

2 Assessing Ecological Sustainability and Diversity of Plant and Animal Communities

2.1 Assessing Terrestrial Ecosystems, Aquatic Ecosystems, and Watersheds

2.1.1 *Terrestrial Ecosystems, Aquatic Ecosystems and Watersheds Overview*

2.1.1.1 Existing Information

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Map Formulation and Delineation Meta Data and References

This vegetation classification was developed for the revision of El Yunque National Forest (EYNF) Management Plan in 2013. The geospatial dataset was created and modified at the International Institute of Tropical (IITF) Forestry GIS and Remote Sensing Lab with expertise from scientists and foresters from the IITF and EYNF. The geospatial data was based on the PRGAP 2000 land cover map (Gould et al. 2007). The original data was modified to better fit forest management needs. We modified the PRGAP land cover by incorporating information from the Holdridge ecological lifezones (Ewel and Whitmore 1973), 600 meter elevation line (USGS), and 3300 millimeter precipitation line (Daly et al. 2003) to create the new vegetation classification. We also created a 100-foot buffer around the rivers (National Hydrography Dataset) inside the Forest to identify riparian forest. The river buffer zones were separated into submontane moist, montane wet and rain, and montane cloud wet and rain riparian forests using a combination of ecological life zones data and the 600 meter elevation line.

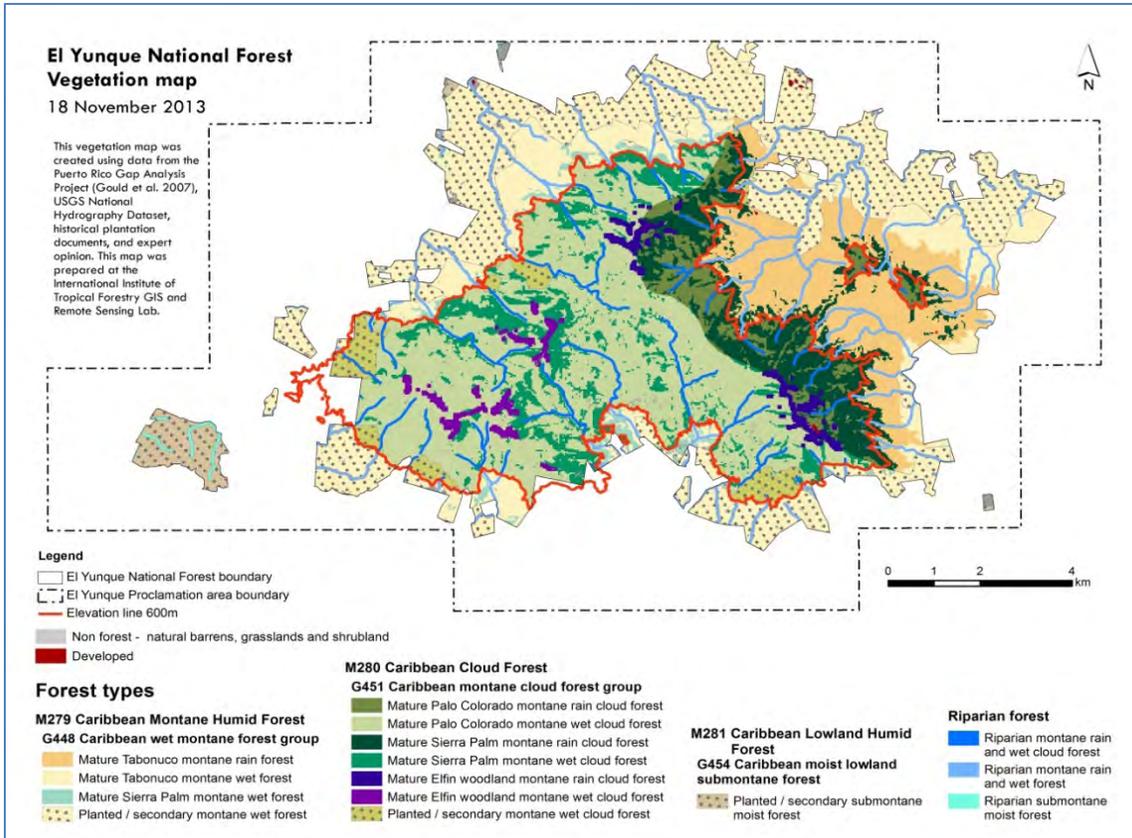
2.1.2 Identifying the Ecosystems to be Addressed in the Assessment and Current Condition

Three types of nomenclature are commonly used to refer to the forests of the EYNF, each serving a particular audience. Local names in Puerto Rico are from Wadsworth (1951); Beard's (1944, 1949) terminology is from the Caribbean, particularly the Lesser Antilles; and Holdridge's (1967) life zone system is commonly used in Central and South America and the Greater Antilles (Weaver 1994).

For the 1997 land and resource management plan the Forest used the "local names in Puerto Rico" to address the Forest ecosystems. This nomenclature has not been consistently used to describe the forest ecosystems by academia, researchers, and land managers.

Vegetation classification provides a common language for the effective management and conservation at all scales. The vegetation can be described by its repeating patterns in species composition and/or growth forms and structure and relationships to the environment in which found. As with any taxonomy, we use vegetation classification to simplify the patterns in order to communicate and share information.

We initiated our mapping efforts using IITF (Bill Gourd) Land Cover 2000–National Vegetation Classification (NVC) map (for more detail see Appendix A). This map follows a hierarchy of NVC down to "groups." The hierarchy of the NVC continues down with "associations" and "alliances," which focus and refines more on the ecosystems vegetation or environmental conditions at the scale needed to assess timber stands. Map 2-1 shows the result of our assessment of the ecosystems present at EYNF.



Map 2-1. El Yunque National Forest vegetation

Source: Quiñones, M.; Rivera, L.A.; Gould, W.A. 2013. El Yunque National Forest vegetation map. Terrestrial Ecosystem Assessment chapter of the land and resources management plan revision for El Yunque National Forest. Vector data. USDA Forest Service, San Juan, Puerto Rico.

Forest Type Description

M279 Caribbean Montane Humid Forest

Montane Forest is the zone in mountainous regions where the influence of altitude (vertical relief) results in local climatic regimes that are sufficiently different from those in the adjacent lowlands as to cause a complex vertical climate-vegetation-soil zonation. This includes vegetation at the base of a mountain when it is different from lowland vegetation (Panagopoulos 1999). Humid forest is the vegetation in frost-free areas dominated by trees that are always wet from rain (Panagopoulos 1999).

G448 Caribbean Wet Montane Forest Group

Wet Montane Forest encompasses areas with mean annual precipitation within the approximate range of 2000 to 4000 millimeters (78 to 156 inches) per year (Ewel and Whitmore 1973) and (Miller and Lugo 2009).

	Mature Tabonuco Montane Wet Forest
	Mature Tabonuco Montane Rain Forest
	Mature Sierra Palm Montane Wet Forest
	Planted/Secondary Montane Wet Forest

Mature Tabonuco Montane Wet Forest. At EYNF this forest lies between 150 and 600 meters of altitude (Weaver 2012). This forest contains epiphytic ferns, bromeliads, orchids, and lianas; and also contains more than 150 species of trees forming a complete canopy at about 20 meters (66 feet) (Miller and Lugo 2009).

Mature Tabonuco Montane Rain Forest. In Puerto Rico, this forest is confined to the EYNF. It is located at intermediate elevations to the windward where it occupies 1,420 hectares, or 13 percent of the EYNF (Weaver 1994). It occupies the wettest zone with a lower rainfall limit of about 4,000 millimeters (150 inches). The area is characterized by a superabundance of precipitation with an annual total of 3,400 millimeters (130 inches) of runoff which is more than twice the annual rainfall input received by most areas of the world. The species found here are the same, for the most part, as those found in the surrounding montane wet forest. The main features of this zone are the high frequency of *Prestoea montana* (Sierra palm) and a superabundance of epiphytes (Miller and Lugo 2009). La Mina Recreational Area lies within this forest type.

Mature Sierra Palm Montane Wet Forest. Sierra Palm Forests are also known as “palm brakes” and are nearly pure stands of *Prestoea montana*. They are frequently found at the same elevation and in the same forest types as the Tabonuco and Palo Colorado, but they achieve maximum dominance as palm brakes in especially steep and wet areas. Palms are also found in Riparian Forest (Palm Floodplain Forest) and on very steep slopes at low elevation. Palms are usually associated with saturated soils and disturbance (Brokaw et al. 2012).

Planted/Secondary Montane Wet Forest. Since the 1930s, planted areas, mainly of mahogany, were established within the EYNF; in 1963 the practice of line planting of mahogany was started until late 1980s (Weaver 2012).

M280 Caribbean Cloud Forest

The tropical montane cloud forest is composed of forest ecosystems of distinctive flora and structure. It typically occurs as a relatively narrow altitudinal zone where the weather is characterized by persistent, frequent, or seasonal cloud cover at the vegetation level. Clouds influence the atmospheric interaction through reduced solar radiation and vapor deficit, canopy wetting, and general suppression of evapotranspiration. The net precipitation (throughfall) in such forests is significantly enhanced (beyond rainfall contribution) through direct canopy interception of cloud water (horizontal precipitation or cloud stripping) and low water use by the vegetation. Endemism is often very high and occurs on a global scale within a wide range of annual and seasonal rainfall regimes and altitudinal position (Hamilton et al. 1994).

G451 Caribbean Montane Cloud Forest Group

In the EYNF the cloud condensation level is around 600 meters, which means that the whole aboveground structure of the forest above this elevation is frequently within clouds. This

increases humidity, decreases radiation input, saturates all plants and soil surfaces, and supports epiphytic growth and aquatic systems in tank bromeliads and other crevices (Brokaw et al. 2012).

As rainfall increases toward higher elevations of the EYNF as a result of adiabatic cooling, forest structure shifts to an increased presence of epiphytes and to a higher density of shorter and smaller trees and shrubs. The lifting condensation level, which occurs typically around 600 meters above sea level, determines where clouds will form and, thus, where the cloud forest community begins (Harris et al. 2012).

All vegetation above the cloud condensation level is classified as wetlands. Cloud forests, when compared with the lower elevation forest types, contain an abundance of epiphytes, including liverworts and mosses (Bryophyta) (Harris et al. 2012).

	Mature Palo Colorado Montane Wet Cloud Forest
	Mature Sierra Palm Montane Wet Cloud Forest
	Mature Palo Colorado Montane Rain Cloud Forest
	Mature Sierra Palm Montane Rain Cloud Forest
	Planted/Secondary Montane Wet Cloud Forest

Mature Palo Colorado Montane Wet Cloud Forest. This forest extends up to about 900 meters and the dominant tree is palo Colorado (*Cyrilla racemiflora*). In this forest type soils are often saturated, and root mats on the soil surface are common. The canopy reaches about 15 meters in height (Brokaw et al. 2012). Bromeliads are common on the forest floor, particularly those of the genus *Guzmania* (Harris et al. 2012).

Mature Sierra Palm Montane Wet Cloud Forest. Large stands of the sierra palm begin to occur at approximately 500 meters elevation and extend up to the mountain peaks on steep slopes and ravines adjacent to elfin cloud forests. Palm forests are generally classified as either Palm Brake (i.e., Palm Slope) or Palm Floodplains Forests, depending on the specific environmental and geomorphic conditions present. Palm Brake Forests are found on steep slopes where soils undergo long periods of saturation, while Floodplains Forests are periodically inundated with water (Harris et al. 2012).

Mature Palo Colorado Montane Rain Cloud Forest. This forest occupies less area than any other in Puerto Rico and is only found in EYNF in a narrow band on the windward slopes of the Luquillo Mountains, immediately above the Mature Tabonuco Montane Rain Forest. Having an average annual rainfall of 4,533 millimeters and a relative humidity of 98.5 percent (Ewel and Whitmore 1973), this area is subjected to strong winds and extensive exposure to clouds (Miller and Lugo 2009).

The vegetation is similar to the Mature Palo Colorado Montane Wet Cloud Forest, but with a greater abundance of epiphytes, epiphyllae, palms, and tree ferns (Ewel and Whitmore 1973).

This forest type is concentrated on windward slopes and summits and occupies 1,180 hectares, or about 10 percent of the EYNF (Weaver 1994). This area calculation includes the Mature Sierra Palm Montane Rain Cloud Forest.

Mature Sierra Palm Montane Rain Cloud Forest. This forest is the Palm Brakes located on the previously described Mature Palo Colorado Montane Rain Cloud Forest area.

Planted/Secondary Montane Wet Cloud Forest. These are areas planted during the 1930s which are located above the 600 meters elevation above sea level, the El Yunque cloud condensation level.

G452 Caribbean Montane Elfin Thicket Group

The vegetation characteristics of this group include reduced tree stature and increased stem density. Canopy trees usually exhibit gnarled trunks and branches; dense, compact crowns; and small, thick, and hard (sclerophyll) leaves. This group contains a high proportion of biomass as epiphytes (bryophytes, lichens and filmy ferns) and a corresponding reduction in woody climbers. Soils are wet and frequently waterlogged and highly organic in the form of more humus and peat (histosol) (Hamilton et al. 1994).

Elfin forest is characterized by low tree species richness, high stem density, low canopy height, small tree diameter, low leaf area index, low specific leaf area, and low amounts of aboveground biomass compared to lower forest types (Weaver 2012).

Saturated soils, impeded root respiration, high winds, high soils leaching, low nutrient availability, low temperatures, high fog incidence, reduced solar insolation, high humidity, and reduced transpiration have all been suggested as causal agents in stunting, either individually or in combination (Weaver 2012).

Elfin Forest’s narrow ranges of temperature, precipitation, and cloud cover make this forest particularly vulnerable to changes in environmental factors, such as those changes proposed to occur as a result of global climate change (Harris et al. 2012).

	Mature Elfin Woodland Montane Wet Cloud Forest
	Mature Elfin Woodland Montane Rain Cloud Forest

Mature Elfin Woodland Montane Wet Cloud Forest. In the EYNF this forest is located above 900 meters of altitude. The canopy height is typically 3 to 5 meters, although a variant of elfin forest growing in more protected sites such as small valleys near mountain peaks can reach a height of 10 meters. In elfin forest, the trees and ground are covered with mosses and epiphytes, and the sierra palm can be common in some areas (Brokaw et al. 2012). *Tabebuia rigida*, *Ocotea spathulata*, and *Eugenia borinquensis* are the most common species in this vegetation type (Weaver 1994). Exposed ridges have a windswept sculpted appearance. This forest of twisted and stunted trees and shrubs is found on the highest peaks in 760- to 1,070-meter (2,500- to 3,500-foot) altitude zone (Miller and Lugo 2009). This forest in the EYNF is represented in El Toro and El Cacique Peaks area.

Mature Elfin Woodland Montane Rain Cloud Forest. This forest is similar to the Mature Elfin Woodland Montane Wet Cloud Forest, and is represented at El Yunque Peak, Pico del Este and Pico del Oeste. The lower rainfall limit is about 4,000 millimeters per year and is located on the windward faces of the Luquillo Mountains.

M281 Caribbean Lowland Humid Forest

G454 Caribbean Moist Lowland Submontane Forest. Moist Forest is delineated by a mean annual rainfall of 1,000 or 1,100 millimeters to about 2,000 or 2,200 millimeters (Ewel and Whitmore 1973).

Lowland is land area with vegetation reflecting limits set by regional climate and soil/site conditions, where elevation is not the primary gradient affecting vegetation zonation (Panagopoulos 1999).

Submontane is an area where the influence of altitude (vertical relief) does not result in local climate regimes that are sufficiently different from adjacent lowlands as to cause a complex vegetation-climate-soil zonation. This generally includes the foothills of a mountain range, the lowland vegetation at the base of a mountain that displays vegetation zonation (Panagopoulos 1999).

	Planted/Secondary Submontane Moist Forest
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Planted/Secondary Submontane Moist Forest

At the EYNF a tract of land (219.7 hectares) known as La Condesa, acquired during the 1940s and planted by 1947 (Weaver 2012), is the only area represented by this forest type. At present it is composed of various timber species and secondary native species that have entered a secondary succession species.

Riparian Forest

A riparian zone or riparian area is the interface between land and a river or stream. Plant habitats and communities along the river margins and banks are called riparian vegetation, characterized by hydrophilic plants. A Riparian Forest is the woodlands along the banks of stream or river. At the EYNF the width of this riparian forest is considered 100 feet from each river or stream bank.

Some examples of this vegetation type have being described for EYNF as conceptual model of wetland eco systems or generalized geohydrologic setting of wetlands; Montane Pterocarpus Forest and Riverine Palm and Riparian Forest (Harris et al. 2012; Miller and Lugo 2009). A detailed vegetation survey of the designated riparian zone still needs to be completed.

	Riparian Submontane Moist Forest
	Riparian Montane Rain and Wet Forest
	Riparian Montane Rain and Wet Cloud Forest

Riparian Submontane Moist Forest (58.96 acres). This is the riparian vegetation along rivers and streams of the Planted/Secondary Submontane Moist Forest at EYNF.

Riparian Montane Rain and Wet Forest (1350.14 acres). This is the riparian vegetation along rivers and streams of the forests below the 600 meters of elevation at EYNF.

Riparian Montane Rain and Wet Cloud Forest (704.73 acres). This is the riparian vegetation along rivers and streams of the forests above the 600 meters of elevation at EYNF.

Survey data from Pike and Scatena (2009) indicates mosses and short grasses dominate at a stage often inundated by sub-effective flows. Herbaceous vegetation is associated with intermediate discharges that correspond to the threshold for sediment mobilization. Near-channel woody shrubs and trees establish at elevations along the channel margin inundated by a less frequent discharge that is coincident with the effective discharge of bed-load sediment transport.

In montane reaches that lack a floodplain, a boundary that is characterized by the incipient presence of soil, woody shrubs, and trees corresponds to the same flow frequency as the bankfull discharge of nearby alluvial channels. The reference discharge based on these riparian features in steep land sites has an average exceedance probability between 0.09 and 0.30 percent, and a recurrence interval between 40 and 90 days. We conclude that flows with similar frequencies influence the establishment of riparian vegetation, soil development, and substrate characteristics along channel margins in similar ways. Thus, these riparian features can be used as an indicator of hydrogeomorphic site conditions to identify active channel boundaries that occur at a constant flow frequency throughout the study stream network (Pike and Scatena 2009).

Vegetation transects along a fluvial disturbance gradient from the middle of the channel into the adjacent forest follows a consistent pattern. Cushion mosses colonize in-channel boulders; whereas herbs, ferns, and grasses grow along channel margins; and woody shrubs and trees establish on higher, less frequently flooded surfaces. Vegetation stature similarly increases with the relative elevation above the channel. Short-stature vegetation grows along the channel and tall, closed-canopy woody vegetation and tall grasses grow on the banks and hill slopes (Pike and Scatena 2009).

Although there are consistent vegetation patterns at a given reach, not all of the types of vegetation are present everywhere because the abundance of certain species can also be influenced by differences in microclimate, light availability, and land-use legacies (Heartsill-Scalley 2003; Brown et al. 2006). In areas surrounded by forests, the riparian understory vegetation is mainly composed of shrubs, herbs, and ferns. The riparian zones surrounded by pastures and mixed land use are commonly dominated by grasses, vines, and bare soil.

Mosses and lichens that require shade are more common in steep land streams having a ample canopy cover. Conversely, wider lowland channels have a greater amount of incident light and consequently have a greater abundance of grasses. Furthermore, unlike many arid and semi-arid riparian forests, there is no distinct riparian forest community in the headwater streams of the Luquillo Mountains. Riparian forests along many alluvial streams in arid and semi-arid regions often have a unique composition and greater productivity than the surrounding vegetation due to increased availability of water. Yet in the continually humid climate of the Luquillo Mountains, both riparian and non-riparian forests have ample moisture availability and are consequently similar in composition, but can be different in structure and biomass (Pike and Scatena 2009).

There is no distinct Luquillo riparian forest community, but some tree species are more abundant along the streams. Valley floors are typically dominated by palms, herbs, and by light-gap colonizing species; whereas the dominant hardwoods are confined to more stable ridges (Scatena 1990). Native species commonly found alongside the steep land streams include: *Guarea glabra* (alligatorwood), *Pterocarpus officinalis* (dragons blood tree), *Inga vera* (river ko ko), and *Prestoea montana* (sierra palm). Nonnative tree species are common along lowland to mid-elevation streams and are generally associated with reforestation of former agricultural land (O'Connor et al. 2000; Brown et al. 2006). Common nonnatives found alongside the streams are: *Syzygium jambos* (rose apple), *Spathodea campanulata* (African tulip tree), *Mangifera indica* (mango), and *Bambusa* spp. (bamboo) (Pike and Scatena 2009).

Following a disturbance (such as flood, treefall gap, hurricane), grasses and herbs can begin colonizing within days and are typically well established within weeks to months (Scatena et al. 1996). Likewise, early successional trees can become established within a year. Given this rapid establishment of vegetation, it is assumed in this study, and supported by our observations over the years, that there is a general balance between the frequency and magnitude of floods and the vegetation and soil features adjacent to the stream channel. Small floods frequently cover in-channel and side-channel boulders that are habitat for cushion mosses and lichen. Intermediate-magnitude floods inundate channel bars and low-lying benches, mobilize coarse sediment, and disturb the substrate occupied by herbs and grasses. Larger floods can have sufficient power to flatten in-channel vegetation, particularly grasses and shrubs, but rarely uproot trees. Only the rarest and largest floods, like those observed during Hurricane Hugo (Scatena and Larsen 1990), uproot matured riparian trees, scoured the banks, and completely rework the channel morphology. These observations indicate that vegetation structure is a highly sensitive indicator of flow frequency and that differences in vegetation near the active channel can be used to define flow regimes and flow frequencies (Pike and Scatena 2009).

Riparian Vegetation. The average elevation of the first occurrence of the different riparian vegetation types (mosses, grasses, herbs, shrubs, trees) are zoned with respect to elevation along the cross-sectional profile of the channel. Canopy cover, the abundance of leaf litter, and soil development also increase from the channel to the adjacent forest. Our surveys and observations in other streams in the region indicate that this zonation is best developed along channels that have open or partially open canopies where there is sufficient light for grasses and herbaceous vegetation to establish and also sufficient shade for the development of cushion mosses. While local environmental conditions (such as light, substrate, hydraulic shielding) can constrain the establishment of vegetation at any particular location, the average elevation of the first occurrence of different vegetation forms, litter cover, and soil development is consistently related to the frequency of flow inundation both within and between sites. Moreover, mosses, herbs, and grasses start establishing at elevations that are inundated weekly or monthly, and are slightly above the baseflow water level. Shrubs and trees are present at higher stages where they are inundated, at least briefly, several times a year (Pike and Scatena 2009).

The average elevation of the first occurrence of the different vegetation types is also related to sediment transporting flows and the effective discharge. Mosses and short grasses dominate at a stage below the threshold of sediment transport, but above the most frequent flows (the peak in the probability density function of discharge) (Pike and Scatena 2009). That is, they first occur at stages that are frequently inundated by sub-effective flows. Herbs first occur at a stage associated with intermediate discharges that are around the threshold for sediment mobilization. Woody shrubs and trees establish at a less frequent discharge that is coincident with the effective discharge of bed load sediment. The greatest variation in the vegetation types occurs around the threshold for sediment mobilization, where grasses, herbs, shrubs, and trees commonly occur together (Pike and Scatena 2009).

Planted Forest/Secondary Forest or Novel Forests?

There are 7,784.5 acres of lands at EYNF for which the actual National Vegetation Classification System vegetation association or alliances cannot be exactly determined with the information available at EYNF. Preliminarily, we identified these lands as Planted/Secondary Forest due to their past land uses and documented history. After a brief discussion of the definitions of the terms “plantation” and “secondary succession” and the more recent concept of “Novel Forest,” we have concluded that Novel Forest is the more appropriate preliminary descriptive name to this

vegetation type until future research or silvicultural analysis and/or monitoring could determine the actual vegetation type or types present in these lands.

Plantations. Forest plantations, generally intended for the production of timber and pulpwood, increase the total area of forest worldwide. Commonly mono-specific and/or composed of introduced tree species, these ecosystems are not generally important as habitat for native biodiversity. However, they can be managed in ways that enhance their biodiversity protection functions and they are important providers of ecosystem services such as maintaining nutrient capital, protecting watersheds and soil structure as well as storing carbon. They may also play an important role in alleviating pressure on natural forests for timber and fuelwood production. Plantations are always young forests in ecological terms. Typically, trees grown in plantations are harvested after 10 to 60 years, rarely up to 120 years. This means that the forests produced by plantations do not contain the type of growth, soil, or wildlife typical of old-growth natural forest ecosystems. Most conspicuous is the absence of decaying dead wood, a crucial component of natural forest ecosystems. Plantations show orderliness and uniformity. Enrichment planting, linear, or line planting, do not constitute conventional plantations. Older stands of planted forest may take on many features of natural forest, which further blurs definitions. Planted forest can also be managed less intensively for conservation, protection, or other socioeconomic purpose (Evans and Turnbull 2004).

FAO (2001) defines plantations as “Forests stands established by planting or/and seeding in the process of afforestation or reforestation. They are either: Of introduced species (all planted stands) or, Intensively managed stands of indigenous species, which meet all the following criteria: One or two species at plantation even age class, regular spacing.”

“Intensively managed stands” intend to exclude stands established as plantations but are now considered seminatural because they have not been managed intensively for a significant period.

There are many types of plantations ranging from short-rotation industrial plantations through to close-to-nature plantations that vary in intensity of management and other management practices according to whether the objectives are to maximize wood production, to maximize environmental values or some combinations of production and conservation objectives.

Planting can function as successional catalyst to assist natural regeneration of the trees and shrubs by modifying the microclimate of their understory, increasing soil organic matter. There have been attempts to accelerate the recovery of degraded forest and deforested lands to restore productivity, biodiversity, and other values. Plantations can produce valuable forest products and at the same time accelerate regeneration of species-rich forest ecosystems.

Ecosystems can be characterized by their species composition and structure, complexity and function, and biomass nutrient content (Evans and Turnbull 2004).

Secondary Succession. Ecological succession is the gradual process by which ecosystems change and develop over time. Nothing remains the same and habitats are constantly changing. In the process of succession, the species present in an area will gradually change. Succession takes place because the environmental conditions in a particular place change over time. Each species is adapted to thrive and compete best against other species under a very specific set of environmental conditions. If these conditions change, then the existing species will be replaced by a new set of species, which are better adapted to the new conditions.

If left undisturbed, the area will pass through a number of further different successional stages, each with its own characteristic mix of species. All of these different successional stages are known collectively as a “sere.” Each new community will be better adapted to the changed environment, which has been provided by the previous community.

Eventually, a climax or “final” community is reached. At this point, the succession will not go any further. However, this does not imply that there will be no further change. Secondary succession is the series of community changes which take place on a previously colonized, but disturbed or damaged habitat. Examples include areas which have been cleared of existing vegetation (such as after tree-felling in a woodland) and destructive events such as fires or agriculture (Wikipedia).

Successional processes are not always directional or predictable, and multiple pathways can lead to a range of mature forest types rather than a single, stable endpoint.

Novel Forest. Plant succession after anthropogenic disturbances often results in novel combinations of species and Novel Forests. Research in Puerto Rico documents the emergence of Novel Forests, which are different in terms of species composition, dominance, and relative importance of species from forests that were present before the Island was deforested. These Novel Forests emerged without assistance. They are a natural response to the new environmental conditions created by human activity. Natural processes have remixed or reassembled native and introduced plant and animal species into novel communities adapted to anthropogenic environmental conditions. Novel Forests are expected to protect soils, cycle nutrients, support wildlife, store carbon, maintain watershed functions, and mitigate species extinctions.

Abandoned planted areas of introduced species behaved like native forests and allowed the establishment of a rich understory of native species, which then mixed with the introduced species to form a different forest type than originally present. Experimental plantings of introduced species overcame arrested succession and native forest species reestablished below their canopy. Emerging forests had higher tree species richness than those that were native, and functioned as did native forests, but at different rates (Lugo 2009).

The presence, dominance, and relative importance of tree species in these Puerto Rican forests made them different from the species composition, dominance, and relative importance of species of forests that were present before the Island was deforested. Also, the species composition of the original forest would never return, and would forever be different because introduced species had become part of the new mix of species (Lugo 2009).

The reality is that succession can proceed through many paths to maturity, and the speed, direction, and species composition is influenced by environmental conditions including the types of species available and capable of competing for site dominance. The result that we see in Puerto Rico is that the forests of today are novel; they contain combinations of species not known to have existed before and the relative abundance of these species is different from those of the past (Lugo 2009).

We are entering an era of novel tropical forests because human activity continues to modify landscapes in ways that are unfavorable to the regeneration of traditional community assemblages, particularly in the periurban environment and after the cycle of deforestation, agricultural use, and abandonment of lands. Novel environmental conditions created by human activity favor the remixing of species and formation of Novel Forests. Novel Forests will probably behave ecologically as native forests do (i.e., protect soil, cycle nutrients, support

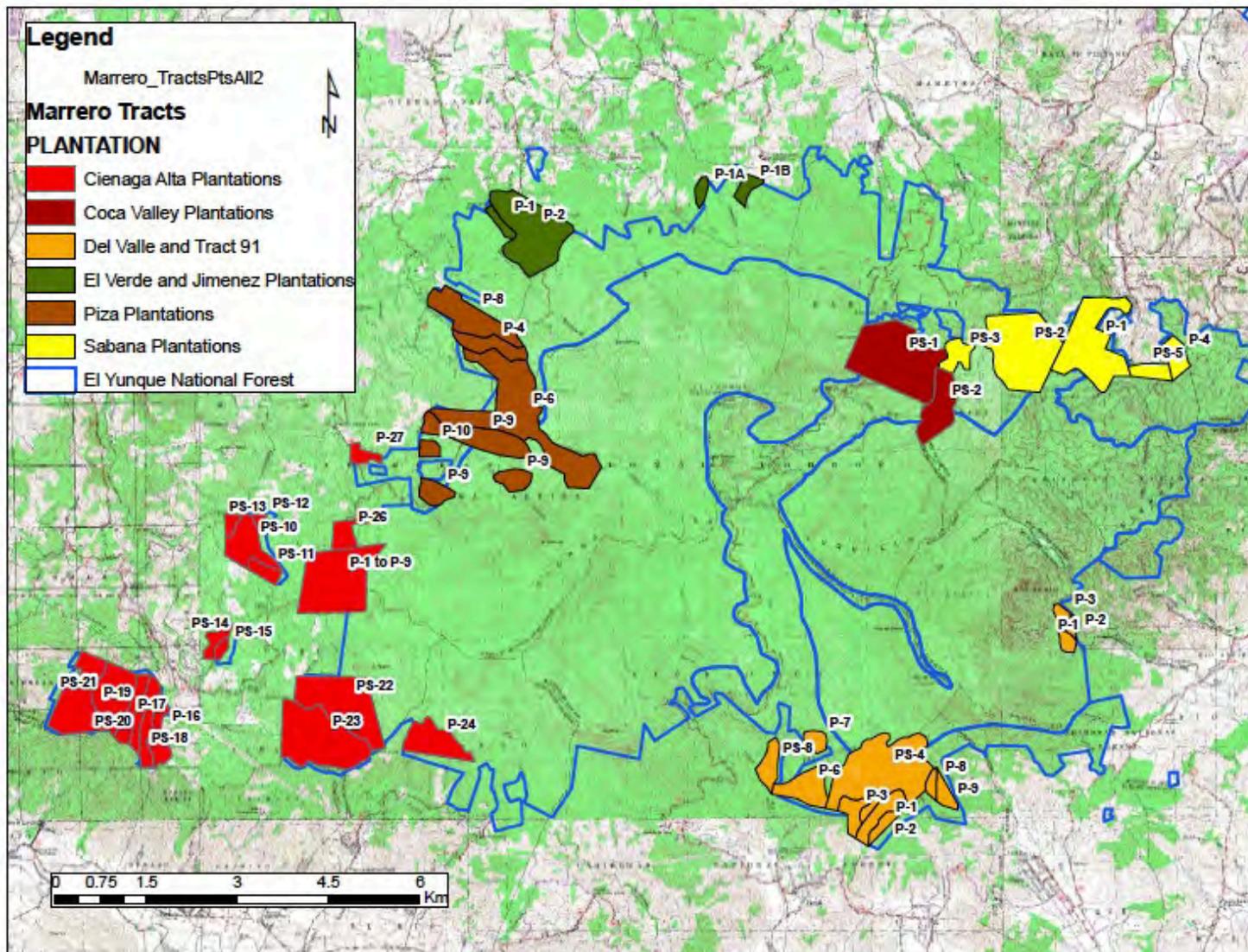
wildlife, store carbon, and maintaining watershed functions). Moreover, Novel Forests mitigate species extinctions as they, like secondary forests, are in successional paths to maturity and species accumulation. Nature's response to the Holocene cannot continue to be ignored or remain undetected by ecologists. The dawn of the age of tropical novel forests is upon us and must not be ignored (Lugo 2009).

2.1.2.1 El Yunque National Forest Situation

From 1934 to 1942, 54 different planted areas were established in the Sierra de Luquillo (see Map 2-2). The final goal of this planting effort was the establishment of a forest, which is (1) all-aged, and (2) composed of sawtimber and durable round-timber species capable of reproducing itself. Many of the acres planted were considered failures or established in areas that were later "dropped" from management activities.

A total of 4,065,966 seedlings plus 44,690.3 pounds of seeds were used in a total of 3,925.6 acres, of which 2,866 acres were actually planted, in which about 27 species were represented. The relative merits of mixed and pure stands had not been determined under Puerto Rican conditions, but it appears that a mixed stand being more natural, may prove more satisfactory. In the Luquillo Forest volunteer forest growth rapidly improves the soil and thus creates favorable soil conditions for tree growth. Also it maintains favorable humidity and reduces weeds and vines. Climax species, which as a rule are more exacting, do not appear until the site has been improved by pioneer species. The very heterogeneous site and cover resulted in very uneven and mixed stands where trees occur in all ages from 1 to 11 years (Marrero 1947).

In summary, that period of reforestation efforts, at the landscape scale, was an enrichment planting that functioned as a catalyst to secondary succession and an introduction to the Luquillo Mountain of a group of novel species many of which got established and are regenerating naturally. As a result, many of the forest functions and characteristics lost during the deforestation period had since been restored. Some of the lands reforested during this era are now part of the El Toro Wilderness and Baño de Oro Research Natural Area (see Map 2-2).



Map 2-2. EYNF reforestation efforts between 1934 and 1942

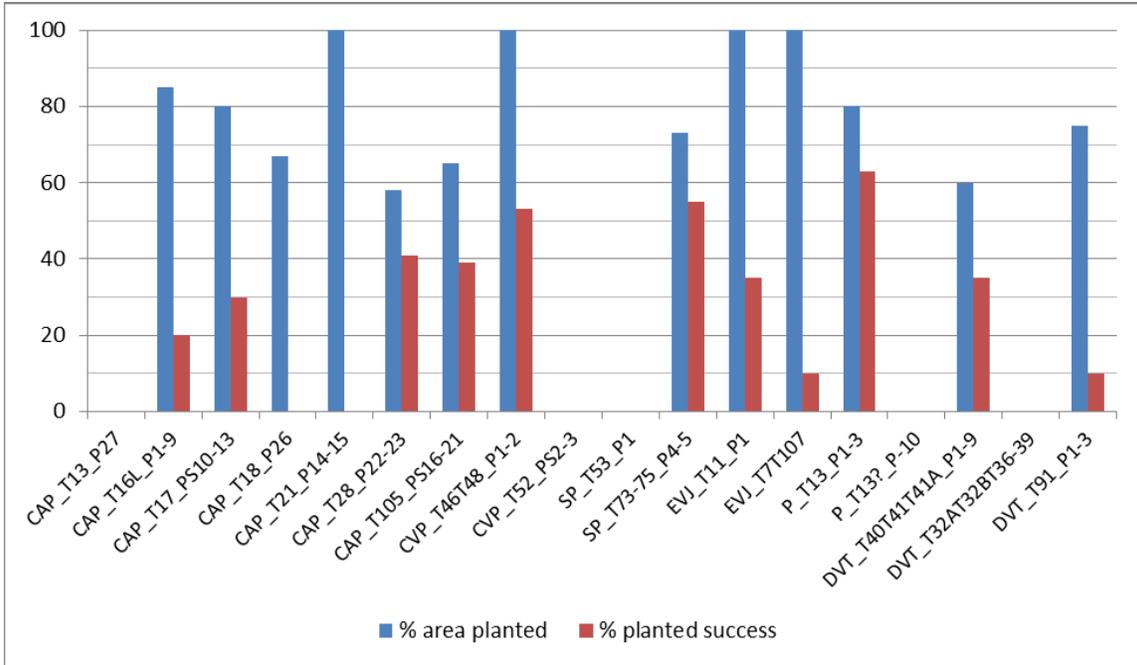


Figure 2-1. Percentage of tract planted and success

Source: Marrero (1947)

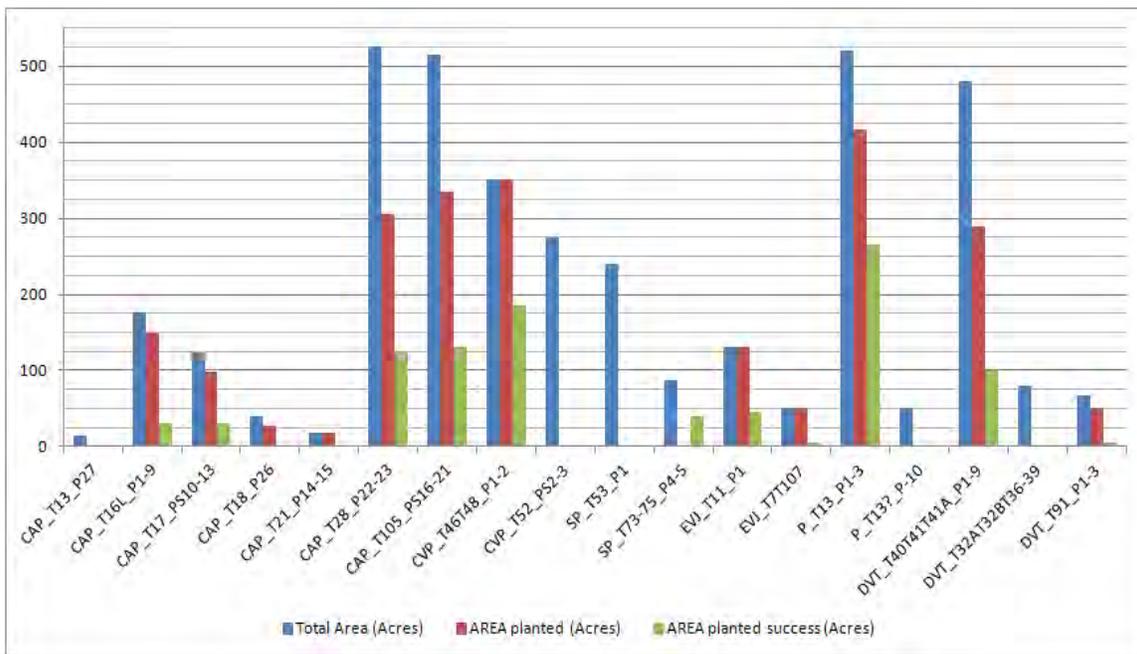


Figure 2-2. Total acres of tract, acres planted and acres establish

Source: Marrero (1947)

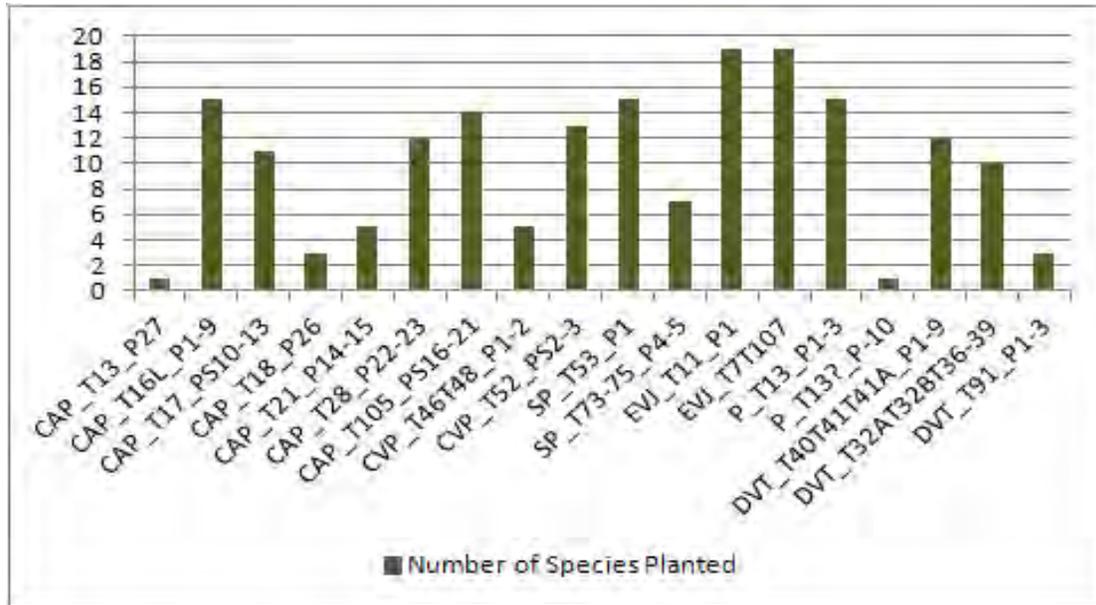


Figure 2-3. Number of species planted per tract

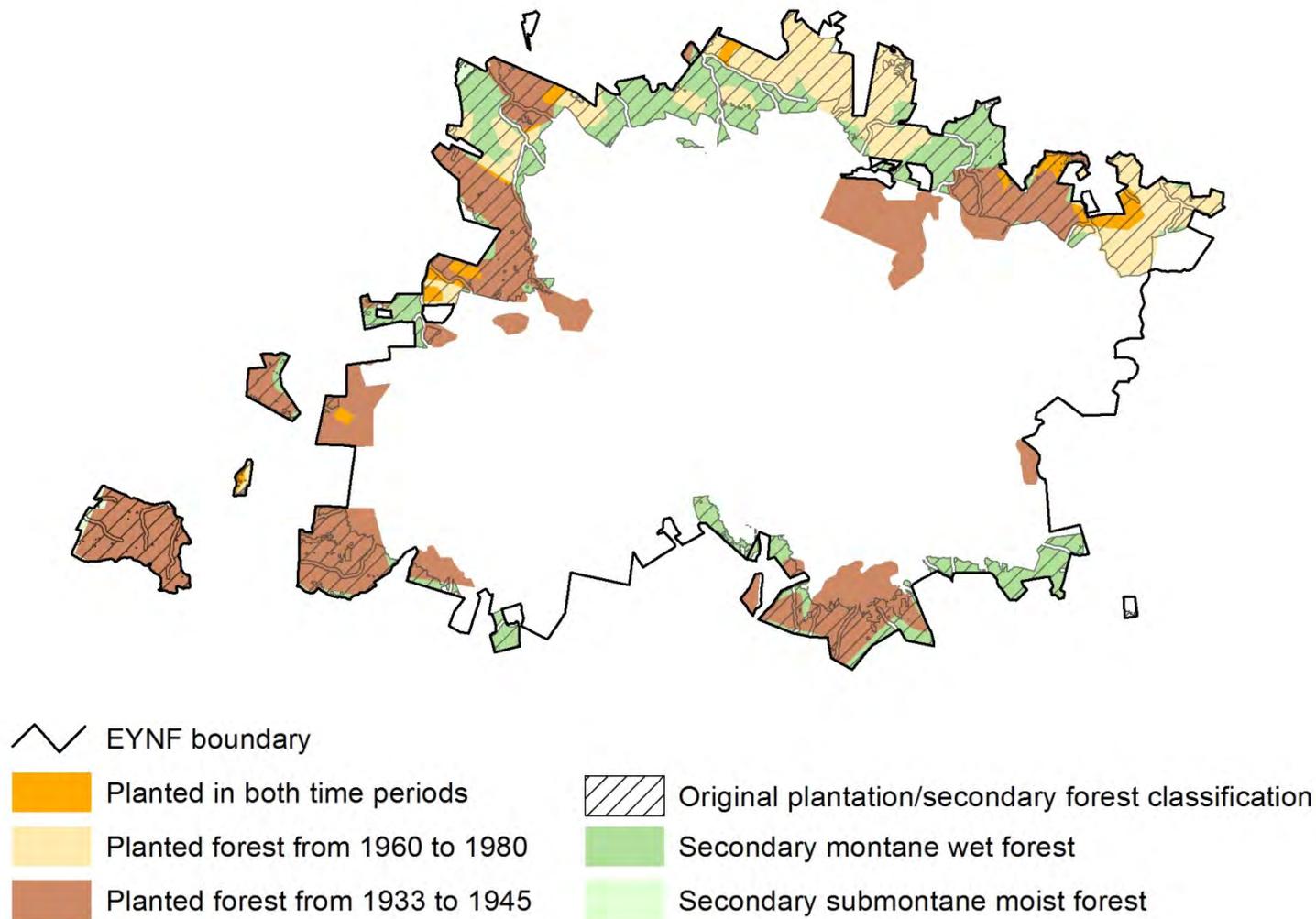
Source: Marrero (1947)

From the 1960s into 1980s block and line plantings continued in the EYNF, mainly of mahogany as the feature species, along with blue mahoe, teak, gmelina, kadam, and Caribbean pine. The appeal to the 1987 land and resource management plan put a hold to the commercial timber management program, but the Plan allocated 1,200 acres to a Timber Management Demonstration Program (see Map 2-4). These lands included areas planted during the 1930s, 1960s and 1980s. The more recent ones were line planting. In this system the spacing was 8 feet by 20 to 25 feet at a rate of 250 trees per acre, allowing the secondary forest to exist between mahogany rows. These plantings needed intense management to control vines, weeds, insects, and shade with the intention to promote the plantings to a dominant canopy closure. There were 1,200 acres of young mahogany line planting when Hurricane Hugo (category 4) struck the Forest in 1989. Only 800 acres were able to be treated for recovery, the other 400 were abandoned to secondary succession. After 1990 no silvicultural analysis or treatment has been done on any lands of EYNF (see Map 2-5).

