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AN ASSESSMENT OF CLIMATE CHANGE IN THE LUQUILLO MOUNTAINS OF PUERTO RICO

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ABSTRACT: Changes in the surface temperature of the coastal plain of 1 to 2°C and/or a 11 to 33% change in annual rainfall could dramatically alter the distribution of forest vegetation within the Luquillo Experimental Forest (LEF) of northeastern Puerto Rico. The magnitude of these changes are within those that have been recorded in the past and are projected for the future. Past climatic records, tree species distributions, and projections of future climate indicate that the LEF has become and will continue to become drier. These changes can affect local water budgets and should be considered in planning future developments in the area.
Key terms: humid tropical forests, climate change, cloud forests

INTRODUCTION

The upland forests of Caribbean islands are major water sources and important recreation and conservation areas. Because of their importance to the economy and ecology of the islands, understanding their response to climate change is essential to resource management in the region. This paper reviews evidence of past climate change and projections of future change in the region and assesses their potential impact on the Luquillo Experimental Forest (LEF) of Puerto Rico. The LEF is administered by the USDA Forest Service and covers 11,491 ha in northeastern Puerto Rico. Global synoptic systems, trade winds, and land-sea interactions influence the mountains subtropical maritime climate. In an average year a total of 3864 mm/yr of rainfall falls on the forest (Garcia et al. 1996) and at least once every decade annual rainfall is below one standard error of the long term mean (Fig. 1)

