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# Effects and outcomes of Caribbean hurricanes in a climate change scenario

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## Abstract

Hurricanes are complex disturbance systems with significant effects on vegetation and built-up land. This paper summarizes research on the effects and outcomes of hurricanes on Caribbean forests. Twelve effects and outcome topics are presented: sudden and massive tree mortality; delayed patterns of tree mortality; alternative methods of forest regeneration; opportunities for a change in successional direction; high species turnover and opportunities for species change in forests; diversity of age classes; faster biomass and nutrient turnover; species substitutions and changes in turnover time of biomass and nutrients; lower aboveground biomass in mature vegetation; carbon sinks; selective pressure on organisms; and convergence of community structure and organization. Effects of hurricanes on urban systems are also discussed. While there is scientific uncertainty as to whether hurricane frequencies and intensity will change as a result of global climate change, available understanding on the effects and outcomes of hurricanes can be used to anticipate possible effects of either increasing or decreasing hurricane frequency and intensity. Proposed mitigation actions and research priorities can be effective and desirable even if the frequency and intensity of hurricanes remains unchanged.

*Keywords:* Hurricanes; Disturbance; Caribbean; Tropical forests; Large and infrequent disturbances; Wind storms

> The level of societal risk to hurricane impact is a function of the frequency, strength, and duration of landfalling hurricanes, and on the degree of preparedness and types of mitigation strategies available to and employed by different segments of society (from Diaz and Pulwarty, 1997a, p 3).

> If we are not careful, we may end up where we are going. [Chinese proverb in Diaz and Pulwarty (1997b), p 201].

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## 1. Introduction

The global hurricane belt includes all tropical oceans between latitudes 40°S to 40°N except the southern Atlantic (Tannehill, 1938). Hurricanes can induce changes in landform, change vegetation, and influence human life quality and the economy over vast areas. Hurricanes also play an important role in the climate of the world as their formation, size, intensity, and movement, are influenced by the world's heat balance and momentum. They transport excess heat and moisture from the tropics to temperate and boreal latitudes. Hurricanes also alter local climate over the medium term by modifying vegetation cover and altering evapotranspiration and runoff rates.

Hurricanes form over ocean waters with surface temperatures of at least 26°C, but many other factors determine whether a hurricane will be formed or not. For example, hurricane activity in the Atlantic has been correlated with the West African monsoon, Atlantic thermohaline variability, global surface sea temperature, and decadal variation in major ocean circulations (Gray et al., 1997). Many of these correlates are influenced by phenomena associated with El Niño. Hurricanes of higher intensity impact the USA coastline when the Sahel experiences wet years than when it experiences periods of dry years. Because of the close interaction between hurricanes, climate, biota, and human activity, it is important to understand the effects, if any, of global climate change on hurricane behavior and/or occurrence.

A single hurricane can travel thousands of miles and changes continuously in size and intensity until it dissipates into a low pressure system and harmless rain. On a given region, such as the Caribbean, the tracks of hurricanes exhibit a wide range of spatial (latitudinal) and temporal (at seasonal, annual, and decadal periods) variability in frequency, size, and intensity (Neuman et al., 1978; Gray et al., 1997). When they pass over land masses, hurricanes interact with local topography and conditions and their passage results in heterogeneous impacts (Boose et al., 1994).

Table 1
Frequency (recurrence interval) and intensity of a variety of disturbances that accompany a hurricane[a]

| Disturbance | Recurrence interval (years) | Intensity |
|---|---|---|
| Hurricane Hugo | 60 | Category 3–4 |
| Rainfall | 5 | 100–339 mm |
| Flooding | Approx. 5 | Scattered areas |
| Peak basin runoff | 10–31 | 58–138 mm/h |
| Wind speed | 100 | > 148 km/h |
| Tornadoes | 60? | ? |
| Storm surge | 30 | 1.8–2.4 m above high tide |

[a] Not all hurricanes produce all of the disturbances shown, and the intensity and frequency of each of the accompanying event changes over the landscape and with each hurricane. These values roughly correspond to estimates for north-eastern Puerto Rico for the passage of Hurricane Hugo (USGS, 1989; Scatena and Larsen, 1991).

A hurricane disturbance is a complex event. Hurricanes are accompanied by wind and rain — two forces that can be disturbances in their own right. High rainfall can cause floods and interacts with topography and geologic substrate to induce mass wasting events, e.g. land, mud, and debris slides. Wind behavior during a hurricane is com-

Table 2
Criteria by which hurricane intensity is defined according to the Saffir/Simpson (SS) scale (Gray et al., 1997)

| SS scale | Central pressure (mbar) | Maximum sustained wind speed (m/s) | Storm surge (m) | Relative potential destruction |
|---|---|---|---|---|
| 1 | 980 | 33–42 | 1.0–1.7 | 1 |
| 2 | 965–979 | 43–49 | 1.8–2.6 | 10 |
| 3 | 945–964 | 50–58 | 2.7–3.8 | 50 |
| 4 | 920–944 | 59–69 | 3.9–5.6 | 100 |
| 5 | < 920 | > 69 | ≥ 5.6 | 250 |

plex and intense downbursts and localized tornadoes can occur under certain conditions. Moreover, winds induce heavy seas which result in storm waves, wave swash, and flooding on coastal areas and large waves at sea. Damage to coastal zones due to mechanical effects of waves and flooding can be significant. In short, hurricanes induce different types of disturbance events each with its own frequency and intensity, independent of the frequency and intensity of the hurricane system itself (Table 1). Hurricane intensity is usually described by the Saffir/Simpson Hurricane Scale (Table 2).