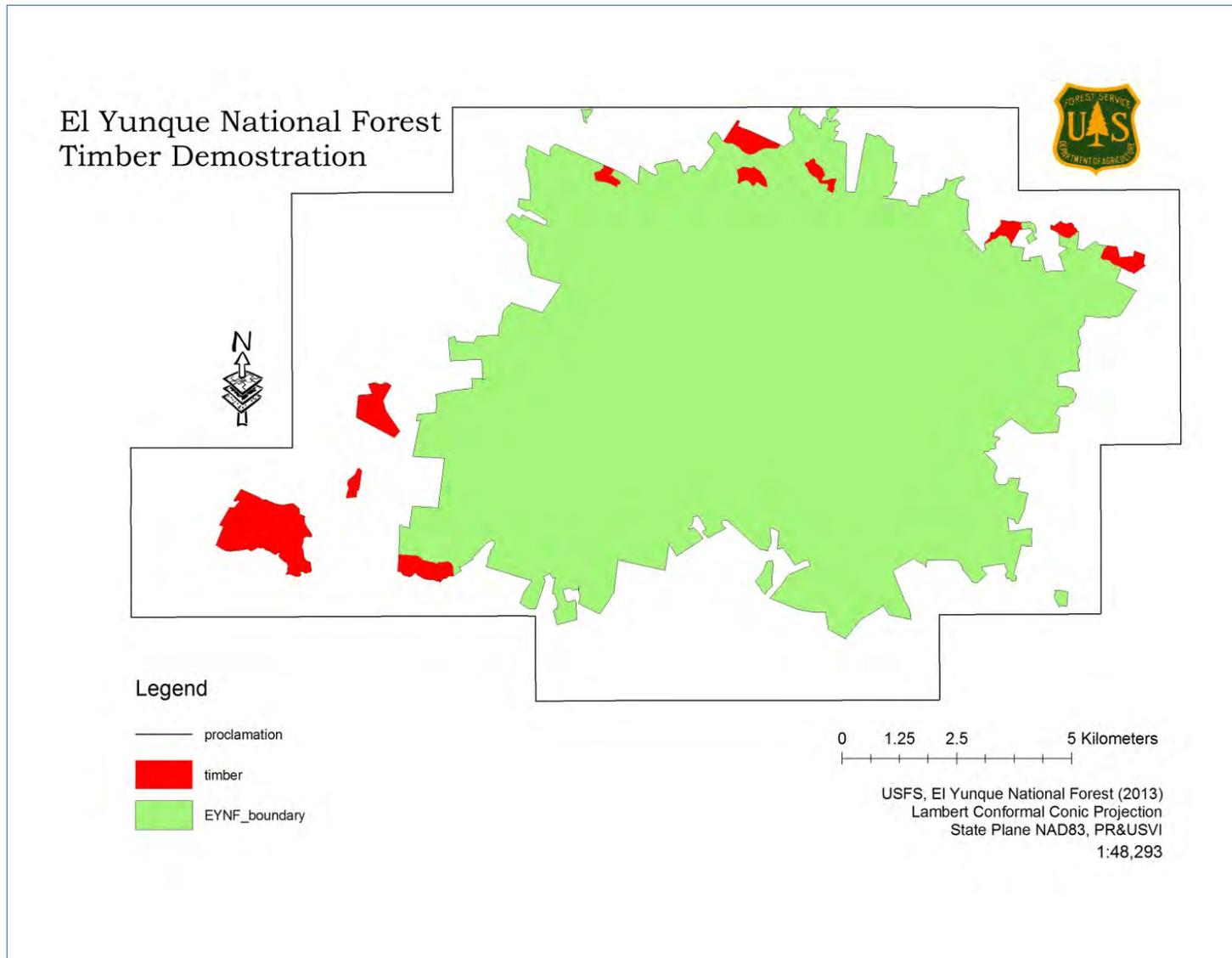
During 1998 another Hurricane (Georges, category 3) struck the Forest compounding the previous Hurricane effects. It is expected that after more than 20 years of no silvicultural treatment to those lands and two direct hits by hurricanes, plus six tropical storms and nine other hurricanes impacting the Island, the effect to the Forest is similar to what happened in the Luquillo Mountains after the reforestation efforts during the 1934 to 1942 period (the establishment of a Novel Forest).

Thus again we have a Novel Forest that is expected to persist for generations to come; therefore, those lands (aside from several small stands) are the new Vegetation type of EYNF and it will be very difficult to separate planted forest from secondary succession forests or to call a particular site a plantation, just because it was planted in the past. A thorough silvicultural analysis is needed to determine the condition, composition, structure and function of these lands.

Planted and secondary forest

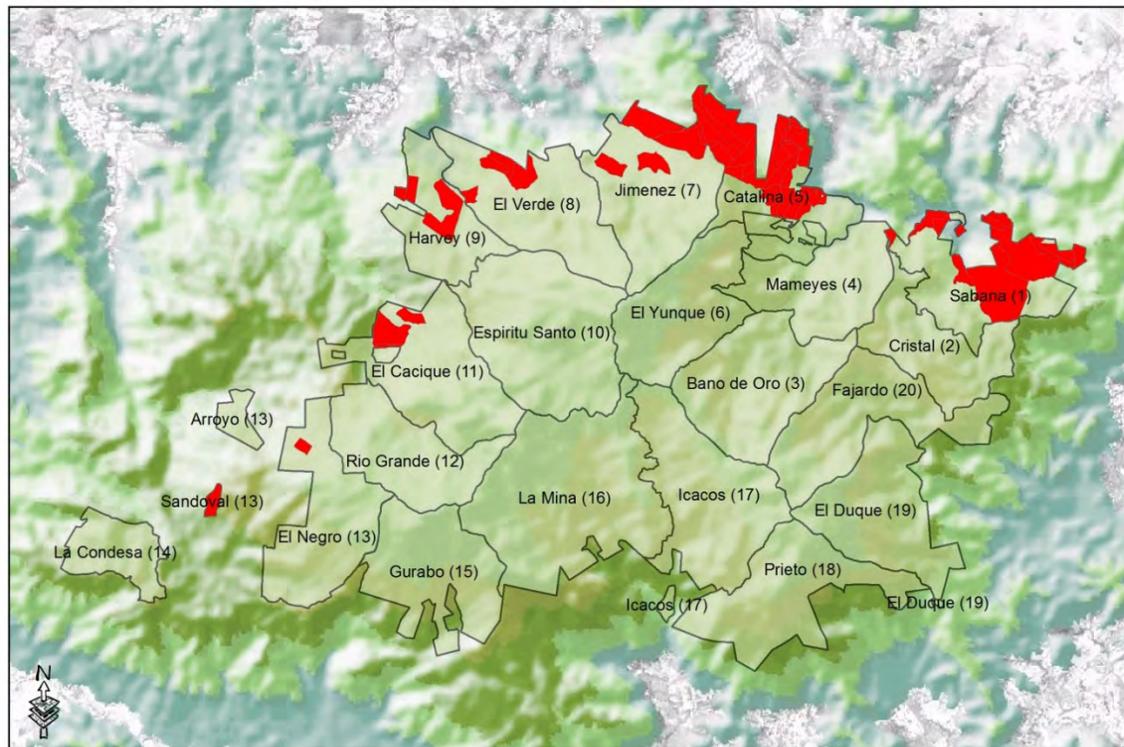


Map 2-3. Areas planted in the 1930s, 1960s into the 1980s in our new ecosystem type matrix; Planted/Secondary Forest Area



Map 2-4. Timber demo stands (LRMP 1997 Management Area 8)

El Yunque National Forest, Forest Planted 1960's/1970's/1980's



Legend

- Status**
- planted (2,063 Acres)
 - compartments

0 0.5 1 2 3 4 5 6 7 8 9 10 11 Kilometers

USFS, El Yunque National Forest (2013)
Lambert Conformal Conic Projection
State Plane NAD83 PR&USVI
1:51,620

Map 2-5. Compartments and stands showing areas planted mostly with mahogany



Sierra de Luquillo enshrouded in clouds; view from the Atlantic Ocean (photo by Luis A. Rivera)

Vegetation and Environment of the Cloud Forest (A Functional Wetland)

The Luquillo Mountains are a major source of water for the Island and an important recreation site. The mountains supply more than 20 percent of the Island's municipal water each year, with the E YNF providing an average of 276 cubic hectometers of water per year for municipal uses (Scatena and Johnson 2001). The nine rivers that drain the Luquillo Experimental Forest all have steep gradients, boulder- and bedrock-lined channels with steep-pool morphology, and waterfalls (Ahmad et al. 1993). The yearly water production of E YNF is estimated at 73.5 billion gallons per year ([LRMP] USDA Forest Service 1997).

Puerto Rico receives precipitation from at least five major weather systems: the northeast trade winds, tropical depressions and hurricanes, northern cold fronts, systems originating in the Pacific, and systems originating in the Amazon basin. Headwater basins in the E YNF have complex hydrologic regimes dominated by variability at two scales: daily and multiyear.

All forests above the cloud condensation level (600 meters of altitude) at the E YNF are cloud forests, including the elfin forests (Harris et al. 2012).

The most widespread and abundant canopy-forming species—the sierra palm, *Prestoea montana*—occurs from the lowest elevations of the Luquillo Experimental Forest to elevations of more than 1,000 meters above sea level. Tree species along the Sonadora stream elevation gradient in the E YNF have various distribution patterns, with species such as *Prestoea montana* and *Psychotria berteriana* occurring in great abundance at all elevations. From mid-elevations to higher elevations, *Rhedia portoricensis* and *Magnolia splendens* are more abundant, while *Cyathea bryophylla* and *Lobelia portoricensis* are found only in the highest elevation sites. The intensively sampled elevation transects of Barone et al. (2008) demonstrate that boundaries of vegetation associations are not as clear as boundaries in surrounding palm forests (Harris et al. 2012).

Silver et al. (1999) documented a soil oxygen concentration gradient with elevation and a long topography at the Luquillo Experimental Forest and found that tree species density decreased as the average soil oxygen concentration declined along a ridge, slope, valley catena. It appears from

this study and the observations of Frangi (1983) that all plant communities above the cloud condensation level are wetland communities. Above this level, soil oxygen concentrations decrease, soil saturation increases, and plant species density and distributions are affected (Harris et al. 2012).

In addition to the tabonuco-dominated, low-elevation forests, wetlands in the EYNF found below the cloud condensation level include riparian forests. In the lower elevations of the Mameyes river watershed, the wetland tree *Pterocarpus officinalis* forms stands along riparian areas. A *P. officinalis* stand of approximately 3.7 hectares occurs at 500 meters above sea level in the EYNF; it is described as a montane riverine forest system with organic soil over clay. Other species within this rare wetland forest type include *Casearia arborea*, *Cordia borinquensis*, *Inga laurina*, *Manilkara bidentata*, the tree fern *Nephelea portoricensis*, and the palm *Prestoea montana*. The upper canopy is 25 to 30 meters in height, and a second canopy layer is found at 15 meters, with abundant epiphytes and woody vines. *Pterocarpus officinalis*, a species with a wide Caribbean distribution, also occurs in small groups of individuals along streamsides at elevations below the EYNF boundary (Harris et al. 2012).

More diverse riparian communities dominate other low-elevation wetland areas. In the Luquillo Forest dynamics plot along the Prieta and Toronja streams, Heartsill-Scalley et al. (2009b) calculated the minimum distance of individual stems (greater than 10 centimeters DBH) to the nearest of the two streams. The species with stems in close proximity to streams were *Clusia rosea*, *Coccoloba diversifolia*, *Margaritaria nobilis*, *Ixora ferrea*, *Trichilia pallida*, and *Guettarda valenzuelana*, with a median distance to streams between 21 and 29 meters. *Margaritaria nobilis* and *C. diversifolia*, however, were most abundant closer to the streams, with 75 percent of their stems within 30 to 40 meters of the stream. Other species had 75 percent of their stems within 40 to 50 meters from the stream and included *Clusia rosea*, *Guatteria caribaea*, *G. valenzuelana*, *Byrsonima wadsworthii*, and *Eugenia stahlii* (Harris et al. 2012).

Cloud and Wetland Forests Above the Cloud Condensation Level (600 Meters of Altitude)

As rainfall increases toward higher elevations of the EYNF as a result of adiabatic cooling, forest structure shifts to an increased presence of epiphytes and to a higher density of shorter and smaller trees and shrubs. The lifting condensation level, which occurs typically around 600 meters above sea level, determines where clouds will form and, thus, where the cloud forest community begins. The lower elevation cloud forest (about 600 to 800 meters) is characterized by the late-successional species *Cyrilla racemiflora* (palo colorado), but is dominated on a stem density basis by *Prestoea montana*, *Micropholis garciniifolia*, and *Calycogonium squamulosum*. Bromeliads are common on the forest floor in the palo colorado forest particularly those of the genus *Guzmania*. Weaver (1991, 2000) has described the tree species in this vegetation association in great detail and discussed lateral gradients in relation to aspect (leeward versus windward) observed regarding both composition and structure.

Large stands of the sierra palm (*Prestoea montana*) begin to occur at approximately 500 meters elevation—at the intersection of Premontane Wet and Rain Forest Life Zones—and extend up to the mountain peaks on steep slopes and ravines adjacent to Elfin Cloud Forests (Brown et al. 1983; Weaver and Murphy 1990; Lugo et al. 1995). Palm Forests are generally classified as either Palm Brake (i.e., Palm Slope) or Palm Floodplain Forest, depending on the specific environmental and geomorphic conditions present. Palm Brake Forests are found on steep slopes where soils undergo long periods of saturation, while Floodplain Forests are periodically inundated with water (Brown et al. 1983; Frangi and Lugo 1985; Lugo et al. 1995). Common tree species in the Palm Brake Forest include *Daphnopsis philippiana* and *Calycogonium*

squamulosum in addition to the palm *Prestoea montana*, a species that is found in all EYNF elevation gradients (Harris et al. 2012).

Lugo et al. (1995) found that the species composition and species density of Palm Brakes varied with aspect. More species occur on leeward slopes than windward slopes, presumably due to greater rainfall and soil saturation in the windward slopes. Long-term records of species density changes in these Palm Brakes also showed that after the 1932 hurricane and the initial enrichment of sites due to pioneer species, the number of species decreased over the next 40 years in the windward slopes, while in the leeward slopes species continued to accumulate. Apparently differences in the long-term patterns of soil saturation determined the number of tree species capable of surviving in these contrasting Palm Brakes. Lugo and Scatena (1995) observed that the length of successional sequences after disturbances were shorter above the cloud condensation level when compared to communities below the cloud condensation level (Harris et al. 2012).

The most common trees based on stem density in the Palm Floodplain Forest include *Croton poecilanthus*, *Micropholis crysophylloides*, and *Eugenia eggersii*, but the trees with the highest aboveground biomass are *Magnolia splendens* and *Sloanea berteriana*. In contrast to the adjacent Palo Colorado and Elfin Forest Types, the most abundant bromeliad in the Palm Floodplain Forest, *Guzmania berteriana*, is found more commonly along canopy tree trunks than on the forest floor, whereas *Selaginella* spp. and other bryophytes cover the ground at various distances from the river floodplain (Harris et al. 2012).

All vegetation above the cloud condensation level is classified as wetlands (Frangi 1983; Scatena 1993; Heartsill-Scalley 2005). Many environmental gradients reach their extreme values at the mountain peaks (e.g., highest wind speeds, lowest air temperatures, lowest incoming sunlight, highest rainfall, lowest soil oxygen concentrations, etc.). The vegetation responds in unique ways including unique vegetation structures, unique even between the forests of East Peak and West Peak (Howard 1968). Most notable is the woody vegetation of the Elfin Forest with an abundance of vascular flowering plants that adopt an epiphytic habit, particularly in the seedling and immature stages. At elevations above about 800 meters, the Elfin Cloud Forest is characterized by abundant stems of the tree fern *Cyathea bryophylla*, stunted individuals of the tree species *Ocotea spathulata* and *Tabebuia rigida*, and an abundance of epiphytes, of which the most striking and abundant is the small red bromeliad *Werauhia sintenisii*. This bromeliad is so common that it can be found in densities of up to 32,000 individuals per hectare (Lasso 2001) and contributes 12 percent of the net primary productivity of this forest type. It can also hold up to 3.3 tons of water per hectare and accumulate 25 percent of the phosphorus and potassium rainfall inputs (Harris et al. 2012).

The Elfin Cloud Forest's narrow ranges of temperature, precipitation, and cloud cover make this forest particularly vulnerable to changes in environmental factors, such as those changes proposed to occur as a result of global climate change. In particular, the epiphytic vegetation in the cloud forests may serve as indicators of climate change. For example, Lasso and Ackerman (2003 and 2004) observed an earlier flowering period for the Elfin Forest bromeliad *W. sintenisii* and showed that monthly mean minimum temperatures and monthly mean irradiance in the months leading up to flowering events explained 66 percent of the variation in the number of open flowers per month. It seems that *W. sintenisii* is responding to changes in the Elfin Cloud Forests' environment by timing its flowering to correspond to the cues of the nocturnal minimum temperatures and to the changes in cloud cover as measured indirectly by increases in solar irradiance (Harris et al. 2012).

Another distinction of the Cloud Forests when compared with the lower elevation forest types is the abundance of epiphytes, including liverworts and mosses (Bryophyta). The EYNF contains more than one-half of Puerto Rico's moss flora. One characteristic bryophyte is *Sphagnum portoricense*, whose presence has been identified as an indicator of the striking differences in ecosystem conditions existing between Cloud Forests and lower elevation Tabonuco Forests. With a very low tolerance for desiccation, *S. portoricense* is found next to open water in coastal areas, rivers, or wet banks throughout the rest of its geographical range (from the eastern coast of the United States to Venezuela). Throughout most of the EYNF, *S. portoricense* is present as forest floor mats and surrounding the base of trees and shrubs where stem flow accumulates. However, it is also abundant next to disturbed roadsides and trails in saturated Cloud Forest soils. This species occasionally forms small bogs over exposed soil surfaces of uprooted trees or other small soil surface depressions. Within the EYNF Elfin Cloud Forests, Karlin (2006) describes the distribution of *S. portoricense* as "patchy"; it has been observed more commonly on the easternmost mountain summits (e.g., along the road to and at Pico del Este) while not observed along the trails to El Yunque and El Toro Peaks. The ecology of *S. portoricense* has not been studied extensively, however, and limited information is available regarding the threshold conditions that limit its distribution, growth, reproduction, survival, and roles in succession and competition in the forest types where it occurs. Also, very few notes exist on the distribution of *S. portoricense* before anthropogenic disturbances occurred in the Cloud Forests of the EYNF. One hypothesis is that its present distribution may reflect its ability to colonize after disturbance.

Herbaceous and sphagnum bogs, riparian vegetation, and Palm Floodplain Forests (Frangi 1983; Frangi and Lugo 1985; Lugo et al. 1990) also occur above the cloud condensation level. In environments with high light levels, one can observe herbaceous bog areas that include clumps of *Carex polystachya*, *Eleocharis* spp., large masses of Sphagnum, and other wetland vegetation (Harris et al. 2012).

Although the EYNF supports most of the moss flora found across the Island of Puerto Rico, 19 percent of the moss species found in the EYNF are endemic. It is estimated however, that the Cloud Forests have lost many more moss species than the lowland and mid-elevation forests; one-half of the moss species originally observed in Cloud Forests have not been observed again since their initial reporting. One hypothesis for the loss of species, such as *Thamniopsis incurve*, *Bryoerythrophyllum r ecurvirostre*, *Squamidium i socladum*, *Cyrtohypnum m initulum*, *Schoenobryum c oncavifolium*, and *Breutelia s coparia*, from the Cloud Forests is the loss of suitable habitat resulting from disturbances related to the establishment of a communications infrastructure and road construction in the Elfin Cloud Forests. Although the opening of canopy structure and a resulting loss of forest cover are considered to be the main factors leading to the decline of most moss species, the role of climate change, changes in air quality, and other factors associated with land use change and pollution may also contribute to the decline. One species, *S. portoricense*, seems to be able to occupy disturbed areas in the Elfin Cloud Forest. The distribution, physiology, and ecology of bryophytes in the EYNF remain to be further described and studied particularly in the Elfin Cloud Forest (Harris et al. 2012).

From the total of 1,487 plant species listed on the Puerto Rico 2012 Final Regional Wetland Plant List (prepared by the U.S. Army Corps of Engineers), 559 or 38 percent of the list are reported to be present at the EYNF (see Appendix B).

Soils Above the Cloud Condensation Level (Above 600 meters of Altitude)

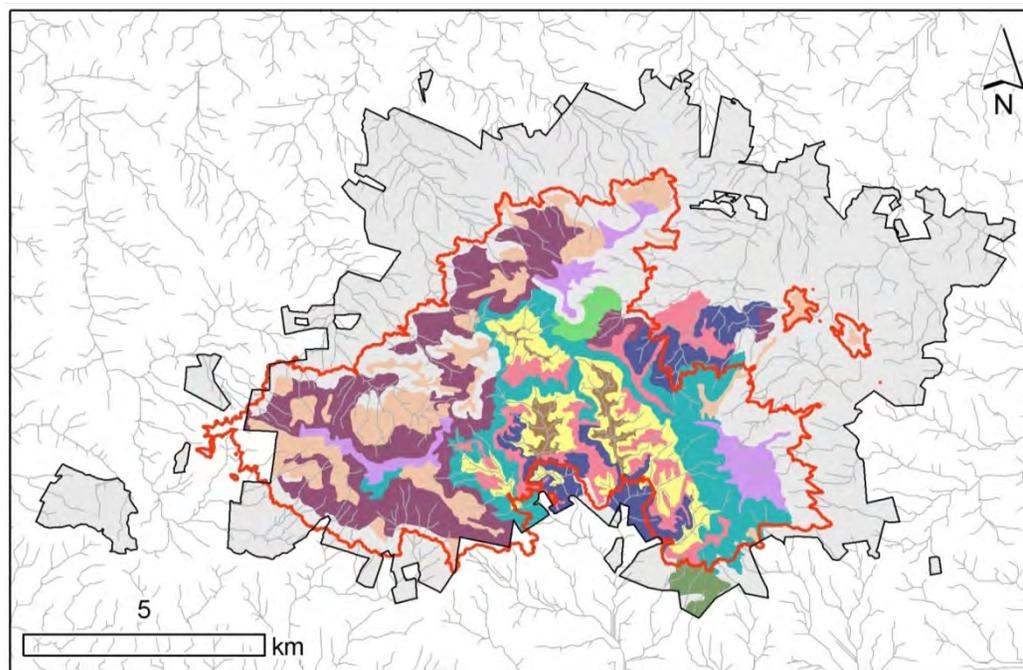
The three essential characteristics of wetlands are hydrophytic vegetation, hydric soils, and wetland hydrology (Cowardin and others 1979; U.S. Army Corps of Engineers 1987; National

Research Council 1995; Tiner and Burke 1995). Criteria for each of the characteristics must be met for an area to be identified as wetlands. Undrained hydric soils that have natural vegetation should support a dominant population of ecological wetland plant species. Hydric soils that have been converted to other uses should be capable of being restored to wetlands. Hydric soils are defined by the National Technical Committee for Hydric Soils as soils that formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part (*Federal Register* 1994). These soils are either saturated or inundated long enough during the growing season to support the growth and reproduction of hydrophytes if hydrologically unaltered (Natural Resources Conservation Service 2012).

The following map units, or parts of map units which are complexes, meet the definition of hydric soils and have at least one of the hydric soil indicators. This list can help in planning land uses and updates the hydric soils previously noted in the Caribbean National Forest (USDA Soil Conservation Service 1993). Due to scale limitations, however, on-site investigation is recommended to determine the presence of hydric soils on a specific site (National Research Council 1995; Hurt et al. 1998).

- 135 Prieto very cobbly clay loam, 25 to 50 percent slopes
- 212 Yunque-Moteado complex, 20 to 65 percent slopes (Moteado part)
- 214 Yunque-Los Guineos-Moteado complex, 5 to 30 percent slopes (Moteado part)
- 215 Palm-Yunque complex, 35 to 85 percent slopes, extremely stony (Palm part)
- 223 Picacho-Ciales complex, 5 to 30 percent slopes (Ciales part)
- 231 Guayabota-Yunque complex, 30 to 60 percent slopes (Guayabota part)
- 311 Dwarf muck, 10 to 65 percent slopes, windswept

Map units that are made up of hydric soils may have small areas, or inclusions, of nonhydric soils in the better drained or convex portions of the landform. Map units made up of nonhydric soils may have inclusions of hydric soils in the poorer drained or concave portions of the landform (NRCS 2012). Most of the soils above the 600 meters of altitude are hydric soils (Natural Resources Conservation Service 2012). See Appendix C for more information on hydric soils of EYNF.



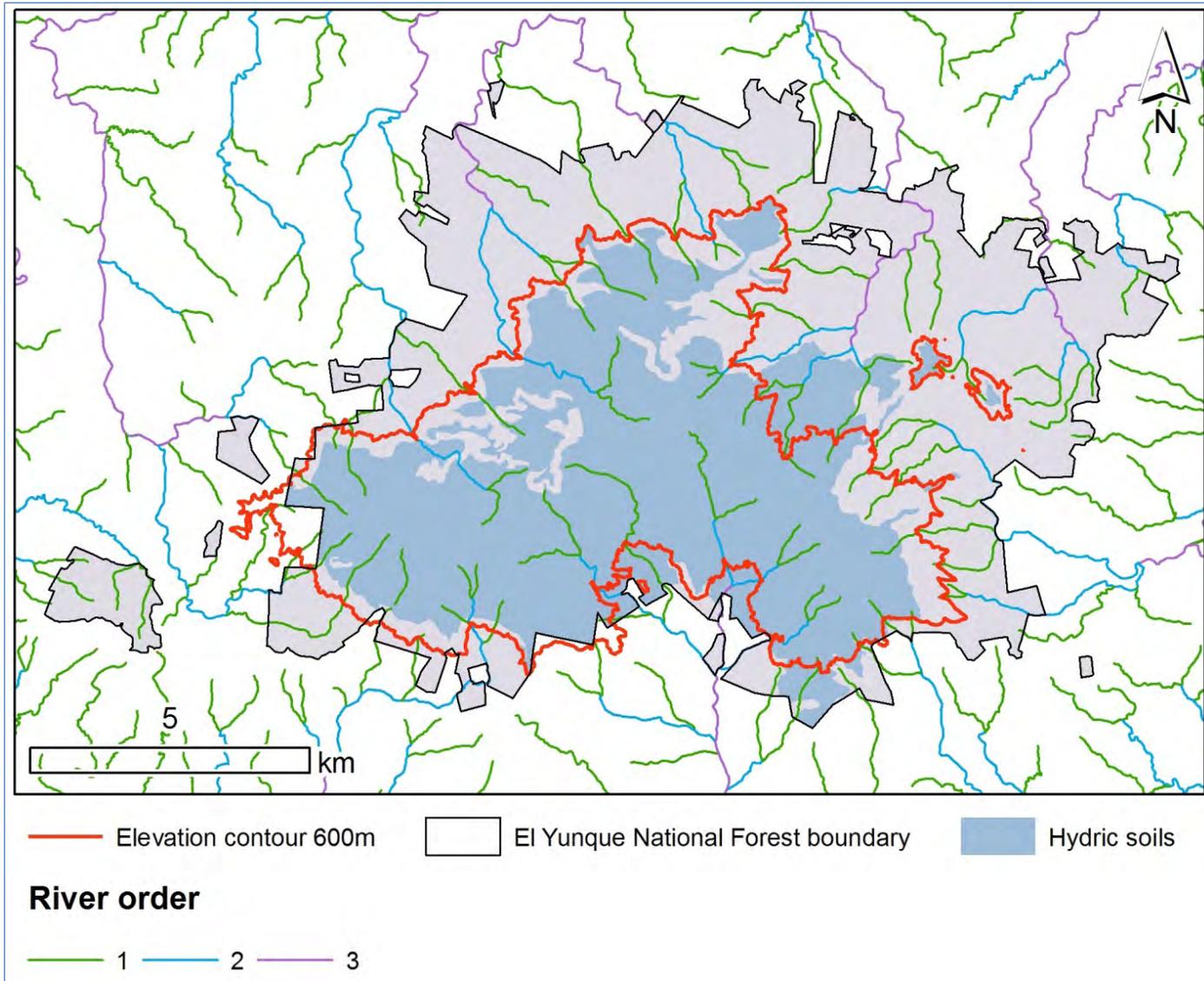
— Elevation contour 600m □ El Yunque National Forest boundary
 — Drainage model □ Non hydric soils

Hydric soils

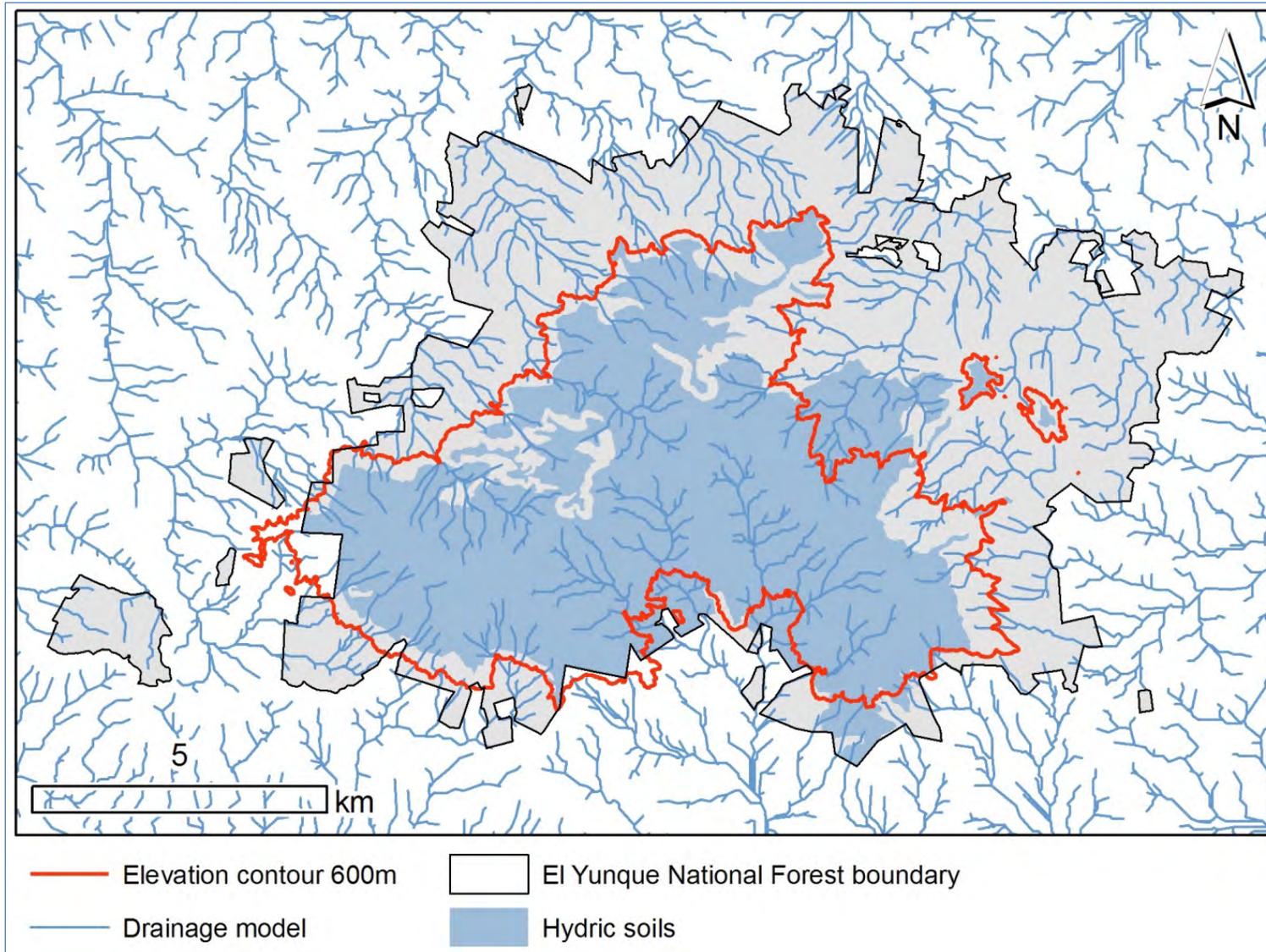
 DwF	 IcA	 PcE	 PiG	 YqE
 GuF	 PaG	 PiE	 PrF	 YuF

- DwF** Dwarf-El Duque complex, 5 to 60 percent slopes, windswept
- GuF Guayabota-Yunque complex, 20 to 60 percent
- IcA Icacos loam, occasionally flooded
- PaG Palm-Yunque complex, 40 to 90 percent slopes
- PcE Picacho-Ciales complex, 5 to 40 percent slopes
- PiE Picacho-Utuado complex, 5 to 40 percent slopes
- PiG Picacho-Utuado complex, 40 to 90 percent slopes
- PrF Prieto very cobbly clay loam, 20 to 60 percent
- YqE Yunque-Los Guineos-Moteado complex, 5 to 40
- YuF Yunque-Moteado complex, 20 to 60 percent

Map 2-6. Hydric soils on the ELNF



Map 2-7. Hydric system of the EYNF above the 600 meters of altitude



Map 2-8. Drainage model of the EYNF

2.1.3 Spatial Scales for Assessing Ecosystem Integrity

Table 2-1. Spacial scale for assessing ecosystem integrity

EYNF Classification	Area (acres)	Spatial Scale
M279 Caribbean Montane Humid Forest		
G448 Caribbean Wet Montane Forest Group		
Mature Tabonuco Montane Rain Forest	3,470.54	Landscape
Mature Tabonuco Montane Wet Forest	2,619.04	
Mature Sierra Palm Montane Wet Forest	496.19	
Plantation/Secondary Montane Wet Forest	5,843.41	Stands
M280 Caribbean Cloud Forest		
G451 Caribbean Montane Cloud Forest Group		
Mature Palo Colorado Montane Rain Cloud Forest	918.43	Landscape
Mature Palo Colorado Montane Wet Cloud Forest	7,419.78	
Mature Sierra Palm Montane Rain Cloud Forest	2,142.01	
Mature Sierra Palm Montane Wet Cloud Forest	2,034.50	
Mature Elfin Woodland Montane Rain Cloud Forest	341.54	
Mature Elfin Woodland Montane Wet Cloud Forest	298.17	
M281 Caribbean Lowland Humid Forest		
G454 Caribbean Moist Lowland Submontane Forest		
Plantation / Secondary Submontane Moist Forest	505.85	Stands
Riparian Forest		Lineal landscape
Riparian Montane Rain and Wet Cloud Forest	704.73	
Riparian Montane Rain and Wet Forest	1,350.14	
Riparian Submontane Moist Forest	58.96	
Non Forest		N/A
Non Forest-Natural Barrens, Grasslands and Shrubland	296.95	
Developed	18.93	
Grand Total	28,519.18	

Table 2-2. Key ecosystem characteristics

Ecosystems Key Ecosystem Characteristics	Composition– Species Richness	Structure– Vertical and Horizontal	Functions– Ecological Processes	Connectivity	Ecosystem Integrity
Mature Tabonuco Montane Rain Forest	Similar to NRV ¹	Similar to NRV	Similar to NRV	Similar to NRV	Similar to NRV
Mature Tabonuco Montane Wet Forest	Similar to NRV	Similar to NRV	Similar to NRV	Similar to NRV	Similar to NRV
Mature Sierra Palm Montane Wet Forest	Similar to NRV	Similar to NRV	Similar to NRV	Similar to NRV	Similar to NRV
Mature Palo Colorado Montane Rain Cloud Forest	Similar to NRV	Similar to NRV	Similar to NRV	Similar to NRV	Similar to NRV
Mature Palo Colorado Montane Wet Cloud Forest	Similar to NRV	Similar to NRV	Similar to NRV	Similar to NRV	Similar to NRV
Mature Sierra Palm Montane Rain Cloud Forest	Similar to NRV	Similar to NRV	Similar to NRV	Similar to NRV	Similar to NRV
Mature Sierra Palm Montane Wet Cloud Forest	Similar to NRV	Similar to NRV	Similar to NRV	Similar to NRV	Similar to NRV
Mature Elfin Woodland Montane Rain Cloud Forest	Similar to NRV	Similar to NRV	Similar to NRV	Similar to NRV	Impacted by recreation and communications facilities
Mature Elfin Woodland Montane Wet Cloud Forest	Similar to NRV	Similar to NRV	Similar to NRV	Similar to NRV	El Toro Peak impacted by recreational trail
Plantation/Secondary Montane Wet Forest	Various	Various; some sites near NRV	Some sites near NRV	Mainly similar to NRV; has two isolated tracts	Contains introduced species
Plantation/Secondary Submontane Moist Forest	Various	Various	No data	Isolated tract	Contains introduced species
Riparian Montane Rain and Wet Cloud Forest	Similar to NRV	Similar to NRV	Similar to NRV	Similar to NRV	Water use in recreation and consumption
Riparian Montane Rain and Wet Forest	Similar to NRV	Similar to RNV	May be similar to NRV	Similar to NRV	Water extraction
Riparian Submontane Moist Forest	No data	No data	No data	Isolated from main EYNF	Impacted by non-authorized recreational use

¹ NRV = Natural range of variation.

