wetlands (e.g., cushion bogs), contain important global reserves of carbon. Carbon storage falls into the category of *regulating services* and depends on climatic conditions like temperature, as well as human influences on the landscape. Under scenarios of future warming, the ability of these ecosystems to store or sequester carbon from the atmosphere could be reduced and they may become net sources of greenhouse gases.

Climate change-induced shifts in species distribution and abundance may affect biodiversity-related ecosystem services. Biodiversity influences the provision of ecosystem services, through the strong links of biological species to processes like pollination, climate regulation, and disease control, among others (Millennium Ecosystem Assessment 2005). In high Andean landscapes, correlations between biodiversity and human population density suggest that people have long depended on biodiversity-related ecosystem services (Fjeldså 2007). Key to the provision of biodiversity-related services is often species composition, not necessarily the number of species inhabiting an ecosystem. With climate change in the Andes, loss of sensitive species or range shifts could affect composition of ecological communities, with implications for disease control and agricultural activities.

Interactions between climate change, its consequences on Andean ecosystems and their services, and human use of resources are likely. Shifts in human behavior are expected to occur in response to climate change; these shifts could exacerbate impacts of climate change on ecosystems. Aquatic systems also provide a good example. As patterns of water flows are altered by climate change, increased modifications of freshwater systems by dams and water withdrawals are likely to occur. For example, in the case of glacier-fed rivers, it is projected that river flows will first increase as glaciers melt, but then recede to lower levels than historically reported once glaciers vanish. In the case of páramo-fed rivers, warmer temperatures could dry páramos and compromise their function as slow releases of water to rivers. Consequently, the buffer that currently exists to maintain river flows regardless of seasonal variability in rainfall could disappear with the glaciers and with drying páramos. When river flows exhibit more marked seasonal differences in flow, there may be more pressure to alter the timing of discharge through construction of storage dams to meet human needs for water. Alternatively, improving or increasing Andean cushion bogs could be a way to ameliorate water regulation (Yager et al. 2008, Yager 2009, Benítez et al. 2010). This is just one example of the kinds of feedbacks that might occur in the future as climate change affects the ecosystem services upon which human populations depend in the tropical Andes.

Conclusions

The effects of climate change have been documented on every continent, and observed biological changes have subsequently been attributed to climate change in many places (see Parmesan 2006 for a review). Published information establishing this link is still scant for the tropical Andes in terms of individual species or taxonomic groups, and perhaps even more so in terms of ecosystem level trends. The summary of observed and hypothesized effects of climate change on tropical Andean ecosystems presented in this volume provides a first attempt at filling this gap in current knowledge.

Regional models predict the magnitude of climate change in the high tropical Andes to be among the most severe globally, comparable to that of the Northern Hemisphere's high latitudes, particularly in terms of warming at high elevations. The difference in the tropical Andes is the direct impacts climate change will have on the lives and livelihoods of millions of people, many who are economically vulnerable and directly dependent on the goods and services that tropical Andean ecosystems impart. A clear cultural link exists between human societies and surrounding ecosystems, as established by the long history of human inhabitance and use of the tropical Andean landscape. Anticipated climate induced changes to the availability of water and agriculture-related ecosystem services are of particular concern in the near future in the tropical Andes. The value of ecosystem services at risk from climate change is high. Once lost, many of these services may be irreplaceable.

Human activities (e.g., forest clearing, river alteration, mining, grazing) already exert increasing pressure on tropical Andean ecosystems and their ability to provide key ecosystem services (Jarvis et al. 2010). Climate change is superimposed on these other human-induced alterations of the landscape. While the uncertainty of future climate change projections presents a challenge to resource management decisions, immediate efforts to mitigate the negative consequences of other stressors in the region should be encouraged. Strategies for more integrated and adaptive management of natural resources are necessary for addressing present and future effects of climate change on tropical Andean ecosystems, and reducing the vulnerability of human populations to subsequent reduction and loss of critical ecosystem services (Andrade-Pérez et al. 2010).

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