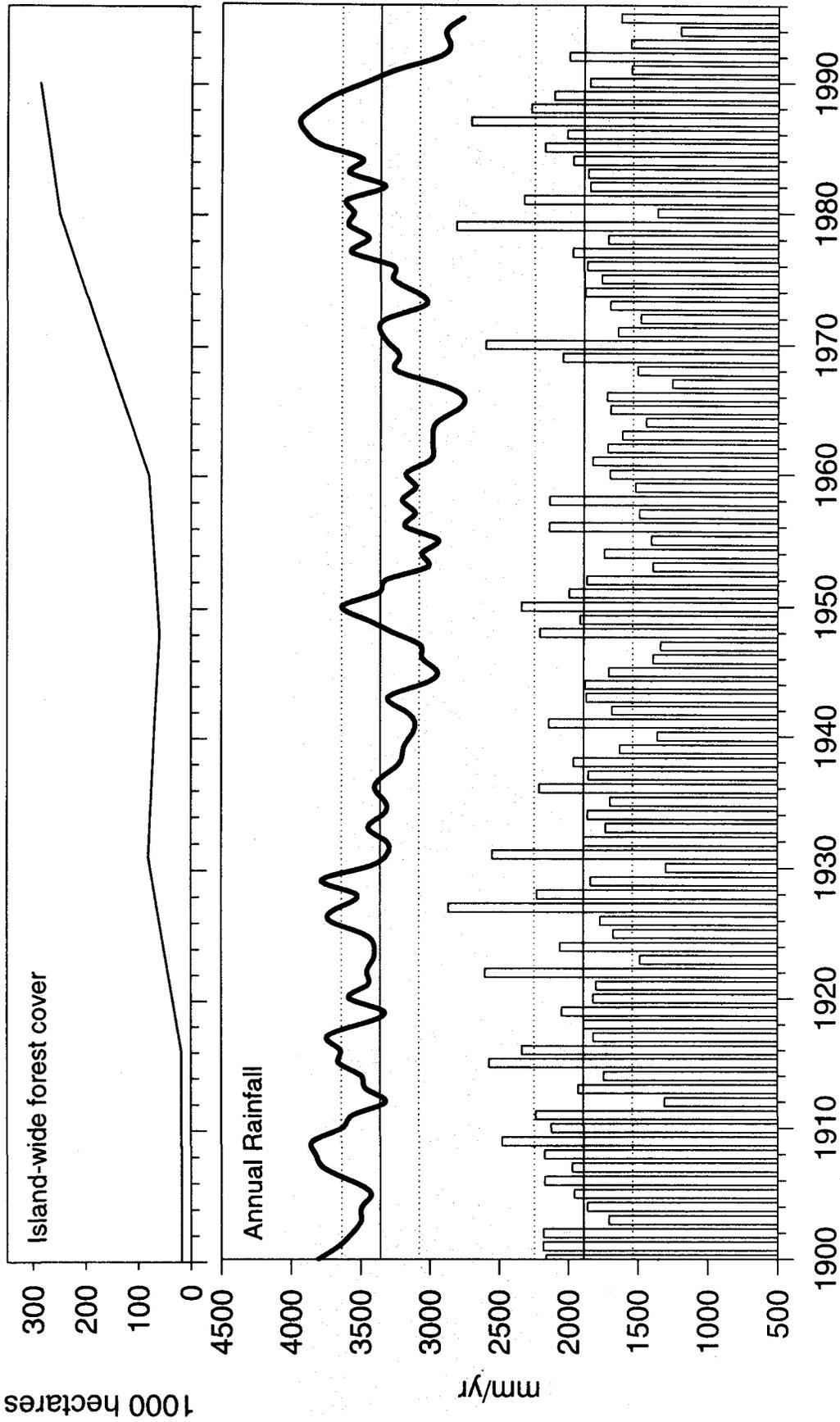
EVIDENCE OF PAST CLIMATE CHANGE

Studies of Oligocene paleobotany indicate that approximately 35-45 million years ago Puerto Rico had coastal, brackish water, upland tropical to subtropical, and an arboreal cool-temperate vegetation communities (Table 1, Graham and Jarzen 1969). Of the 44 genera identified in this study, 70% presently grow in Puerto Rico, three grow on other Caribbean islands, and seven are found on ecologically comparable environments in Latin America. Only 7% of the genera were temperate tree species that require a habitat that is not presently available in the region.

During the Pleistocene there were large changes in sea surface temperatures (SST) in the equatorial Atlantic near Puerto Rico (Table 1). A permanent Pleistocene snowline may have existed between 2300 and 2600 masl in the Dominican Republic and parts of the Caribbean were probable more arid than today (Schubert and Medina 1982, Schubert 1988). Pollen assemblages from Africa and Latin America also suggest that montane forests occurred at lower elevations (Piperno et al. 1991, Servant et al 1993).

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Figure 1. Island-wide forest cover and estimated long-term rainfall in the Tabonuco Forest of the Luquillo Experimental Forest, Puerto Rico



Bar = annual rainfall at Canovanas, upper line = estimated four year running average based on regression between Canovanas and El Verde; mm/yr at El Verde = $1.62 (\text{Canonavas}) + 291.6$, $r^2 = 0.73$.
 Island-wide forest cover from Franco et al. 1997

The Holocene was also a period of variable climate (Table 1). Climatic reconstruction from Haitian lake sediments suggest relatively dry conditions during the early Holocene (Hodell et al. 1991). This was followed by a wetter mid Holocene, and a return to drier conditions during the late Holocene. This dry-wet-dry pattern has been reported for other parts of the tropics and may reflect changes in Hadley circulation and shifts in the Inter-Tropical Convergence zone (Servant et al. 1993).

Table 1: Summary of paleoecological and historic evidence of climate change in Puerto Rico and adjacent Caribbean islands. Where kyr BP = thousands of years before present, SST = sea surface temperatures.

Location	Period	Source	Observation
Puerto Rico (Pollen)	Oligocene	Graham & Jarzen, 1969	Subtropical and cool temperate communities
Equatorial Atlantic (algae)	Pleistocene	McIntyre & Molfino, 1996	23,000 yr cycle in nutricline correlated to orbital procession
Bahamas (isotopes)	Pleistocene	Slowey & Curry, 1992	Subtropical gyre was cooler, shallower and depleted of nutrients
Barbados (corals)	Pleistocene	Guilderson et al. 1994	SST were 5C colder 19 kyr BP
Dominican Republic	Late Pleistocene	Schubert & Medina, 1982	Late Pleistocene snowline at 2200-2300 meters
Haiti (isotopes)	Holocene	Hodell et al. 1991	Arid 10.5-10 kyr BP, wet 8.2-2.5 kyr BP, dry (2.5-1.0 kyr BP)
Bermuda (isotopes)	Holocene	Keigwin, 1996	1C cooler SST 0.4 & 1.7 kyr BP, 1C warmer 1kyr BP
Puerto Rico (Charcoal in Laguna Tortugero)	Holocene	Burney & Burney 1994	Charcoal increases abruptly after 5.3 kyr BP. Maybe related to human occupation
Puerto Rico and Hispanola	Historic	Reading 1990	Decades of high and low hurricane activity
St. Croix	Historic 1899-1978	Rogers 1988	Seasonal precipitation correlated to high/low Southern Oscillations
Subtropical North Atlantic	Historic 1957-1992	Parrilla et al. 1994	Warming of 800 m to 2,500 m ocean water at 1C/100 yr.
Cuba	Historic	Cermak et al. 1992	Soil warming by climate and deforestation
Puerto Rico (species distributions)	Historic	This paper	Occurrence of large, upper elevation, high rainfall species in areas of lower rainfall

Historic records indicate that both local and global scale processes can directly influence local climate. Moreover, rainfall and atmospheric inputs have been related to North African droughts and anthropogenic inputs from the Northern Hemisphere (Prospero and Nees 1985, McDowell et al. 1994). Annual and seasonal rainfall in the Caribbean have been correlated with different modes of the Southern Oscillation (Rogers 1988) and seasonal shifts in temperature in San Juan have been related to changes in solar precession (Thomson 1995). Hurricane frequency has also been correlated with the beginning of a glacial retreat in the Andes and in New Guinea, record low-water levels in Lake Chad, El Nino activity, and Saharan rainfall (Reading 1990). Surface and subsurface sea temperatures have also varied by several degrees during the late Holocene and in recent decades (Table 1).