2.1.4 Key Ecosystem Characteristics

Table 2-3. Summary of ecosystem description

Name of Ecosystem	Average Annual Rainfall	Average Annual Temperature (°C)	Altitude Range	Canopy Description (including under-story) ¹	Number of Species present	3 Most Common Species ¹	Species Density per Hectare	Soil ¹	Hydrology
Mature Tabonuco Montane Wet Forest	2,000–4,000mm (78–156 in)	23.9	150–600m (492–1,968 ft)	Four level canopy	>50 species of trees	<ul style="list-style-type: none"> ▪ <i>Dacryodes excelsa</i> ▪ <i>Prestoea montana</i> ▪ <i>Sloanea berteriana</i> 	50	Non hydric soils	<ul style="list-style-type: none"> ▪ Rio Mameyes ▪ Rios Espiritu Santo ▪ Rio Sabana
Mature Tabonuco Montane Rain Forest	4,650mm (183 in)	21.2	400–700m (1,312–2,296 ft)	4	>150 species of trees	<ul style="list-style-type: none"> ▪ <i>Prestoea montana</i> ▪ <i>Dacryodes excelsa</i> ▪ <i>Sloanea berteriana</i> 	50	Both hydric soils	<ul style="list-style-type: none"> ▪ Rio Fajardo ▪ Rio Mameyes; ▪ Rio Sabana
Mature Sierra Palm Montane Wet Forest	2,000–4,000mm (78–156 in)	23.9	150–600m (492–1,968 ft)	Simple	63 species	<ul style="list-style-type: none"> ▪ <i>Prestoea montana</i> ▪ <i>Cecropia schreberiana</i> ▪ <i>Henriettea squamulosa</i> 	25–30	Hydric soils	<ul style="list-style-type: none"> ▪ Rio Icacos ▪ Rio Espiritu Santo; ▪ Quebrada Soñadora
Plantations (Secondary Montane Wet Forest)	3,670mm (144 in)	24.6	180–600m (492–1,968ft)	3	39 (Rio Grande) 4/8 (Sabana)	<ul style="list-style-type: none"> ▪ <i>Swietenia macrophylla</i> ▪ <i>Swietenia mahagoni</i> ▪ <i>Cedreal odorata</i> 	14 on 8.3 ha 8 on 8.48 ha 17 on 8.56	Most non-hydric	<ul style="list-style-type: none"> ▪ Rios: Icacos ▪ Quebrada Soñadora ▪ Sabana ▪ Mameyes ▪ Espiritu Santo
Mature Palo Colorado Montane Rain Cloud Forest	4,533mm (178 in)	18.6	600–900m (1,968–2,952 ft)	3	88	<ul style="list-style-type: none"> ▪ <i>Cyrilla racemiflora</i> ▪ <i>Ocotea spathulata mez</i> ▪ <i>Microphoiiis chrysophylloides</i> 	35–40	Hydric soils	<ul style="list-style-type: none"> ▪ Rio Mameyes ▪ Rio Fajardo
Mature Palo Colorado Montane Wet Cloud Forest	4,190mm (164 in)	18.4	700–1,000m (2,296–3,280 ft)	3	53	<ul style="list-style-type: none"> ▪ <i>Cyrilla racemiflora</i> ▪ <i>Ocotea spathulata mez</i> ▪ <i>Microphoiiis chrysophylloides</i> 	35–40	Hydric soils	<ul style="list-style-type: none"> ▪ Rio Cubuy, ▪ Rio Espiritu Santo ▪ Icacos ▪ Quebrada Soñadora
Mature Sierra Palm Montane Rain Cloud Forest	4,533mm (178 in)	18.6	600–900m (1,968–2,952 ft)	Simple	88	<ul style="list-style-type: none"> ▪ <i>Prestoea montana</i> ▪ <i>Cyrilla racemiflora</i> ▪ <i>Ocotea spathulata mez</i> 	35–40	Hydric soils	<ul style="list-style-type: none"> ▪ Rio Mameyes ▪ Rio Fajardo

Name of Ecosystem	Average Annual Rainfall	Average Annual Temperature (°C)	Altitude Range	Canopy Description (including under-story) ¹	Number of Species present	3 Most Common Species ¹	Species Density per Hectare	Soil ¹	Hydrology
Mature Sierra Palm Montane Wet Cloud Forest	4,190mm (164 in)	18.4	700–1,000m (2,296–3,280 ft)	Simple	53	<ul style="list-style-type: none"> ▪ <i>Prestoea montana</i> ▪ <i>Cyrilla racemiflora</i> ▪ <i>Ocotea spathulata mez</i> 	25–30	Hydric soils	<ul style="list-style-type: none"> ▪ Rios: Icacos ▪ Cubuy ▪ Espiritu Santo ▪ Quebrada Soñadora
Mature Elfin Woodland Montane Rain Cloud Forest	4,345mm (171 in)	18.6	900–1,025m (2,952–3,362 ft)	Simple	54	<ul style="list-style-type: none"> ▪ <i>Tabebuia rigida</i> ▪ <i>Ocotea spathulata</i> ▪ <i>Eugenia borinquensis</i> 	15–20	Hydric soils	<ul style="list-style-type: none"> ▪ Quebrada Sonadora ▪ Rio Fajardo ▪ Rio Mameyes
Mature Elfin Woodland Montane Wet Cloud Forest	4,345mm (171 in)	18.6	900–1,025m (2,952–3,362 ft)	Simple	54	<ul style="list-style-type: none"> ▪ <i>Tabebuia rigida</i> ▪ <i>Ocotea spathulata</i> ▪ <i>Eugenia borinquensis</i> 	15–20	Hydric soil	<ul style="list-style-type: none"> ▪ Rios: Cubuy ▪ Icacos ▪ Espiritu Santo
Plantation	2,000–2,200mm (78–86 in)	18-24	350–550m (1,148–1,804 ft)	3	29	<ul style="list-style-type: none"> ▪ <i>Swietenia macrophylla</i> ▪ <i>Swietenia mahagoni</i> ▪ <i>Cedreal odorata</i> 	29 on 8ha	Non-hydric	<ul style="list-style-type: none"> ▪ Rio Canovanillas
Riparian Montane Rain and Wet Forest	No data available	18-24	600m (1,968 ft)	No data	29	<ul style="list-style-type: none"> ▪ <i>Pterocarpus officinalis</i> ▪ <i>Casearia arborea</i> ▪ <i>Cordia borinquensis</i> 	No available data	Non-hydric	<ul style="list-style-type: none"> ▪ Rio Mameyes ▪ Rio Espiritu Santo ▪ Rio Sabana
Riparian Montane Rain and Wet Cloud Forest	No data available	18-24	600m (1,968 ft)	No data available	27	No data available	27 on 0.25ha	Hydric soils	<ul style="list-style-type: none"> ▪ Rios: Icacos ▪ Cubuy ▪ Espiritu Santo ▪ Quebrada Soñadora ▪ Mameyes, Fajardo
Riparian Submontane Moist Forest	No data available	18-24	No data available	No data available	No data available	No data available	No data available	Non-hydric	<ul style="list-style-type: none"> ▪ Rio Canovanillas

¹ See Appendix D for more detail.

2.1.5 Assessing Ecosystem Integrity

See Section 2.1.1 and 2.1.2.

2.1.6 Describing the Natural Range of Variation

The natural range of variation is an analysis tool for assessing the ecological integrity of selected key ecosystem characteristics. The natural range of variation represents the distribution of conditions under which ecosystems develop. The natural range of variation approach gives context for evaluating the integrity of current conditions, and identifying important compositional, structural, and functional elements that may warrant restoration (FSH 1909.12.15a).

The people who occupied Puerto Rico prior to the arrival of the Europeans had little effect on its vegetation, and at the time of European contact, virtually all of the Island's 890,000 hectares was covered with forest. During the years that followed, land clearing and timber use, particularly during the 19th century, were responsible for the destruction of Puerto Rico's climax forests. By 1950 it was estimated that only 3,400 hectares of the Island still supported climax vegetation, most of which was on public lands in the mountainous interior. About 2,300 hectares of the total, or two-thirds, was in the Luquillo Mountains (Weaver 1989). Four forest types—Tabonuco, Colorado, Dwarf (Elfin), and Palm—are recognized locally.

The Tabonuco Forest, dominated by the tabonuco tree, *Dacryodes excelsa*, lies between 120 and 600 meters elevation. The Colorado Forest is situated between 600 and 900 meters and is named after *Cyrilla racemiflora*, the palo colorado tree. The Dwarf (Elfin) Forest occurs from the upper Colorado Forest border to the 1,075-meter mountain summit and derives its name from the closely spaced, stunted trees that characterize it. The Palm Forest, dominated by *Prestoea montana*, the sierra palm, is found on steep slopes and in ravines mainly above 500 meters in elevation (Weaver 1989).

The forests of the Luquillo Mountains were later classified according to the Holdridge (1967) life zone system. In this system four main forests were recognized: the Subtropical Wet, the Subtropical Rain, the Lower Montane Wet, and the Lower Montane Rain Forest (Weaver 1989). The forest also contains a 500 acres tract of land (separate from its main body) in the Subtropical Moist Forest Zone (the fifth one) which was totally under agriculture at the time of acquisition.

In the Holdridge system, the Colorado Forest is considered the zonal association within both the Lower Montane Wet and Rain Forest life zones. Where they occur in both life zones, Palm Forests are an edaphic association and Dwarf (Elfin) Forests are an atmospheric association (often enveloped in clouds) (Weaver 1989).

Weaver (2012), using a database that covers more than 70 years of surveys, studies and monitoring activities, has described the four principal forest types and its tree species. Miller and Lugo (2009) describes the terrestrial ecosystems at the Luquillo Mountains using the Ewel and Whitmore (1973) work published by the USDA Forest Service, Ecological Life Zones of Puerto Rico and the U.S. Virgin Islands.

Considerable new research has added insight to the structure and function of these forested zones. Much of the research has been carried out through the auspices and cooperation of the USDA Forest Service's International Institute of Tropical Forestry in Rio Piedras, Puerto Rico (Miller and Lugo 2009).

The four-forest-type model has served well to describe general patterns at a coarse scale. The tradeoff is the simplification of vegetation patterns observed at finer scales. Advances in the way researchers analyze and understand data on vegetation distribution and patterns signal a need to develop a new paradigm of vegetation as sociations in the Luquillo Experimental Forest. Therefore, the environmental gradient concept has replaced the four-forest types model and presents a more thorough view of vegetation associations within the Luquillo Experimental Forest (Harris et al. 2012).

This model describes the forest as “Low-Elevation Vegetation Below the Cloud Condensation Level” at the 600 meters of elevation and the “Cloud and Wetland Forests Above the Cloud Condensation Level” (Harris et al. 2012).

EYNF with the cooperation of IITF has developed a new vegetation map following the traditional and the newest knowledge about the forest ecosystems and the U.S. National Vegetation Classification System. The assessment for the revision of the 1997 LMP has produced four forest types in the Caribbean Wet Montane Forest Group; seven in the Caribbean Montane Cloud Forest Group; one in the Caribbean Moist Lowland Submontane Forest and three in the Novel Riparian Forest Group. A detailed comprehensive description of each of these ecosystems will be developed in order to assess the status of ecosystem integrity for key ecosystem characteristics.

2.1.7 Current Condition and Trend of Key Ecosystem Characteristics and Integrity

See Section 2.1.1 and 2.1.2.

2.1.8 Status of Ecosystem Integrity

See Section 2.1.1 and 2.1.2.

2.2 Assessing Aquatic Ecosystems

The aquatic ecosystem is an important ecosystems component in the EYNF for both human and aquatic organism needs. This section gives a summary of the role of the Forest aquatic ecosystems with the best available science delineating an appropriate scale to assess key characteristics. There also will be a reference to the natural range of variations and a description of the current conditions and trends. A comprehensive review of aquatic ecosystem integrity can be inferred from a available information that provides an indication of potential needs for this ecosystem.

2.2.1.1 Introduction

The EYNF aquatic ecosystems can be defined by two elements: first in relation of the type of streams and rivers that occurs in the planning area. Second in the composition and structure of aquatic faunal communities that persists in EYNF streams. In this situation, the aquatic ecosystem can be characterized as heterotrophic, meaning that they are capable of utilizing only organic materials as a source of food, and are tropical montane in morphology with a variable degree of steepness.

The streams in EYNF originate in the eight watersheds of the Luquillo Mountains. These steep mountains are formed by volcanoclastic and igneous rocks that exert a strong localized lithologic influence on the stream channels. Longitudinal profiles also show the influence of multiple rock types (Figure 2-4). Landslides along steep hillslopes (greater than 12 degrees) deliver coarse

sediment (greater than 2,000 millimeters) to the channels and also may influence channel gradient and geometry (Pike 2008).

EYNF streams have steep gradients, channels lined with coarse boulder-sized sediment, numerous bedrock cascades, and abrupt waterfalls (up to 30 meters in height) (Ahmad et al. 1993). First-order perennial streams have bouldery channels in steeply sloped reaches, and clay and soil-lined channels in reaches with more gentle slopes. Second- and third-order streams have steep gradient reaches, exposed bedrock channels, large boulders, and periodic waterfalls. Due to rapid decomposition, these channels lack the large coarse woody debris dams that create aquatic habitat in many channels in humid temperate environments (Covich and Crowl 1990). Fourth- and fifth-order (wide and slow moving waters) streams occur only at the lower elevations along the coastal plain, which is outside of the EYNF. Most habitats are categorized as either pools or riffles (rapids-like setting). Water quality in the watersheds of the EYNF is relatively pure. According to McDowell (1994), water chemistry data indicate that major cations and anion concentrations do not exceed water quality standards.

The climate is maritime subtropical, with mean annual temperatures ranging from an average of 22 °C in the winter to 30 °C in the summer (Ramirez and Melendez-Colon 2003). Due to the tropical climate, stream temperatures display little longitudinal and temporal variation. Rainfall is a near-daily occurrence, and mean annual rainfall is approximately 3,500 millimeters per year at mid-elevations (Garcia-Martino et al. 1996).

Geomorphic processes influence the spatial distribution and abundance of aquatic fauna throughout a stream ecosystem. Also, overlapping habitat preferences of species can affect community composition, food webs, and ecological function (Reagan and Waide 1996). Therefore, key EYNF aquatic ecosystem characteristics are divided by physical and biological attributes. Physical attributes are identified as channel morphology, canopy openness, substrate size, and stream flow (Table 2-4). Biological attributes are species richness, relative abundance of species, functional dominance relationship, and trophic structure.

EYNF common aquatic species include the following: seven freshwater shrimp species (*Xiphocaris elongata*, *Atya scabra*, *Micratya poeyi*, *Macrobrachium faustinum*, *Macrobrachium heterchirus*, *Macrobrachium carcinus*, and *Macrobrachium renulatum*), one crab species (*Epilobocera sinuatifrons*), and five fish species (*Sicydium plumieri*, *Awaous banana*, *Agonostomus monticola*, *Anguilla rostrata*, and *Gobiomorus dormitor*). There are no rare or federally listed aquatic species on the EYNF.

Population trends from long-term monitoring sites conducted by the EYNF in many of the watersheds show a stable count of common aquatic species on the EYNF. Many of the freshwater shrimp live their entire life cycle within the river systems that they are found. Endemic freshwater fishes have the same biological cycle, except the American eel (*Anguilla rostrata*). The American eel is a catadromous fish species, where adults travel to breeding areas in the Sargasso Sea to the north and the next generation of young eels return to the EYNF streams.

There are no managed sport fishes on the EYNF due to natural conditions proving too challenging with high occurrence of flash flooding and high competition for resources. Invasive aquatic species have been insignificant to the aquatic ecosystems at this time and past administrative standards and guidelines have been a proponent for healthy native wildlife and aquatic species populations.

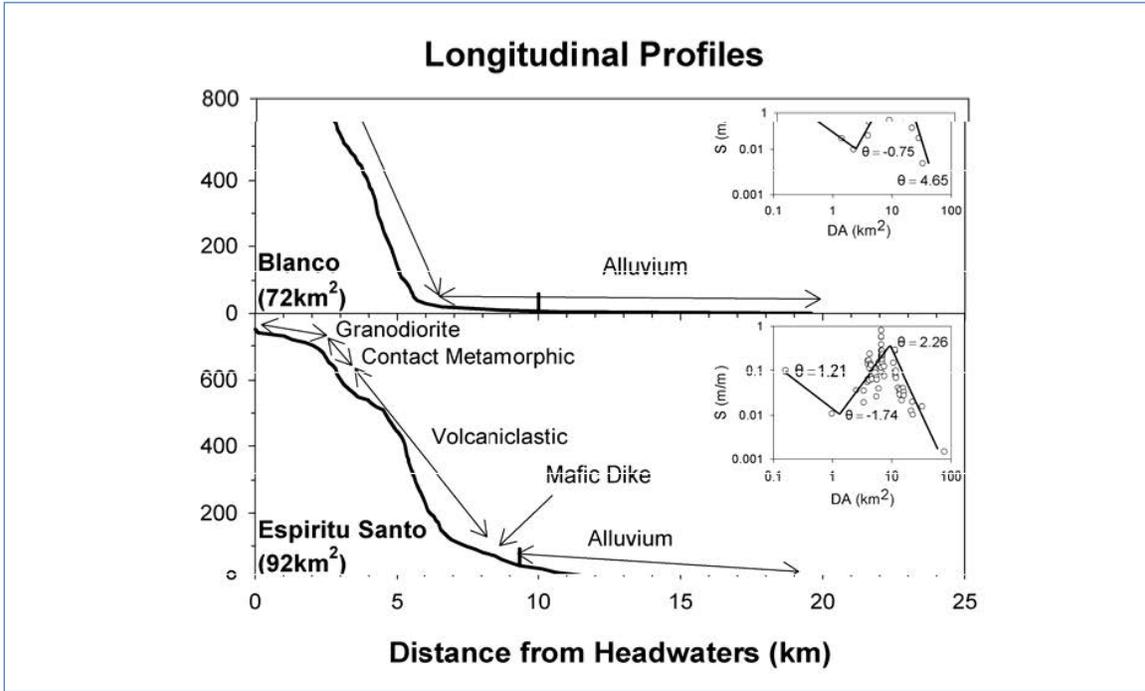


Figure 2-4. Longitudinal profiles of the rivers of EYNF

Source: Pike (2008)

EYNF aquatic ecosystems are made up of eight river systems that originate within the Forest boundary and flow off to the ocean, therefore extending well outside of the EYNF boundary.

The rivers of the EYNF are known for their biodiversity and conservation management in the surrounding watershed. One of the last undammed rivers on Puerto Rico is one of the major rivers that originates on EYNF and can be used as reference stream and therefore can be used to estimate the natural range of variance for EYNF aquatic ecosystems.

Table 2-4. Key characteristics of aquatic ecosystems

Characteristic Composition	Structure/Function on the EYNF	Connectivity
1) Channel morphology	Wide array of distinct types ranging from very narrow and steep locals to small reaches of flat gradients and relatively wide sections.	Extent of stream dewatering and channel alteration
2) Canopy openness	Most vegetation found in the riparian zone provides a high level of coverage. Light is still able to shine in open sites above the water.	A mixed set of native, naturalized and invasive vegetation species
3) Substrate size	Wide variety of bedrock to sand substrate.	Sediment transport including timing and duration
4) Stream flow	Dependent on the rain patterns that occur orographically, flows are known as turbulent.	Hydrologic flow regimes including time, duration, magnitude
5) Species richness and distribution	High level of diadromous fishes, catadromous eels, palaemonid shrimp, freshwater crabs, and neritid snails.	Presence of species and ability of native species to move throughout the plan area and into adjacent areas
6) Relative abundance of species	Found throughout the EYNF, but in different habitat types the rivers exhibit large abundance and occurrences.	Rate of migration
7) Trophic structure	Similar to other pan-tropical islands, predators consist of eels, and omnivorous fish and shrimps. Large consumers in streams are the atyid shrimps that are both scapers and filter feeders and freshwater crabs. Snails feed on lichens and algae.	Functional dominance relationship

2.2.1.2 Current Conditions and Trends

For all key characteristics, general current conditions and trends show a correlation with rainfall. In a comparison of Long Term Ecological Research (LTER) sites, Post and Jones (2001) found that streams of the Luquillo Mountains are among the quickest to respond to rainfall, owing to their shallow flow paths. The conditions that are physical (Figure 2-4) are stable and due to little anthropocentric management. [This section to be further developed].

2.2.1.3 Status of Ecosystem Integrity

[Placeholder: Still in development].

2.2.1.4 Assessing system drivers and stressors

[Placeholder: Still in development].

2.2.1.5 Literature Cited

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2.3 Assessing Air

2.3.1.1 Existing Information and Conditions

Relevant existing information regarding air quality is jointly gathered by the Puerto Rico Environmental Quality Board and the Environmental Protection Agency.

EYNF does not carry on any management activity that would adversely impact air quality. Fire is not a significant issue within the Forest and no prescribed burns are practiced within the boundaries.

The northeastern region of Puerto Rico has a climate defined by the surrounding ocean and easterly trade winds. EYNF does not have any classified air sheds. The Forest interacts with and is affected by global air sheds that originate over the Atlantic Ocean, Africa, Northeastern United States, and Central America. Generally stable and unpolluted conditions are interrupted by periodic episodes of African dust.

Due to its extreme changes in elevation within the Forest, there are vast differences in rainfall, relative humidity, wind velocity, cloud cover, temperature, atmospheric saturation deficit, and solar radiation. Looking at the chemical characterization of cloud water samples we can look at the average concentrations of organic aerosols and inorganic aerosols, nitrogen, total nitrogen, among others and compare them to similar locations.

2.3.1.2 Trends

Climatic data shows that climate has been stable in Puerto Rico for millions of years, with the exception of a period of drying that the region has been going through over the past 100 years.

An apparent trend is that of the appearance of African dust in the air. African dust incursions have been recorded year round; however, they are strongest and most noticeable during the summer months (Prospero and Lamb 2003). Mineral dust can have many effects on the communities of the region as well as the climate itself. There is a great impact on visibility, public health, and it may even suppress or reduce precipitation or change the chemical composition of cloud water (Prospero and Lamb 2003).

Data was collected at Pico del Este during June and July of 2007. The peak is about 35 kilometers from San Juan and 20 kilometers from the South Atlantic Ocean. The mountaintop is humid, frequently surrounded by a bundant cloud cover. The data concerned the differences in chemical composition of clouds in periods of African dust in the Tropical Montane Cloud Forest Region. Data on concentrations was collected for such items as total organic carbon, dissolved organic carbon, total nitrogen.

Average concentrations of total organic carbon, chemical oxygen demand, and total nitrogen were found to be more similar to remote sites than areas in close proximity to human activities (Gioda et al. 2009). The average concentrations of the aerosols were found as follows: total organic carbon, 1.09; chemical oxygen demand, 0.85; and total nitrogen, 1.25 mg L⁻¹.

Organic carbon and nitrogen fractions were studied during two sampling periods: a clean period, when air masses were coming from the direction of the North Atlantic Ocean and had no African dust; and the African dust period, when there were dust events with air masses being influenced by air from northwest Africa. The lowest concentrations of total organic carbon, 0.45 mg L⁻¹

were found during the clean period while the highest concentrations, 1.61 mg L⁻¹, were during the African dust period.

There has been a record of average temperatures in El Yunque rising for the past 30 years (Lasso and Ackerman 2003). Rising temperatures caused by climate change can cause changes in wind patterns and precipitation rates, both of which have potential to increase pollutants (Bytnerowicz et al. 2007). Stressors other than climate change include general air pollution and reductions in air quality, from long-range transport of dust and contaminants (Pringle and Scatena 1999), ozone, nitrogen oxides, and mercury. These can lead to acid rain, dry deposition (Stallard 2001) and other things.

Increased amounts of nitrogen deposition have also been recorded, at rates of 0.08 kilogram nitrogen per hectare per year between 1986 and 2004, with nitrogen dioxide emissions increasing on the Island at an average of 7.8 percent per year (Ortiz-Zayas et al. 2006). Increased nitrogen deposition can cause shifts in community structure and increases in fungal and bacterial abundance (Cusack et al. 2011). It may also lead to changes in forest nutrient (Mohan et al. 2009), carbon, and nutrient cycles in forests (Cusack et al. 2011).

2.3.1.3 Contribution

Generally, air quality is good given the proximity to the ocean, and prevailing easterly winds. During the summer months, air quality may be impacted by the presence of a strong Saharan air layer. Long range transport of contaminants could be an issue in the future.

The overall air quality is characterized by several aspects. Cloud cover, solar radiation, organic and inorganic compounds all contribute to the atmosphere surrounding the mountains of El Yunque. The chemical composition of clouds can inform us about concentrations of both organic and inorganic aerosols that affect the forest environment, and public health of the visitors and surrounding community.

2.3.1.4 Gaps in Information

More information and data taken on other peaks and from other locations in the Forest could help improve understanding of the impact of aerosols and the changing chemical composition of the clouds on climate and the forest environment.

2.3.1.5 Conclusion

The conditions of the air surrounding El Yunque have remained relatively constant in the past; however, they have begun to change in recent years due to increased anthropogenic activity and climate change. Many of the increased concentrations of aerosols and other contaminants can lead to bigger consequences for the forest environment and the surrounding communities, have negative effects on nutrient cycles and precipitation, and reduce air quality. Some of these effects have already begun to show, and are expected to worsen with deteriorating conditions.

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2.4 Assessing Soil Resources and Quality

2.4.1.1 Existing Information

Detailed soil information is available for EYNF in the SSURGO (Soil Survey Geographic database), digital soils data produced and distributed by the Natural Resources Conservation Service (NRCS)-National Cartography and Geospatial Center. This coverage is current and certified as of October 24, 2012. This is the best available, most current information related to the soils of EYNF. GIS data was downloaded and integrated for further reference and analysis.

2.4.1.2 Current Conditions

The survey area is within the rugged terrain of the Sierra de Luquillo Mountains. Relief within the area can be characterized as extreme and includes numerous dissected, steep to very steep slopes that are broken by narrow ridges. Elevations range from about 100 feet at the northern

boundary to 3,533 feet at El Toro Peak (30 to 1,077 meters). The main drainage systems for the Forest are the Mameyes, Fajardo, Espiritu Santo, Río Grande, Río Sabana, and Icacos watersheds.

Factors of Soil Formation

Note: From “The Soils of the Caribbean National Forest” 2002.

This section describes the factors of soil formation as they relate to the soils of the EYNF and explains the major processes in the development of soil horizons.

Climate. Temperature and precipitation influence the rates of chemical and physical processes in the soil. The survey area has a warm, maritime tropical climate that is influenced by trade winds interacting with the Luquillo Mountains.

Rainfall. The amount of annual rainfall increases substantially as elevation increases in the survey area. The average rainfall ranges from about 97 inches (246 centimeters) at the lower elevations to more than 200 inches (381 centimeters) at the highest elevations of the Cloud (Dwarf) Forest. There is no sharply defined wet or dry season in the survey area. The peak rainfall is usually in May, and the driest period is in March.

Temperature. The temperature in the survey area decreases as elevation and rainfall increase. Three soil temperature regimes occur in the survey area: isohyperthermic, isothermic, and isomesic. The Caguabo, Coloso, Cristal, Humatas, Luquillo, Prieto, Sonadora, and Zarzal soils are in the isohyperthermic regime. The Ciales, Guayabota, Icacos, Los Guineos, Moteado, Palm, Picacho, Utuado, and Yunque soils are in the isothermic regime. The Dwarf soils are in the isomesic regime. The highest temperatures in the survey area occur in August or September, and the lowest temperatures occur in January or February. The leaching of nutrients becomes more efficient as elevation increases. This increased efficiency, is evidenced by decreasing faunal biota in the soils and overstory, at the higher elevations. Organic matter tends to accumulate at the higher elevations due to the higher rainfall and cooler temperatures.

Plant and Animal Life. Plants, animals, bacteria, fungi, and humans affect the formation of soils. The impact of plant and animal life on soil formation is especially significant in wet tropical climates because activity occurs year-round. The type of vegetation affects the content of organic matter and the amount of nutrients released to the soil. Animals, particularly burrowing animals and insects, keep the soil open and porous. Bacteria and fungi decompose plant material into organic matter and promote the incorporation of the organic matter into the soil. Research into overstory fungi and epiphytes indicates a significant amount of decomposition occurs before organic debris reaches the forest floor. Human activities that alter the soils in the survey area include clearing, construction, and recreational activities. Nutrient recycling in organic matter is crucially important in tropical climates.

Parent Material. Parent material is the weathered mass from which soil forms. Parent material generally determines the chemical and mineral composition of the soil. The soils in the EYNF formed in materials of volcanic origin extruded in the sea and then subjected to weathering and erosion.

Topography. Topography, or relief, modifies the effects of the other soil-forming factors. In many places that have similar parent material, differences in topography result in differences in the kind of soil that forms.

For example, soils in convex areas typically are drier than soils in flat areas because water moves away from the convex areas. In contrast, soils in concave areas can display wetness indicators resulting from the concentration of surface and subsurface water. Cristal and Zarzal soils formed in similar parent material and are adjacent to each other. Because of topography, however, Zarzal soils are better drained than the Cristal soils. Soils in the survey area that are subject to flooding include the Coloso, Icacos, and Luquillo soils. They receive new sediments during each period of flooding, show little profile development, and are considered young soils.

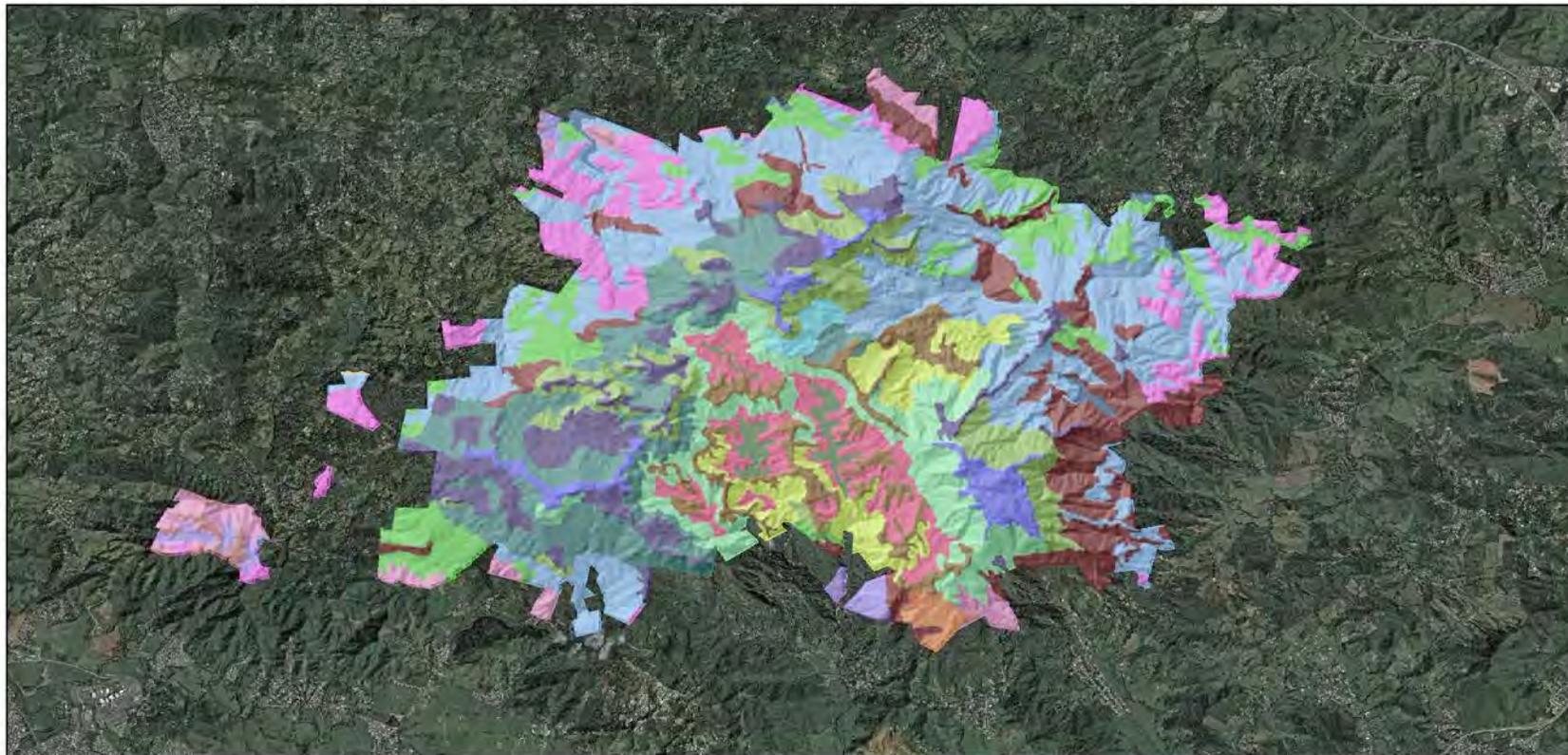
Time. Time is needed for the development of a soil profile; consequently, younger soils have less developed horizons than older soils. Many of the soils throughout the survey area are shallow but have well-developed horizons.

Soil Properties, Carbon and Nutrient Distribution Elevation Gradient

Ping et al. (2013) indicate that the dominant soil-forming parent materials are granodiorite, saprolite, and volcanic rocks that exert a strong influence on the soil properties (Ping et al. 2013). Soils on middle to high elevations are very strongly acidic with low base saturation (less than 20 percent) due to a strong leaching environments. Soils formed in lowlands, dry forest, and coastal wetlands are moderately to weakly acidic with higher base saturation (greater than 40 percent). Generally, organic carbon, nitrogen, and nutrients accumulated in the surface horizons and decrease with depth. Soils formed in areas influenced by landslides or alluvium were the exception to this pattern. Soil organic carbon and nitrogen stores follow the elevation gradient: from 26.7 kilograms organic carbon m^{-2} and 1.4 kilograms nitrogen m^{-2} in soils of the colder and wetter mountain tops to 12.3 kilograms organic carbon m^{-2} and 1.0 kilograms nitrogen m^{-2} in soils of the lower elevation dry forests. The carbon:nitrogen ratio decreased from 20 to 11 as elevation decreased along the gradient. Landscape movement on uplands through landslides, slumps, and fluvial/alluvial processes has a significant effect on variation of carbon stores which must be considered when estimating carbon stores by landscape units. The coastal wetlands have exceptionally high organic carbon stores (greater than 90 kilograms m^{-2}) due to their water-saturated and reducing environment. Soil organic carbon content showed an inverse relation with soil bulk density and played a controlling role on cation exchange capacity and nutrient distribution. Clay content has no effect on cation exchange capacity. Elevation through its influence on precipitation and temperature exerts strong influence in the quantity and quality of terrestrial organic carbon stores, and the depth-distribution pattern of carbon, nitrogen, and other nutrients.

The latest publication on soils reviews how despite the strong indications of biocycling in determining soil characteristics along the elevation gradient in eastern Puerto Rico, soils differed greatly with the variation of rainfall and parent materials. In higher elevations, the soil had lower bulk density and a silty texture in the surface horizon that overlies more dense subsoil with higher clay contents. Ping et al. (2013) attribute such textural discontinuity to reported eolian deposit of Sahara dust, which changes the composition and characteristics of the mineral fraction in the surface horizon relative to those below it. The textural discontinuity retards water infiltration across the interface due to decreased conductivity in the clayey subsoil, restricting internal soil drainage. Adiabatic cooling associated with increasing elevation results in greater precipitation, which with cooler temperature, enhance accumulation of humus (total carbon) in the surface horizons of the upper forest types. However, landscape processes in the uplands such as landslides, slumping, and fluvial/alluvial activity, contributed significant variation in the relationship and must be considered when estimating carbon and nutrient stores over the landscape. Keeping the variation in mind the carbon stores of this area of Puerto Rico fit well with the averages for similar life-zones reported by others. There is strong evidence of leaching of

cations especially in the uplands with depletion of cations in the mineral horizons and movement and deposition of cations in the lowlands. The result is that soil acidity increases with increasing elevation where soil pH is usually less than 4.8. In soils with high clay contents such as the Ultisols, clay has little influence on the soil's ability to retain nutrients because of the predominance of kaolinite in the clay fraction (Jones et al. 1982). Thus, it was not surprising that soil carbon played an overriding role in affecting soil properties such as cation exchange capacity and bulk density. Because of the geographic location, soils in the Luquillo Mountains area receive Na^+ addition from both marine sources via precipitation and Saharan dust.



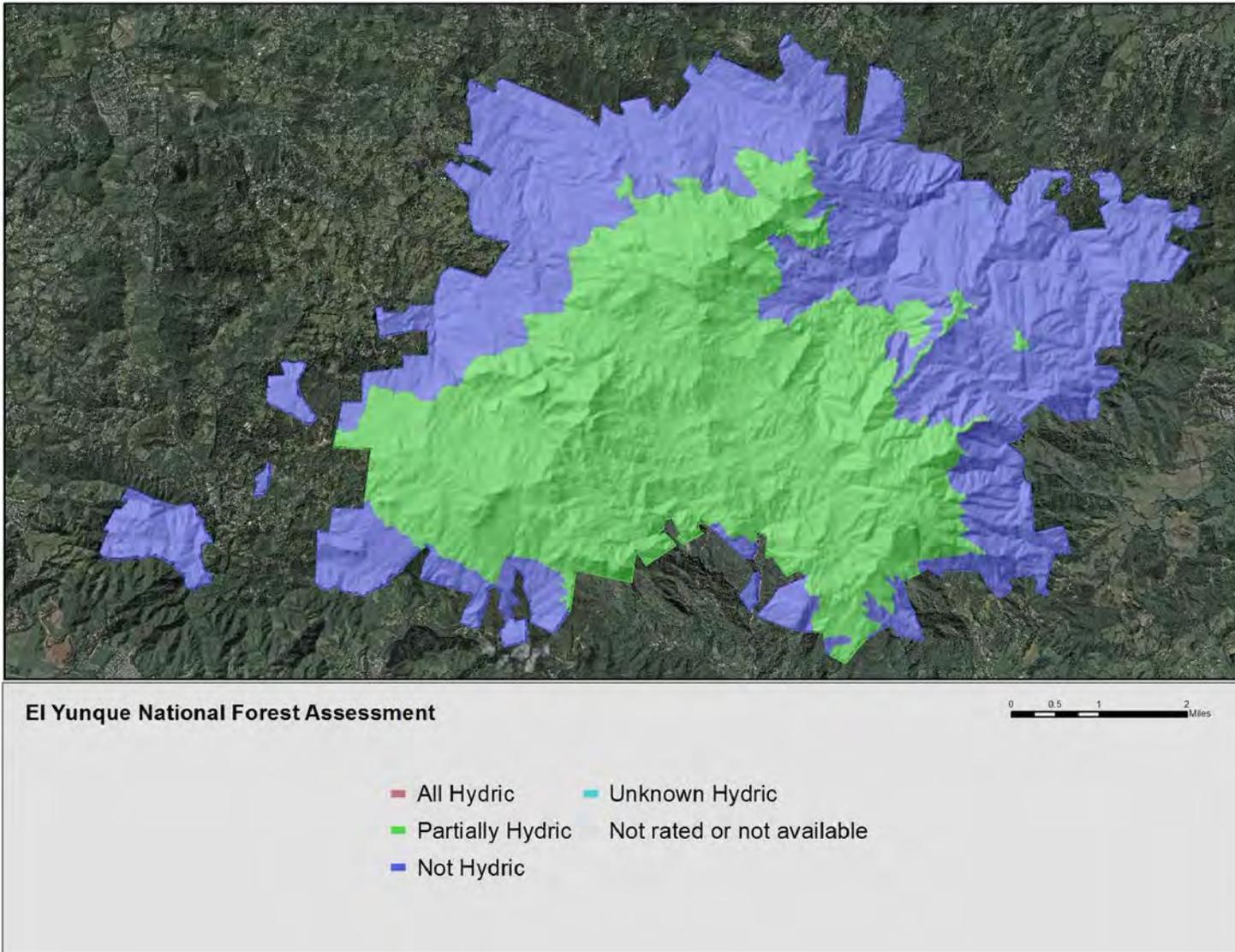
El Yunque National Forest Assessment



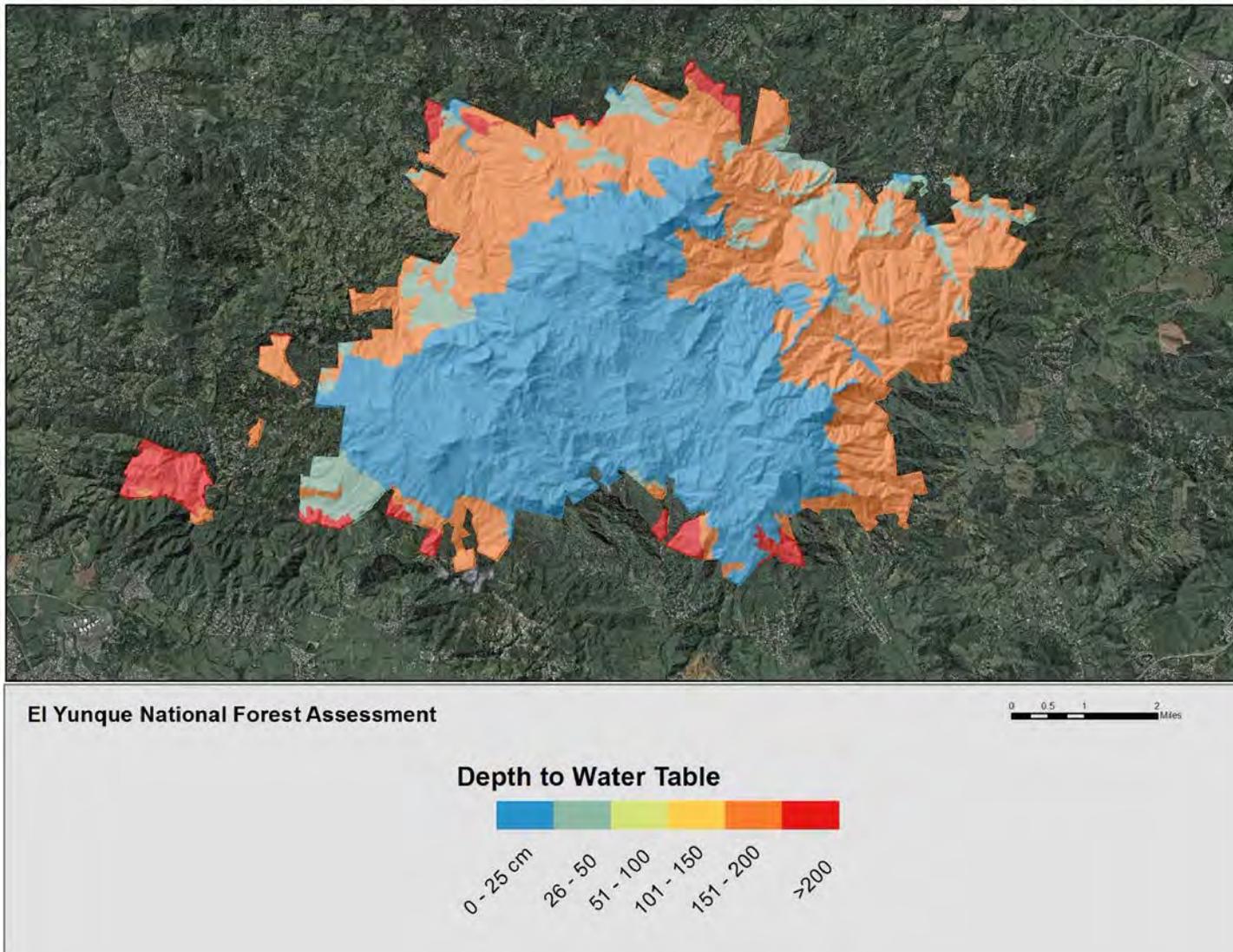
Soil Map Units

- | | | |
|---|--|--|
| ■ Caguabo gravelly clay loam, 12 to 20 percent slopes | ■ Luquillo-El Verde complex, 0 to 5 percent slopes, occasionally flooded | ■ Sonadora-Caguabo complex, 20 to 40 percent slopes |
| ■ Cristal-Zarzal complex, 5 to 40 percent slopes | ■ Palm-Yunque complex, 40 to 90 percent slopes, extremely stony | ■ Sonadora-Caguabo complex, 40 to 90 percent slopes |
| ■ Dwarf-El Duque complex, 5 to 60 percent slopes, windswept | ■ Pandura-Very stony land complex, 40 to 60 percent slopes | ■ Yunque cobbly clay, 40 to 90 percent slopes, extremely stony |
| ■ Guayabota-Yunque complex, 20 to 60 percent slopes | ■ Picacho-Ciales complex, 5 to 40 percent slopes | ■ Yunque-Los Guineos-Moteado complex, 5 to 40 percent slopes |
| ■ Humatas clay, 40 to 60 percent slopes, eroded | ■ Picacho-Utuado complex, 40 to 90 percent slopes | ■ Yunque-Moteado complex, 20 to 60 percent slopes |
| ■ Humatas-Zarzal complex, 5 to 40 percent slopes | ■ Picacho-Utuado complex, 5 to 40 percent slopes | ■ Zarzal very cobbly clay, 40 to 90 percent slopes |
| | ■ Prieto very cobbly clay loam, 20 to 60 percent slopes | ■ Zarzal-Cristal complex, 20 to 60 percent slopes |