## 2. Impacts of hurricanes

Hurricanes have been the subject of considerable study as meteorological events and in terms of their effects on human systems (Tannehill, 1938; Riehl, 1954; Tomblin, 1981; Diaz and Pulwarty, 1997a). Their effects on natural ecosystems are now being studied in greater detail both in tropical and temperate latitudes (Walker et al., 1991, 1996; Waide and Lugo, 1992; Lugo and Waide, 1993; Foster et al., 1997, 1998). Due to their recurrence and power, hurricanes contribute to shaping vegetation and ecosystem processes. However, Caribbean forests in different geographic locations appear to respond differently to hurricanes. For example, regeneration after Hurricane Joan in Nicaragua (Vandermeer et al., 1996) was different than regeneration after Hurricane Hugo in the Luquillo Mountains (Scatena et al., 1996). This, in my opinion, has to do with the greater hurricane frequency in Puerto Rico (approx. 50 hurricanes per century — all intensities) than in Nicaragua (< 10 hurricanes per century). This paper is based on experience in Puerto Rico, which is a harbinger of what happens to vegetation and ecosystem processes under high hurricane frequencies.

## 3. Known and potential effects of hurricanes on Caribbean vegetation

The passage of Hurricane Hugo in 1989 over long-term ecological research sites in Puerto Rico gave us an opportunity to examine in detail the effects of this event on the structure, composition, and functioning of tropical forests in the Luquillo Mountains (Walker et al., 1991, 1996). Below, the findings of much of this research are summarized in twelve statements of effects or outcomes. These statements provide a base from which we can evaluate how changes in hurricane frequency and intensity due to climate change might influence forest ecosystems.

- *Sudden and massive tree mortality.* The pattern of tree mortality after the passage of a hurricane is different from normal tree mortality. Normal rates of tree mortality averaged 1.6% per year over the neotropics ($n = 68$), rarely exceed 3% per year, and generally occur gradually (Lugo and Scatena, 1996). Tree mortality after a hurricane is generally instantaneous — and while variable — averages 41.5% ($n = 23$). The ecological effects of a catastrophic, massive, and sudden tree mortality event contrast with those of background, local, and gradual tree mortality in terms of the direction of succession after the event, community dynamics, nutrient cycling, and possibly selection pressure on individuals (Lugo and Scatena, 1996).
- *Delayed patterns of tree mortality.* Delayed tree mortality — that which is observed months-to-years after the event — can be as high or higher in magnitude than tree mortality measured immediately after the event (Frangi and Lugo, 1998). For tree populations that are of low density, a delayed pattern of tree mortality can be of sufficient magnitude to cause local — at the 1 ha level — extinctions of populations.
- *Alternative methods of forest regeneration.* Hurricanes cause two contrasting regeneration pathways — large gap opening where species composition is vastly different from the species composition in small gaps (Cammack, 1990; Scatena et al., 1996), and — mineral soil regeneration in landslide areas, where the regeneration of forest conditions can be delayed (Guariguata, 1990; Zarin, 1993; Zarin and Johnson, 1995). These contrasting modes

of regeneration result in a patchwork of vegetation with contrasting species composition and different rates of growth.