In addition to these global scale influences, local environmental change can influence Caribbean climate. Changes in the vertical temperature profile in Cuban soils indicate that climatic warming has increased surface temperatures at a rate of 1 to 1.2°C per century over the past 200-300 years (Cermack et al. 1992). Deforestation in the past 100 to 200 years has caused additional increases. Geomorphic evidence indicates that tectonic uplift and deforestation has changed the

aerial extent and vegetation cover of the coastal plain surrounding the LEF during late Holocene to recent times (Clark 1997). Because a 1°C increase in surface temperature can cause a 375 m change in the heating level of condensation of the trade winds that pass over the LEF (Malkus et al. 1953), changes in the microclimate of the coastal plain may influence the cloud base, rainfall, and ultimately the distribution of tree species within the LEF. The cursory correlation between annual rainfall in the LEF and island-wide forest cover supports the notion that changes in forest cover can influence rainfall in the LEF (Fig. 1).

Perhaps the most persuasive evidence of past climate change in the LEF is the presence of isolated stands of large Colorado (Cyrilla racemiflora L.) trees that occur below 400 masl. This species is currently a dominant tree in areas above the 600 masl cloud base and is most common in the LEF where mean annual rainfall averages 4191 mm/yr (Garcia et al. 1996). However, some of the largest Cyrillas known in the LEF occur in areas that are surrounded by younger Tabonuco-type forest vegetation and receive less than 3000 mm/yr. These large Cyrillas maybe over 600 years old (Weaver 1996) and their presence at lower elevations suggest that the upper elevation of drier Tabonuco-type forest vegetation may have increased in the past several centuries.