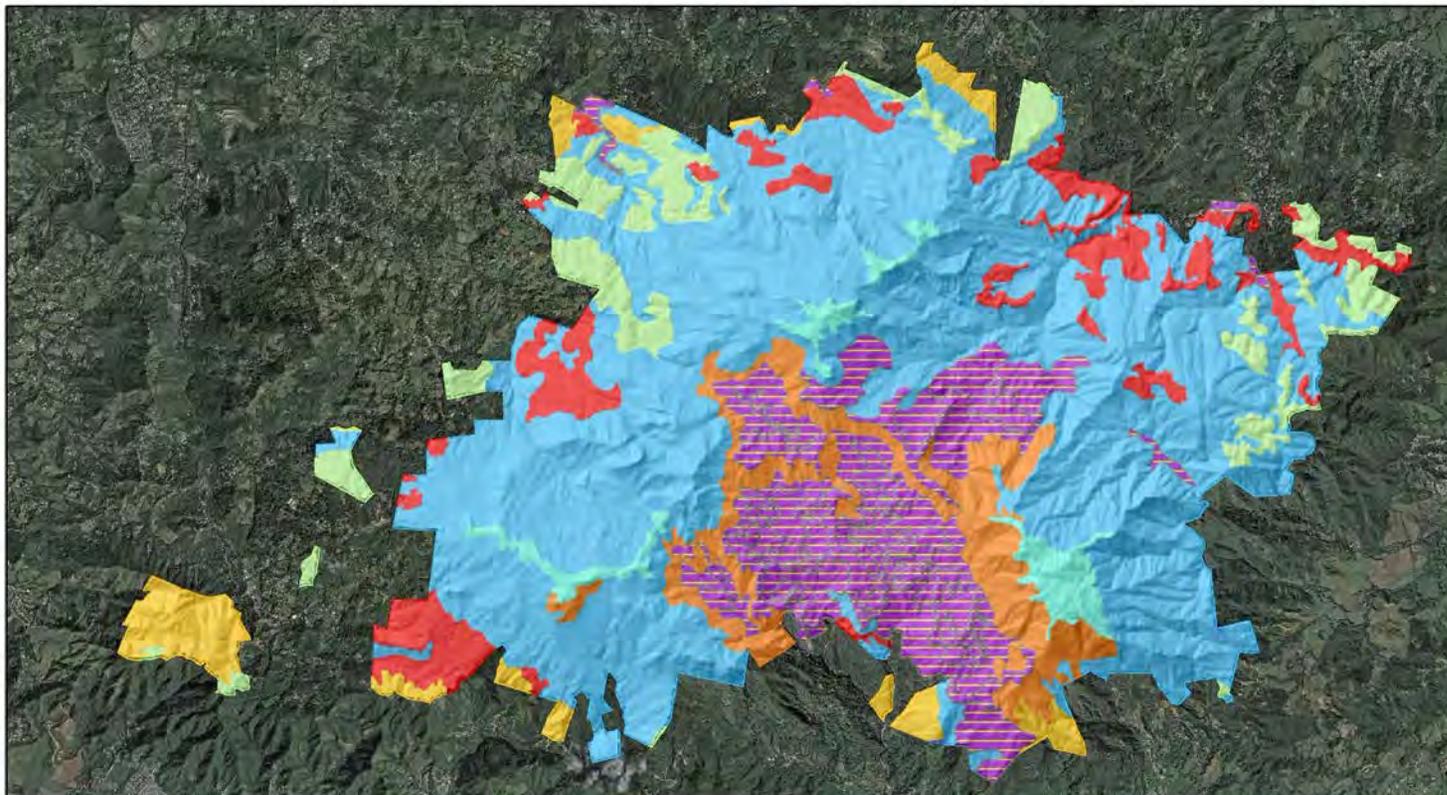
Map 2-9. El Yunque soil map units



Map 2-10. El Yunque hydric soils



Map 2-11. El Yunque National Forest depth to water table



El Yunque National Forest Assessment

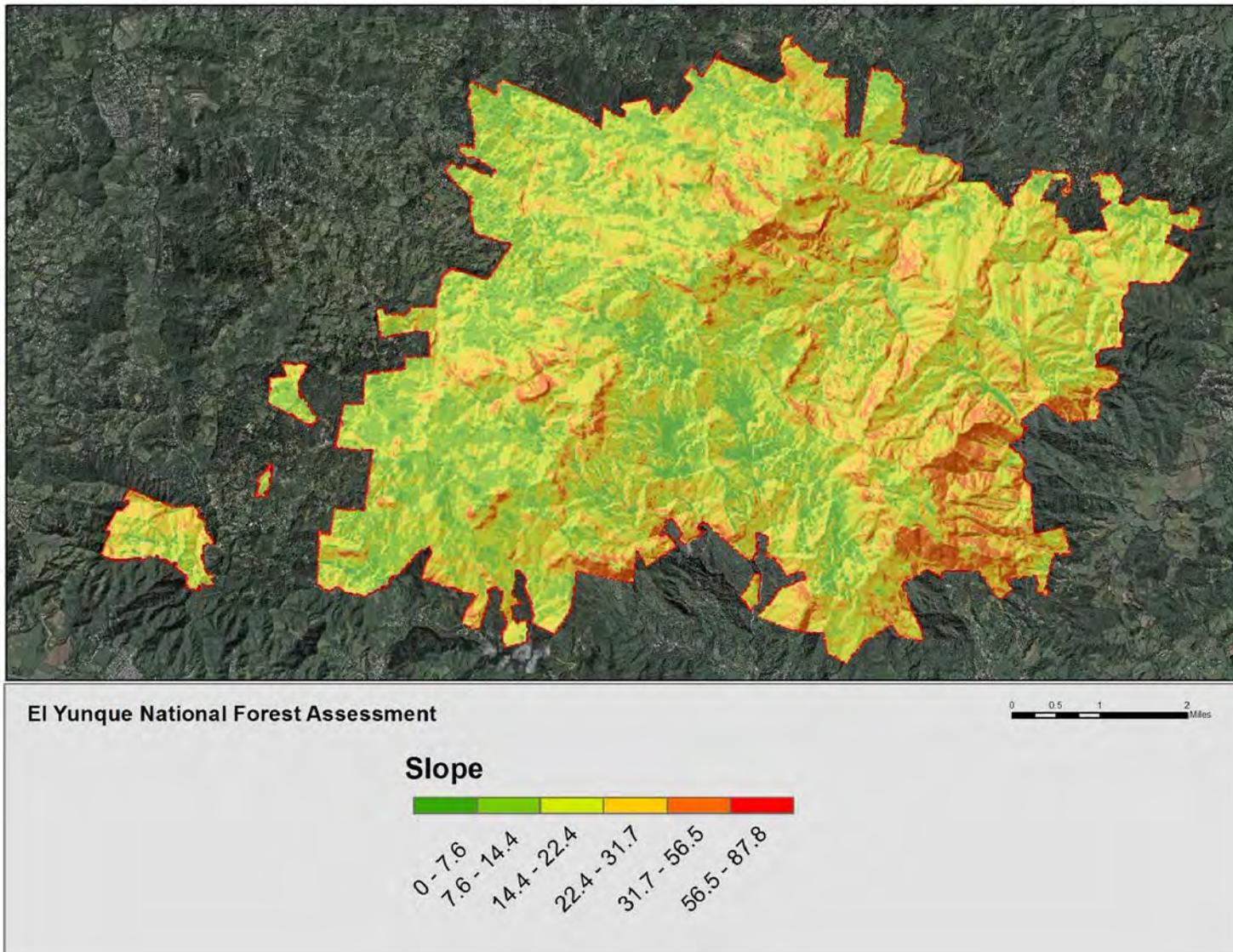


Parent Material Name

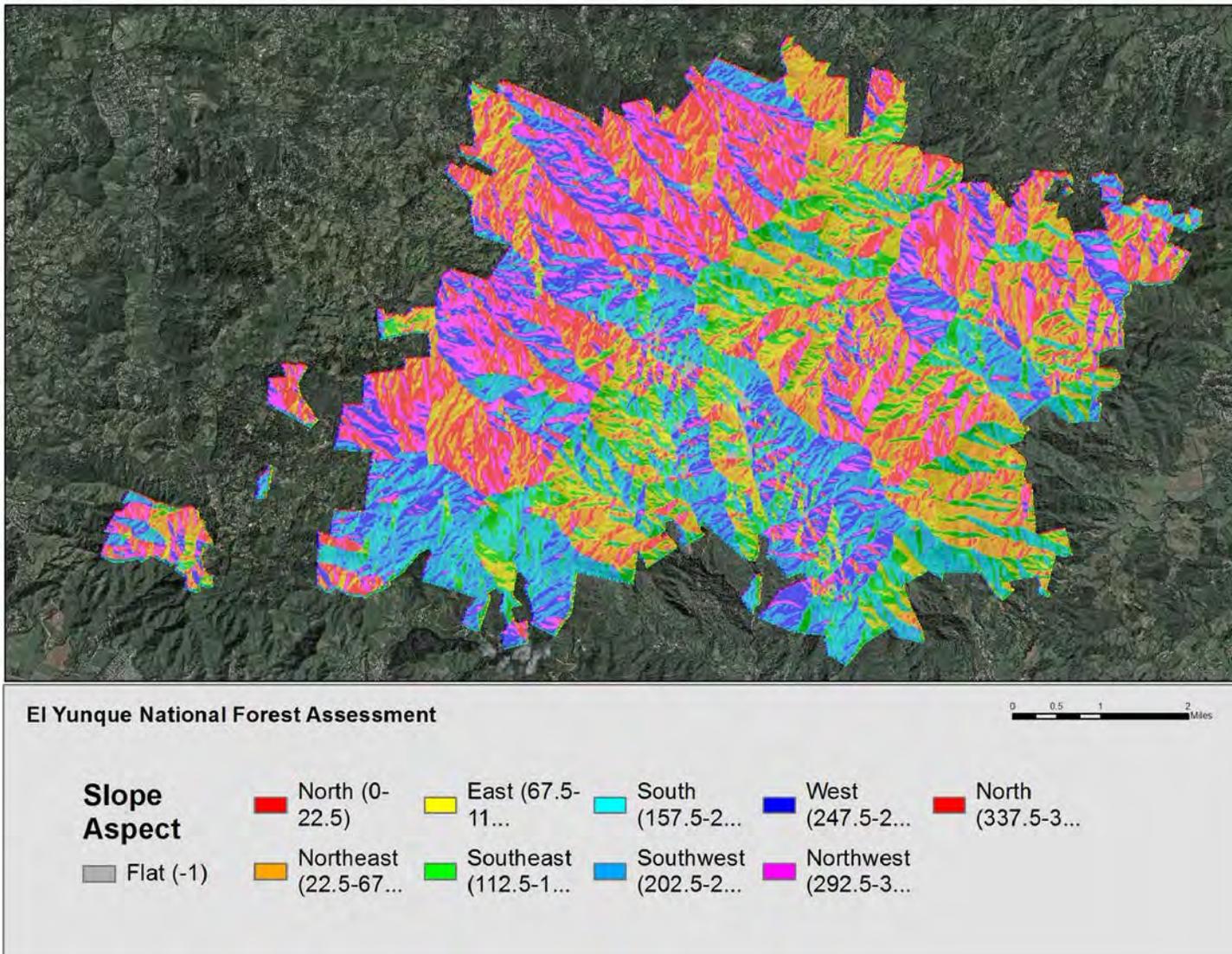
- clayey colluvium derived from volcanic rock over silty and clayey residuum weathered from volcanic rock
- colluvium derived from volcanic rock and/or residuum weathered from volcanic rock
- Hato Puerco Formation residuum weathered from mudstone
- residuum clayey and loamy materials

- residuum weathered from igneous rock
- residuum weathered from sandstone
- residuum weathered from volcanic rock
- weathered materials
- Not rated or not available

Map 2-12. El Yunque National Forest parent material



Map 2-13. Slope on the El Yunque National Forest



Map 2-14. Slope aspect on the El Yunque National Forest

2.4.1.3 Trends and Drivers

- Within forest boundaries, soil loss of integrity is a function of landslides, and subsequent erosion.
- Landslides are common both far and near from roads.
- Vegetative succession, an essential element of soil erosion control, is controlled by soil factors (Shiels et al. 2008)
- Illegal off-road vehicle use could be severely impacting soils and accelerating erosion.
- Because of the geographic location, soils in the Luquillo Mountains area receive Na⁺ addition from both marine sources via precipitation and Saharan dust.

2.4.1.4 Key Findings

- ▶ Soils within EYNF boundaries appear to possess good integrity, with disruption caused by landslides and subsequent erosion. Today, agriculture is not practiced within EYNF. The majority of the lands are considered not suitable for large scale agriculture.
- ▶ There is a preponderance of partially hydric soils and mostly are in the D Hydrologic group (maps x and xx).
- ▶ Within forest boundaries, soil loss of integrity is a function of landslides, and subsequent erosion.
- ▶ Landslides are common both far and near from roads.
- ▶ Vegetative succession, an essential element of soil erosion control, is controlled by soil factors (Shiels et al., 2008).
- ▶ Illegal off-road vehicle use could be severely impacting soils and accelerating erosion.

2.4.1.5 Information Needs

Soils data for EYNF is complete and up to date. Given the importance of vegetation on soil formation, it would be useful to map soils on EYNF as to determine their potential speed of vegetation succession as a proxy to determine restoration/intervention priorities of affected areas (as in landslides).

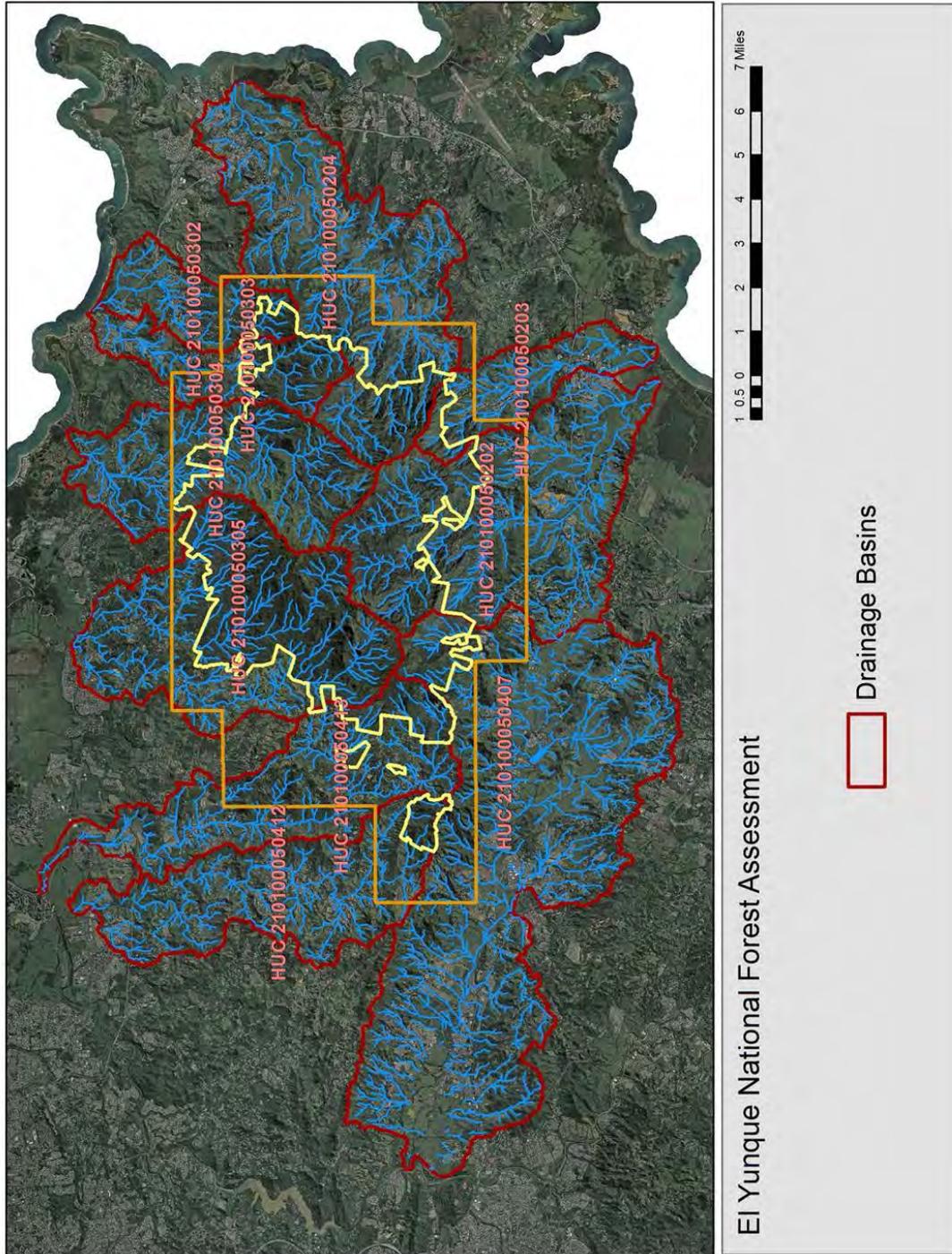
An assessment of off-road vehicle use within Forest boundaries would provide information related to its impact on soil erosion and water quality.

2.5 Assessing Water Conditions

2.5.1 Introduction

Water used for public consumption may be the most important product of the Luquillo Mountains. Estimated as the cost paid by the consumer, water extracted from the streams that drain the Luquillo Mountains is worth about \$25 million per year. Because of the importance of understanding where the water is most available and how the quantity changes with individual storms, season, and on annual to decadal time scales, water budgets have been developed for El Yunque National Forest.

The budgets are used to show how much precipitation, stream runoff, and evapo-transpiration have occurred in four watersheds in the study area during the 1990s. The water budgets are strongly controlled by elevation and orientation with respect to prevailing (trade) winds. Because of the steep gradients in these mountain watersheds, runoff is rapid and stream flow peaks are very brief. More information about the social uses, quantity, extraction, balance and other issues, not involving water quality, can be found at the Aquatic Ecosystem Assessment and Watershed Assessment (See sec 2.2 and sec. 3.3).



Map 2-15. Drainage Basins

2.5.2 Existing Information

Water resources are jointly managed by several state and Federal agencies on the Island. Water quality is regulated by the Puerto Rico Environmental Quality Board (EQB) and the Environmental Protection Agency (EPA), while extraction is regulated by the Puerto Rico Natural and Environmental Resources Department (DRNA) and monitored by the US Geological Survey (USGS). Ample information regarding the water resources of El Yunque National Forest, including real time monitoring of stream flows exists. Water quality data is available from EPA. A new stream (drainage) network was developed for EYNF utilizing existing elevation data. This information provides a more accurate representation of perennial streams. The minimum area for stream formation on EYNF is 6 ha (Pike, 2008; Scatena, 1989). Water related information, including linkage to water quality documents, has been integrated on a geographical information system included with this assessment.

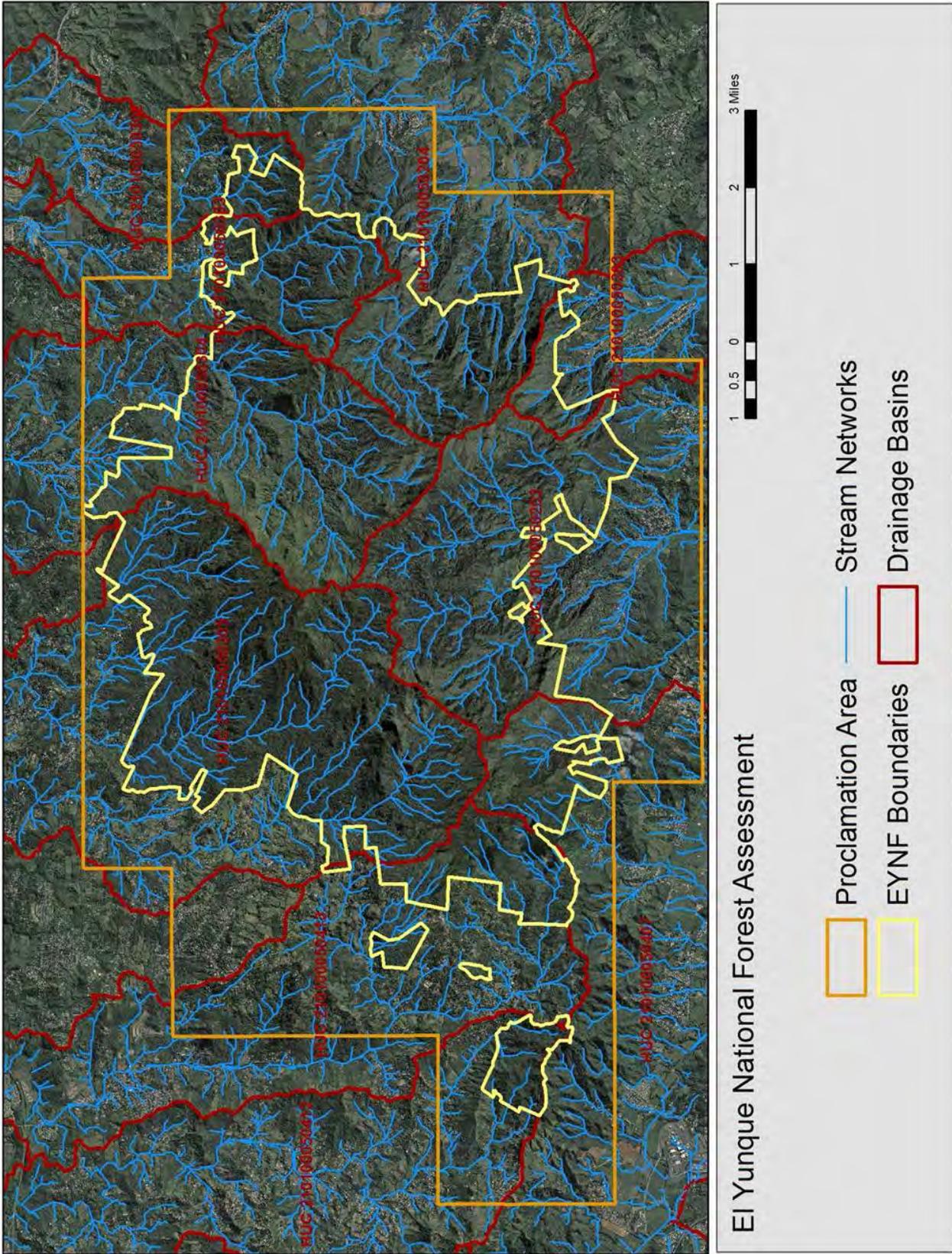
2.5.3 Current Conditions

Water resources and quality are a concern for El Yunque National Forest (EYNF). When Assessing Water Resources, the responsible officials should consider the following at the appropriate watershed scale:

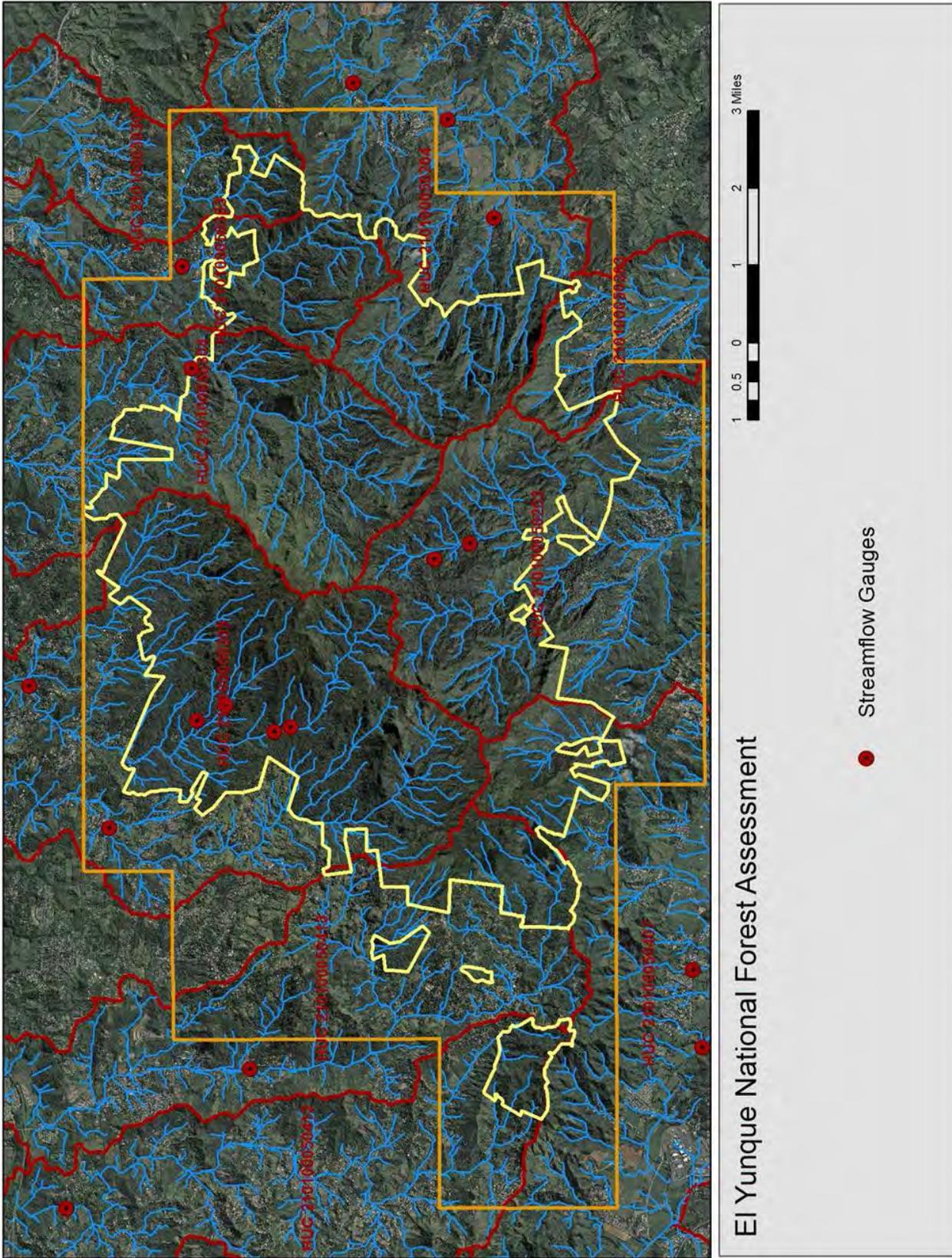
1. The condition of watersheds relevant to plan area, paying particular attention to the presence of impaired or contaminated waters within or adjacent to the plan area and the larger area of analysis. For NFS lands, the responsible official should consider the information generated through the Watershed Condition Classification Technical Guide (WCC)(USDA Forest Service 2011a) and the Step A of the Watershed Condition Framework (WCC)(USDA Forest Service 2011b) and the designated WCF Priority Watersheds:
 - a. Streamwater quality within El Yunque National Forest is excellent, and these streams are considered to be the cleanest and most natural on the island (Santos Roman et al. 2003). Water temperature in headwater streams is relatively consistent throughout the year and ranges between 18 and 24 °C (Covich and McDwoell 1996). The average pH of streamwater is 7.2.
2. The Quantity, quality, timing, and distribution of water across the plan area and area of analysis, including for groundwater resources and groundwater-dependent ecosystems:
 - a. The Icacos and Mameyes watersheds, located in the eastern half of the mountains, are the wettest of the four watersheds in the Luquillo Mountains, annually receiving more than 4,300 millimeters and 3,800 millimeters, respectively, of combined rainfall and cloud drip. The Canovanas and Cayaguas watersheds, located in the rain shadow to the east and southeast of the mountains, receive roughly half the precipitation recorded for the Icacos and Mameyes watersheds.
 - b. Because of the influence of windward-leeward effects differences in hydrologic regimes in the four watersheds associated with bedrock geology or land cover are difficult to detect. Groundwater storage is small compared to with annual runoff in all watersheds. Geology appears to control the recession characteristics of the

- rivers; recession is faster in volcaniclastic soils, probably because of impermeable clay layers, than a granitic rocks.
- c. There are 34 water intakes withdrawing over 46 million gallons per day from the Forest, in some basins, up to 82% of the median flow is diverted, on a typical, 70% of water generated within the Forest is diverted before reaching the ocean, up from 54% in 1994 (Crook et al. 2007).
3. The historic context (such as NRV) for water resources under the hydrologic systems developed:
 - a. Although the headwaters of these rivers have been protected for more than a century, and some have been protected since Columbus landed on the island, the lowlands support a mixture of urban, suburban, and agricultural land uses. In recent decades, land use in the periphery of the Luquillo Mountain has changed drastically as agricultural lands have been abandoned and changed to forests or developed areas (Grau et al. 2003; land cover maps in Lugo et al. 2000 and, 2004). Increases in population combined with increases in number of homes and resorts, have also increased the demands for the region's natural and aquatic resources.
 - b. Because Puerto Rico is a Commonwealth Territory of the United States, island residents are subject to the environmental regulations of the U.S. Environmental Protection Agency and other Federal agencies. Many Federal agencies are involved in the island's water management, including the U.S. Geological Survey, which monitors the island's water quality and quantity; the U.S. Army Corps of Engineers which is responsible for navigable waters and wetlands; the U.S. Geological Survey, which manages threatened and endangered species and wetlands; the Natural Resources Conservation Service, which helps farmers implement best land and soil conservation practices; the Forest Service and National Park Service, which manage national forests and national parks, respectively.
 4. The flow regimes needed to sustain the biotic and abiotic integrity of aquatic ecosystems, from the NRV.
 - a. Minimum flows are not being maintained, impairing ocean connectivity, including observed 0 flow on the Río Icacos (Crook et al., 2007)
 5. The reasonably anticipated future patterns of perturbation (such as, influence of changing climate flood, drought, altered precipitation, and evapo-transpiration patterns) and reasonably foreseeable future water withdrawals and diversions, water storage facilities (surface and subsurface), municipal watersheds, sole source aquifers, and source water protection areas within the plan area and the area of analysis:
 - a. Water shortages are a chronic problem in eastern Puerto Rico. Reservoir storage is lost because of high sedimentation rates (associated with storms) (Webb and Soler-Lopez, 1997).

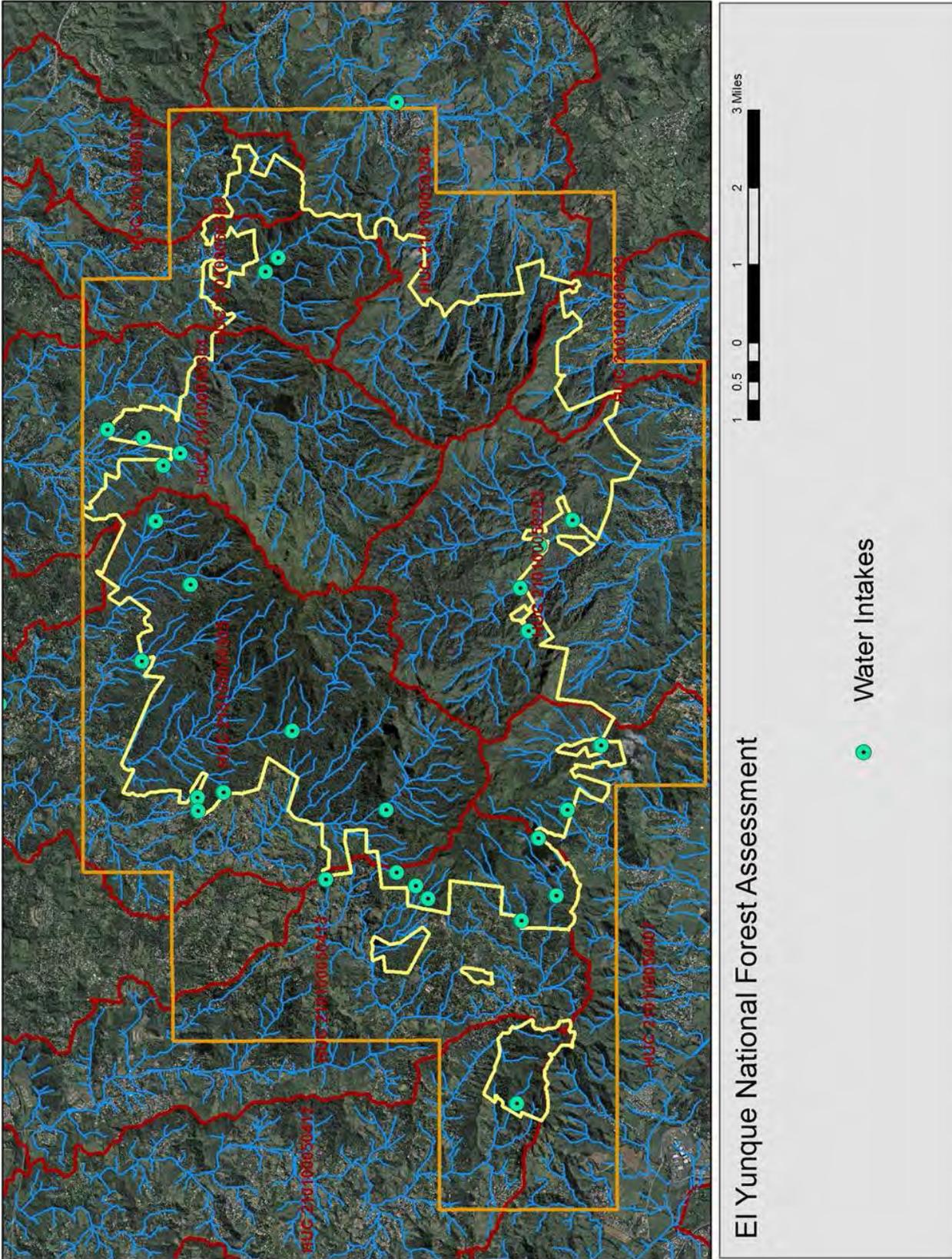
- b. Climate models produced by the Intergovernmental Panel on Climate Change have forecast that the trend of increasing dryness in Puerto Rico will continue. An increase in the frequency and severity of droughts, and changes in temperature and humidity of the lower atmosphere, could lead to an increase in the altitude of the typical cloud base and the concomitant upward shift of ecological zones on mountains (Still and others, 1999; Lawton and others, 2001; van der Molen and others, 2006).
- c. The higher elevation of the cloud base could help to decrease orographic precipitation, which provides about 30 percent of annual precipitation in the Luquillo Mountains, and could reduce part of the Puerto Rico's water supply (Scholl and others, 2009).
- d. The intensity and number of large hurricanes in the Atlantic are predicted to increase this century, which could lead to greater loss of infrastructure, human life, and habitat as a result of mass wasting, flooding, and defoliation (Emanuel, 2005).

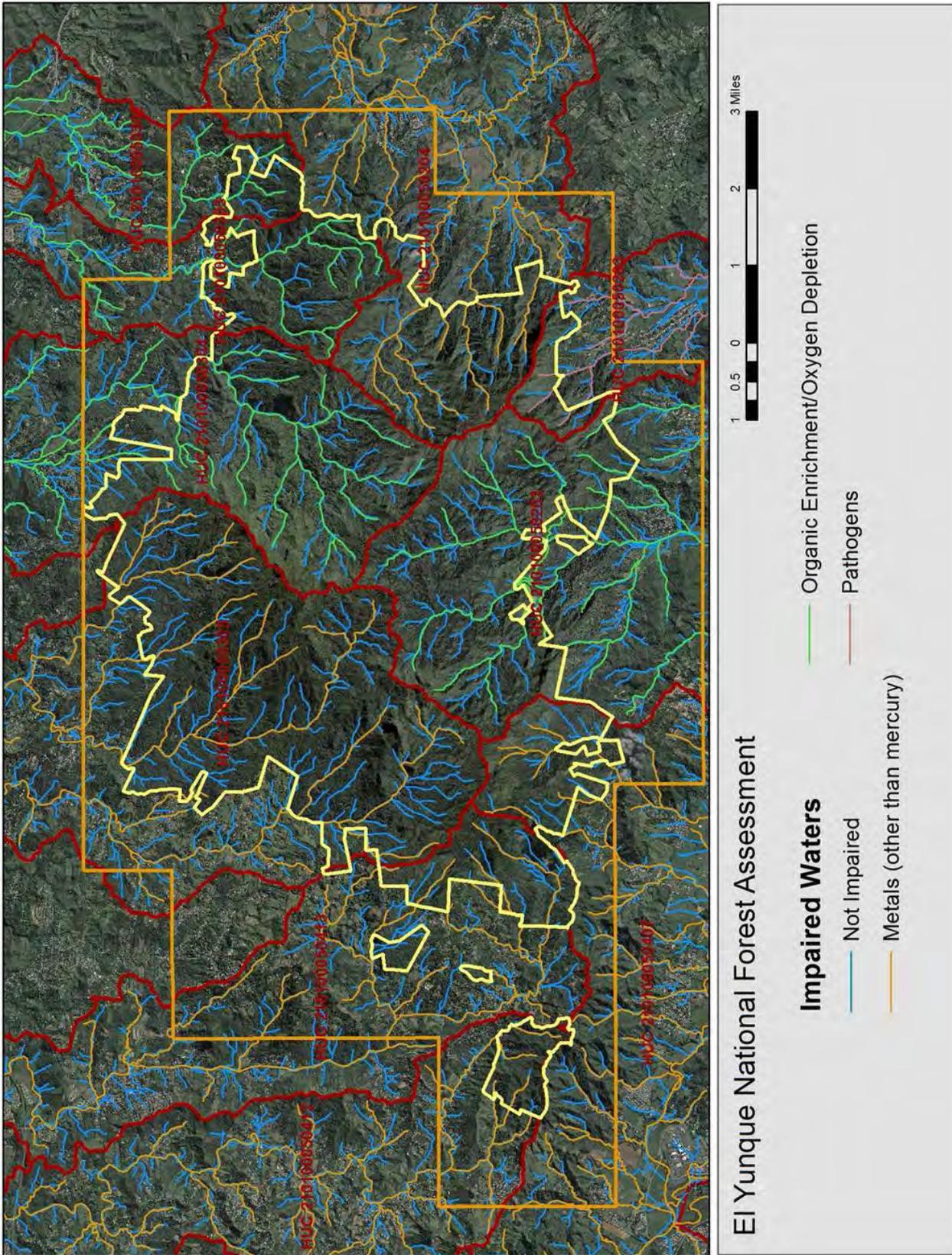


Map 2-16. Land boundaries and waterflow



Map 2-17. Streamflow in El Yunque National Forest





Map 2-19. Impaired Waters

2.5.4 Trends and Drivers

Water resources on EYNF are a result of rain and cloud condensation, given that groundwater contribution to stream flow is negligible (Scatena, 1989 ; Crook 2007). Orographic precipitation, generated by the collision of trade winds with the Sierra de Luquillo, causes heavy rains in the northeast sections of Puerto Rico. Hurricanes are a regular part of the climate, as are tropical storms and depressions, convective storms, northeasterly trade winds, Saharan dust, and winter cold fronts.

Above the lifting condensation level at about 600m elevation, cloud cover reduces solar radiation, to about 63 percent of nearby coastal areas, (Briscoe, 1966). Also it brings precipitation, interception and cloud drip, (cloud drip comes from the direct deposits of water from clouds onto vegetation) to the natural system. 13,000 acres or forty-six percent of the forest is above the 600m elevation line. Vegetation above the 600m elevation line is classified under Montane Cloud Forest. This classification is given because here vegetation is affected directly by clouds (cloud cover, reduced solar radiation, interception, cloud drip and precipitation). More specifically, in the windward sites where winds come from the east, vegetation is classified under Montane Rain Cloud Forest. Exposition to trade-winds brings a lot of clouds filled with water that will be precipitated in this side of the Sierra Luquillo. On the contrary, vegetation on the leeward site is classified under Montane Wet Cloud Forest. Precipitation is not to the same degree as the windward site, here is less. Across the forest as a whole, mean annual precipitation averages approximately 3,879 mm/yr (millimeters per year) (García Martín et al. 1996). A similar scenario is observed for cloud drip. Leeward sites on Pico del Este receive about 60 percent less cloud drip than windward sites (Weaver, 1972).

As with precipitation, runoff was higher from Icacos and Mameyes (windward site) watersheds than from the Canovas and Cayaguas (leeward site) watersheds.

Withdrawals from Forest produce waters are detailed on table xx4

Information Gaps

- A new water budget utilizing better withdrawal estimates.
- LiDAR data should be utilized to update stream network, since existing topographic data lacks the proper resolution.
- Climate change scenarios should be incorporated into water withdrawal strategies.

Key Findings

1. Distribution and Response
2. Hydrologic Flow Cycle

2.5.5 Literature Cited

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- We acknowledge the Template for Assessing Climate Change Impacts and Management Options (TACCIMO) for its role in making available their database of climate change science. Support of this database is provided by the Eastern Forest Environmental Threat Assessment Center, USDA Forest Service.

2.6 Assessing System Drivers and Stressors

2.6.1 Introduction

The Luquillo Mountains are a heterogeneous landscape, produced by environmental variation, a varied disturbance regime, and varied responses to disturbances in space and time (Brokaw 2012). Background treefall gaps (gaps not caused by hurricanes) open up 0.24 to 1.8 percent of Tabonuco Forest per year (Scatena and Lugo 1995); landslides denude a minimum of 0.08 to 0.30 percent of the Luquillo Mountains each century (Guariguata 1990); and severe hurricanes strike the Luquillo Mountains every 50 to 60 years (Scatena and Larsen 1991) and cause treefall gaps, landslides, and floods. Thousands of lesser storms, floods, and droughts have occurred over the millennia. Moreover, various kinds of human disturbance have affected nearly all forest area below 600 meters above sea level (Foster et al. 1999). The Luquillo Mountains represent many other tropical landscapes in which disturbance produces heterogeneity (Foster 1980).

How do the organisms of the Luquillo Mountains respond to this great variety, high frequency, and long history of disturbances? To describe these responses, we use the conceptual approach. The response depends on the pre-disturbance conditions and the disturbance severity, which determine the conditions at the onset of response, and on the characteristics of the responding species. The initial conditions created by a disturbance can be classified as abiotic (including structure) and biotic and are thought of as “residuals,” or primary effects. Residuals are the physical manifestations of disturbance, that is, what remains of the abiotic, biotic, and structural features. These residuals shape the response to disturbance, creating secondary effects in the form of “legacies,” or the long-term subsequent behavior of the ecosystem as determined by the residuals. Residuals and legacies of disturbance help explain the present condition of ecosystems (Foster et al. 2003).

The conditions at any given time can be described in terms of ecological space. Ecological space may be visualized as a multidimensional hyper-volume that reflects abiotic, biotic, and structural components of a system. Disturbance changes this hyper-volume by modifying these components at points located in geographical space. For instance, forest canopy changes can turn a previously shaded, cool, moist geographical point at ground level into a sunny, hot, dry point. In turn, biotic responses to disturbance, such as forest regrowth, can change conditions at that geographical point back to those of the earlier, shady, cool, moist ecological point. In such a situation, geographical space has not changed; ecological space has. The trajectory of response in ecological space depends on the intensity, duration, and extent of the disturbance, and then on the degree of resistance and resilience of biotic responses (Lugo et al. 2002). Resistance is the degree to which a system is not affected by disturbance, as, for example, when trees are affected but not killed. Resilience is the time required for a system to return to a state that is similar to that before the disturbance, as when trees recover their pre-disturbance biomass.

With these concepts in mind, we describe the responses of organisms, populations, communities, and ecosystems to the variety of disturbances in the Luquillo Mountains. We look at residuals and legacies, at resistance and resilience, and at mechanisms or processes of response. This discussion is organized according to descriptions of disturbances that act at landscape scales, including background treefalls, hurricanes, floods, droughts, landslides, and various human disturbances. Most sections begin with a description of residuals—of how disturbance affects the biotic and structural environments and proceed to a discussion of legacies, or longer-term

responses. We conclude with a discussion of the variation in responses to different disturbances and of interactions among disturbances. Variations and interactions among responses weave the tapestry of the Luquillo Mountains, encompassing landscape variation in space, and they also produce the layers of the palimpsest, encompassing persisting variations in time. We also discuss the response to disturbance, but emphasize the role of key species and their control of ecosystem processes (Brokaw 2012).

2.6.1.1 Disturbance Regimen

Key Points

► The Luquillo Mountains are affected by a wide array of environmental processes and disturbances. Events that concurrently alter the environmental space of several different areas of the Luquillo Mountains occur every 2 to 5 years. Events such as hurricanes that cause widespread environmental modification occur once every 20 to 60 years.

► The most common disturbance-generating weather systems that affect the Luquillo Mountains are (1) cyclonic systems, (2) noncyclonic intertropical systems, (3) extratropical frontal systems, and (4) large-scale coupled ocean-atmospheric events (e.g., North Atlantic Oscillation, El Niño-Southern Oscillation). Unlike some tropical forests, disturbances associated with the passage of the Inter-Tropical Convergence Zone or monsoonal rains do not occur.

► Hurricanes are considered the most important natural disturbance affecting the structure of forests in the Luquillo Mountains. Compared to other humid tropical forests, Luquillo has a high rate of canopy turnover caused by hurricanes, but a relatively low rate caused by tree-fall gaps. Historically, pathogenic disturbances have not been common. Human-induced disturbances have historically included tree harvesting for timber and charcoal, agriculture, and agroforestry. In the past few decades, water diversions, fishing and hunting, and road building have been important disturbances. Present and future human-induced disturbances are related to regional land use change, the disruption of migratory corridors, and forest drying related to coastal plain deforestation and regional climate change.

► Hurricane-related storm discharges can cause significant geomorphic modifications to Luquillo stream channels, and stream water concentrations of sediments and nutrients can be elevated for months to years following a major hurricane. However, the largest floods are not necessarily associated with hurricanes, and the annual peak discharge can occur in any month of the year, but is most common in the late summer and fall.

► Over the entire Island of Puerto Rico, 1.2 landslide-producing storms occur each year. In the Luquillo Mountains, landslides are typically covered with herbaceous vegetation within 2 years, have closed canopies of woody vegetation in less than 20 years, and have aboveground biomass of the adjacent forest after several decades.

2.6.1.2 Introduction

The Luquillo Mountains, like many humid tropical environments, is a dynamic ecosystem affected by a wide array of environmental processes and disturbances. Quantifying the magnitude, frequency, and impact of these natural disturbances on both geographical and ecological space is essential to understanding and managing these forests. We review the causes, frequencies, and discrete and cumulative impacts of disturbances on the Luquillo Ecosystem, and subsequently discuss the ecosystem's recovery after disturbance.

Disturbances can be defined as relatively discrete events that alter the structure of populations, communities, and ecosystems (White and Pickett 1985; Lugo and Scatena 1996; Walker and Willig 1999). “Disturbance regime” refers to the sum of disturbances acting on a particular location. Natural disturbances are specified by the United Nations in the International Decade of Natural Disaster Reduction where earthquakes, windstorms, tsunamis, floods, landslides, volcanic eruptions, wildfires, insect infestations, drought, and desertification are treated. Treefalls, pathogens, exotic invasions, and meteor impacts are also known to affect humid tropical forests. Of these 14 types of disturbances, 10 are known to have caused community-level impacts in northeastern Puerto Rico during the past century. These disturbances have also acted on a landscape that has undergone dramatic land use changes associated with forest harvesting and clearing, agriculture, urbanization, water diversions, and other modifications to hydrologic and nutrient cycles.

Quantifying the effects of disturbances on landform morphology and ecosystem development has been traditionally themed in geomorphology and ecology (Wolman and Miller 1960; Connell 1978). It is now generally recognized (Lugo and Scatena 1996) that the effect of a disturbance on the morphology of a landscape or the structure of an ecosystem depends on the following:

- The type of disturbance (i.e., flood, fire, landslide, biologic, anthropogenic, etc.)
- The intensity of the force exerted (i.e., wind velocity and duration, rainfall magnitude and intensity, earthquake magnitude, etc.)
- The ecosystem component that is directly impacted by the forces exerted (i.e., soil, biomass, leaf area, etc.)
- The spatial extent and the spatial distribution of impacts
- The return period or frequency of the event
- The initial condition and resistance of the system
- The resilience of the system and the magnitude of the constructive or restorative processes that occur between disturbances

Mortality is also a complex process that occurs over many spatial and temporal scales. Mortality events can range from “background events” to large-scale “catastrophic events” (Lugo and Scatena 1996). Background mortality is typically associated with senescence, competition, and succession. Catastrophic mortality occurs when a forest is mechanically or chemically impacted by an external force such as a hurricane, a landslide, or toxic waste. When expressed as percentage of stems or biomass per year, the background mortality is typically less than 3 percent per year. The median value of the background mortality in 68 pantropical moist, wet, and rain forest stands was 1.6 percent per year; this is similar to values reported from the Luquillo Mountains, as well as from temperate and boreal forests (Lugo and Scatena 1996). In contrast, catastrophic events can cause 100 percent mortality in small areas (Brokaw 2012).

2.6.1.3 Response to Disturbance

Key Points

Background treefall gaps (not caused by hurricanes) are filled with plant regrowth as in other tropical forests. There is limited response by animals to treefall gaps, probably because background treefall gaps are relatively less important in these forests, which experience chronic, widespread hurricane effects.

- Despite substantial effects on trees, the tree species composition changed little in the Tabonuco Forest after two recent hurricanes.
- Animal species show various responses to the changes in forest architecture and food resources caused by hurricanes. Bird species tend to be plastic in habitat and dietary requirements, probably due to the large changes in forest structure caused by hurricanes and regrowth, which require birds to change their foraging locations and diets.
- Although hurricane-produced debris is substantial (litterfall up to 400 times the average daily amount), decomposition, nutrient export, and trace gas emissions after hurricanes change only briefly, as rapid regrowth reasserts control over most ecosystem processes.
- In general, terrestrial ecosystem functions recover faster than structure.
- Hurricanes dump debris in streams, and floods redistribute inorganic and detrital material, as well as stream organisms, throughout the benthic environment along the stream continuum.
- Succession in landslides is slow and primarily limited by the availability of seed and by low nutrient availability; early plant colonists, especially ferns, have a strong influence on later dynamics.
- Past land use is the most important determinant of species composition in Tabonuco Forest, despite repeated hurricane effects and underlying environmental variation such as in soil and topography.
- The native organisms of the Luquillo Mountains are more resilient after natural than human disturbances.

2.6.2 Climate Change

2.6.2.1 Introduction

This document provides a literature review regarding the vulnerability of resources in the EYNF and throughout the Caribbean to climate change. Information in this report was produced from content in the USDA Forest Service's *Template for Assessing Climate Change Impacts and Management Options (TACCIMO)* in collaboration with the International Institute of Tropical Forestry and managers from EYNF as part of the plan assessment phase of the land and resource management plan revision for the national forest. *Note:* Information specific to EYNF and Puerto Rico appear first in each section denoted by (when available), followed by more general results. It is also important to note that the Luquillo Experimental Forest has the same boundary as EYNF, that is, the national forest and the Luquillo Experimental Forest are the same, and both terms are used interchangeably throughout this document.

The purpose of this report is to provide a comprehensive and concise summary of the current scientific findings on the effects of climate change on natural resources in Puerto Rico and the greater Caribbean region to increase understanding and to inform forest planning. Although summarized literature focuses on EYNF and Puerto Rico, the scientific information in this report represents a wide range of ecological communities throughout the greater Caribbean region and the tropics. Comparison among ecological systems necessitates an understanding of underlying environmental conditions at various scales that may be beyond the scope of information presented here (Brokaw et al. 2012). Information in this report is summarized from a variety of scientific studies employing varying methodology, and may rely on site-specific measurements, modeling, or professional scientific opinion. Studies presented use varying models and emission scenarios

that provide differing and sometimes conflicting projections for the future climatology of the Caribbean, especially in the discussion of precipitation patterns. Some of the predicted effects of climate change lack precision as to when they may occur, and many of the effects may not be seen in local ecosystems until 50 to 100 years from now. Therefore, it is crucial that the specific information presented in this report is considered within the larger body of climate change science, studies of recent trends, and best practices for natural resource management. In addition, this report does not provide weighting of scientific evidence or discussion of management implications. Literature summaries provided in this report prepare the decisionmaker for further analysis, including engaging the public and local experts through a process that assesses the evidence within the broader context of the management decision, often using best professional judgment and other more qualitative methods (Linkov et al. 2009).

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2.6.2.2 Changes to Drivers and Stressors

Climate Trends

Large-scale Circulation Patterns

- ❖ Torres and colleagues (2008) found that the climate of EYNF is sensitive to changes in sea surface temperatures. Sea surface temperatures have increased 1.5 °C over the last century (PRCCC 2013), and are projected to increase about 1 °C by 2050, with the largest increases in the dry season and the late rainy season (Angeles and others 2007). Increasing sea surface temperatures are already causing increased air temperatures in coastal regions of Puerto Rico (Torres et al. 2008).
- ❖ Temperature patterns in Puerto Rico are influenced by the El Niño-Southern Oscillation, while precipitation patterns are largely influenced by the location of the North Atlantic Oscillation (Malmgren et al. 1998), which occurs in a roughly 60-year cycle (Mazzarella and Scafetta 2012). Climate models project future northward shifts in both mid-latitude and tropical jet streams that will affect the North Atlantic Oscillation, especially in the winter season (Woollings and Blackburn 2012).
- Future projections using the parallel climate model show a decrease in average easterly winds over the Greater Antilles for the coming century, but an increase elsewhere in the Caribbean (Angeles et al. 2010).
- A long-term study of climate in the Caribbean (1950 to 2000) found that trade winds in the early rainfall season have increased in magnitude and shifted to a more easterly or south-easterly flow, with global climate change playing an important role in the trend (Comarazamy and González 2011).
- Observed sensitivities of African dust to changes in climate indicate that future climate change could drastically change the amount of African dust reaching the Caribbean (Prospero and Lamb 2003).

Temperature Trends

Historic Trends

- ❖ At the National Weather Service station in Fajardo, Puerto Rico, near the Luquillo Mountains, small but significant increases were found in annual maximum and annual minimum temperatures was detected in long-term (62 year) records (Waide et al. 2013).
- ❖ In the Tropical Montane Cloud Forest at the Pico del Este field station in EYNF, mean monthly minimum temperatures have increased over the past 30 years (Lasso and Ackerman 2003). Similar changes were also found in Monteverde Cloud Forest in Costa Rica, where temperatures have increased about 2 °C (LaVal 2004; Pounds et al. 1999).
- ❖ Using an analysis of weather station data across Puerto Rico from 1900 to present, an average annual increase in temperatures of 0.012 °C to 0.014 °C per year was observed (PRCCC 2013).
- ❖ In the heavily urbanized San Juan Metropolitan Area air temperatures were found to have increased 1.5 °C when compared with similar average past conditions (determined by looking at El Niño-Southern Oscillation indexes) in 1977–1978 (Torres et al. 2008).
- Mean annual temperatures in the Caribbean have increased an average of 0.2 to 0.4 °C each decade since 1976 (IPCC 2001; Uyarra et al. 2005). Average overnight low and daytime high temperatures have also increased in the Caribbean by 1.0 °C and 1.8 °C respectively since 1950 (Comarazamy and González 2011).

Future Trends

- ❖ Scatena (1998) modeled a projected increase in temperatures of 1.5 to 2.5 °C in Puerto Rico by the end of the 21st century, while recent studies using regionally downscaled models from Campbell et al. (2011) predict a larger increase of 2 to 5 °C in the Caribbean.
- ❖ Non-parametric ensembles from Gieretz et al. (2009), using 3rd Coupled Model Intercomparison Project (CMIP3) models from Meehl et al. (2007), show average annual increases in temperature of 1.5 °C by 2020, 2.7 °C by 2050, and 4.6 °C by 2090 for Puerto Rico.
- Projections of future climate for the Caribbean agree that temperatures will increase; yet, the magnitude of increase varies by model and emission scenario as well as regional extent (Biasutti et al. 2012; Christensen et al. 2007; Magrin et al. 2007; Scatena 1998).
- Using the IPCC models, Biasutti et al. (2012) projected warmer annual temperatures and lower temperature variability for the future Caribbean climate.
- By 2020, IPCC models project an increase of 0.4 to 1.8 °C in Latin America (Magrin et al. 2007).
- By the end of the century, the Fourth Assessment Report of the IPCC projects an increase of 1.8 to 5 °C in Central America (Christensen et al. 2007). In Latin America, an increase of 1 to 7.5 °C is expected (Galindo et al. 2010; Magrin et al. 2007).

Precipitation Trends

Historic Trends

- ❖ Across Puerto Rico, rainfall has declined over the 20th century; however, a specific link to climate change has yet to be determined (Waide et al. 2013).
- ❖ Precipitation in Puerto Rico has varied over the past century, with below-average rainfall measured at 87 percent of the normal for 1990 to 1997, and 24 percent above the normal in 1998 (Larsen 2000). In the Luquillo Experimental Forest rainfall was found to have decreased an average of 0.20 millimeters per year from 1988 to 2003 with low rainfall periods most frequently occurring in March (Heartsill-Scalley et al. 2007).
- ❖ The incidence of heavy precipitation at the Pico del Este field station in EYNF has increased over the past 30 years (Lasso and Ackerman 2003).
- Satellite estimates used by Neelin et al. (2006) found a significant drying trend in the Caribbean and Central America since 1950, and point-based estimates show a drying trend of 5 to 30 percent since 1900. Mid- to long-term data also show drying trends in the Bahamas (10 to 15 percent since 1959) and Jamaica (11 percent since 1995) (Martin and Weech 2011; Studds and Marra 2011).

Future Trends

- ❖ Scatena (1998), applying projected future precipitation patterns to the LEF, found that while annual precipitation was projected to remain constant, rainfall variability, including the number of heavy rainfall days, was expected to decrease.
- ❖ Non-parametric ensembles from Girvetz et al. (2009), using CMIP3 models from Meehl et al. (2007), show an average annual decrease in precipitation of 5 percent by 2020, 13 percent by 2050, and 16 percent by 2090 for Puerto Rico.
- Recent modeling work for the Caribbean region using the latest Intergovernmental Panel on Climate Change (IPCC) model results suggests a drying trend (Biasutti et al. 2012; Campbell et al. 2011; Cashman et al. 2010).
- Biasutti et al. (2012) projected a 30 percent decrease in spring and summer precipitation in the Caribbean using the IPCC ensemble model for the end of the century. Analysis also suggests that the number of consecutive dry days will increase consistent with a lengthening of the dry season, while the number of days with rainfall over 10 millimeters expected to decrease (Biasutti et al. 2012).
- Campbell et al. (2011) and Cashman et al. (2010), using regionally downscaled climate models, show a decrease in annual rainfall for the Caribbean, with decreases ranging from 25 to 50 percent by the end of the century and the largest decreases in the southern Caribbean (Campbell et al. 2011).
- Seasonal projections using regionally downscaled models show drying trends in spring, summer, and fall, with the strongest decreases of up to 35 percent in the summer months (Campbell et al. 2011), leading to a drier wet season, and even drier dry season, with a potential wet spell in the winter (Cashman et al. 2010).
- Future changes in precipitation in the tropics vary by model, but also by temporal and spatial extent. Magrin et al. (2007) projected a 20 percent reduction to an 8 percent increase in dry season precipitation, and a 30 percent reduction to a 5 percent increase in

- wet season precipitation for Latin America for 2080. Christenson et al. (2007) projected a decrease in precipitation over Central America using the multi-model data set model for the end of the century. Lintner et al. (2012) found that the occurrences of both very dry and very wet months are projected to increase in the tropics by the end of the century.
- Angeles et al. (2007) using the PCM projected future climate for the Caribbean region for 2050 as warmer and wetter, with more intense rainfall in the rainy season, due to increased sea surface temperatures leading to an increase in available water vapor and a longer and more intense hurricane season (Aguilar et al. 2005). However, models for the Caribbean (Neelin et al. 2006) and Puerto Rico (Scatena 1998) also predict increasingly severe drought over the next 50 years.

Cloud Base Trends

- ❖ For EYNF, changes to the location of the axis of the convergence zone since 1950 was found to affect orographic lifting mechanisms, which has led to a higher cloud base and strong precipitation reductions during the early rainfall season ranging from 45 millimeters at low elevations to up to 150 millimeters at higher elevations (Comarazamy and González 2011).
- ❖ Land cover changes were found to affect the height of the cloud base in the Luquillo Experimental Forest, evidenced by the temporary lifting of the cloud base following the massive defoliation in from Hurricane Hugo (Wu et al. 2006). However, land use and land cover changes in lowland areas upwind from Luquillo Experimental Forest were found to have little influence on precipitation in the cloud forest, while recent conversion from agriculture to forest was found to lower air temperatures (Torres et al. 2008).
- A global study of Cloud Forests using cloud frequency data from 1979 to 2002 found that the number of cloudy days decreased in Cloud Forests occurring in the 10 to 20° latitudinal band, while Cloud Forests near the equator showed an increase in cloudy days (Bruijnzeel et al. 2011).
- Empirical studies indicate that climate change will increase the altitude of the cloud base in tropical mountains due to higher sea surface temperatures (Beniston et al. 1997; Still et al. 1999). This change occurs because warmer seas generate more water vapor and latent heat in the surrounding areas, reducing the changes in temperature with increasing elevation that cause cloud formation (Pounds et al. 1999; Nadkarni and Solano 2002). The “lifting cloud base” will decrease inputs of the mist in cloud forests (Nadkarni and Solano 2002), and may alter the forest type’s hydrology (Eugster et al. 2006).
- In Monteverde Cloud Forest, Pounds et al. (1999) found that dry season mist decreased over the past 30 years, and the mean altitude of the cloud base has risen, owing both to global climate change and widespread lowland deforestation (LaVal 2004). Modeled responses to future climate change project an additional 200-meter rise in the cloud base at Monteverde during the dry season (Sill et al. 1999).

Extreme Weather

Precipitation Extremes

- ❖ Heavy rainfall events have become more common in Puerto Rico, particularly since 2009, with changes linked to high sea surface temperatures (Vélez Rodríguez and Votaw 2012).

- ❖ Historic periods of drought in Puerto Rico, such as the extreme drought experienced in 1993 to 1995, provide a glimpse into future dry periods, which may increase as annual rainfall decreases over time in the Caribbean region (Larsen 2000).
- ❖ In northern Puerto Rico, frequently drenched soils and steep slopes contribute to landslide frequency, while landslides coincide with intense rainfalls in the relatively drier south (Lepore et al. 2012).
- O’Gorman (2012) found a strong correlation between the sensitivity of tropical precipitation extremes to changes in inter-annual temperature variability.
- In the Caribbean, long-term data (since 1950) shows that the maximum number of consecutive dry days is falling while measures of extreme precipitation events are increasing (Peterson et al. 2002).
- Aguilar et al. (2005) found that increases in the percentage of warm days during wet season months (June, July, August, September, October, and November) suggest more insolation and therefore fewer cloudy days in Central America and northern South America. Given increased precipitation intensity alone, fewer rainy days and more warm days would be expected (Aguilar et al. 2005).
- Though more dry extremes are expected in all seasons of Central America, a limited number of studies have produced estimates of extreme seasonal temperature and precipitation frequencies (Magrin et al. 2007).
- Overall, heavy precipitation and dry spell length in the Caribbean, typified by a n intensified hydrological cycle, agree with global averages for extreme temperature and precipitation in dices (Aguilar et al. 2005; Peterson et al. 2002). However, careful interpretation of theoretical arguments for local precipitation time scales is needed, as throughout the tropics more extreme rainfall and drought counts are mostly affected by wet and dry anomalies, suggesting that there will be increased tropical rainfall spatial gradients (Lintner et al. 2012).
- Exacerbating climatic changes, model analyses also indicate a likely increase in drought severity associated with increased deforestation and other land-use change (Werth and Avissar 2002).
- Landslides are caused by strong and persistent precipitation events, and in Latin America are linked with deforestation and deficient land planning and disaster contingency schemes (Magrin et al. 2007). Thus, many already vulnerable cities will likely experience intensified extreme weather risks and hazards (Magrin et al. 2007).

Temperature Extremes

- ❖ In recent years, an analysis of weather station data (PRCCC 2013) shows that Puerto Rico has experienced an increasing number of hot days over 90 °F, and a decreasing number of days under 75 °F. In 2010 and 2011 alone, 100 days with temperatures over 90 °F were recorded.
- Temperature is expected to increase substantially in tropical forested regions over the next two decades, with seasonal temperature extremes becoming more common (Anderson 2011; Duffenbaugh and Scherrer 2011). Unprecedented heat events are expected to occur with increasing regularity at a greater rate in the tropics relative to temperate regions (Anderson 2011).

- Projected changes in monthly minimum and maximum temperature extremes are significant in the Caribbean, while the rest of the world has shown greater warming in mean monthly minimum temperature. In the Caribbean, the extreme intra-annual temperature range is decreasing; meaning the number of very warm days and nights is accelerating while very cool days and nights are lessening in frequency (Peterson et al. 2002).
- Changing temperature extremes from 1960 to 2003 in Central America and northern South America reflect evident warming trends with great spatial coherence (Aguilar et al. 2005). Annual percentage of warm days and nights above the 90th percentile maximum have increased 2.5 percent and 1.7 percent each decade, respectively; while the annual percentage of cold days and nights below the 10th percentile minimum decreased at 2.2 percent and 2.4 percent per decade, translating to a per-decade-rate increase of 0.2 to 0.3 °C in temperature extremes (Aguilar et al. 2005).
- Regional cold spells (more than 6 days in a row) are lasting 2.2 days per decade less, with most of this trend being caused by pre-1980 climate changes (Aguilar et al. 2005).

Tropical Storms

Future Trends

- ❖ O'Brien and colleagues (1992) estimate the expected hurricane frequency in Puerto Rico to be one hurricane every 4 years causing up to 15 percent tree mortality per storm.
- Numerous climate change studies illustrate the escalating frequency and occurrence of extreme weather events, such as windstorms, tornadoes, hail, heat waves, heavy precipitation, El Niño-Southern Oscillation droughts, or extreme temperature lasting from a few hours to several days (Lewis et al. 2009a; Magrin et al. 2007).
- Recent studies using IPCC data predict an increase in hurricane intensity in the Atlantic, with higher wind speeds and greater amounts of precipitation, but a reduction in the overall number of storms (Knutson et al. 2010; Seneviratne et al. 2012). Global projections for the end of the 21st century show a decrease in hurricane frequency ranging from 6 to 34 percent, an increase in wind speed intensity ranging from 2 to 11 percent, and an increase in precipitation intensity ranging from 3 to 30 percent (Knutson et al. 2010).
- Global warming may alter the maximum speed of hurricanes, but the ultimate effects on average speed or hurricane frequency are debated, and no evidence shows that hurricane disturbance area will increase (Emmanuel 1997; Lugo 2000).
- Kelman and West (2009) indicate that warmer sea surface temperatures and changing storm tracks could cause more tropical storms among Small Island Developing States near the equator.
- Using a simple theoretical model of hurricane intensification under warmer surface water and colder upper tropospheric conditions, Emmanuel (1987) showed that resulting changes in sea surface temperatures could increase the damaging potential of hurricanes by a maximum of 60 percent (Hulme and Viner 1998).

Effects of Tropical Storms on Vegetation

- ❖ At the El Verde field station, Angulo-Sandoval and colleagues (2004) found that canopy disturbances via hurricanes and droughts increase available light and may, along with

- associated reductions in herbivorous species, assist in understory shrub and juvenile canopy growth.
- ❖ Hurricanes and strong wind storms alter ecosystem structure and organization as well as biogeochemical processes by transferring large quantities of organic matter and nutrients to the soil over short time periods, resulting in faster short-term decomposition and higher net primary productivity (Lugo 2000; O'Brien et al. 1992; Silver 1998). Long-term disturbance effects of soil nutrient flux have been observed in the Luquillo Experimental Forest canopy to lead to larger potassium and nitrogen losses (Schaefer et al. 2000).
 - ❖ Modeling the effects of increased hurricane frequency and intensity over a period of 500 years, populations of tabonuco (*Dacryodes excelsa*) and motillo (*Sloanea berteriana*), two late successional species in Luquillo Experimental Forest, were found to decline at the expense of early successional species (O'Brien et al. 1992). In addition, the risk to vascular epiphytes would be particularly large compared to other tropical vegetation species (Zotz and Bader 2009).
 - ❖ The high frequency of hurricane disturbances in the Luquillo Mountains cause the accumulating aboveground biomass to be lower than forests stands with smaller frequencies of disturbance. Thus, if disturbances return at intervals shorter than the recovery time of vegetation, less biomass and nutrients will accumulate (Lugo 2000).
 - ❖ In Puerto Rico's Tabonuco Forests, hurricane frequency and intensity dramatically affect the density of trees (O'Brien et al. 1992) and may influence species diversity, with forests under frequent disturbance attaining lower diversity (based on dominance index values) than those under more periodic disturbance (Doyle 1981). However, topography is an important factor in forests surviving hurricanes, with coves and leeward slopes typically incurring less damage (O'Brien et al. 1992).
 - ❖ Long-term studies following hurricane disturbance in the Bisley Experimental Watershed's Tabonuco Forest found significant changes in both forest structure (Heartsill-Scalley et al. 2010) and non-arborescent plant community composition (Royo et al. 2011). While plant diversity returned to or exceeded pre-hurricane levels within 10 years, species composition continued to be altered as vegetation takes time to recover to its original state, with possible interactions with repeated small-scale disturbance from storms and drought (Heartsill-Scalley et al. 2010).
 - ❖ Royo et al. (2011) found a significant increase in fern and vine species in the Bisley Watershed persisting 20 years after Hurricane Hugo.
 - Lugo (2000) describes the following outcomes and effects regarding hurricanes on Caribbean forests: immediate and significant tree mortality, delayed patterns of tree mortality, alternative methods of forest regeneration, successional changes, high species turnover and opportunities for change, diversity of age classes, faster biomass and nutrient turnover, substitution of species, lower aboveground biomass in older vegetation, carbon sinks, selective pressure on organisms, and community structure convergence.
 - If hurricane intensity and frequency increase in the Caribbean, landscapes will be set back to earlier successional stages (less mature and more secondary forests), aboveground biomass and height will decrease from interrupted vegetation growth, and disturbance-tolerant species will replace those preferring long, disturbance-free maturing

conditions. Decreasing hurricane occurrence and severity would have opposite effects (Lugo 2000).

Air Quality

Airborne Pollutants

- ❖ From 1985 to 1998 levels of nitric acid, sulfuric acid, and ammonia deposition were found to have increased significantly in the Luquillo Mountains, with the majority of pollutants coming from long-range transport from the northern hemisphere (Stallard 2001). Long-range transport has contributed to the cloud and rainwater chemistry of the Luquillo Mountains (Gioda 2013). Subsequent long-term studies (1984 to 2007) have shown varying trends of pollutant deposition within the Luquillo Experimental Forest, with increases in concentrations of pollutants at El Verde Field Station and decreases at the Bisley Experimental Watershed (Gioda 2013).
- ❖ Mercury deposition at Río Icacos in EYNF is the highest measured in the U.S., owing to both dry and cloudwater deposition, but retention of the pollutant is minimal due to high disturbance regimes (Shanley et al. 2008).
- Reductions in air quality in the Caribbean region from long-range transport of dust and other contaminants (Pringle and Scatena 1999) leading to acid rain and dry deposition (Stallard 2001) is increasingly becoming an issue.
- Air pollution, particularly from ozone (O₃), nitrogen oxides (N₂O), and mercury (Hg), is already a major forest stressor in many areas globally. Climate change induced trends in temperature, precipitation, and atmospheric circulation patterns may increase the severity and duration of air pollution episodes (Bedsworth 2012) and their effects on forests and people (Joyce et al. 2008).
- Increases in temperature, in addition to changes in wind patterns and precipitation rates caused by climate change, all have the potential to increase pollutants (Bytnerowicz et al. 2007).

Nitrogen Deposition

- ❖ Nitrogen deposition increased in the Luquillo Experimental Forest at a rate of 0.08 kilograms nitrogen per hectare per year from 1986 to 2004. Under business as usual, Ortiz-Zayas et al. (2006) project N₂O emissions to increase in Puerto Rico at an average rate of 7.8 percent per year with fuel combustion as the primary source of these emissions.
- ❖ In a study on the effects of increased nitrogen deposition on soil microbial communities, Cusack et al. (2011) found shifts in community structure with increased fertilization. There was an increase in fungal abundance at higher elevation sites and an increase in bacterial abundance in lower elevation sites in the Luquillo Mountains.
- ❖ Recent studies near San Juan, Puerto Rico, have shown that urbanization increases the effects of nitrogen deposition, finding large gradients in soil properties over short distances (Cusack 2013).
- Changes in forest nutrient cycles, especially through increased nitrogen deposition (Mohan et al. 2009), may favor certain species and lead to a reevaluation of forest management practices (Bytnerowicz et al. 2007).

- Nitrogen deposition is increasing in tropical regions (Cusack 2013), with significant effects on carbon and nutrient cycles in forests (Cusack et al. 2011), and is expected to further increase with global climate change (Mohan et al. 2009).
- Cusack et al. 2012 found that increased fertilization slowed soil respiration rates, increasing the soil carbon pool. However, increased nitrogen deposition also increased the temperature sensitivity of soil respiration, making soil carbon stocks more vulnerable to future warming (Cusack et al. 2012).

Fire

- ❖ Land-use changes will interact with climate change to alter fire regimes in tropical forests (Cochrane and Laurance 2008). In Puerto Rico, where nearly all wildfires are associated with human activity, the feedbacks between climate warming and drying and increased human development have the potential to increase the ecological and economic effects of fire (Robbins et al. 2008).
- ❖ In Puerto Rico, fire frequency was found to be increasing based on historical and paleoecological evidence (Burney et al. 1994; Robbins et al. 2008).
- ❖ Studies of fire-fuel loading in Puerto Rico and the U.S. Virgin Islands found that the amount of woody debris was lower than other tropical and temperate forests despite the dramatic increase in the amount of fuels and litter following tropical hurricanes (Brandis et al. 2008). Hurricane-induced changes can persist for years and increase future fire risk (Gould et al. 2008).
- In moist tropical forests, where fires have been historically rare (Lewis 2006; Silver 1998), an increase in fire from climate change interacting with human-lit fires poses a severe threat to natural ecosystems because very few tree species are adapted to fire (Brodie et al. 2011). Thin bark and a limited ability to resprout following fire are characteristics of moist tropical forest tree species that make them especially vulnerable to fire (Sherman et al. 2008).
- Tropical forest fire frequency has increased over recent decades, with the 1997 to 1998 El Niño-Southern Oscillation event leading to widespread fires in the tropics (Lewis 2006). If climate change leads to more intense El Niño-Southern Oscillation events as predicted (Yeh et al. 2006, 2009) the incidence, magnitude, and duration of fires in the tropics will continue to increase (Brodie et al. 2011; Sherman et al. 2008).
- Global fire occurrence is projected to rise over the next century with climate change (Flannigan et al. 2000), owing to a combination of more frequent cloud-to-ground lightning ignitions and an increase in the conditions that influence the flammability of forest fuels, including temperature, humidity, and precipitation (Brodie et al. 2011; Flannigan et al. 2000; Sherman et al. 2008).
- Fires in Cloud Forests can be highly destructive, as evidenced by high mortality of canopy trees and extensive consumption of thick organic soils following a fire in a Cloud Forest in the Dominican Republic (Sherman et al. 2008). Severe fires in moist tropical forests have the potential to alter microclimates allowing non-cloud forest species to invade, increasing the chance of recurrent fires (Sherman et al. 2008).

Forest Health

- Climate change will affect disease cycles through changes in host-pathogen interactions in the tropics (Stork et al. 2009) and throughout the northern hemisphere and its forests (Joyce et al. 2008; Sturrock et al. 2011).
- Warmer temperatures are predicted to favor conditions for pathogen development, survival, and disease transmission (Joyce et al. 2008), while changes in precipitation will potentially allow pathogens to expand into new areas (Sturrock et al. 2011).
- Current global models project a redistribution of insect species under climate change (Logan et al. 2003). Warming has been shown to increase insect consumption and movement in a temperate forest (Dukes et al. 2008).
- Both insect and disease outbreaks will increase with climate change, as these organisms will be able to accelerate their life-cycles and expand their ranges (Joyce et al. 2008).

Invasive and Introduced Species

- ❖ There are already several invasive species in E YNF, including Africanized bees (*Apis mellifera*) and bamboo. If Africanized bees increase in the future (in locations where Puerto Rican parrots [*Amazona vittata*] nest, there will be further competition between the bees and Puerto Rican parrots (*Amazona vittata*) who utilize the same nesting sites (Blundell et al. 2003). Bamboo is already expanding in the Forest at a slow pace and increased flooding in the future could accelerate its spread (Blundell et al. 2003).
- ❖ Thompson et al. (2007) found that populations of introduced species are currently not likely to expand in the Luquillo Experimental Forest; however, this could change with more intense or frequent disturbance. In a study of the introduced species rose apple (*Syzygium jambos*), María (*Calophyllum calaba*), and Arabian coffee (*Coffea arabica*) in the Luquillo Experimental Forest, Thompson showed that *S. jambos* is the most likely of the introduced species to increase (Thompson et al. 2007).
- ❖ Increasing intensities of disturbance provide an opportunity for nonnative species planted for farming or ornamental purposes to spread and potentially invade natural forests (Thompson et al. 2007). Post-disturbance, lower mortality rates for introduced species when compared to native species will allow them to persist (Thompson et al. 2007).
- Novel communities of native and introduced species on lands in the Caribbean that have experienced deforestation and then land abandonment may provide clues into how biota may respond in non-disturbed locations to climate change and species invasions (Lugo et al. 2012).
- Invasive species movements and expansions may be accelerated by climate change; however, their effects could lead to fewer native species extinctions in tropical forests than in temperate forests (Stork et al. 2009).
- Introduced species not historically considered invasive may become invasive under climate change if they experience increased vigor and rate of spread with warmer temperatures and changes in water availability (Hellmann et al. 2008).

2.6.2.3 Effects on Ecological and Physical Resources

General Biodiversity

Subtropical and Tropical Forest Ecosystems (General)

- Rising temperatures threaten tropical ectotherms and trees whose thermal-tolerance ranges and acclimation potential are small when compared to their temperate-zone counterparts, meaning that even a lower-predicted temperature increase in the tropics may create a strong biological effect (Brodie et al. 2011; Zotz and Bader 2009).
- Pau et al. (2011) suggest that species occupying less variable, aseasonal tropical habitats will be forced to shift their ranges or face population declines in future climate regimes. Further, if biotic factors dictate species' phenologies in these areas, there may be high variation in phenology, meaning some species may have a greater ability to adapt to new climate regimes, while other species may be slower in adapting to novel conditions (Pau et al. 2011).
- Though climate change adaptation potential may exist within the overall gene pool of a species, the alleles needed for assimilation may be specific to a region or population (Guariguata et al. 2008).

Lowland Forests

- Conserving lowland forest will minimize the regional effects on climate change associated with deforestation and simultaneously augment the survival of lowland species as they colonize higher elevational gradients (Chen et al. 2009).
- In Costa Rican lowlands, increasing temperatures are expected to lead to 30 percent and 80 percent declines in epiphyte and ant species, respectively (Brodie et al. 2011).

Montane Cloud Forests

- Because of their cool-adapted, range-restricted nature, Montane Cloud Forest endemic species such as epiphytes and amphibians, are especially vulnerable to increasing insolation and warming, acute heat waves, forest fires, a rising or thogonal cloud-base, and less moisture-stripping potential from clouds (Brodie et al. 2011; Koopowitz and Hawkins 2012; Lasso and Ackerman 2003; Magrin et al. 2007). Thus, these and other tropical montane species are excellent candidates for monitoring the local effects of global climate change (Lasso and Ackerman 2003).
- Changes in temperature are almost certain to have detrimental effects for many tropical montane tree species, whose average altitudinal range is 500 meters, and animals, whose ranges are typically much narrower (Bruijnzeel et al. 2011). To keep pace with these changes, montane species are shifting their ranges upslope and may soon be forced beyond their upper elevational limits due to narrow thermal tolerance ranges (Laurance et al. 2011).
- Montane Forest features that may be affected by rising temperatures include cloud-base height, cloud moisture, and pathogen virulence and diversity (Stork et al. 2009). Effects include reduced cloud cover, drier conditions, and less water capture potential as climate conditions continue to affect higher elevations (Şekercioğlu et al. 2012).
- Because of their smaller geographic spread and high energy and area requirements, highland-specialist bird and mammal species are thought to be more extinction-prone than are lower-zone specialist ectotherms and plants (Laurance et al. 2011).

- While temperature and humidity changes of Cloud Forests are expected from climate change, observational and experimental evidence suggests that Cloud Forest ecosystems may experience additional warming due to deforestation in contiguous lowland areas (Bruijnzeel et al. 2011).

Plant Communities

Subtropical and Tropical Forest Ecosystems (General)

- ❖ Wunderle et al. (2011) expect that because of global climate change and progressively drier summer months in the Caribbean, new species colonizing the Luquillo Experimental Forest may alter the distribution of life zones and forest types. Additionally, warming trends will likely affect timing of breeding and phenology of flowering and fruiting plants (Wunderle et al. 2011).
- ❖ Studying plant communities along an elevational gradient in the Sonadora and Mameyes watersheds in the Luquillo Experimental Forest, Barone et al. (2008) found that abiotic factors may limit the upper boundary of species, while competition limits the lower boundary. Fog, which has been hypothesized to prompt tropical mountain forest type change, may halt the upward expansion of lowland forest species adapted to more aerobic soil conditions (Barone 2008; McGroddy and Silver 2000; Silver et al. 1999).
- In unaltered tropical biomes, Brodie et al. (2011) suggest that rainforest biodiversity response to rising temperatures has not always been strictly negative. Rapid warming of the Paleocene-Eocene Thermal Maximum event 56.3 million years ago increased floral diversity particularly among epiphytic orchids and ferns. However, it has also been suggested that since tropical plant system response is slow to relatively rapid climate warming, species diversity may decline (Magrin et al. 2007), particularly among those plant species with low thermal tolerance occupying high elevational gradients (Laurance et al. 2011).
- Increasing atmospheric CO₂ and ambient temperatures are attributed to faster liana (long-stemmed, woody vines) growth and long-term abundance in undisturbed neotropical forests (Guariguata 2008).
- As disturbance-adapted liana infestations rise, perhaps due to increasing CO₂ concentrations (Granados and Korner 2002) or elevated stem turnover (Phillips and Gentry 1994), increased tree mortality, lower stand biomass, and reduced tree growth may be expected (Lewis et al. 2004).
- Hannah and others (2011) argue for cautionary interpretation of bioclimatic modeling studies, which suggest high vulnerability of tropical tree species to climate change (Ferreira de Siquiera and Peterson 2003; Hughes et al. 1996; Miles et al. 2004), because bioclimatic models do not present the full range of conditions under which species can exist. While many tropical species could survive higher temperatures with no current analog, pronounced changes in the moisture balance or higher CO₂ may be harder to withstand (Hannah et al. 2011).

Secondary Forests

- ❖ Land-use history influences forest species assemblages in subtropical secondary forests within a set of specific environmental conditions (Brandeis et al. 2009). Among the most prominent factors dictating post-disturbance succession of tree and plant communities in Puerto Rico and the U.S. Virgin Islands are spring moisture stress, extreme temperatures,

and topographic variables such as elevation and distance from coast (Brandeis et al. 2009).

- Due to the exchange in dominance of light-demanding pioneer tree species to shade-tolerant species, Chazdon et al. (2005) suggest second-growth forest structures should change faster than mature forests in response to global warming. Therefore, successional dynamics will be helpful in measuring tropical forest response to climate change and land use and land cover change (Chazdon et al. 2005).

Submontane Forests

- Changing climatic conditions themselves are likely to affect lowland species more than are the synergies between climate change and land use (Brodie et al. 2011).
- During drought, competition for water and potentially other soil nutrients pose a limiting factor to mature lowland tree growth and survival, increasing susceptibility to mortality (Chazdon et al. 2005).
- Tall, range-restricted, tree-form plant species inhabiting closed lowland forest are relatively more threatened to climate change than are the climbing and herbaceous plant species present in multiple tropical regions (Bradshaw et al. 2008; Stork et al. 2009).
- Tropical lowland non-vascular epiphytes may be severely affected by increasing temperatures because of their precarious carbon balance, which at higher temperatures could easily become negative (Zotz and Bader 2009).
- Tropical lowland lichens and bryophytes may not be able to endure from even a minor increase in temperature as these organisms are, arguably, living near to the edge of their physiological capabilities (Zotz and Bader 2009).
- In a cross-species, cross-microhabitat study of moss and liverwort tolerances to altered relative humidity in French Guiana lowland tropical forest, dry conditions (43 percent relative humidity) resulted in early desiccation of understory bryophytes whereas the majority of canopy species showed superior desiccation tolerance (Pardow and Lakatos 2013). Thus, canopy species are expected to be able to tolerate drought events and somewhat extended dry seasons of climate change scenarios, while the same conditions are likely to be detrimental to the diversity of understory species (Pardow and Lakatos 2013).

Lower Montane Forests

- ❖ Scatena (1998) interprets the presence of 600-year-old Colorado trees (*Cyrilla racemiflora*) occupying isolated proximities well below the cloud-base in the Luquillo Experimental Forest as evidence of a gradual upward shift in vegetation zonation over that has occurred over the past several centuries. The study estimates that whereas a 33 percent increase in annual rainfall would shift the Colorado Forest species zone down to the boundary of the Luquillo Experimental Forest, either an 11 percent decrease in annual rainfall, a 2.5 °C increase in air temperature, or a 1.1 °C increase in surface temperature would allow the drier, low-elevation Tabonuco-type Forest species to grow in areas currently occupied by Colorado Forest types.
- Submontane species expanding their range upslope could place additional resource and habitat pressure on high-elevation species (Brodie et al. 2011).

- More seasonal rainfall in Lower Montane Neotropical Forests via changing climate regimes would cause a decline in the abundance of the water-impounding Bromeliaceae family (Benzing 1998).

Montane Cloud Forests

- ❖ At the Pico del Este Field Station, higher night-time temperature, increased daytime precipitation, and a nyctation in cloud cover can affect plant communities and ecosystem processes (Lasso and Ackerman 2003).
- Because they occur under narrowly defined environmental conditions, Tropical Montane Cloud Forests are among the world's most sensitive and vulnerable ecosystems to climate change (Lasso and Ackerman 2003).
- In the absence of changes in vegetation water budget and use, climate change is projected to affect hydrological processes specific to Montane Cloud Forests. Both cloud water index and rainfall interception likely to be directly affected through changes in fog and rainfall frequency and intensity and indirectly affected through biomass and compositional changes of canopy epiphytes and bryophytes (Bruijnzeel et al. 2011).
- A 1 °C to 2 °C increase in temperature over the next 50 years would raise the altitude of the cloud-base during the dry season by 2 meters per year and consequently threaten mountainous Tropical Cloud Forest species (Magrin et al. 2007). Plants in low, isolated mountains will not be able to adapt to this shifting cloud-base temperature gradient and may become locally extinct (Magrin et al. 2007).
- Elevated carbon dioxide (CO₂) levels in nutrient-poor conditions common in cloud forests may decrease photosynthetic capacity and may alter flowering plant phenology and gene expression (Lasso and Ackerman 2003).