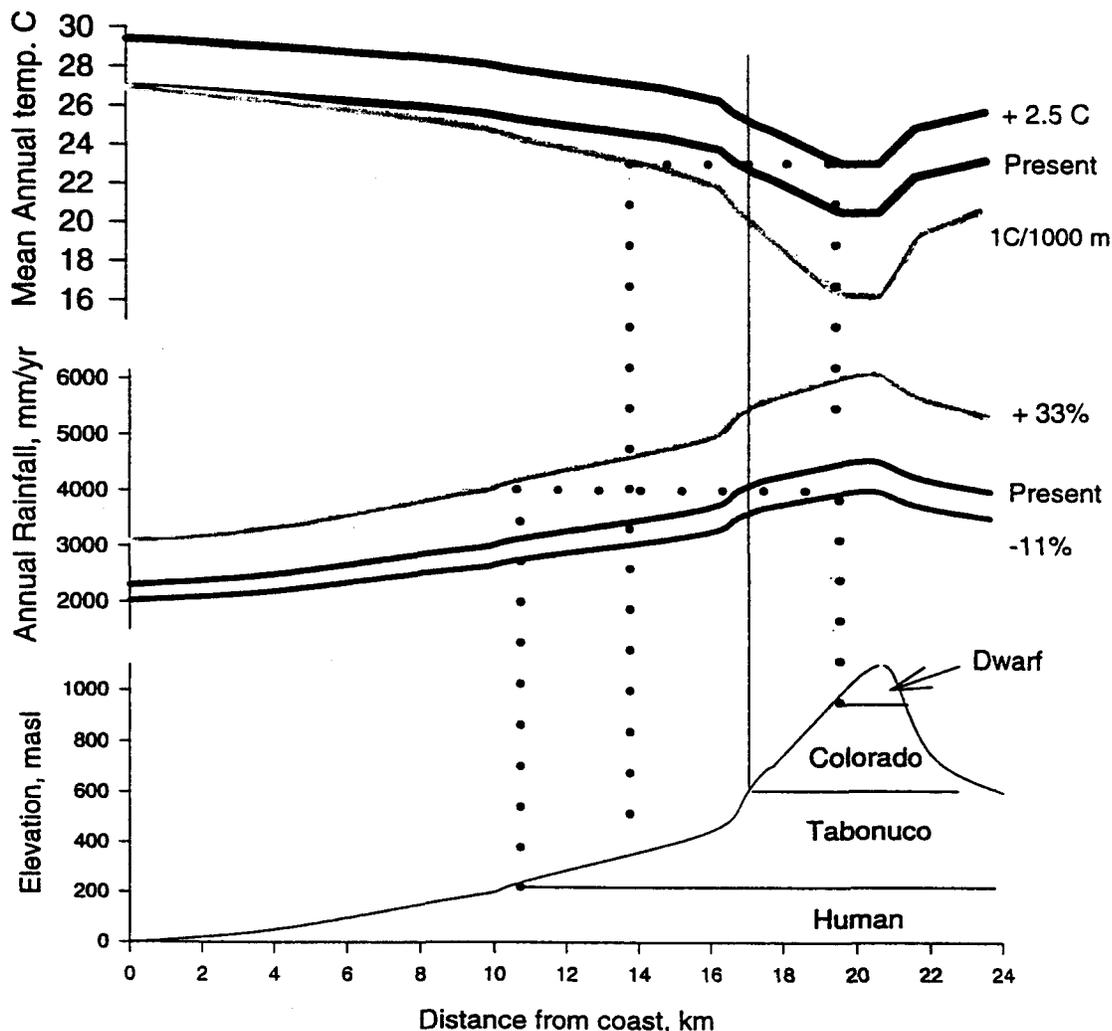
ASSESSING CLIMATIC CHANGES IN THE LUQUILLO EXPERIMENTAL FOREST

Model simulations designed to determine the influence of a CO₂ induced global warming of 1.76°C on humid tropical forests indicate that by 2060 dry season length will increase and soil moisture will decrease in much of the Amazon basin, Africa, and Australia (Hulme and Viner 1995). Although the spatial resolution of this model maybe to coarse to accurately predict changes within the LEF, simulations indicate that annual temperature will increase by 1.5 to 2.5°C in Puerto Rico and eastern Hispanolia. Mean annual rainfall is expected to remain the same but inter-annual rainfall variability, seasonality, soil moisture and the number of days with greater than 5 mm of rain are expected to decrease. Other model and theoretical evidence indicates that hurricanes could become more intense and frequent with CO₂ induced climate changes (Emanuel 1987, O'Brien et al. 1992, Hulme and Viner 1995, Knutson et al. 1998). Computer simulations of the Tabonuco forest ecosystem also indicate that a range of forest compositions (O'Brien et al. 1992) and soil organic matter pools (Stanford et al. 1991) are possible with different hurricane recurrence intervals.

The above summary indicates that both local and global processes effect the climate of the LEF. Global scale processes include changes in SST and atmospheric and oceanic circulation patterns. Locally, increases in the extent of the coastal plain and deforestation and subsequent changes in surface temperatures have presumably decreased the moisture content and increased the average cloud condensation level of the air stream that brings moisture into the LEF. The net result of these changes would be a decrease in annual rainfall and a upward shift in the boundaries of the different forest types. This highly speculative conjecture is supported by the presence of isolated stands of Colorado trees in the LEF, evidence of late Holocene drying in Haiti, and soil surface heating in Cuba.

Although there is considerable uncertainty in the magnitudes of past and future climate change, an assessment of the magnitude of change needed to dramatically alter the distribution of forest types can be made using existing climate-forest type-elevation relationships (Fig. 2). This highly simplified model assumes that the forest boundaries are controlled solely by rainfall or temperature and no implicit or explicit assumptions about the nature or rate of change is made. Nevertheless, with a 11% decrease in annual rainfall species that are currently limited to the drier Tabonuco-type forest would be able to grow in most areas presently occupied by Colorado type forest. Likewise, Tabonuco-type forest could occupy most of the Colorado zone with a 2.5°C increase in the air temperatures or a 1.1°C increase in surface temperature. In contrast, a 33% increase in annual rainfall would be required to move the Colorado zone downward to the boundary of the LEF.

Figure 2. Elevation, mean annual rainfall, temperature profiles, and forest boundaries of the Luquillo Experimental Forest, Puerto Rico under different climate regimes.



The magnitude of these changes in temperature and rainfall (i.e. 1 to 2°C and 11 to 33% change in annual rainfall) are within the range of change that has been recorded in the past (Table 1) and is projected for the future (Hulme and Viner 1995). If realized, these changes could have consequences for forest wide hydrology and regional water supplies. Moreover, given that stream runoff from the Tabonuco type forest is 1367 mm/yr less than that from the Colorado type forest (Garcia et al. 1996), changing all of the Colorado-type forest to Tabonuco type forest would reduce forest wide annual runoff by nearly 17%. Given the increased urbanization that is occurring around the forest boundary and projections that the LEF will become warmer as a result of global warming, it is expected that the forest will continue to dry in the future. These impacts should be considered in planning future water supply systems and coastal plain developments.

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