Cloud Forest Epiphytes

- ❖ Though the most important environmental constraint for vascular epiphytes is water availability. Olaya-Arenas et al. (2011) found the flowering of the orchid *Lepanthes rupestris* in the Luquillo Experimental Forest to be temperature dependent. Given projected warming, they expect a dramatic reduction in the quantity of reproductive individuals and population growth rates of *L. rupestris*, which will in turn affect seeding production, future recruitment and reproductive capacity.
- ❖ At the Pico del Este Field Station, over the last 30 years Lasso and Ackerman (2003) found an increasing mean minimum temperature to be correlated with bromeliad (*Werauhia sintenisii*) induction and a later flowering season.
- ❖ Lasso and Ackerman (2012) found that increasing temperatures which boost nutrient deposition from forest litter fall may raise the reproductive output of one major component in a vascular epiphyte community in Pico del Este. Thus higher temperatures resulting in faster organic soil decomposition may promote epiphyte growth and reproduction unless water becomes the primary limiting factor.
- In Cloud Forest ecosystems, epiphyte loss due to climate change is almost certain, as epiphytes are restricted to the atmospheric-terrestrial interface (Nadkarni and Solano 2002) and thus are highly sensitive to changes in growing conditions (Benzing 1998).
- Climate change will threaten cloud forest epiphytes through increased dryness, due to both higher temperatures and less moisture through cloud water as the cloud base altitude

- rises (Pounds et al. 1999; Still et al. 1999; Zotz and Bader 2009). Experimental evidence suggests reduced cloud cover can also directly affect epiphyte longevity and productivity (Nadkarni and Solano 2002).
- Altitudinal increases in the height of cloud-banks and increased evapotranspiration will affect epiphytes most in the dry season, when Cloud Forests rely heavily on the deposition of cloud droplets (Zotz and Bader 2009).
 - Uncharacteristically warm nights or the lack of adequate cooling after sundown may subject plants that fix carbon through C₃ photosynthesis (e.g., epiphytic bromeliads) to net carbon losses under otherwise adequate growth conditions (Benzing 1998).
 - In an 18-month experiment at Monteverde Cloud Forest, epiphyte exposure to environments with gradually less cloud water—a scenario synonymous with expected ecosystem changes in global climate models—led to a generally negative effect on epiphytic taxon growth, with severity depending on the season of transplant and plant species (Nadkarni and Solano 2002). It is predicted that climate change will not only decrease epiphyte growth and leaf production and increase mortality, but will alter the composition of canopy communities by releasing terrestrial plant seed banks within arboreal soils, thus creating conditions suitable for only the most desiccation-resistant epiphytes (which now occupy low elevation forests) in the canopy of upper Cloud Forest (Nadkarni and Solano 2002).

Animal Communities

General Effects

- ❖ Martín González et al. (2009) found that rainfall and temperature are significant determinants of pollinator composition and importance in the West Indies islands of Puerto Rico, Dominica, and Grenada, with rainfall being the key driver of pollinator variation. Comprehending how these determinants and other dynamics of future climate change influence pollinator processes is vital (Martín González et al. 2009).
- According to Stork et al. (2009), species traits which indicate risk from climate change include: low population densities, narrow niches, low vagility, small range, mature-habitat specificity, large body size, and those dependent on other species for food. Large vertebrates are especially vulnerable.
- Tropical species often have narrow thermal tolerances, and may be already living close to their upper thermal limits (Gunderson and Leal 2012; Huey et al. 2009; Laurance et al. 2011).
- Deutsch et al. (2008) investigated four groups of tropical terrestrial vertebrate ectotherms (insects, frogs, lizards, and turtles) and found that tropical species will reach their critical maximum temperature proportionally faster than similar high-latitude species, despite the tropic's lower absolute rates of warming. Deleterious thermal performance changes are likely in tropical members of all four taxonomic groups (Deutsch et al. 2008; Dillon and others 2010; Tewksbury et al. 2008).
- Pounds et al. (1999) found in the Monteverde Cloud Forest that the interplay of changes in water availability and varying large-scale climate processes, such as the El Niño-Southern Oscillation, may induce population losses among amphibians and reptiles as well as habitat and biological changes in the bird community, as drier warming periods are correlated with such observed changes (Blaustein et al. 2010).

Amphibians

- ❖ Predictions of changing environments and increased hurricane intensity and drought frequency make high elevation (greater than 1,000 meters) Puerto Rican coquí frogs, upland coquí (*Eleutherodactylus portoricensis*) within the Luquillo and Cayey mountains (Barker et al. 2011) and common coquí (*Eleutherodactylus coqui*) within the Luquillo Mountains (Longo et al. 2010; Stallard 2001) particularly vulnerable to future climate change.
- ❖ Stewart (1995) showed that rather than total monthly or annual rainfall, it is the distribution of rainfall, or the prolonged periods of drought, that significantly impact *E. coqui* population densities in the Luquillo Experimental Forest, especially among juveniles.
- ❖ In 1979 to 1989, *E. coqui* declined at the El Verde Field Station (Stallard 2001). In the past three decades, three species of endemic anurans (frogs and toads) have become extinct (Longo et al. 2010), while long-term amphibian monitoring data revealed eight populations of six different species declined in EYNF between 1990 and 2000 (Longo et al. 2010).
- ❖ Studies of four *Eleutherodactylus* species calling patterns in a wetland near Toa Baja, Puerto Rico, by Ospina et al. (2013) found variations in species response to weather variables. Calling activity of *E. coqui* and *E. cochranae* (whistling coquí) was positively correlated with temperature, while calling activity of *E. brittoni* (grass coquí) and the endangered *E. juanariveroi* (plains coquí) was negatively correlated with temperature and precipitation. Future climate change could threaten all four of these species, with more intense pressures on the sensitive *E. brittoni* and *E. juanariveroi* (Ospina et al. 2013).
- ❖ From 1970 to 2000, Burrowes et al. (2004) found a significant increase in temperature each month from May to October, the warm/wet season peaks of amphibian activity in Puerto Rico. Along with increased temperature and dry season length, Donnelly and Crump (1998) suggest decreased soil moisture and increased inter-annual rainfall variability will strongly affect neotropical amphibians at individual, population, and community levels. They found that if a hotter, drier, less predictable climate decreases leaf-litter anuran's main food supply (invertebrates), juveniles will have stunted growth rates and adults may devote less energy to reproduction (Donnelly and Crump 1998).
- Synergistic patterns of climate change and chytrid fungus (*Batrachochytrium dendrobatidis*) (Anchukaitis and Evans 2010; Hannah and Lovejoy 2011) and the extension of the dry season (Barker et al. 2011; Burrowes et al. 2004), as well as increasing temperatures at higher elevations (Brodie 2011) and low precipitation in Cloud Forests (Magrin et al. 2007) may be associated with anuran declines and extinction. It is likely these anurans and other restricted-range amphibian species of tropical Central America will experience high turnover rates as conditions simultaneously become hotter and drier (Blaustein et al. 2001).
- Suboptimal temperature and humidity regimes induced by climate change negatively affect amphibians' behavior and energy budget and alter host-parasite relationships (Donnelly and Crump 1998; Pounds et al. 1999). Shifting conditions in montane areas of Central and South America create nighttime temperatures closer to the thermal optimum for chytrid fungus proliferation, while increased daytime cloud cover prevents frogs from finding pathogen refuges (Blaustein et al. 2010).

- Loss of suitable habitat and drought conditions (Longo et al. 2010) cause anurans to clump around remaining moist areas, making them more vulnerable to disease (Burrowes et al. 2004) and the chytrid fungus in particular (Anchukaitis and Evans 2010).
- Pond-breeding neotropical anurans will likely experience compression of the breeding season and more competition for moist sites suitable for oviposition, leading to more species using a pond simultaneously and higher mortality in early life stages (Donnelly and Crump 1998). Sporadic breeders will be least affected by climate changes altering pond hydrology while prolonged breeders, where male reproductive success is tied to tenure at the breeding site, will be most affected. Explosive breeders, being better adapted to reproduce under high density conditions in a short period of time, will likely be less affected than prolonged breeders. In general, narrowly endemic amphibians will see additional pressures with pond drying (Donnelly and Crump 1998).
- While drier conditions might reduce the likelihood of fungal attack on arboreal amphibian eggs, this could be offset by an increase in parasitic drosophilid fly attacks (Donnelly and Crump 1998).
- Amphibians may become more susceptible to or be killed by warming-induced acid rain, fog, and other types of airborne and stream contamination (Carey et al. 2001; Stallard 2001).

Birds

Habitat Alterations

- ❖ Smith and others (2010) utilized a satellite-derived index of habitat moisture at the Roosevelt Roads Naval Station on the east coast of Puerto Rico to assess the underlying gradient of northern waterthrush (*Seiurus noveboracensis*) habitat quality. They found that extreme-wet-habitat specialists, such as *S. noveboracensis*, are quite vulnerable to even slight deviations of annual precipitation, especially during El Niño and La Niña cycles (Smith et al. 2010).
- Endothermic tropical birds are more likely to be indirectly affected by climate change via its effects on community vegetation and food sources, rather than via direct physiological effects (Şekercioğlu et al. 2012).
- Though it is possible for tropical bird species living in coastal or island habitats to cope with a 2 °C increase in average temperature, more extreme tropical weather events could destroy critical habitat or make foraging impossible (Şekercioğlu et al. 2012).
- As habitat availability, food, and shelter resources become constrained by warming, tropical highland birds' elevational ranges narrow and extinction risk increases (Şekercioğlu et al. 2012). Climate warming in the Montane Cloud Forests of Costa Rica has raised the average altitude at the base of the orographic cloudbank (Pounds et al. 1999), resulting in the colonization of the tropical Cloud Forest by bird species from lower altitudes (Crick 2004).
- Winter habitat quality for neotropical bird migrants is expected to be reduced by the projected drying of the Caribbean Islands (Rodenhouse et al. 2008; Studds and Marra 2011).
- Sea level rise, worsened by tropical storms, may convert some dynamic wetland areas into salt pans, lessening the likelihood of tropical bird colonization (Şekercioğlu et al. 2012).

- Climate change-induced alterations in soil properties of moist tropical forests will decrease net available moisture, changing the forest biochemistry into tropical savannah rather than dry forests (Toms et al. 2012). For birds in tropical dry forests, climate change can increase the rate of habitat loss by introducing stressors such as fire, invasive species, parasites or disease (Toms et al. 2012).

Population and Survival

- ❖ In the short term, hurricane-induced mortality may constrain tropical bird populations of the Luquillo Experimental Forest below their recovery threshold, particularly the endangered Puerto Rican parrot (*Amazona vittata*) because of its confined range, small population size, and low growth rate (Wunderle and Arendt 2011). However, in the long term, hurricanes may be beneficial to bird populations with a adequate size because of increased nutrient cycling and nest cavity creation (Wunderle and Arendt 2011).
- ❖ Migratory ovenbirds (*Seiurus aurocapilla*) abundance in the Guánica Dry Forest in southwest Puerto Rico decreased in response to increased summer rainfall in the United States. Similarly, wintering black-and-white warblers (*Mniotilta varia*) and American redstarts (*Setophaga ruticilla*) experienced decreases in survival with increasing amounts of the previous year's first 6 months of rainfall in the U.S. (Dugger et al. 2004).
- ❖ Faaborg et al. (2013) also found significant declines in the wintering populations of *S. aurocapilla*, *M. varia*, and *S. ruticilla*, as well as declines in the overall diversity of neotropical migrant birds in Guánica Forest. Winter survival rates remained steady over time, meaning that declining populations are due to a decline in recruitment of birds at the site, possibly due to habitat quality changes induced by climate change that has led birds to winter elsewhere (Faaborg et al. 2013).
- Though they enjoy longer lifespans than temperate birds, tropical birds are comparatively more vulnerable to climate change because of their smaller clutch size, less active nature, and lower tolerance of climatic variability (Şekercioğlu et al. 2012). Moreover, tropical birds specialists are considered to be more vulnerable to climate change than are generalists (Toms et al. 2012).
- Şekercioğlu (2008) states that sedentary tropical birds are five times more likely to face climate change-induced extirpation in the 21st century than are long-distance migrants.
- Nearly 80 percent of bird species restricted to tropical dry forests are considered to be at risk for climate change alterations (Toms et al. 2012).

Behavioral Responses

- ❖ As shown by Arendt (2000; 2006), following major hurricane alteration of forest vegetation, nest predation by rats, nest usurpation by swarming bees, and the prevalence and intensity of philornid ectoparasites increased in nests of *A. vittata*, and a surrogate study species, the peep early-eyed thrasher (*Margarops fuscatus*). Thrasher reproduction, survival rates, and predator response differed between hurricanes Hugo (1989) and Georges (1998) (Wunderle and Arendt 2011).
- ❖ Merola-Zwartjes and Ligon (2000) found that Puerto Rican todies (*Todus mexicanus*) from the Guánica Dry Forest had significantly lower basal metabolic rates than did those from the cooler rain forest site at the Luquillo Experimental Forest. While a lower rate of endogenous heat production is typical in species inhabiting warm environments compared to the same species in cooler climates (Dawson and O'Connor 1996), Guánica

- T. mexicanus* should benefit from lower basal metabolic rates because of reductions in both the potential for heat loading and the need for evaporative cooling (Merola-Zwartjes and Ligon 2000).
- Cavity-nesters (owls, woodpeckers, and parrots) should expect more competition for remaining tree hollows from both tropical birds and cavity-dwelling mammals. According to Pounds et al. (1999), in Monteverde Cloud Forest, keel-billed toucans (*Ramphastos sulfuratus*) are nest predators that have recently expanded their range into montane highlands, where they both compete with resplendent quetzals (*Pharomachrus mocinno*) for sites and prey on their nests.
 - Many tropical birds, such as the white-throated thrush (*Turdus assimilis*), prefer to breed in the wet season due to the abundance of resources. Since climate changes are increasingly longer and variable dry seasons and droughts, migratory and reproductive routines of tropical birds may be affected and populations may decline (Şekercioğlu et al. 2012).
 - Pounds et al. (1999) observed that from 1973 to 1998 the distribution of lower and pre-montane bird species in the Monteverde Cloud Forest in Costa Rica shifted upslope and back downslope an average rate of 19 species per decade, with present lower-montane species remaining stable and pre-montane species increasing.
 - Isotope research by Fraser et al. (2008) in Nicaragua showed that several partial-frugivore species, including pollinators such as hummingbirds, make yearly altitudinal migrations, which may be greatly impacted by global warming.
 - Studds and Marra (2011) found in southwest Jamaica that *S. ruticilla* adapted the timing of their spring migratory patterns in relation to an increasingly severe and unpredictable winter dry season. Birds migrating between North America and the Caribbean must therefore attempt to breed earlier, contending with fewer and more variable winter food resources (Studds and Marra 2011).
 - In the West Indies islands of Dominica, Grenada, and Puerto Rico, Martín González et al. (2009) found that although there was no significant relationship between tropical bird pollinator richness and importance and climatic factors, birds visited a higher proportion of plant species and played a more central role in the pollinator network towards the wet end of the rainfall gradient. Thus, for the Caribbean as in Central and South America, birds tend to become more important as pollinators as rainfall increases (Martín González et al. 2009).

Reptiles

- ❖ Traits such as core temperature and maximum critical thermal temperature of some Puerto Rican *Anolis* species vary over altitudinal gradients, while other species, such as the Puerto Rican yellow-chinned anole (*Anolis gundlachi*), from El Verde Field Station and El Yunque Peak sites, show no trait variation (Rogowitz 1996). The ability of *Anolis* to thermally adapt their metabolism to changing ambient temperatures may be weak to negligible (Gunderson et al. 2011). In 14-day experiments at El Verde and El Yunque sites, *A. gundlachi* experienced no change in metabolism from exposure at 15 °C lower than usual, but suffered a significant decline in metabolism and a consequent loss of body mass from exposure to temperatures 30 °C above normal (Rogowitz 1996).
- ❖ Huey et al. (2009) utilized observational data and a conservative 100 year increase of 3 °C over 1970 temperatures to assess body temperature responses of lowland *Anolis* and *Sphaerodactylus* lizards living in Puerto Rican forests, many of which are already

experiencing temperatures beyond their thermal safety margins. They found many tropical lowland lizards are at risk from even a small increase in operative temperatures since convection dominates heat exchange in forests (body temperatures increase at the same rate as air temperatures) and the thermal environment is already warm relative to lizard's thermal sensitivity (Gunderson and Leal 2012; Huey et al. 2009).

- ❖ While increased summer heat stress is likely to reduce daily activity time and sprint performance of Puerto Rican lizards, particularly during midday, warmer winters will create more favorable reproductive conditions (Huey et al. 2009). Moreover, some species residing in high-latitude or Cool Montane Forest environments should benefit with increased activity times and growth rates (Huey et al. 2009). Gunderson and Leal (2012) show that in assuming a 3 °C increase in ambient temperature, the mean performance capacities of the Puerto Rican crested anole (*Anolis cristatellus*) in dry, sparsely vegetated xeric habitats of Puerto Rico are predicted to decrease by 26 percent to 32 percent, while mean performance of lizards in cool, vegetated mesic habitats should expect an increase of 3 to 5 percent.
- ❖ Gunderson et al. (2011) suggest that acclimation alone does not sufficiently account for patterns of water loss rate variation found between populations of the *A. cristatellus* in Cambalache and Guánica dry forests. Supporting literature of the few lizard species studied thus far show negative correlations between arid habitats and water loss rates even if lizards from each species population are exposed to identical climatic conditions preceding water loss measurement (Gunderson et al. 2011; Hertz 1979; Hillman and others 1979; Perry et al. 2000).
- Climate warming may cause tropical forest lizards to suffer increased predation and competition from warm-adapted, open-habitat lizards such as the Mid-American ameiva (*Ameiva festiva*) (Huey et al. 2009).
- Two highland anoline lizard populations (the cloud forest anole and montane anole) in Monteverde Cloud Forest declined since the increase in the number of mist-free days in the late 1980s and disappeared by 1996, whereas the gray lichen anole (*Anolis intermedius*) remained stable being better adapted to warmer, drier conditions (Pounds et al. 1999).
- Smaller body size makes individual lizards more prone to water loss, thus affecting their ecology, especially in water-restricted tropical locations such as the Guana Island of the British Virgin Islands (Nicholson et al. 2005).
- In a study by Patiño-Martínez et al. (2012), sex ratios in hatchlings of leatherback sea turtles (*Dermochelys coriacea*) in the southwestern Caribbean Sea were clearly female skewed by an average of 92 percent over three nesting periods. Backed by previous research that establishes patterns of thermal sensitivity for gender determination (Godley et al. 2001; Hawkes et al. 2009), their model predicts that increased temperatures via climate warming could lead to a complete feminization of hatchlings within a decade. However, deeper and smaller nesting sites lower on the shore on lighter colored beaches, where metabolic heating effects would be less detrimental, could create conditions more appropriate for future male hatchling sea turtle succession (Patiño-Martínez et al. 2012).

Invertebrates

- ❖ Microclimate and soil characteristics are more likely to be significant determinants of terrestrial gastropod distributions than are the indirect influences of vegetation, which

- provide gastropods with habitat structure and resources (Presley et al. 2011). In the Luquillo Experimental Forest, hurricanes Hugo (1989, category 3) and Georges (1998, category 3) caused a relocation of biomass from canopy to the forest floor, which increased the resource base for terrestrial gastropods, but unfavorably altered microclimate conditions (Block and Willig 2006).
- ❖ As observed in mosquito larval habitats of Río Piedras, Puerto Rico, sequences of rainfall followed by lack of rainfall have led to sharp population declines of mosquitoes (*Aedes aegypti*) (Chaves et al. 2012). Even though the study demonstrates that population outbreaks are largely correlated with extreme climatic events, Chaves et al. (2012) contend that the observed mosquito population dynamics support neither the linear predictions of increased mosquito abundance, nor the claim that dynamics can be swayed by vector control programs, underlining the need for further research.
 - In the West Indies islands of Puerto Rico, Dominica, and Grenada, richness, plant interaction, and importance of bee species within the pollinator community decreased with increased rainfall, while dipterans' (true flies) importance increased with rainfall, thus partially replacing one another as major insect pollinators (Martín González et al. 2009). Meanwhile wasps benefited from increased species richness with higher rainfall, and lepidopterans (butterflies and moths) showed no significant trend with rainfall or temperature (Martín González et al. 2009).
 - In species- and assemblage-level analyses, Chen et al. (2009) showed a steady increase in the average elevation of moths on Mount Kinabalu, Borneo, between 1965 and 2007, with the average elevation of species rising 67 meters. The findings of an uphill shift in habitat, coupled with previous research of tropical insect thermal sensitivity (Addo-Bediako et al. 2000; Deutsch 2008; Jazen 1967) indicate that tropical insects, given their diversity, may dominate species threatened with extinction from climate change (Chen et al. 2009).

Mammals

- ❖ Increased tropical extreme weather event frequency has a marked, yet species-specific, deleterious effect on bat populations, principally among tree-roosting bats, attributable to tree loss and more native hunting rather than direct hurricane mortality (Jones et al. 2009). Research (Gannon and Willig 2009) suggests the recovery rate of the Puerto Rican cave-roosting Jamaican fruit bat (*Artibeus jamaicensis*) depends on hurricane severity, with recovery occurring more rapidly after Hurricane Hugo (1989, category 5) than after Hurricane Georges (1998, category 3), while populations of the tree-roosting, red fig-eating bats (*Stenoderma rufum*) declined after Hugo.
- Increased temperatures may also impact bat populations. In Costa Rica, LaVal (2004) found no net change in the number of bats captured in Monteverde Cloud Forest Reserve over a 27-year period, but revealed a growing number of lowland bat species at higher elevations—a phenomenon hypothesized to be due to the climatic effects resulting from a 2 °C increase in minimum temperatures (Pounds et al. 1999).

Freshwater (Aquatic and Riparian) Ecosystems

- ❖ For two species of freshwater shrimp (*Atya lanipes* and *Xiphocaris elongate*) in the Luquillo Experimental Forest, Covich et al. (2003) observed a two to three-fold increase in average shrimp densities within upper-altitude pools due to the effects of droughts.

This has led to severe crowding and hence less reproductive success for shrimps as well as a significant shift in the size-class distribution.

- ❖ When the migratory “cue” of flowing water is barred from juvenile freshwater shrimps, they are impounded in low-elevation bottlenecks, making them prey for fish and birds (Crook et al. 2009). During the drought year of 1994 in EYNF, poor stream flow and low stream connectivity limited the ability of shrimp larvae and juveniles to advance to the next life-stage (Crook et al. 2009). In the same drought year, the lowest mean abundance of palaemonid river shrimp (*Macrobrachium* spp.) in 28 years was recorded in the Espiritu Santo drainage of the Luquillo Mountains, with hurricane and storm flows having relatively little effect on population (Covich et al. 2006).
- Due to climate change, extended droughts in tropical rainforests may significantly affect freshwater aquatic communities through crowding of species, leading to habitat contraction and a decrease in reproductive output (Covich et al. 2003).
- Warmer temperatures, in combination with altered flows in due to increased drought, may limit dissolved oxygen availability in freshwater environments by promoting macrophyte growth including algal blooms (Cashman et al. 2010; Ficke et al. 2007). High macrophyte growth rates may also lead to sediment trapping and excess nutrients (Ficke et al. 2007).
- Extended droughts in the dry season may significantly affect aquatic organisms by decreasing dissolved oxygen content (Mulholland et al. 1997).
- Riparian areas will see changes in structure and composition due to altered precipitation and run-off regimes as well as changes in the distribution of plant and animal species (Seavy et al. 2009).
- Globally, riparian areas will play an important role under climate change by providing thermal refugia for sensitive species based on the riparian area’s ability to buffer against extreme temperatures due to a high water content and shade provided by dense vegetation (Seavy et al. 2009).

Water Resources

Water Balance

- ❖ Scatena (1998) found that projected future changes of increased temperatures and precipitation could change vegetation types in the Luquillo Experimental Forest and alter Forestwide hydrology. If the Tabonuco-type Forest expands upslope into the area currently inhabited by the Palo Colorado-type Forest, Forestwide runoff could decrease as much as 17 percent due to the lower runoff rates for the Tabonuco-type (Scatena 1998).
- ❖ Harmsen et al. (2009) modeled the effects of climate change on groundwater in Puerto Rico and found that projected large increases in precipitation for the rainy season will produce a net increase in annual aquifer recharge, while projected decreases in precipitation in the dry season will have minimal effect. An increase in aquifer recharge suggests that groundwater levels could increase, reducing saltwater intrusion in some coastal aquifers (Harmsen et al. 2009).
- The effect of climate change on the water balance in Cloud Forests is largely influenced by changes in rainfall (Bruijnzeel et al. 2011).

- Changes in evapotranspiration due to increased temperatures could decrease runoff, even in dry regions (Galindo et al. 2010).

Water Quantity and Quality

- ❖ Climate change is likely to amplify existing pressures on water resources and water availability in northeastern Puerto Rico, especially in combination with increased urban development and water extraction (Crook et al. 2007).
- ❖ More intense rainfall events leading to increased runoff in the wet season can also lead to decreased water quality through increased turbidity and erosion as well as flooding (Cashman et al. 2010). Watersheds that respond quickly to precipitation, such as in the Luquillo Mountains, may be especially affected (Schellekens et al. 2004).
- ❖ As a small Island, freshwater resources in Puerto Rico will be affected not only by changes in precipitation, but also by changing hurricane cycles and saltwater intrusion from sea level rise (Kelman and West 2009).
- Although overall precipitation levels in the Caribbean may remain similar in the future, dry years and water shortages may become more frequent or more severe (Biasutti et al. 2012) as the rainy season becomes wetter and the dry season becomes drier (Harmsen et al. 2009).
- Extended periods of extreme low flows in the dry season may result in increased pollutant concentrations and excessive nutrients in Caribbean streams (Cashman et al. 2010; Covich et al. 2003).

Soil and Geologic Resources

Soil Health

- ❖ Soils in the Luquillo Mountains will be affected by climate change through increased variability in the decay of organic matter, changes to the patterns of soil oxygen concentrations, and changes in the accessibility of soil nutrients to plants (González et al. 2013).
- ❖ The Luquillo Mountains receive deposits of African dust that can change the composition and texture of soils, potentially affecting nutrient storage. Projected increases in African dust deposits with climate change may further affect soils on mountain peaks (González et al. 2013).
- ❖ In the LEF, soil oxygen content decreased significantly with increasing annual rainfall, exhibiting soil oxygen levels below half of ambient concentrations in greater than 30 percent of Palo Colorado Forest and greater than 60 percent of Elfin Cloud Forests studied over the 18 month period (Silver et al. 1999). Soil oxygen concentration was consistently found to be responsive to both long term annual and short term precipitation events (Silver et al. 1999).
- ❖ Silver (1998) found that riparian microsite soil conditions in the Luquillo Experimental Forest shifted between predominately aerobic and anaerobic in relation to 14-day rainfall cycles, with aerobic soils supporting relatively more plant biomass but less soil organic carbon and nutrient availability. Meanwhile anaerobic soils became a net source of CH₄.

- ❖ Puerto Rican soils in the oxisols and ultisols classes may experience losses in soil organic matter due to temperature- and/or rainfall-induced water stress, implying that a lengthening dry season is likely to impact tropical forest soils, the resident vegetation, and the associations and interactions between them (Silver 1998).
- In tropical forests, seasonal soil decomposition is closely tied to wetting and drying cycles, meaning that seasonal adjustments in temperature and moisture due to climate change are likely to affect decomposer communities, soil resource quantity and distribution, and litter quality (Silver 1998).
- The negative correlation found by Silver (1998) between litter fall and elevation is likely an indirect response to a changing climate, as less litter fall is associated with a lower temperature. Since litter fall and decay rates are tightly coupled with nitrogen and phosphorus cycles, tropical ecosystem decay may be vulnerable to temperature changes (Silver 1998).
- Under conditions of higher temperature and CO₂ supplement, soil respiration and net primary productivity will be affected by water and nutrient availability (Silver 1998). An expected increase in CO₂ levels is likely to have a significant impact on the biogeochemical cycles of tropical ecosystems (Silver 1998).
- Prolonged drought could disrupt and decouple the highly synchronized nutrient cycles of tropical wet forest ecosystems and exacerbate nutrient stress in water-inhibited areas. On the other hand, greater precipitation quantity and frequency in dry tropical forests will likely increase decomposition rates as well as nutrient availability and uptake (Silver 1998).

Soil Carbon and Trace Gas Dynamics

- ❖ Under the climate change scenario of increasing temperature and decreasing rainfall (Scatena and Lugo 1998), simulation results from Wang et al. (2002) provide that higher and lower elevations of the Luquillo Experimental Forest can expect losses in soil organic carbon (up to 4.5 megagrams per hectare) while middle elevations will experience smaller increases (up to 2.3 megagrams per hectare). This suggests the effects of climate change on soil decomposition and soil organic carbon storage and flux will not be uniform across elevations (Wang et al. 2002) because of the indirect effects of temperature and precipitation (McGroddy and Silver 2000).
- ❖ Over the entire Luquillo Experimental Forest, Wang et al. (2002) found significant differences in simulated total soil organic carbon storage from low elevations of Tabonuco Forest (20 megagrams per hectare) to high elevations of the elfin forest (230 megagrams per hectare), with leaf area and average monthly temperature and rainfall being the most significant indicators of soil organic carbon.
- ❖ Li et al. (2006) found continuous nitrogen addition in tropical soils of Luquillo Experimental Forest to significantly enhanced decay-resistant soil organic carbon (heavy-fraction organic carbon, HF-OC) sequestration, with a negligible effect on total soil organic carbon pool. More broadly, the study found nitrogen accumulation to considerably increase aboveground leaf litter production and concentration while stimulating litter decay and fungal biomass growth (Li et al. 2006).

- ❖ Despite the assumption that pasture to forest conversion will result in net carbon loss from soil, Silver et al. (2004) found substantial net carbon sequestration in mature secondary lowland forest soils in the Cubuy Annex of the Luquillo Experimental Forest.
- ❖ Based on drought responses of three study sites within the Bisley Experimental Watershed, Wood and Silver (2012) found that decreased rainfall in humid tropical forests may cause a negative feedback to climate through lower soil CO₂ emission and higher methane (CH₄) and nitrous oxide (N₂O) soil consumption. They project future precipitation changes are likely to significantly affect the production and consumption of trace gases in soils.
- ❖ In wet tropical forests, hurricane-induced alterations of soil processes are significant. Given a doubling of major hurricane frequency to once every 25 years (Krishnamurti et al. 1998), hurricane contribution to Puerto Rico's soil N₂O flux could increase to 30 percent of the period's total emissions (Erickson and Ayala 2004). Thus, future contributions of soil fluxes in Puerto Rico to the global N₂O budget are potentially great (Erickson and Ayala 2004).
- Together, nitrogen deposition and temperature alterations are likely to affect tropical soil CO₂ fluxes and carbon storage (Cusack et al. 2012). Even small alterations in soil organic carbon storage may change the role of tropical forests as a carbon source or sink (Wang et al. 2002).
- More intense and frequent droughts may favor species that are better able to allocate and store carbon to deep roots and lower soil horizons (Silver 1998).
- Fine root stocks are responsible for 30 to 70 percent of soil CO₂ flux (Schlesinger 1977) and are found by McGroddy and Silver (2000) to increase significantly with soil moisture. Fine root flux was positively correlated with total soil carbon content but negatively correlated with soil respiration rates, suggesting slower root turnover in wet soils.
- Greater precipitation quantity and frequency in dry tropical forests may cause more soil carbon to be stored aboveground, and will probably increase surface soil organic carbon pools (Silver 1998).
- Surface soil carbon pools in the wet tropical forest of Golfo Dulce Forest Reserve, Costa Rica, fluctuate respective to increases and decreases in litter inputs, whereas alterations in carbon inputs of temperate forest ecosystems are not as marked on carbon pools (Leff et al. 2012).

Soil Organisms

- Because of their high internal temperature optimum, thermo-tolerant bacterial community members dominate the warmer tropical soils (Balsler and Wixon 2009). Though microbial soil processes will likely adjust to changes in rainfall, additional stressors of climate change may lower microorganism diversity or productivity, thus reducing microbial pool resiliency (Silver 1998).

Vegetation Management

Carbon Dynamics

- ❖ Silver et al. (2004) identify the carbon sequestration potential of a 55-year-old reforested area within the Cubuy Annex of the Luquillo Experimental Forest to be significant in the

later 33 years of growth, accumulating carbon (1.4 ± 0.05 megagrams of carbon per hectare per year) at rates faster than documented in more mature, old-growth humid tropical forests. Similarly, Marín-Spiotta et al. (2007) identify an 80-year-old patch of secondary forest in Sierra de Cayey, Puerto Rico, with significant carbon sequestration rates in aboveground biomass.

- Climate change's ultimate effect on undisturbed tropical forest is a contented issue between those who argue that forests will continue to be net carbon sinks because of increased productivity via higher ambient CO₂ levels, and those who note that forests will be carbon sources because higher temperatures may increase plant and soil respiration and slow plant growth (Laurance et al. 2011; Wood et al. 2012) or because drought will lead to increased forest dieback (Allen et al. 2010; McDowell et al. 2011; Van Mantgem et al. 2009).
- Meta-analyses of the effects of temperature on carbon storage and fluxes across a broad range of tropical forest sites have found that total net primary productivity, litter production, tree growth, and below-ground carbon allocation all increase with increasing mean annual temperature (Cleveland et al. 2011; Raich et al. 2006; Silver 1998) and the temperature to precipitation ratio (Brown and Lugo 1982). However, soil carbon decomposition and turnover time also increase with increasing mean annual temperature, indicating that atmospheric carbon uptake via increased forest productivity could be offset by increased soil carbon loss with warming (Raich et al. 2006).
- Numerous atmosphere-biosphere modeling studies suggest that warmer tropical forests will likely become an increasing source of carbon to the atmosphere from increased heterotrophic soil respiration (Cramer et al. 2001), increased plant respiration (White et al. 2000), decreased net primary productivity or photosynthesis (Cramer et al. 2001; White and others 2000), and/or forest dieback (White et al. 2000).
- Eddy covariance data from the Brazilian Amazon combined with a simple gas-exchange model suggest that net ecosystem exchange is quite sensitive to temperature increases, and that the forest may switch from a carbon sink to a source with only a 1.2 °C increase in mean annual temperature (Grace et al. 1996).
- An Amazonian eddy covariance dataset over 1 year showed an overall trend of carbon source behavior at temperatures above about 27 °C (Doughty and Goulden 2008), and a 3-year dataset from a rain forest in Costa Rica showed reduced carbon sink behavior at air temperatures above 20 °C (Loescher et al. 2003). A longer term (4 years) eddy covariance study in the Amazon found the strongest controls of the components of net ecosystem exchange to be phenology and light, rather than temperature (Hutyra et al. 2007).
- Tian et al. (1998) modeled the presence of a CO₂ “fertilization” effect which increased the net ecosystem production of undisturbed tropical ecosystems in the Amazon Basin from 1980 to 1994. They found plant growth to be directly stimulated by a net CO₂ gain of 3.3 petagrams carbon and indirectly enhanced by greater plant water use efficiency. Silver (1998) contends that greater water use efficiency may result in increased soil moisture, potentially offsetting the drier soil expected from warmer and drier conditions.
- Terrestrial ecosystem models attribute year-to-year fluctuations in carbon storage and net primary productivity potential to El Niño-Southern Oscillation phase shifts and inter-annual temperature variations (Tian et al. 1998). Thus, while normal wet and cool conditions make the Amazon Basin a net carbon sink, El Niño events induce drier and

- warmer weather, decreasing net primary productivity and increasing relative humidity, thus making the Amazon a net carbon source in such years (Tian et al. 1998).
- Chave et al. (2008) found an overall increase in aboveground biomass among numerous old-growth forests throughout the tropics in recent decades.

Nutrient Factors Limiting Productivity

- Whereas higher temperatures could increase tropical soil organic matter decomposition rates, thus generally increasing soil nutrient availability and plant growth rates (Wood and others 2012), additional nitrogen inputs may acidify the soil, deplete base cations, and activate aluminum ions, which when combined may decrease soil nutrient availability and plant growth rates (Lewis et al. 2004). Furthermore, increased nutrient availability in response to rising temperatures could result in additional loss of nutrients to leaching if those nutrients are not rapidly utilized by the vegetation (Hedin et al. 2003; Wood et al. 2012).
- Current modeling efforts highlight the large role nutrient cycling could play in the response of the carbon cycle to climate change (e.g., Wang and Houlton 2009), and the few tropical fertilization studies that exist support this conclusion; however, how climate change will influence nutrient cycling in tropical forests remains largely unknown (Wood et al. 2012).
- Nutrient availability has been shown to affect forest productivity and foliar nutrient concentrations, as well as rates of net photosynthesis and dark respiration (Meir et al. 2001; Wood et al. 2009; Cleveland et al. 2011). Nutrient availability can also increase carbon loss to the atmosphere via positive effects on soil respiration and decomposition rates (Cleveland and Townsend 2006; Wood and Silver 2012).
- Wardle et al. (2005) and McKane (2005) suggested that the availability of nutrients strongly limits productivity in highly weathered soils, such as those found in many tropical forests, and that forests on such soils have the potential to be more productive if their soils were more nutrient rich.
- Cleveland et al. (2011) provide some evidence that soil phosphorus content and availability in moist and wet lowland tropical forest has both direct and indirect effects on the tropical carbon cycle.

Growth and Yield

- ❖ Brandeis et al. (2009), employing a cluster analysis of plot-level vegetation data from Puerto Rico and the U.S. Virgin Islands, found that vegetation assemblages in Puerto Rico are driven primarily by spring moisture stress, but also by maximum and minimum temperatures, elevation, and distance from the coast.
- Long-term (5 or more years) inventory plots in tropical forests around the globe have revealed contrasting trajectories of stand-level growth and biomass turnover. Datasets in tropical Africa and the Amazon have shown increasing growth rates (Lewis et al. 2009b; Phillips et al. 2004). Plots in Costa Rica, Panama, and Malaysia revealed decelerating growth (Clark et al. 2003; Feeley et al. 2007). A recent meta-analysis of large (16–52 hectares), long-term tropical forest inventory plots across three continents (America, Africa, and Asia) showed an increase in biomass over 20 years in seven of ten plots analyzed (Chave et al. 2008).
- Possible drivers of increasing biomass increment include: CO₂ fertilization (Lewis et al. 2009a; Lloyd and Farquhar 2008), recovery from past disturbance (Chave et al. 2008), or

a shift in community composition towards faster growing species (Laurance et al. 2004). Observed growth declines have been attributed to temperature-induced increases in plant respiration rates (Clark et al. 2003; Feeley et al. 2007; Wagner et al. 2012); decreased net photosynthesis from increasing temperature beyond the thermal optimum (Doughty and Goulden 2008); or light limitation from increased liana shading of canopy trees, or from global dimming (Feeley et al. 2007).

Effects of Temperature

- The ultimate physiological responses of tropical trees to climatic warming are still highly debated (Doughty and Goulden 2008; Lloyd and Farquhar 2008; Wood et al. 2012), with some suggesting trees in the tropical lowlands are near a high temperature threshold (Doughty and Goulden 2008).
- Recent *ex situ* studies suggest that the photosynthetic capacity of tropical plants may not be able to thermally acclimate to warming temperatures (Wood et al. 2012). Leaf-level gas-exchange studies in Australia have shown that tropical species have lower photosynthetic thermal acclimation potential than temperate species, suggesting that tropical species may be more susceptible to climate change because they develop under lower seasonal and day-to-day temperature variation (Cunningham and Read 2002). *In situ* experiments in the Amazon also showed no evidence of photosynthetic thermal acclimation in response to 13 weeks of 2 to 5 °C warming of existing leaves (Doughty 2011).
- It is unclear whether or not tropical plants will be able to thermally acclimate under naturally warming conditions, which occur more slowly than experimental warming conditions (Wood et al. 2012).
- Cleveland et al. (2011) found the mean annual temperature explained the largest amount of variance in aboveground net primary productivity across moist and wet tropical forests types. Though after isolating the cool, upland forests with low net primary productivity and the warm, lowland forests with higher net primary productivity, the relationship became insignificant (Cleveland et al. 2011).
- Recent studies suggest that an increasing night-time temperature may affect tropical tree growth and induce tree mortality (Clark et al. 2010; Wagner et al. 2012).
- Rain forest gap-phase regeneration will undergo slow changes in tandem with a warmer, more seasonal climate (Whitmore 1998).
- Warming may alter the morphology and biomass allocation patterns of trees in addition to affecting diameter growth rate (Wood et al. 2012). A global meta-analysis of the effects of temperature on tree growth found warming to increase foliage biomass, decrease root biomass, and produce taller, thinner stems, although tropical tree growth decreased overall when compared to either boreal or temperate species (Way and Oren 2010). In contrast, a study of tropical tree seedlings in Australia showed increased root:shoot ratios under warming treatments (Cunningham and Read 2003).
- Research on tropical rainforest species in Australia found that optimum growth occurred under temperatures that are much higher than is ideal for photosynthesis, indicating that growth can continue to increase with rising temperatures even as photosynthesis declines (Cunningham and Read 2003). The apparent disconnect between photosynthesis and growth showed that carbon source and sink activity could have more influence over a tree's growth rate than CO₂ exchange (Wood et al. 2012).

Effects of Rainfall (Including Temperature-Moisture Interactions)

- ❖ Increases in rainfall alone could raise net primary productivity by increasing nutrient availability to the generally aerobic soil of the Luquillo Experimental Forest lowland areas (Chacon et al. 2006; Wang et al. 2003; Wood and Silver 2012).
- ❖ In the Luquillo Experimental Forest, Wang et al. (2003) found that when holding all else constant, rainfall variation creates a small net increase in gross primary productivity and net primary productivity. Increasing only temperature, on the other hand, entails a much larger reduction in both gross primary productivity and net primary productivity due to an increase in plant maintenance respiration and a decrease in stomatal conductance, with Tabonuco Forest being especially sensitive to temperature changes. The greatest negative effect to net primary productivity and gross primary productivity were observed in a simulation of 11 percent less rainfall and a 2.5 °C higher temperature (Wang et al. 2003).
- ❖ Wang et al. (2003) utilized TEMs to simulate an increase in temperature and precipitation, which they found to greatly lower the net primary productivity potential of the Luquillo Experimental Forest. Melillo et al. (1993) found similar results applying TEMs to a tropical evergreen forest.
- ❖ Water stress assessments for a generic crop at Adjuntas, Mayagüez, and Lajas, Puerto Rico, yielded a 20-year average relative crop yield reduction that projected from 2000 to 2090 decreased water stress (from 12 to 6 percent) in the wet season and increased stress (from 51 to 64 percent) in the dry season (Harmsen et al. 2009).
- Tropical rain forest seedlings will be affected by decreased rainfall, greater seasonality and variability, and lower soil moisture associated with climate change (Whitmore 1998).
- Where data have been combined globally, the sensitivity of rainforest tree mortality rates to soil moisture deficit (e.g., drought) appears to vary strongly by region, with the more humid rainforests of Southeast Asia showing substantially larger increases in mortality than those of Amazonia (Allen et al. 2010; Phillips et al. 2004).
- Hydraulic architecture may have a strong effect on how species react to global climate change. Trees with shallow roots may be at a competitive disadvantage compared to deeper rooted species (Stork et al. 2007). In Amazonian forests, deep-rooted trees passively transfer water at night from deep moist soil to shallow dry soil, or from moist shallow to dry deep soil layers, a phenomenon called hydraulic redistribution (Oliveira et al. 2005). If other tropical forests trees exhibit similar redistributive behaviors, the effects of increased evaporative demand with warming may be buffered for shallow-rooted species (Wood et al. 2012).

Effects of Elevated CO₂ Concentrations

- ❖ Tabonuco Forest species in the Luquillo Mountains experienced a much greater decrease in respiration and thus higher net primary productivity than Colorado, Palm, or Elfin forests under conditions of increased CO₂, temperature, and rainfall (Wang et al. 2003).
- In their TEM simulation, Melillo et al. (1993) found the direct effects of enriched CO₂ levels to be the most significant contributor to increases in net primary productivity, as elevated CO₂ may decrease tree respiration rate.

- All else equal, lower stomatal conductance in response to higher CO₂ concentrations would increase water-use efficiency among tropical trees and could assist tree growth when water is a limiting factor (Lewis et al. 2004).
- Among tropical plants, CO₂ has repeatedly been found to stimulate photosynthesis, accumulate more carbohydrates in plant tissue, and often deplete nitrogen reserves. However, tropical plant growth was found by Körner (1998) to be responsive to CO₂ only when there were abundant nutrients or deep shade and/or isolation.
- Early successional tropical tree species with high fertilization and relative growth rates are found to be more responsive to CO₂ (Körner 1998; Lewis et al. 2004).
- Though CO₂-enhanced growth is expected to improve understory seedling survival and juvenile growth rates, young lianas may advance out of the forest shade and take greater advantage of the CO₂ enrichment. Such a biodiversity effect could shift the forest to earlier succession life stages and thus reduce the carbon storing potential of the forest (Körner 1998; Lewis et al. 2004).
- Recent research projected temperature increases may not decrease photosynthetic rates of tropical trees if the optimum temperature for photosynthesis rises and photorespiration declines with corresponding increases in CO₂ levels (Lewis et al. 2004).

2.6.2.4 Effects on Social and Economic Resources

Recreation and Tourism

- ❖ Intensive land development, high coastal population density, and the effects of large tourism-based industry intensify the vulnerability of Puerto Rico to climatic variability, and there is limited human and capital infrastructure to address such problems (Lewsey et al. 2004).
- Climate change may affect tourism through changes to local ecosystems and resources that impact scenic values as well as changes to weather patterns that may disrupt recreational activities, which can lead to changes in visitor use (Prideaux et al. 2010).
- Wet tropical forests are unlikely to see changes in tourism demand due to the projected changes in forest structure and composition with climate change, because most visitors have little knowledge of rainforest complexity and will not be able to observe these changes unless they are so extensive they cannot be ignored (Prideaux et al. 2010). However, increased average high temperatures may affect demand due to visitor discomfort when recreating outdoors and an increased chance of heat-related illnesses (Prideaux et al. 2010).
- Projected increases in disturbance events may lead to reduced tourist access in natural areas in an effort to protect public safety following events such as fire, insect outbreaks, blowdowns, and flooding. Extreme weather events may increase damage to facilities and structures, and increase the need for road repairs (Joyce et al. 2008).
- Climate change may lead to the redistribution of climatic aspects in tourist regions, which can affect tourism seasonality (e.g., changes in the length of the warm-weather tourism season), demand (e.g., increased destination choice in the winter), and travel patterns (e.g., changes in travel timing and destination). The Caribbean region, where year-round warm weather is the principle tourism resource, may see increasing competition from other regions as warm seasons expand globally (Scott et al. 2004).
- In tropical coastal areas, negative effects of climate change through coral reef bleaching and sea-level rise effects on beaches could affect economies that are dependent on

tourism (Uyarra et al. 2005). In a survey of tourists in Bonaire and Barbados, Uyarra et al. (2005) found that 80 percent of tourists were unwilling to revisit the Islands if coral reef bleaching and beach loss occur, unless they were able to pay a lower price.

- A study of beach-front resorts in the Caribbean found that with as little as 1 meter sea level rise 29 percent of properties would be partially or fully flooded, while 50 to 60 percent of properties would experience erosion damage (Scott et al. 2012).

Land Use and Planning

Urban Interactions

- ❖ According to data retrieved from the San Juan ATLAS Mission, the San Juan Metropolitan Area has greater sensible heat receptivity and therefore produces higher air temperatures (2.5 to 3 °C) (Comarazamy et al. 2010).
- ❖ Additional urban and natural simulations showed bands of clouds and minimal precipitation in southwest San Juan Metropolitan Area, which may be due to less intense northeasterly trade winds transporting less available moisture horizontally (Comarazamy et al. 2010).
- ❖ Results from eight urban and suburban forests in the Urban Long Term Research Area of Rio Piedras, Puerto Rico, suggest that urbanization can alter ecosystem processes, microbial activity, and soil organic matter cycling, with a potential for a positive urban effect on soil mineral nitrogen pools in nitrogen-rich tropical forests (Cusack 2013).
- Improved road conditions due to longer dry seasons are likely to influence land-use decisions, making colonization and logging of the remaining “remote” forest more economically feasible, thus reducing tropical forest biodiversity in exchange for economic exploitation (Brodie et al. 2011).
- Tropical land cover change, resulting from direct human activities, interacts with anthropogenic ecosystem drivers such as climate change and affects watershed supply (Uriarte et al. 2011).
- Urbanized landscapes can further exacerbate climate warming at the local scale, while highly vegetated tropical forests can have a moderate cooling effect (Lim et al. 2005).
- Anthropogenic creation of pasture has created lower cloud condensate and lifting condensation, levels of which are several times greater over tropical forested lowlands (Van der Molen 2010).

Energy Production

- ❖ Because of its climatological current and future wind blows minimum of 4.84 meters per second, the entire Caribbean region can use advanced wind turbine technology and can likely become energy self-sufficient. Wind energy, with small seasonal future variation, is particularly viable in both the dry season and early rainfall season, where wind power potential reaches at least class 4 in Puerto Rico and the Lesser Antilles (Angeles 2010).
- The Caribbean region is expected to continue to have high solar energy availability in the future (currently with values greater than 5.5 kilowatt hour per square meter per day) making it an excellent candidate for sourcing renewable energy (Angeles et al. 2007). Particularly, the southwest Caribbean is the highest net surface solar energy source, with the early rainfall season hosting the best potential for solar energy collection and the dry

season values ranging from 4 to 7 kilowatt hour per square meter per day (Angeles et al. 2007).

Coastal Resources

Sea Level Rise Trends

- ❖ Based on monthly mean sea level data from 1962 to 2006 (NOAA 2013), mean sea levels in San Juan, Puerto Rico, have risen at a pace of 1.65 millimeters per year (± 0.52 millimeters per year).
- Average global sea level rise over the 20th century occurred at an average rate of 1.7 millimeters per year, with recent accelerations to 3.1 millimeters per year since the mid-1990s (Biasutti et al. 2012; Church and White 2006). In the Caribbean specifically, sea levels have risen at a rate of about 1 millimeter per year over the 20th century (Cashman et al. 2010).
- The IPCC 4th assessment projected with very high confidence (greater than 90 percent chance) a global rise in sea levels of at least 0.2 meters by 2100, with high end projections of a 2 meter rise in sea levels by 2100 (Parris et al. 2012).
- Projections using the upcoming 5th edition of the IPCC assessment report estimate a global rise in sea levels of 0.57 to 1.10 meters by 2100 (Jevrejeva et al. 2012). However, this rise in sea level will not be uniform, with sea levels in the Caribbean and Atlantic projected to be as much as 5 centimeters higher than the global average (Galindo et al. 2010).

Sea Level Rise Effects

- ❖ In Sabana Seca on the northern coast of Puerto Rico, a study by Rivera-Ocasio et al. (2007) found that small increases in salinity due to sea level rise could have substantial effects on coastal bloodwood (*Pterocarpus officinalis*) forests. Mangrove forests in the Caribbean region were also found to be vulnerable to sea level rise, as well as increased temperatures and hurricane frequency (Magrin et al. 2007).
- ❖ In small (e.g., Antigua and Barbuda) and large (e.g., Puerto Rico) island states, sea level rise will cause a loss of land area, which could potentially lead to coastal erosion and loss of infrastructure as well as inland migrations of populations (Kelman and West 2009; Lewsey et al. 2004).
- Urbanization throughout the Caribbean, created from the combination of tourism growth and deficient land-use planning and development controls, has rendered coastal infrastructure vulnerable to extreme weather and rising sea levels characteristic of climate change (Lewsey et al. 2004).
- Saltwater intrusion into coastal aquifers due to sea level rise is already a threat to freshwater supplies in many Caribbean Islands, and saltwater intrusion in the Caribbean is projected to increase with climate change (Cashman et al. 2010; Lewsey et al. 2000).
- Sea level rise, worsened by tropical storms, risks turning dynamic tropical wetland areas into salt pans, which may affect the colonization of some tropical birds (Şekercioğlu et al. 2012)

2.6.2.5 Knowledge Gaps and Uncertainties

Knowledge of observed and projected climate change is continually evolving as scientists research the mechanisms and responses of the Earth's climate system to increased levels of CO₂ (IPCC 2001, 2007, 2013). In tropical and sub-tropical forests in particular, significant knowledge gaps exist in predicting the response of natural systems to climate change. There is a lack of large-scale manipulative experiments exposing species to warming an d elevated CO₂ in the tropics and sub-tropics, and these studies are critical to understanding whether responses to climate change will be positive or negative (Zhou et al. 2013).

In addition, regionally downscaled climate models projecting temperature and precipitation patterns at fine-scales are not readily available for locations within the Caribbean region, including Puerto Rico (Cepero 2013). While existing large-scale global climate models are useful in determining potential future trends (Angeles et al. 2007), in Puerto Rico's mountainous regions the lack of fine-scale data is especially troublesome as variations in climate with elevation over short horizontal distances cannot be captured by existing climate models (Meehl et al. 2007), especially in predictions of extreme events (ECLAC 2010). Because of the lack of high-resolution climate projections, there are also few models representing potential implications of climate change for ecosystem functions and characteristics in the Caribbean region (Cepero 2013). Natural resource managers and planners can look to studies of measured historical trends, as well as past periods of extreme climate events and the response of species to stress to help forecast future responses (Walther et al. 2002), as are presented in this report alongside future projections. However, knowledge gaps remain in the research of both historical responses and future trends for local ecosystems in the tropics and sub-tropics, and only a small number of the total plant and animal species in the region have been studied. While this section points out several examples of research needs, a broader assessment of knowledge gaps related to climate change in EYNF, Puerto Rico, and the Caribbean region is needed.

Uncertainties exist with any study forecasting trends in climate. The scientific literature assessed here employs various measures of uncertainty related to specific effects of climate change. While it is impractical to describe each measure of uncertainty here, it is important to understand the inherent uncertainties in the broader discussion of climate change. The Intergovernmental Panel on Climate Change (IPCC) provides an overview of key uncertainties in both historic observations and projections of climate change in its most recent fifth assessment report (IPCC 2013) to help readers understand the uncertainties surrounding drivers and effects of climate change. The IPCC relates the probability of changes to terms describing likelihood using the following metrics: certain (100 percent probability), virtually certain (99–100 percent), very likely (90–100 percent), likely (66–100 percent), about as likely as not (33–66 percent), unlikely (0–33 percent), very unlikely (0–10 percent), and exceptionally unlikely (0–1 percent). Key measures of uncertainty from the IPCC (2013) related to projected future conditions described in this report are:

- Globally, climate warming since the 1950s is certain, and it is likely that the 30-year period from 1983 to 2012 was the warmest period in the last 1,400 years. It is virtually certain that temperatures will continue to increase through the late 21st century.
- It is very likely that climate change has contributed to a global increase in the frequency and intensity of temperature extremes. It is virtually certain that these events will become more frequent through the late 21st century.
- It is likely that climate change has influenced global precipitation patterns since the 1960s, including the intensification of both drought and heavy precipitation events. It is

very likely these events will become more frequent and/or intense through the late 21st century.

- It is virtually certain that there has been an increase in intense hurricanes in the North Atlantic Ocean since the 1970s. It is more likely than not that these events will continue to increase in intensity through the late 21st century.
- It is virtually certain that sea surface temperatures have warmed since the 1970s. It is certain that sea levels are rising, and it is likely that the rate of sea level rise has accelerated over the 20th century. It is virtually certain that sea levels will continue to rise through the late 21st century.

It is important to note that the uncertainties presented here are not comprehensive. More detailed information can be found in the IPCC’s AR5 report (IPCC 2013).

2.6.2.6 Key Findings

► **Climate Trends.** Average temperatures in the Caribbean region have increased over the past 40 years (Uyarra et al. 2005). Around the Luquillo Mountains, a small increase in annual maximum and minimum temperatures has been detected in long-term (62 year) records (Waide et al. 2013). Scientists predict warming will continue at an accelerated pace (IPCC 2007); however, climate models vary in the degree of warming (Table 2-5). Projected decreases in precipitation in the Caribbean suggest drier wet seasons, and even drier dry seasons (Cashman et al. 2010). Increasing sea surface temperatures may lift the base altitude of cloud formation (Still et al. 1999) and alter atmospheric circulation patterns (Woollings and Blackburn 2012). Any change in the cloud base height will further decrease precipitation in EYNF (Comarazamy and González 2011). Climate change may also affect the distribution patterns and concentrations of air pollutants through changing wind and precipitation patterns (Bytnerowicz and 2007) as well as increased temperatures (Bedsworth 2011).

Table 2-5. Climate model projections for increases in temperature at end of century

Source	Spatial Extent	Projection
Scatena (1998)	Puerto Rico	+1.5 to +2.5 °C
Girvetz et al. (2009); Meehl et al. (2007)	Puerto Rico	+2.2 to +2.7 °C
Campbell et al. (2011)	Caribbean	+2 to +5 °C
Christensen et al. (2007) (IPCC)	Central America	+1.8 to +5 °C
Magrin et al. (2007) (IPCC)	Latin America	+1 to +7.5 °C

Table 2-6. Climate model projections for changes in precipitation at end of century

Source	Spatial Extent	Projection
Girvetz et al. (2009); Meehl et al. (2007)	Puerto Rico	-10 to -30% annually
Campbell et al. (2011)	Caribbean	-25% to -50% annually
Biasutti et al. (2012) (IPCC)	Caribbean	-30% in spring and summer
Magrin et al. (2007) (IPCC)	Latin America	-40% to +10% annually

► **Extreme Weather.** Heavy rainfall events have become more common in Puerto Rico in recent years, particularly since 2009, with changes linked to high sea surface temperatures (Vélez Rodríguez and Votaw 2012). The frequency of extreme precipitation events is expected to continue to increase, leading to potential increases in inland flooding and landslides (Magrin et al. 2007; Seneviratne et al. 2012). Hurricane events are likely to become less frequent but more severe, with increased wind speeds, rainfall intensity, and storm surge height (Karl et al. 2009; Knutson et al. 2010). In the Caribbean, the occurrence of very warm days and nights is accelerating, while very cool days and nights are becoming less common (Peterson et al. 2002), increasing the likelihood of extreme heat waves (Anderson 2011). Additionally, as annual rainfall decreases over time in the Caribbean region, longer periods of drought are expected in the future (Breshears et al. 2005; Larsen 2000). In Puerto Rico, where nearly all wildfires are associated with human activity, the interactions between climate warming and drying and increased human development have the potential to increase the effects of fire (Robbins et al. 2008).

► **Terrestrial Ecosystems.** Higher temperatures, changes in precipitation patterns, and any alteration in cloud cover will affect plant communities and ecosystem processes in EYNF (Lasso and Ackerman 2003). Increasing night-time temperatures may affect tropical tree growth and induce tree mortality (Clark et al. 2010; Wagner et al. 2012). Both intensified extreme weather events and progressively drier summer months in the Caribbean are expected to alter the distribution of tropical forest life-zones (Wunderle et al. 2011), potentially allowing low-elevation Tabonuco Forest species to colonize areas currently occupied by Palo Colorado Forest (Scatena 1998). Because they occur under narrowly defined environmental conditions, EYNF's Cloud Forests are among the world's most sensitive ecosystems to climate change (Lasso and Ackerman 2003). Cloud Forest epiphytes (e.g., bromeliads) may experience moisture stress due to higher temperatures and less cloud cover with a rising cloud base, affecting epiphyte growth and flowering (Nadkarni and Solano 2002; Zotz and Bader 2009). Plant communities on isolated mountain peaks will be most vulnerable, as they will not be able to adapt to the shifting cloud base by moving to higher elevations (Laurance et al. 2011; Magrin et al. 2007).

► **Aquatic Ecosystems.** Shifts in rainfall patterns due to climate change will lead to periods of flooding and drought that can significantly affect aquatic ecosystems and water resources (Seager et al. 2009). Increases in heavy downpours in Puerto Rico and more intense hurricanes in the wet season can lead to greater erosion and sedimentation in waterways (Carpenter et al. 1992; Cashman et al. 2010; Karl et al. 2009). Riparian areas will see changes in structure and composition due to altered temperature, precipitation and run-off regimes as well as changes in the distribution of plant and animal species (Seavy et al. 2009). Extended droughts in the dry season may significantly affect aquatic organisms by decreasing dissolved oxygen content (Mulholland et al. 1997). Freshwater aquatic communities during drought will experience crowding of species, leading to habitat squeezes and a decrease in reproductive output (Covich et al. 2003). In EYNF streams, extended periods of extreme low water flows may result in increased pollutant concentrations and excessive nutrients (Cashman et al. 2010; Covich et al. 2003).

► **Wildlife.** Climatic warming may push the narrow thermal tolerances of many species in tropical environments above their upper limits (Huey et al . 2009; Laurance et al . 2011), prompting population losses and habitat changes that will affect animal communities (Blaustein et al. 2010). Because of their cool-adapted, range-restricted nature, high-elevation amphibians, including Puerto Rican Coquí frogs, are especially vulnerable to future changes (Barker et al. 2011; Brodie et al . 2011; Longo et al . 2010; Stallard et al . 2001). More frequent drought conditions may increase the vulnerability of both reptiles and amphibians to water loss, parasites, and diseases including amphibian chytrid fungus (Anchukaitis and Evans 2010; Burrowes et al. 2004; Rogowitz 1996). Reduced rainfall may lead to decreased habitat quality for neotropical bird migrants wintering in EYNF (Studs and Marra 2011), while cavity-nesting birds, including the Puerto Rican Parrot (*Amazona vittata*), could see an increase in habitat competition and nesting predation with an increase in major hurricane disturbances (Arendt 2000; Pounds et al. 1999).

► **Recreation.** The Caribbean region, where year-round warm weather is the principal tourism resource, may see increasing competition from other regions as warm seasons expand globally (Scott et al . 2004). Sea level rise will affect coastal resorts, which may affect tourist and recreationist preferences throughout Puerto Rico (Lewsey et al . 2004; Magrin et al . 2007). Climate change may affect recreation in EYNF through changes to local ecosystems and resources that affect scenic values, as well as changes to weather patterns that may disrupt recreational activities and lead to changes in visitor use (Prideaux et al. 2010). Visitors to EYNF may see effects to the local plant and animal communities that make the forest unique (Scatena 1998). An increase in extreme weather events may increase damage to facilities and structures, reduce tourist access in some areas, and increase the need for road repairs (Joyce et al. 2008).

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2.6.2.8 Literature Cited

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2.7 Assessing Threatened, Endangered, Proposed and Candidate Species and Potential Species of Conservation Concern

2.7.1 *Threatened, Endangered, Proposed, and Candidate Species—Terrestrial Wildlife*

2.7.1.1 Existing Information

- Puerto Rican Parrot Recovery Plan
- Puerto Rican Parrot Memorandum of Understanding
- Recovery Plan for the Puerto Rican Broad-winged Hawk
- Recovery Plan for the Puerto Rican Sharp-shinned Hawk
- Action Plan for the Elfin-woods Warbler
- Candidate Conservation Agreement for the Elfin-woods Warbler (in draft)
- Recovery Plan for the Puerto Rican Boa
- Presence/absence surveys

2.7.1.2 Informing the Assessment

Per the Land Management Planning Rule (USDA Forest Service 2012), the Forest Service is directed to provide for the diversity of plant and animal communities within Forest Service authority and consistent with the inherent capability of the plan area and maintain or restore ecosystem integrity and diversity.

This section of the assessment addresses available information regarding the ecology and distribution of federally recognized endangered, threatened, proposed, or candidate wildlife species. These recognized at-risk species are either terrestrial or aquatic wildlife that have been identified through the legal process of the Endangered Species Act of 1973 as amended through either the U.S. Fish and Wildlife Service (USFWS) or National Oceanic and Atmospheric Administration–Fisheries division. The EYNF has six federally listed terrestrial wildlife species, no federally listed aquatic species, one delisted species, and one extirpated species.

2.7.1.3 Current Condition

Current conditions will be defined as in the definition of assessment in the new Forest Service planning rule (USFS, 2013a). Each species addressed shall contain current legal status and ranking.

Rankings are based on the NatureServe G-rankings criteria for a species viability, which is designated by a number from 1 to 5, preceded by a letter reflecting the appropriate geographic scale of the assessment (G = Global), N = National, and S = Subnational). The numbers have the following meaning:

- 1 = critically imperiled
- 2 = imperiled
- 3 = vulnerable
- 4 = apparently secure

5 = secure

For example, G1 would indicate that a species is critically imperiled across its entire range (i.e., globally), and the species is at very high risk of extinction. A rank of S3 would indicate the species is vulnerable and at moderate risk within a particular state or province, even though it may be more secure elsewhere (NatureServe 2013). The ranking is based on these factors:

- 1) Range extent
- 2) Area of occupancy
- 3) Population size
- 4) Number of occurrences
- 5) Number of occurrences or percent of area occupied with good viability/ecological integrity
- 6) Overall threat impact
- 7) Intrinsic vulnerability
- 8) Long-term trend
- 9) Short-term trend

There is also the category of least concern (LC) meaning the species is well established, but some species are still federally listed due to one or more of the above-mentioned factors. According to the planning rule the agency will address those species with G1 and G2 rankings (USDA Forest Service 2012b).

Puerto Rican Parrot (*Amazona vittata*): Endangered

Ranking–G1 (Infonatura 2012)

The Puerto Rican parrot (*Amazona vittata*) was listed as endangered in 1968. Under the 2009 recovery plan for the Puerto Rican parrot, this endemic species is the only native parrot in the United States and it was considered one of the ten most endangered birds in the world. The bird is not historically dependent on a specific habitat on the EYNF and had wide ranges throughout Puerto Rico. “Amazona parrots in general are known to range widely within the forest types they inhabit, regularly flying long distances to obtain food” (Snyder et al. 1987). A continuing interagency recovery effort between



Photo: USFWS

the Forest Service, USFWS, and the Puerto Rico Department of Natural and Environmental Resources (PRDNER) presently supports a minimum of 25 to 28 individuals surviving in the EYNF in eastern Puerto Rico and 22 to 28 in the Río Abajo Forest in north central Puerto Rico. Two captive population aviaries hold more than 228 individuals: the Iguaca Aviary and the José L. Vivaldi Aviary in the EYNF and west-central Puerto Rico, respectively. According to the population viability analysis (2007) of the Puerto Rican parrot, the species is still slowly coming out of a genetic bottleneck and through the interagency effort has been addressing limiting population growth factors to assist the parrot reach a more viable status. The recovery effort has also realized that the EYNF is not the preferred habitat of the Puerto Rican parrot and foresees a more promising population growth in a third wild flock location in the western section of Puerto Rico. As an overall summary the species was at 13 individuals in 1976 and presently has a total population, including captive birds, at approximately 400 individuals (Velez 2013).

Puerto Rican Broad-winged Hawk (*Buteo platypterus brunnescens*): Endangered

Ranking–LC (IUCN 2012)

The Puerto Rican broad-winged hawk is a subspecies of the broad-winged hawk and is endemic to Puerto Rico. “ This species occurs in elfin woodland, sierra palm, caimitillo-granadillo, and tabonuco forest type of the Rio Abajo Commonwealth Forest (Western Puerto Rico), Carite Commonwealth forest (Southeastern Puerto Rico) and EYNF” (USFWS 2010). It was federally listed as endangered in 1994. The hawk’s population was estimated at about 125 individuals Islandwide in 1994 (USFWS 2010). There have been very few observations of the broad-winged hawk in annual bird counts, but it is known to still exist on the EYNF. The raptor is known to prefer forest types with an open mid-story vegetation structure due to the prey species, such as lizards and small birds, which it prefers.



Photo: USFWS

Puerto Rican Sharp-shinned Hawk (*Accipiter striatus venator*): Endangered**Ranking–LC (IUCN 2012)**

The Puerto Rican sharp-shinned hawk was listed in 1994 and is a subspecies of the sharp-shinned hawk. There are more individuals outside of the EYNF, but a survey by Delannoy (1992) reported only a solitary territorial hawk pair in the south-central part of the Forest. This area is located within the Palo Colorado Forest type in the Lower Mountain Forest Life Zone (Ewel and Whitmore 1973). Sixty individuals of Puerto Rican sharp-shinned hawks were counted in Islandwide surveys conducted in 1983, and a breeding density of 0.73 hawks per square kilometer was estimated (Cruz and Delannoy 1986). In 1985, 72 individuals were counted and a breeding population of 0.76 hawks per square kilometer (230 to 250 Islandwide) was estimated in Islandwide surveys (Cruz and Delannoy 1986). In 1992, a total of 285.6 square kilometers



Photo: USFWS

was censused yielding 82 sharp-shinned hawks: 80 outside of the EYNF and 2 within the Caribbean National Forest (EYNF). An overall population of 129 individuals has been estimated for these forests (Delannoy 1992). As of late, an individual has been observed during population indices counts for the Puerto Rican parrot which may show a new area of occurrence for the small raptor in the western section of the EYNF (Cano, 2013). The hawk prefers an open mid-story vegetation structure for its preferred prey species, lizards and small birds.

Elfin Woods Warbler (*Dendriocia angelae*): Candidate Species**Ranking–G3 (Infonatura 2012)**

The Elfin-woods warbler was listed as a candidate species in 1982. The species is endemic to Puerto Rico and has been reported in humid montane forest habitats. Initially thought to occur only in the Luquillo Mountains (EYNF), this species was later discovered in the Maricao, Toro Negro, and Carite Commonwealth forests (Gochfeld et al. 1973; Cruz and Delannoy 1984a; Raffaele 1998). Kepler and Parkes (1972) described the Elfin-woods warbler from the high elevation Elfin Woodland Forests (640 to 1,030 meters or 2,099 to 3,378 feet) and occasionally Palo Colorado Forests in EYNF. Wiley and Bauer (1985) later reported the species from the Elfin Forests and lower elevation forests



Photo: USFWS

(370 to 600 meters or 1,213 to 1,968 feet) such as Palo Colorado and Sierra Palm forests in the EYNF. According to Arendt (2013), “since its discovery and classification there has been concern regarding the status and future of the owl to its limited range and dwindling habitat...and predicted repercussions of escalating climate change.” Thus, there may be a decreasing habitat quality trend occurring on the EYNF that includes food resources and vegetation structures that the bird requires. Presently the USFWS has initiated a candidate conservation agreement with the EYNF because the Forest is one of the last two locations in Puerto Rico that the warbler is found.

Puerto Rican Boa (*Epicratus inornatus*): Endangered

Ranking–LC (IUCN 2012)

Listed as a n e ndangered species in 1970, this boa is found mostly i n t he n orthern h alf o f t he Island of P uerto R ico. Rivero (1998) indicated that the Puerto Rican boa is distributed throughout the Island, being more abundant in the “mogotes” of the north and much less abundant in the dry southern region of the Island. Wunderle et al (2004) studied habitat use of the boa the EYNF and indicated that although the boa were located



Photo: USFWS

in a variety of microhabitats (i.e., vine enclosed broadleaf trees and shrubs, vine tangles, bamboo, dead trees, buildings and streams), t he h ighest m ean p ercentage o f f ixes f or boas tracked b y t elemetry occurred i n broadleaf t rees f ollowed b y g round or b e low g round sites. This r adio t elemetry s tudy b y Wunderle a t E YNF m onitored 24 s nakes w ith a t otal 70 t agged P uerto R ican boas w ith transponders (pit-tags). Boas were found incidentally during daylight and evening hours while walking or driving to sites with radio-marked boas. According to Wunderle et al. (2004), much of the boa’s apparent rarity is related to the observer’s ability to visually detect this cryptic species within t he forest. As a n example, Wunderle e t a l. (2004) failed to v isually d etect telemetry-tracked boas an average of 85 percent of their telemetry relocations. They indicated that given this detection difficulty in the forest, it is likely that the species is more abundant than generally perceived.

White-necked Crow (*Corvus leucognathus*): Extirpated from Puerto Rico

Ranking–G3 (Infonatura 2012)

The endangered white-necked crow no longer exists on the Island of Puerto Rico, but is still occurs in neighboring Dominican Republic (Island of Hispaniola). The bird had an original range of both of the Greater Antilles Islands (Puerto Rico and Hispaniola), but over time became reduced to occur on only one Island. D ue to considerable low l and forest c learance and hunting the species was last seen i n Puerto Rico in 1963. There is a low potential for reintroduction of this s pecies, but t he E YNF w ould be a l ikely location f or it s recovery.

There will be no analysis of trends or drivers for this species since the species does not occur on the EYNF.



Photo: Birdlife International

Peregrine Falcon (*Falco peregrinus*): Delisted

Ranking–LC1 (Infonatura 2012)

The USFWS has determined that the American peregrine falcon (*Falco peregrinus anatum*) is no longer an endangered or threatened species pursuant to the Endangered Species Act of 1973, as amended (USFWS 1999). This bird species was listed in the 1997 Forest Plan and received a recovered determination based on available data indicating that this subspecies has recovered following restrictions on organochlorine pesticides in the United States and Canada, and following the implementation of successful management activities. Hence, the species has been delisted due to recovery (USFWS 1999).



Photo: USFWS

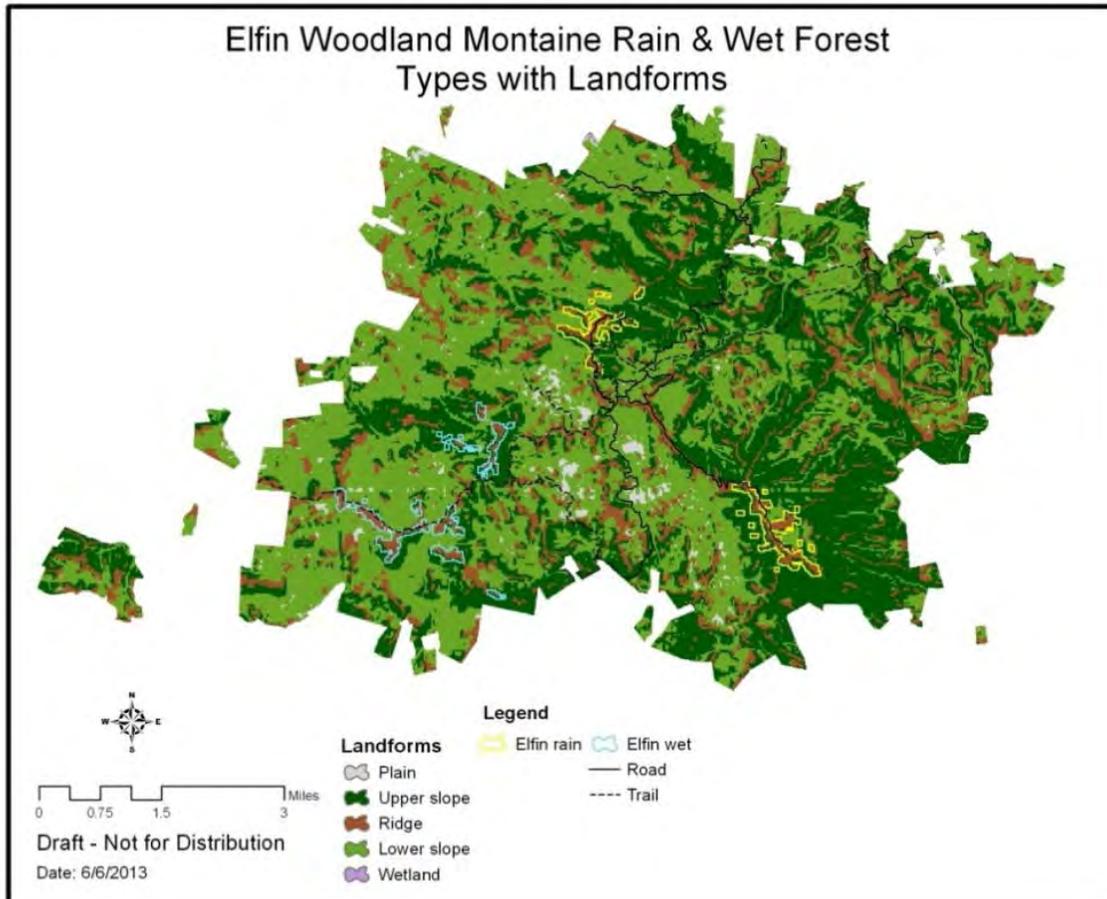
2.7.1.4 Trends and Drivers

The following are drivers of the trends described for the species above:

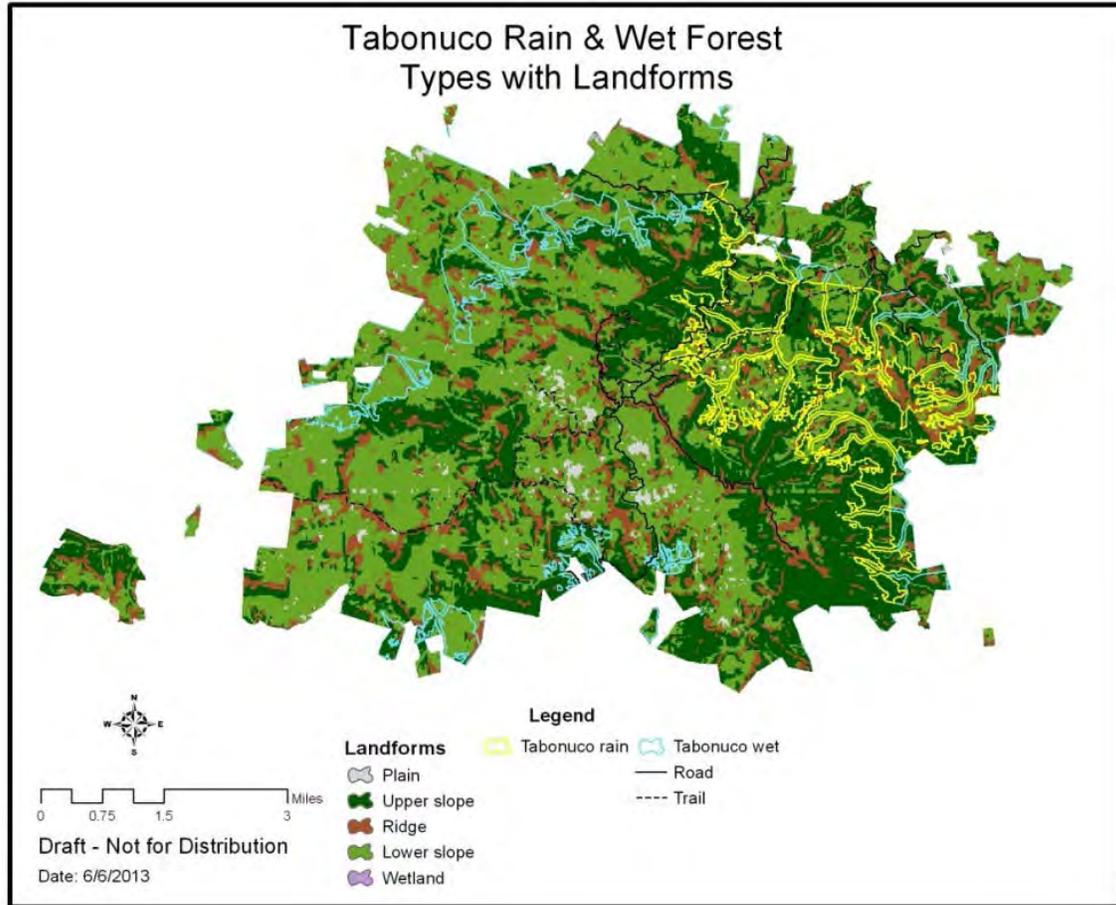
- Availability of artificial nests, active management on population limiting factors, and addition of captive-raised Puerto Rican parrot to the wildflock
- Presence and absence data
- Total area of Elfin-woods (Cloud Forest) vegetation type for the Elfin-woods warbler
- Mapped areas of Palo Colorado, Tabonuco vegetation type

Trends

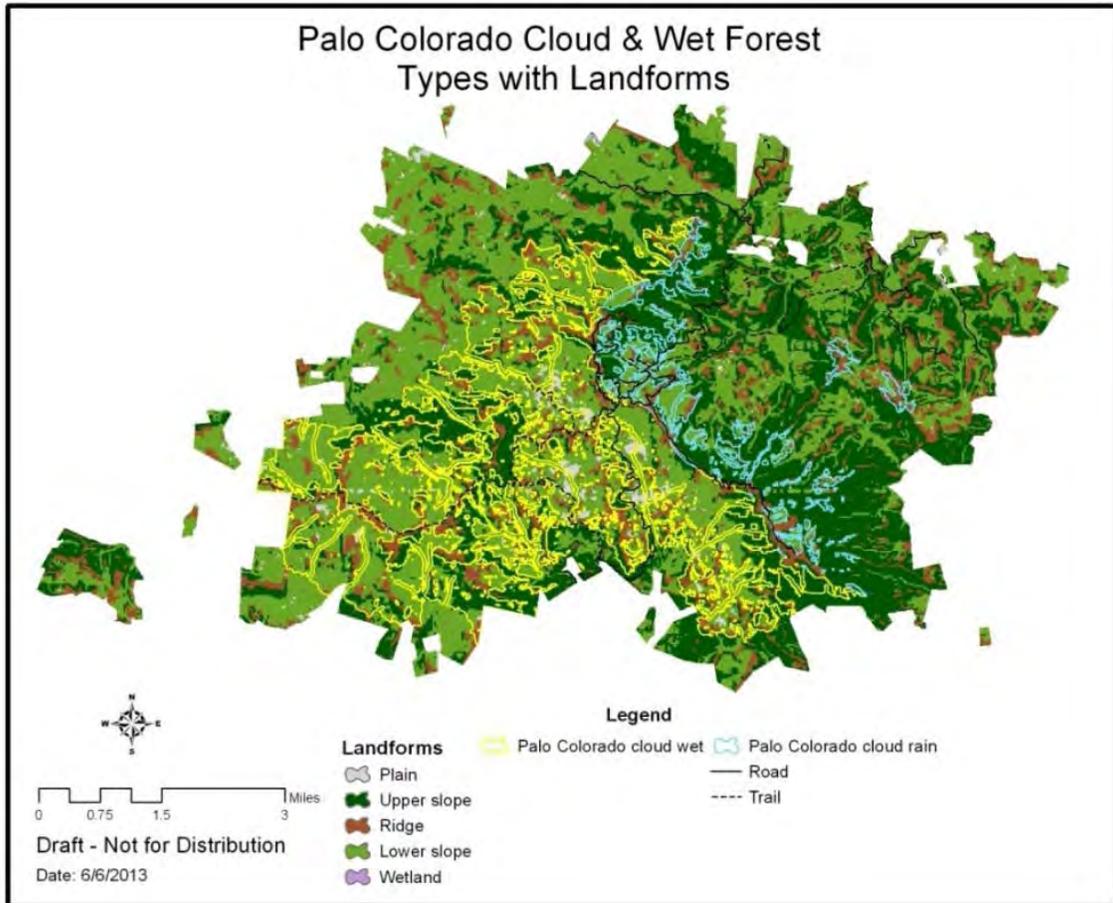
Trends are an estimated direction of the species' population through empirical data. These conclusions are to be accepted as an approximation within an acceptable range provided by the scientific data.



Map 2-20. Elfin Woodland Forest types with landforms from Gould et al. (2008)



Map 2-15. Tabonuco Forest type with landforms from Gould et al. (2008)



Map 2-22. Palo Colorado Forest type with landforms from Gould et al. (2008)

Puerto Rican Parrot

shows population trend of wild flock of Puerto Rican parrot on the El Yunque 1973 to 2006.

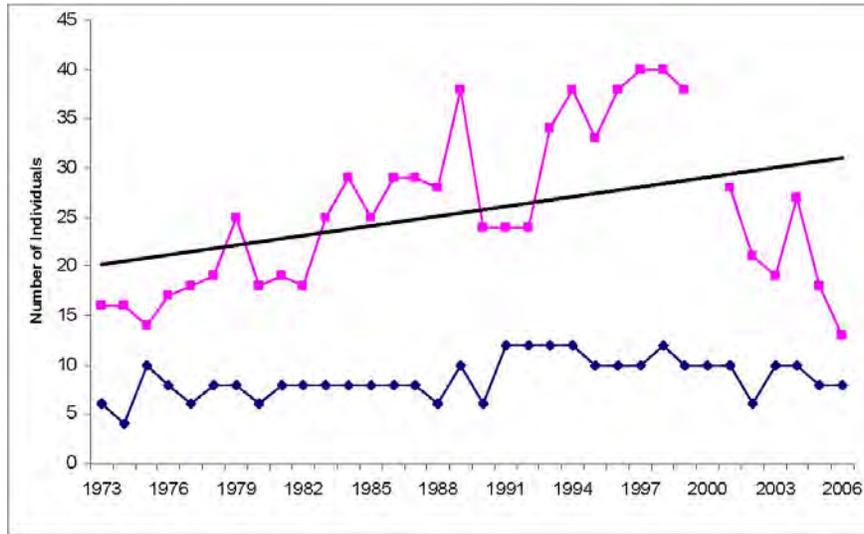


Figure 2-5. Population trend of a wild flock of Puerto Rican parrots on the El Yunque 1973 to 2006 (USFWS 2009)

Note: Puerto Rican parrots counted during pre-breeding surveys (March and April) in the EYNF from 1973 to 2006. The number of breeding individuals recorded each year is also depicted in the lower part of this figure. The average observed rate of increase (Caughley 1977) is expressed as the finite rate (λ).

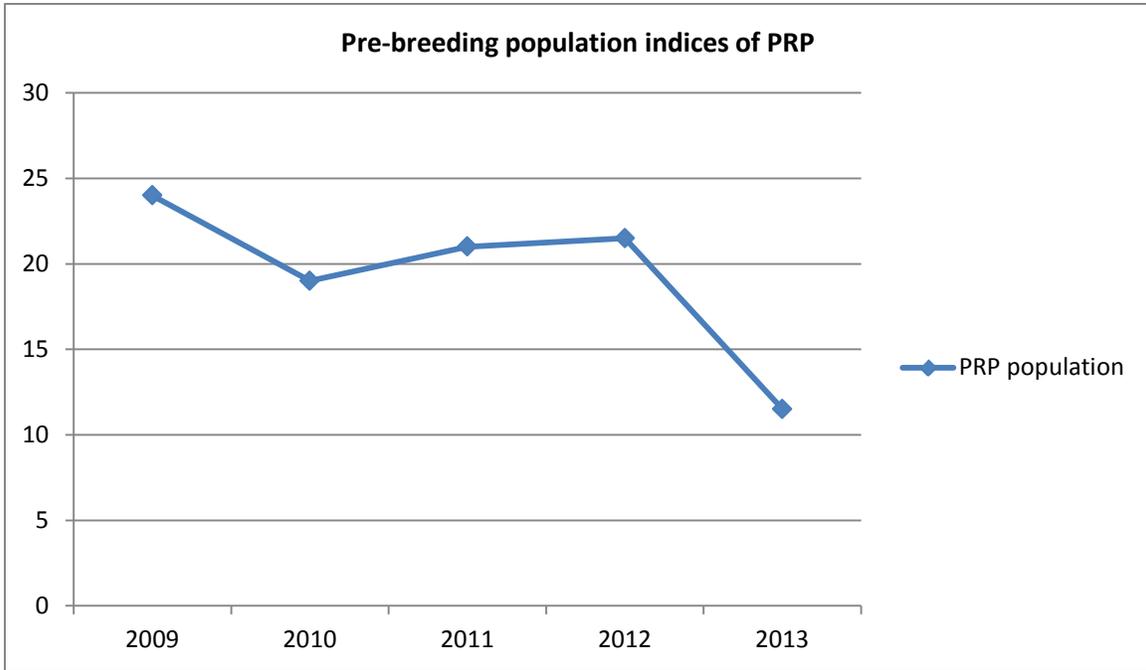


Figure 2-6. Population trend of a wild flock of Puerto Rican parrots on the El Yunque 2009 to 2013 (USFWS 2013)

Note: Average Puerto Rican parrots counted during pre-breeding indices (March and April) in the EYNF.

Indices are not to be confused with a census that shows the total count. These two graphs exhibit the erratic movements of the Puerto Rican parrot pre-breeding population, which is the period before the breeding pairs lay eggs and any new PRP from the aviaries. Trends can be explained through predation, hurricanes, genetic bottleneck, and carry capacity of the area. On Map 2- notice that the Palo Colorado wet habitat is mostly in the western section of the EYNF, this is an important habitat for the continued occurrence of the parrot. This forest type is of great concern for many other species needs and will be monitored for potential changes.

In the short term, hurricane-induced mortality may constrain tropical bird population of the Luquillo Experimental Forest (EYNF) below the recovery threshold, particularly the Puerto Rican parrot because of its confined range and small population size and growth rate (Wunderle and Arendt 2011). However, in the long term, hurricanes may be beneficial to bird populations with adequate size because of increased nutrient cycling and nest cavity creation (Wunderle and Arendt 2011).

Puerto Rican Broad-winged Hawk

Table 2-7. Present observation trend of the Puerto Rican broad-winged hawk (Delannoy 1992)

Forest	Census Area (km ²)	Number of Hawks	Estimated Population
Luquillo (EYNF)	206.4	58	124.20

The Puerto Rican broad-winged hawk’s density and population estimates varied considerably among forests, being highest at Rio Abajo Forest and lowest in EYNF (Delannoy 1995). New information on the abundance and demographic features of the population of the Puerto Rican

broad-winged hawks at the Rio Abajo Commonwealth Forest indicates a n abundance of approximately 52.2 individual (Hengstenberg and Vilella 2004).

Hengstenberg and Vilella (2004) also found that the vast majority (97 percent) of Puerto Rican broad-winged hawk movements and home ranges at Rio Abajo Forest were confined to the boundaries of the forest. Adult birds used private lands less than 1 percent of the time, whereas juveniles used private lands 6 percent of the time, suggesting that adults are able to secure the most suitable tracts of continuous, closed-canopy forest, while juveniles used areas on the periphery of the forest. The species on the Island shows a general downward trend. Both Tabonuco and Palo Colorado forest types show important habitat locations. Notice the locations of roads and trails in relation to the Tabonuco Rain and Palo Colorado Wet habitat types. These habitat types are dominated by upper and lower landforms (Gould et al. 2008), which tend to be susceptible to possible effects from recreation developments. According to Stork et al. (2009) species traits which presage risk from climate change include: low population densities, narrow niches, low vagility, small range, mature-habitat specificity, large body size, and those dependent on other species for food. Large vertebrates are especially vulnerable.

Puerto Rican Sharp-shinned Hawk

Table 2-8. Average density and estimated population of the Puerto Rican sharp-shinned hawk (Delannoy 1992)

Forest	Census Area (km ²)	Number of Hawks	Average Density ±S.E	Min-max	Estimated population +S.E
Luquillo (EYNF)	285.6	82	-	-	129.30

Both Tabonuco and Palo Colorado Forest types (Map 2 - and Map 2 -) show important habitat locations. Notice the locations of roads and trails in relation to the Tabonuco Rain and Palo Colorado Wet habitat types. These habitat types are dominated by upper and lower landforms (Gould et al. 2008), which tend to be susceptible to possible effects from recreation developments. According to Stork et al. (2009) species traits which presage risk from climate change include: low population densities, narrow niches, low vagility, small range, mature-habitat specificity, large body size, and those dependent on other species for food. Large vertebrates are especially vulnerable. On the EYNF these raptor species fall into the category of threats that are mentioned above for large vertebrate species.

Puerto Rican Boa

Population is moving towards higher rigor of population viability. Wunderle et al. (2004) compared their results and observations with the previous home range study conducted by Puente-Rolón and Bird-Picó (2004). Their analysis indicate that snakes foraging in productive food patches are expected to have smaller home ranges than those in less productive patches (Stickel and Cope 1947). Consistent with this prediction are the studies at a bat cave (productive area) in the karst region of north-central Puerto Rico (Puente-Rolón and Bird-Picó 2004), which indicate smaller home range sizes than those in the Luquillo Experimental Forest (EYNF). Although telemetry fixes were obtained more frequently at the cave site that in El Yunque (48 hours versus 4 to 5 days), and boas were studied for fewer months (10 versus 12), it is likely that the substantial differences in home range size between the two sites resulted from differences in prey abundance and dispersion. These differences in boa home range are consistent with an expectation of smaller home ranges associated with a rich food environment, represented by

abundant bats at the cave, in contrast to the larger home ranges at the EYNF, where prey were likely more widely dispersed and occur at lower densities.

Elfin-woods Warbler

The species is now restricted to two populations: one in the Maricao Commonwealth Forest (southwestern Puerto Rico) and one in the EYNF (northeastern Puerto Rico), located about 145 kilometers apart. The species distribution in the EYNF is more concentrated in the Palo Colorado (0.48 per point count station) and Elfin (0.42 per point count station) forests than Tabonuco (0.01) and Sierra Palm forests (0) (Anadón-Irizarry 2006). Anadón-Irizarry (2006) surveyed 155.2 hectares of upland woods habitat in the El Yunque Forest, and recorded 196 Elfin-woods warblers in 7 counts for an average of 0.18 warblers per hectare per count. Palo Colorado had the highest density with 0.30 warblers per hectare per count. Arendt (2013) summarizes that overall trends shows a significant decline trend “from c.0.2 individuals/ha in 1989 in elfin woodland to c.0.02/ha in 2006, and from 1 to 0.2 in palo colorado forest.” This warrants for immediate discussion to “reclassify the warbler as globally “Endangered”, especially in light of increasing climate change” (Arendt 2013). The habitat of importance is the Elfin Woodland Montane Forest type. Trends are an estimated direction of the species’ population through empirical data. These conclusions are to be accepted as an approximation within an acceptable range provided by the scientific data. Map 2- shows that both rain and wet habitat types consists of ridges, which are the most sensitive landforms due to multiple factors (i.e., development, effects from climate change).

Drivers

Drivers are the abiotic and biotic factors that play a role in the species’ status.

1) Man-made habitat alteration within known occurrence area

Man-made changes to habitat usually come in the form of vegetation or soil removal for either recreation or infrastructure purposes on the EYNF. These disturbances at times have an unknown long-term effects within a complex ecosystem. In other conspicuous examples a high distinction of change can be observed from the cumulative effects of these structures. For example a radio/radar tower or its support structure usually produces noise, has lights, or creates gas fumes. These structures may become sources for the spreading of invasive species or habitat conversion. Long-term changes, especially in sensitive vegetation types, are a considerable risk for species dependent on them. Through continuing complex effects of vegetation structures or effects to forage resources, these changes can take the shape of population level behaviors or specific habitat availability.

2) Hurricane intensity

Hurricanes, when over category 1, are known catalyst of change. The best example is Hurricane Hugo, a category 5, which denuded the entire EYNF in 1989. This had the same effect as a stand-replacement fire, where the dynamics of all species on the forest either benefitted or suffered in a new regeneration of vegetation types.

3) Invasive species

Terrestrial species such as mongoose (*Herpestes auropunctatus*), black rats (*Rattus rattus*), feral dogs (*Canis familiaris*) and cats (*Felis catus*); and honey bees (*Apis mellifera*); are suspected of affecting the population level, niche availability, and individual behavior of endemic species in locations where they interact. Undocumented observations of monkeys have also been a note of

interest due to their continued proximity to the EYNF. As of yet, there are no significant aquatic invasive species to address.

The EYNF has a significant presence of invasive tree and plant species. Species such as African tulip tree and Asian bamboo have affected the mid-story structure of the forest. Endangered, threatened, proposed, or candidate bird species requiring an open mid-story may have been affected over time by this new habitat structure through changes to food resources and other population growth factors.

4) Climate change (i.e., rain trends, average temperature change)

The effects of these abiotic factors occur in the long term, with possible responses from a dryer Caribbean region that includes susceptibility to amphibian, lizard, and bird species.

5) Effects from geological processes (i.e., Sahara dust into the Caribbean and volcanic ash from nearby Montserrat)

An apparent trend is that of the appearance of African dust in the air. African dust incursions have been recorded yearround; however, they are strongest and most noticeable during the summer months (Prospero and Lamb 2003). Mineral dust can have many effects on the communities of the region as well as the climate itself. There are observations of other effects to air and water compositions through organic and mineral deposits from these geological processes into EYNF's complex ecosystem.

2.7.1.5 Information Needs

The following information needs have been identified:

- Verification/validation of the availability and suitability of existing or potential Elinwoods warbler habitat.
- Relationship of managed habitats on NFS lands relative to currently available habitats on adjacent lands for potential use by endangered, threatened, proposed, or candidate species.

2.7.2 Potential Species of Conservation Concern

2.7.2.1 Existing Information

1. Coqui literature and comprehensive studies
2. Native lizard reports and comprehensive studies
3. Red-fig eating bat literature
4. Neotropical migratory bird reports and comprehensive studies

2.7.2.2 Informing the Assessment

Per the Land Management Planning Rule (USDA Forest Service 2012), the Forest Service is directed, within Forest Service authority and consistent with the inherent capability of the plan area, to maintain or restore ecosystem integrity and provide for the diversity of plant and animal communities. Furthermore, the Forest Service is to recognize and manage species of conservation concern.

To be considered a species of conservation concern, the species must be known to occur in the plan area and the regional forester must have determined that the best available scientific information indicates substantial concern about the species' capability to persist over the long term in the plan area. Per the above, the responsible official must comply with the Forest Service Handbook (FSH 1909.12, Chapter 10, 13.52), which directs that potential species of conservation concern should not be identified when a species is secure and their continued long-term persistence in the planning area is not at risk or insufficient scientific information is available to conclude that there is a substantial concern about the species' capability to persist in the plan area over the long term.

Coordination with the Puerto Rico Department of Natural and Environmental Resources (PRDNER) and other interested parties to gather additional distribution and ranking data would provide a basis for prioritizing conservation needs. Because the status of federally listed species and NatureServe global ranks can change, this assessment is considered "draft" until the new Forest Plan revision is signed.

The initial assessment of terrestrial wildlife vertebrate and invertebrate species occurring on the EYNF was completed using criteria described in the Planning Rule and Forest Service Handbook. The Puerto Rico "Comprehensive Wildlife Conservation Strategy" was the best available source of information for vertebrate and invertebrate species in Puerto Rico.

Ecosystem Integrity

Ecosystem integrity includes elements addressing biological diversity: species (population) viability; connectivity; corridors and linkages; neotropical birds; sink/source habitat and monitoring. These are discussed below.

Biological Diversity. Forest management practices that retain a full array of forest ecological components and species habitats (i.e., biological diversity) are expected to provide "inocula" to reestablish species into suitable habitats.

Species Viability. Species viability is influenced by total population size, habitat, and catastrophic fluctuations at the ecoregion or larger scale. A viable species is defined as consisting of self-sustaining populations that are well distributed throughout the species' range. Self-sustaining populations are those that are sufficiently large and have sufficient genetic diversity to display the array of life history strategies and forms that will provide for their persistence and adaptability in the planning area over time (USDA Forest Service 1999).

Connectivity (Corridors and Linkages). Per Samson et al. (1997), "Connectivity...refers to both the abundance and spatial patterning of habitat and to the ability of members of a population to move from patch to patch of similar habitat. Moreover, as a concept, it relates more to habitat specialists with limited dispersal abilities with a lower range of fragmentation." An approach to provide connectivity is through a corridor. Estill (1996) stated "[P]roject analysis does not evaluate a large enough area to effectively address a corridor system...if corridors or linkages are needed, they should be addressed at scales larger than the project." Samson (1997) further states that, "Corridors can, and often do, include habitats of a quality less than required for other life history requirements."

Migratory/Neotropical Birds. "Within the National Forests System, conservation of migratory/neotropical birds focuses on providing a diversity of habitat conditions at multiple spatial scales ensuring that bird conservation is addressed when planning for other land management activities" (FS Agreement #08-MU-1113-2400-264). Neotropical birds breed and

rear young in the Northern Hemisphere and migrate south to winter. According to Estill (1996), “They are widely distributed and use a variety of habitats... The changes (as the result of forest management) that occur in habitat at the project level are so small in scale compared to their total range that it is difficult to discuss effects on the (se) species as a whole.”

Ecosystem Diversity

Initial assessment of ecosystem diversity within a plan area relies on a review of the broad landscape-level ecological conditions (coarse filter) and animal species diversity within their expected landforms (fine filter). The abundance and distribution of wildlife species are linked to the availability, distribution, and inherent productivity of preferred habitats. Comparing current and historical vegetative and structural diversity may indicate if available species habitat deviates from historical conditions. Deviation below historical levels can result in available habitat limiting species populations and distribution.

Habitat loss is generally recognized as the greatest impact on the sustainability of productive and diverse wildlife populations. The combination of vegetative and structural diversity defines habitat diversity for wildlife. Through an ecosystem approach, the forest plan provides the framework to maintain or restore ecosystem elements of function, connectivity, security and quality conditions necessary to conserve most species. Conditions or features continually shift in response to ecosystem processes, forest disturbances, or invasive species. These factors characterize the biological potential of the habitat to support an overall or local population of a given species.

Identifying Potential Species of Conservation Concern

The following information was used to identify species which merit consideration as potential species of conservation concern. The identification of terrestrial wildlife vertebrate and invertebrate species that occur on the National Forests was completed using data collected from a number of sources:

1. NatureServe (Infonatura)
2. Puerto Rico Comprehensive Wildlife Conservation Strategy
3. Discoverlife.org
4. Puerto Rico Gap Project
5. Presence/absence data

The species of conservation concern list is derived from the NatureServe ranking system as discussed in section 2.6.1.3 of this assessment. As directed in USDA Forest Service (2013b), species of conservation concern with a status rank of G/T 1–2 on the NatureServe system will be considered. These species are already addressed because many of them are already federally threatened, endangered, potential or candidate species. Those species with a status rank of G/T 3 or S 1–2 will also be considered as species of conservation concern. For a full criterion for species of conservation concern categorizations refer to USDA Forest Service (2013b). The following defines the each status categorization.

As a special note on the wildlife and aquatic species found on the EYNF, there are very few Caribbean tropical species with S-rankings due to insufficiently assessments and distinctive fauna within the National Forest System. After consulting Jeff Holmes (2013), ecological sustainability evaluation tool contractor, the EYNF will include in its factors another crosswalk to translate best

available data to this section with notification to the PRDNER (see Appendix H). Although species that were used in the last Forest Plan (1997) as management indicator species may no longer occur due to species of conservation concern criterion, many are still monitored through annual surveys conducted by the EYNF.

Table 2-9. Subnational (S) conservation status ranks (NatureServe 2013)

Status	Definition
S1	<i>Critically Imperiled</i> —At very high risk of extirpation in the jurisdiction due to very restricted range, very few populations or occurrences, very steep declines, severe threats, or other factors.
S2	<i>Imperiled</i> —At high risk of extirpation in the jurisdiction due to restricted range, few populations or occurrences, steep declines, severe threats, or other factors.
S3	<i>Vulnerable</i> —At moderate risk of extirpation in the jurisdiction due to a fairly restricted range, relatively few populations or occurrences, recent and widespread declines, threats, or other factors.
S4	<i>Apparently Secure</i> —At a fairly low risk of extirpation in the jurisdiction due to an extensive range and/or many populations or occurrences, but with possible cause for some concern as a result of local recent declines, threats, or other factors.
S5	<i>Secure</i> —At very low or no risk of extirpation in the jurisdiction due to a very extensive range, abundant populations or occurrences, with little to no concern from declines or threats.

2.7.2.3 Current Conditions and Trends

Potential Wildlife Species of Conservation Concern

Using the best available scientific information available, species known to occur in the plan area for which there is substantial concern about the species' capability to persist over the long term in the plan area.

Table 2-10. Wildlife species of conservation concern

Scientific Name	English Common Name	Spanish Common Name	S-Ranking	PRDNER Rank ¹
Amphibian: Coqui Species Group (PRDNER 2008)				
<i>Eleutherodactylus eneidae</i>	Mottled coqui	Coqui de eneida	S1	CR/EC
<i>Eleutherodactylus karlshmidti</i>	Web-footed coqui	Coqui palmeado	S1	CR/EC
<i>Eleutherodactylus unicolor</i>	Burrow coqui	Coqui duende	S2	DD/BV
<i>Eleutherodactylus locustus</i>	Warty coqui	Coqui martillito	S2	VU/EC
<i>Eleutherodactylus richmondi</i>	Ground coqui	Coqui caoba	S2	VU/EC
<i>Eleutherodactylus gryllus</i>	Cricket coqui	Coqui grillo	S2	DD/BV
<i>Eleutherodactylus hedricki</i>	Tree-hole coqui	Coqui de hedrick	S2	DD/EC
<i>Eleutherodactylus portoricensis</i>	Puerto Rican coqui or upland coqui	Coqui de la montana	S2	VU/EC
<i>Eleutherodactylus wightmanae</i>	Wrinkled coqui	Coqui melodioso	S2	DD/BV

Scientific Name	English Common Name	Spanish Common Name	S-Ranking	PRDNER Rank ¹
Reptiles: Lizard (PRDNER 2005)				
<i>Anolis cuvieri</i>	Puerto Rican giant anole	El legarto verde	S2	DD
<i>Anolis occultus</i>	Puerto Rican pygmy anole	Legartijo pigmeo	S2	DD/BV
Mammal (PRDNER 2008)				
<i>Stenoderma rufum</i>	Red fig-eating bat	Murcielago frutero nativo	S2	VU/EC
Bird (PRDNER 2005)				
<i>Icterus dominicensis</i>	Black-cowled oriole	Calandria	S2	DD/BV
<i>Dendroica caerulescens</i>	Black-throated blue warbler	Reinita azul	S2	DD
<i>Falco peregrinus</i>	Peregrine falcon	Falcon peregrinus	S1	CR/EC
Fishes and Aquatic Species (PRDNER 2005)				
<i>Anguilla rostrata</i>	American eel	Anguilla	S1	DD
<i>Awaous banana</i>	River goby	Saga, gobio de rio	S2	DD
<i>Dormitor maculatus</i>	Fat Sleeper	Mapiro	S2	DD
<i>Eleotris pisonis</i>	Spinycheek sleeper	Moron	S2	DD
<i>Gobiomorus dormitor</i>	Bigmouth sleeper	Guavina bocon	S2	DD
<i>Macrobrachium carcinus</i>	River shrimp	Camaron de rio	S2	LR-da,BV
<i>Macrobrachium crenulatum</i>	A shrimp	Camaron	S2	LR-ca/EC

¹ The PRDNER rank is from Puerto Rico comprehensive wildlife conservation strategy (Garcia 2005) and the Puerto Rico natural patrimony species list (Rivera 2008, 2013). The PRDNER adapted the following five categories from the international union of conservation of nature red list (IUCN 2012): Critically Endangered (CR); Endangered (EN); Vulnerable (VU); Low Risk (LR); and Data Deficient (DD).

A brief description of the ecology and distribution for this potential species of conservation concern for the EYNF follows.

Amphibians

The **Coqui species** group consists of endemic species of tree frogs all of the genera *Eleutherodactylus* that are known through annual counts and scientific literature on the EYNF. Unlike most generally known amphibians these frogs are born from their eggs in a small adult form; there is no tadpole stage that requires a freshwater environment (Joglar 1998). These amphibians are also known to have brooding mechanisms such as laying eggs that are protected by the males. Similar to other tree frog species these species have a susceptibility to significant environmental changes.

There are nine species of coquies that qualify for species of conservation concern categorization. Many of these coqui species are specific to an ecological niche or habitat type and have had limitations to the expansion of their population distribution. Joglar (1998) recorded many of the different habitat preference on the EYNF for these species, as an example, some only occur on high elevations with moist conditions while others prefer vegetation types that provides large leaves and plants that can create microhabitats that completes their lifecycles.

Since the mid-1970s, the chytrid fungus (*Batrachochytrium dendrobatidis*) has been identified on the Island of Puerto Rico and an expected greater impact to mid-elevation frog populations (Longo 2010). The PRDNER also considers the need to accumulate more information of the amphibian group due to the risk from the disease to the natural resources.

Trends show that as a whole, coqui species are declining (Longo 2010). The prevalence of chytrid in the mountain ranges of the Island (Burrows et al. 2010); is having serious impacts to occurrences of all of the nine species listed above.

Reptiles

The **Puerto Rican giant anole lizard** is an endemic, arboreal lizard species. The species prefers mature tabonuco and sierra palm habitat, where the lizard can exist in the upper and mid-portions of these vegetation types. The species is difficult to detect in occurrence surveys because it blends-in with its surroundings. Current conditions show the species at sites in the upper elevations of the EYNF through accidental occasions from the Puerto Rico Road 191 in 2013 and 2008.

The **Puerto Rican pigmy anole** is another endemic species. [In development].

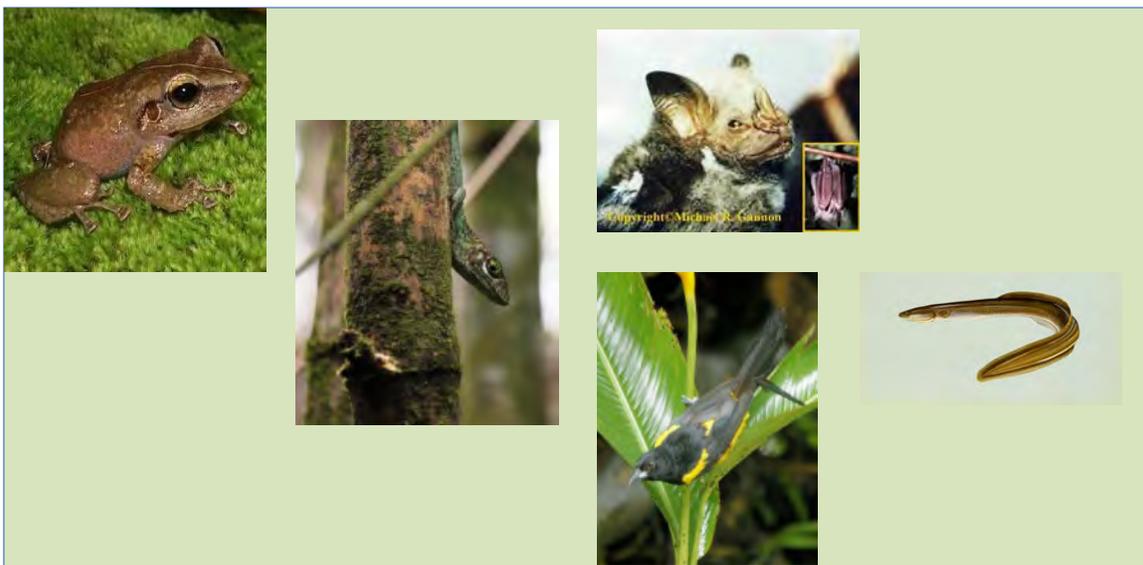
Mammals

The **Red fig-eating bat** is endemic to the Greater Antilles and occurs on very few islands. This species appears most common in the Luquillo Experimental Forest (EYNF), where at one time it represented at least 25 percent of bats captured in Tabonuco Forest (Willig and Bauman 1984). The International Union for Conservation of Nature Resources classifies this species as vulnerable to extinction (Hutson et al. 2001). At this time the red fig-eating bat has one of the smallest geographic distributions, which contributes to being exposed to a risk of extinction in the future (Gannon et al. 2005).

The bat's present conditions can be traced back to the devastating effects from Hurricane Hugo in 1989. Immediately after the hurricane, captures of the red fig-eating bat decreased by 80 percent and population level did not return to pre-hurricane levels until 5 years following the storm (Gannon 2002). A total of 113 individual red fig-eating bats were captured within the planning area of the EYNF (Gannon 2005).

Birds

The Black-cowled Oriole. [In development]



The **black-throated warbler** qualifies to be on the species of conservation concern list through its susceptibility to both its summer habitat and winter habitat that includes the EYNF. There is a little research done in Puerto Rico on its population, but it is known to be occurring on the Island through Audubon Christmas bird counts. The species is known to prefer continuous stands of native vegetation where the bird can glean insects from leaves to eat. These insects, such as warble flies, occur in many of the riparian and mid-story levels of vegetation types that are sensitive to temperature changes.

The **Peregrine Falcon**. [In development]

Fishes and Aquatic Species

The **American eel** are well documented aquatic wildlife species and are eligible because of shrinking numbers and distribution. The eel require clean and flowing water, so waterfalls and dams act as an obstacle that can, however, be overcome through the use of the eel's modified pectoral fins that act as suction cups on rocky substrates during high water occurrences within the EYNF. [In development]

The remainder of the fish group includes the four goby species named as either a goby or sleeper and will be address as a species group due to similar needs and conditions. [In development]

The two invertebrate species of freshwater shrimps shall be address as a species group due to similar needs and conditions. [In development]

2.7.2.4 Drivers

The following drivers are occurring and affecting terrestrial and aquatic wildlife.

1) Man-made habitat alteration within known occurrence area

Man-made changes to the habitat usually come in the form of vegetation removal for either recreation or infrastructure purposes. The more impacting are the infrastructure due to their lasting activities. A radio/radar tower or support structure usually produces noise, has lights, or creates gas fumes. The changes for recreation purposes, especially in sensitive vegetation types, adds human presence, which can be a huge risk for species dependent on those areas. Appendix H includes a species richness index map of the EYNF with roads and trails included. The map, which shows the conflict of biological resources and infrastructure structures, displays the concentration of species richness and the locations of roads and trails.

2) Hurricane intensity

Hurricanes when over category 1 are known catalyst of change. The best example is Hurricane Hugo, a category 5, which denuded the entire EYNF in 1989. This had the same effect as a stand-replacement fire, where the dynamics of all species on the forest either benefitted or suffered in a new regeneration of vegetation types.

3) Invasive species

Terrestrial species such as mongoose (*Herpestes auropunctatus*), black rats (*Rattus rattus*), feral dogs (*Canis familiaris*) and cats (*Felis ca t us*) are suspected of affecting the population level, niche availability, and individual behavior of endemic species in locations where they interact. Undocumented observations of monkeys are of interest due to their proximity to the EYNF. As of yet, there are no significant aquatic invasive species to address.

4) New diseases

New infectious fungus, molds, and viruses in recent decades have been a new issue due to their unknown direct, indirect, and cumulative effects to an ecosystem. Our highly susceptible population of coquis would certainly have impacts from the chytrid disease on the EYNF. Other disease threats to wildlife include West Nile virus, dengue, and rabies.

5) Climate change (i.e., rain trends, average temperature change)

The effects of these abiotic factors would be in long term, as the Caribbean region becomes drier. Amphibians, lizards, and bird species would be the most susceptible.

6) Geological occurrence (Sahara dust into the Caribbean and volcanic ash from nearby Montserrat)

An apparent trend is that of the appearance of African dust in the air. African dust incursions have been recorded yearround; however, they are strongest and most noticeable during the summer months (Prospero and Lamb 2003). Mineral dust can have many effects on the communities of the region as well as the climate itself. There are observations of other effects to air and water compositions through organic and mineral deposits from these geological processes into EYNF's complex ecosystem.

7) Collection of specimens for either consumption or scientific use

As more of the local populations experience changes, the direct collections of many of our vertebrate and invertebrate species are threatened by depletion of individuals from present population levels.

2.7.2.5 Information Needs

- 1) Individual species population levels within the planning to compare with baseline data.
- 2) Identify any food resources status for the coqui, lizard, and bird species; this includes surveys of insect fauna presence/absence with earlier scientific studies.
- 3) Aquatic invertebrate population data for the viability of the aquatic fauna.
- 4) Occurrences of poisoning events on the rivers of the EYNF.

2.7.2.6 Key Findings and Recommendations

These findings and recommendations provide a set of future goals that may be used for the standards and management areas designations. The results are a summary of the information found through this document.

There are within the designation of at-risk species in the new planning rule two sections of categorization, “ 1) federally recognized threatened, endangered, proposed and candidate species... and 2) species of conservation concern” (USDA Forest Service 2013b).

- For the EYNF under the federally listed endangered, threatened, proposed, or candidate category there are five listed species: the Puerto Rican parrot, Puerto Rican broad-winged and sharp-shinned hawks, Puerto Rican booby, and Elf-in-woods warbler. One listed species has been extirpated, the white-necked crow.

- ▶ The species of conservation concern category consists of nine species of coqui, two species of anole lizards, one bat species, four bird species, five species of fishes and two species of freshwater shrimp.
- ▶ The Elfín-woods warbler is now in a higher priority for the USFWS and is presently conducting a candidate conservation plan with the EYNF to meet the challenge of reducing range. The conservation plan is an attempt to avoid being categorized as endangered.
- ▶ Regarding the four federally listed birds: Puerto Rican parrot, Elfín-woods warbler, Puerto Rican sharp-shinned hawk and Puerto Rican broad-winged hawk, population conditions on the EYNF are greatly affected by the present vegetation structure. To improve habitat quality, there is a need for wildlife stand improvements for these species to address changed conditions and vegetation structure diversity in corridors throughout the EYNF.

2.7.2.7 Authority for Management of Wildlife and Fisheries Species

Under Forest Service Manual (FSM) 2600 is summary of the authority for the National Forest System lands to manage wildlife and fisheries resources, which encompasses all of the approximate 29,000 acres of the EYNF. The following is a selected list of specific laws and regulations for the EYNF to provide desired conditions, standards, and guidelines.

1. Migratory Bird Treaty Act of 1918
2. Multiple-Use, Sustained Yield Act of 1960
3. Agricultural Appropriation act of 1908
4. Fish and Wildlife Coordination Act
5. National Environmental Policy Act of 1970
6. Forest and Rangeland Renewable Resources Planning Act of 1974
7. Federal Water Pollution Control Act of 1956
8. National Forest Management Act of 1976
9. Sikes Act of 1960
10. Endangered Species Act of 1973
11. Candidate Conservation Agreements
12. USDA Department regulation 9500-4

2.7.2.8 Literature Cited

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2.8 Identifying and Assessing At-risk Flora Species in the El Yunque National Forest

2.8.1.1 Information

In order to identify the species at-risk on the EYNF the following references and Databases were examined:

1. Puerto Rico Endangered Plants Initiative (PREPI), PREPI_SpecimenData.accdb, The New York Botanical Garden, 2011.
2. Addressing Target Two of the Global Strategy for Plant Conservation (GSPC) by Rapidly Identifying Puerto Rican Plants at Risk. Gary A. Krupnick, James S. Miller, Holly A. Porter-Morgan, Pedro Acevedo-Rodriguez, National Museum of Natural History, Smithsonian Institution, Washington D.C., USA. The New York Botanical Garden, Bronx NY, USA, 2012.
3. "Toward Target 2 of the Global Strategy for Plant Conservation: an expert analysis of the Puerto Rican flora to validate new streamlined methods for assessing conservation status" Puerto Rican Plant Conservation Status Database developed by the Smithsonian Institution, the New York Botanical Garden and the International Union for the Conservation of Nature (IUCN); J. Miller et al. 2012
4. A Systematic Vademecum to the Vascular Plants of Puerto Rico, Franklin S. Axelrod, 2011.
5. Discover Life Database at <http://www.discoverlife.org/>
6. USDA, Natural Resources Conservation Service, PLANTS Database at <http://plants.usda.gov/>

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From the information screened, a total of 636 plant species were identified on the EYNF and entered into the Ecological Sustainability Evaluation tool for further analysis (see Appendix H). From the Element Priority Report (Ecological Sustainability Evaluation tool), 51 species were identified as species at-risk (see Appendix H): 8 are federally listed, 26 are in the G1 rank, 16 are in the G2 rank, and 1 is in the G3 rank.

The native status, last date of official recorded occurrence, and the local or Federal legal conservation status was determined for the 51 species. From this information, an initial potential list of 14 plants of species of conservation concern was recommended for further analysis and determination. This list of potential species of conservation concern identified in the assessment may be modified during the planning process before approval of the plan (FSH 1909.12.52).

2.8.1.2 Current Conditions

Federally Recognized Species

EYNF has eight federally listed species within its boundaries. All have been declared endangered by the USFWS and all have a Recovery Plan developed and approved by USFWS.

During the 2011, El Yunque assisted USFWS in the preparation of a 5-year review for the following species: *Styrax portoricensis*, *Ilex obcordata*, *Eugenia haematocarpa*, *Callicarpa ampla*, *Ternstroemia luquillensis* and *T. subsessilis*.

Styrax, *Eugenia*, *Pleodendrum* and *Callicarpa* spp. have been reproduced at El Yunque via seeds or air layering. Overall, the individuals, thus populations of these species, have increased at El Yunque and at other protected lands in Puerto Rico where they have been reintroduced or new populations located via surveys.

A 2001 survey showed an increase of four times the number of *Lepanthes eltoroensis* individuals reported at the time when the Recovery Plan for the species was developed in 1996. The total known population and expected new sites where the population may also exist lies protected within the El Toro Wilderness Area.

Ternstroemia luquillensis and *T. subsessilis* were not able to be located during the 5-year review field surveys at EYNF. There is an information gap about these two species due to the lack of monitoring surveys and official recent reports. Reconnaissance field surveys for the historic recorded sites will be implemented to determine the actual status of the species at EYNF.

Ilex obcordata showed to be stable and new populations sites were documented for the species at EYNF during the 5-year review surveys.

Identifying Potential Species of Conservation Concern

From the list of vegetation species analyzed via the ESE Tool, the following list of species of conservation concern was developed for further consideration.

Table 2-11. Proposed list of potential species of conservation concern

	Species	Rank	Federal Status	Status Class	Last Occurrence	Conservation Status	Information Gap	Species of Conservation Concern
1	<i>Lepanthes caritensis</i>	G1		Endemic	2003	Endangered		X
2	<i>Lepanthes stimsonii</i>	G1		Endemic	2002	Endangered		X
3	<i>Miconia foveolata</i>	G1		Endemic	2010	Vulnerable		X
4	<i>Solanum woodburyi</i>	G1		Endemic to Luquillo Mountains	2000	Endangered		X
5	<i>Calyptranthes luquillensis</i>	G1		Endemic to Luquillo Mountains	2001	Endangered		X
6	<i>Laplacea portoricensis</i>	G1		Native	2010	Critically Endangered		X
7	<i>Ardisia luquillensis</i>	G1		Endemic	2013	Endangered		X
8	<i>Brachionidium parvum</i>	G1		Native	2000	Near Threatened		X
9	<i>Ravenia urbanii</i>	G1		Endemic	1999	Endangered		X
10	<i>Eugenia borinquensis</i>	G2		Endemic	2011	Vulnerable		X
11	<i>Eugenia stahlii</i>	G2		Endemic	2010	Vulnerable		X
12	<i>Eugenia eggersii</i>	G2		Endemic	2004	Critical Element; State Status		X
13	<i>Calyptranthes woodburyi</i>	G2		Endemic	2001	Endangered		X
14	<i>Magnolia splendens</i>	G3		Endemic to Luquillo Mountains	2010	Critical Element; State Status		X

Evaluating Relevant Information for At-Risk Species

See Appendix H.

Status of At-Risk Species

Within the boundaries of the EYNF, there are 225 species of native trees, 88 of which are classified as endemic or rare. Sixty-eight of those endemic or rare species are limited to Puerto Rico and 23 of those are found only within the Forest boundaries. The list of 23 species includes 7 which range slightly beyond the Luquillo Mountains, but 16 have their entire natural range within the EYNF. The EYNF has the sole responsibility for the management and protection of these species (Little and Woodbury 1976).

No endemic tree species of Puerto Rico is known to have become extinct. The mountains forests, centers of endemism, remained nearly undisturbed for centuries. There is no indication that any rare plant, and trees in particular, may have been eliminated by human activities before the arrival of plant collectors. Almost all the endemic tree species named long ago from Puerto Rico have been found by later collectors including the present authors. Likewise, nearly all rare border or peripheral species of older lists have been located (Little and Woodbury 1980).

Several endemic tree species apparently need additional protection because they are very rare and limited in area, and because they grow on privately owned lands subject to other uses and destruction of the habitat. Several rare endemic tree species should be watched or monitored because of their restricted occurrence (Little and Woodbury 1980).

Endangerment implies an immediate or, at very least, an impending imperilment; rarity can be a very subjective concept. Endangered species are always rare although the reverse is not invariably true. Also, rarity can be assessed in terms of individuals or populations (Figueroa Colon and Woodbury 1996).

Table 2-12. Ecological sustainability evaluation report for species at-risk

	Species	Rank	Federal Conservation Status	Status Classification	Last Occurrence	Conservation Status	Information Gap	Potential Species of Conservation Concern
1	<i>Callicarpa ampla</i>	G1	Endangered	Endemic	2011			
2	<i>Eugenia haematocarpa</i>	G1	Endangered	Endemic	2011			
3	<i>Ilex obcordata</i>	G1	Endangered	Endemic	2011			
4	<i>Lepanthes eltoroensis</i>	G1	Endangered	Endemic to Luquillo Mountains	2001			
5	<i>Pleodendron macranthum</i>	G1	Endangered	Endemic	2011			
6	<i>Styrax portoricensis</i>	G1	Endangered	Endemic	2011			
7	<i>Ternstroemia luquillensis</i>	G1	Endangered	Endemic	1988		X	
8	<i>Ternstroemia subsessilis</i>	G1	Endangered	Endemic	1980		X	
9	<i>Brachionidium ciliolatum</i>	G1		Endemic	1969	Critically Endangered	X	
10	<i>Lepanthes caritensis</i>	G1		Endemic	2013	Endangered		X
11	<i>Lepanthes dodiana</i>	G1		Endemic	1998	Endangered	X	
12	<i>Lepanthes selenitepala</i> <i>ssp. ackermanii</i>	G1		Endemic	2011	No data		
13	<i>Lepanthes stimsonii</i>	G1		Endemic	2002	Endangered		X
14	<i>Marlierea sintenisii</i>	G1		Endemic	1963	Endangered	X	
15	<i>Miconia foveolata</i>	G1		Endemic	2010	Vulnerable		X
16	<i>Miconia pycnoneura</i>	G1		Endemic	No data	Endangered	X	
17	<i>Pilea multicaulis</i>	G1		Endemic	No data	Critically Endangered	X	
18	<i>Symplocos lanata</i>	G1		Endemic	1988	Vulnerable	X	
19	<i>Ternstroemia heptasepala</i>	G1		Endemic to Luquillo Mountains	1995	Critically Endangered	X	
20	<i>Varronia wagnerorum</i>	G1		Endemic to Luquillo Mountains	1988	Critically	X	

	Species	Rank	Federal Conservation Status	Status Classification	Last Occurrence	Conservation Status	Information Gap	Potential Species of Conservation Concern
						Endangered		
21	<i>Xylosma schwaneckiana</i>	G1		Endemic	1995	Endangered	X	
22	<i>Solanum woodburyi</i>	G1		Endemic to Luquillo Mountains	2000	Endangered		X
23	<i>Calyptanthes luquillensis</i>	G1		Endemic to Luquillo Mountains	2001	Endangered		X
24	<i>Cybianthus sintenisii</i>	G1		Endemic to Luquillo Mountains	No data	Endangered	X	
25	<i>Pilea yunquensis</i>	G1		Endemic	1996	Least Concern	X	
26	<i>Laplacea portoricensis</i>	G1		Native	2010	Critically Endangered		X
27	<i>Ardisia luquillensis</i>	G1		Endemic	2013	Endangered		X
28	<i>Maythenus elongata</i>	G1		Native	1995	Vulnerable	X	
29	<i>Brachionidium parvum</i>	G1		Native	2000	Near Threatened		X
30	<i>Brunfelsia lactea</i>	G1		Endemic	1994	Least Concern	X	
31	<i>Brunfelsia portoricensis</i>	G1		Endemic	1992	Least Concern	X	
32	<i>Psidium sintenisii</i>	G1		Endemic	1971	Endangered	X	
33	<i>Ravenia urbanii</i>	G1		Endemic	1999	Endangered		X
34	<i>Lindsaea stricta</i> var. <i>jamesoniiformis</i>	G1		Native	No data	Critical Element	X	
35	<i>Eugenia borinquensis</i>	G2		Endemic	2011	Vulnerable		X
36	<i>Eugenia stahlia</i>	G2		Endemic	2010	Vulnerable		X
37	<i>Garcinia portoricensis</i>	G2		Endemic	No data	Vulnerable	X	
38	<i>Gonocalyx portoricensis</i>	G2		Endemic	2003	Endangered		
39	<i>Lepanthes veleziana</i>	G2		Endemic	2012	Least		

	Species	Rank	Federal Conservation Status	Status Classification	Last Occurrence	Conservation Status	Information Gap	Potential Species of Conservation Concern
						Concern		
40	<i>Lepanthes woodburyana</i>	G2		Endemic	2012	Least Concern		
41	<i>Mikania pachyphylla</i>	G2		Endemic	1993	Endangered	X	
42	<i>Morella holdrigeana</i>	G2		Endemic	1979	Endangered	X	
43	<i>Justicia martinsoniana</i>	G2		Endemic	No data	Least Concern	X	
44	<i>Urera chlorocarpa</i>	G2		Endemic	1967	Endangered	X	
45	<i>Ternstroemia stahlii</i>	G2		Endemic	2000	Least Concern		
46	<i>Eugenia eggersii</i>	G2		Endemic	2004	Critical Element		X
47	<i>Banara portoricensis</i>	G2		Endemic	1986	Critically Endangered	X	
48	<i>Calyptranthes woodburyi</i>	G2		Endemic	2001	Endangered		X
49	<i>Conostegia hotteana</i>	G2		Native	No data	Least Concern	X	
50	<i>Coccoloba rugosa</i>	G2		Native	1992	Vulnerable	X	
51	<i>Magnolia splendens</i>	G3		Endemic to Luquillo Mountains	2010	Critical Element		X