- *Opportunities for a change in successional direction.* Plant succession has an opportunity to change direction after a hurricane because of three conditions that result from the event: (1) the increased number of species that gain access to canopy gaps; (2) the possibility of long distance seed dispersal by vectors such as hurricane winds or animal populations that are forced to forage over longer distances due to scarcity of food resources; and (3) the new site conditions created by gaps, landslides, tip up mounds, and laying dead stems.
- *High species turnover and opportunities for species change in forests.* Opportunities for invading plant species are created by the same conditions that lead to a change in successional direction. Differential tree mortality and differences in regeneration strategies also lead to dramatic species turnovers at the 1-ha patch level (Doyle, 1982; Lugo and Scatena, 1995). As an example, Frangi and Lugo (1998) found that 5 years after Hurricane Hugo, 13 tree species not represented in the canopy entered, and four disappeared, in a palm floodplain forest in the Luquillo Mountains.
- *Diversity of age classes.* The vegetation after the passage of a hurricane is characterized by a diversity of stand ages due to differential effects of the hurricane on stand structure, species composition, and site conditions (Scatena and Larsen, 1991). The effects of the hurricane are not homogeneous because of the variation in hurricane intensity as it passes over the forest and the differences in vegetation resistance to winds and rain. The causes of the variation in storm strength are: (1) the presence of physical and biotic modifiers of the disturbing force; (2) the spatial and temporal variation in the disturbing force; and (3) the spatial variability in the stands subjected to the disturbance. Paradoxically, it is common to find mature stands that survive the hurricane in proximity to regenerating even age stands, as well as mixed-age stands.
- *Faster biomass and nutrient turnover.* A hurricane transfers large amounts of biomass and nutrients from the aboveground to the forest floor (Frangi and Lugo, 1991). Once on the ground, this material decomposes rapidly and its decomposition is accompanied by a rapid regrowth of vegetation and transfer of nutrients from the forest floor and soil back to aboveground vegetation (Scatena et al., 1996). Processes occur at rates that are faster than measured before the hurricane. For example, Scatena et al. (1996) reported that for a 5-year period after Hurricane Hugo, net aboveground primary productivity rates averaged 21.5 Mg/ha per year, almost triple the rate prior to the hurricane. Scatena (1995) found that the turnover of nutrients and biomass in the Luquillo Mountains of Puerto Rico was synchronized to the return time of disturbance events. Thus, if hurricanes such as Hugo return once every 60 years, vegetation recovery in terms of biomass and nutrient accumulation took place in a similar length of time. Faster turnover rates in ecosystem compartments allow for faster recovery after the disturbance, and thus, less lasting effects of particular disturbance frequencies and intensities. If the disturbance returns at intervals shorter than the recovery time of vegetation, the system is proportionally degraded to lower states of biomass and nutrient accumulation.
- *Species substitutions are often associated with changes in turnover time of biomass and nutrients.* The succession of species after Hurricane Hugo was associated with dramatic changes in the turnover of nutrients and biomass (Scatena et al., 1996). Nutrient-rich and fast turnover herbaceous species (including ferns and vines) invaded open areas first and stored nutrient quantities equivalent to the nutrient transfer from the canopy to the forest floor. These species were substituted by trees with slower nutrient and biomass turnover rates, but with nutrient-rich tissue, e.g. *Cecropia schreberiana*, *Psychotria berteriana*, and *Guarea glabra*. Tree species with a longer live span with a slower nutrient turnover and

lower nutrient concentration in tissue followed early successional species, e.g. *Dacryodes excelsa*, *Manilkara bidentata*, and *Sloanea berteriana*.

- *Lower aboveground biomass in mature vegetation*. Because of the high frequency of hurricane disturbance in the Luquillo Mountains, the amount of biomass that can accumulate aboveground between events is lower than would occur if the stand was not disturbed. As a result, when conditions are similar, locations with higher disturbance frequencies exhibit lower aboveground biomass than locations with lower frequencies of disturbance (Scatena and Lugo, 1995).
- *A carbon sink*. Hurricanes create carbon sinks by: burying woody debris under landslides; transporting wood to environments where wood decomposition is slower, i.e. streams, estuaries, and oceans; and by the rapid biomass accumulation following the event. Aboveground biomass reaches almost pre-hurricane values in 7 years (Scatena et al., 1996; Frangi and Lugo, 1998) and coarse woody debris remain in situ for decades resulting in greater carbon mass on site than before the hurricane.
- *Selective pressure on organisms*. At a frequency of one category 5 hurricane every 100 years, and assuming no climate change, the Luquillo Mountains would have been exposed to approximately 200 000 catastrophic events over the last 20 million years. Such a high magnitude and frequency of disturbance relative to the longevity of organisms must exert strong selection on organisms, particularly in terms of the time available for reproduction and senescence (Lugo and Scatena, 1996).
- *Convergence of community structure and organization*. Over millennia, hurricane disturbances and other factors in the Caribbean region have contributed to convergence in the physiognomy and organization of its forests. This includes an even and smooth canopy structure (Odum, 1970), short stature (Odum, 1970; Doyle and Girod, 1997), low aboveground biomass (Lugo et al., 1976; Doyle and Girod 1997), and high species dominance (Lugo, 1991).

## 4. Social impacts of hurricanes

Hurricanes are among the most socially devastating natural disturbances, easily exceeding earthquakes, fires and volcanoes (Tomblin, 1981; Pielke and Pielke, 1997; Diaz and Pulwarty, 1997b). Hurricanes cause billions of dollars in losses due to destruction of infrastructure, life, and property (Tomblin, 1981; Rappaport and Fernández-Partagás, 1997). Hurricane Hugo caused 30 billion dollars in damage in the USA and Puerto Rico and soon after Hurricane Andrew, 11 insurance companies became insolvent and 140 either pulled out or greatly curtailed property insurance in South Florida. Moreover, hurricanes also affect people's psyches as the level of anxiety and other syndromes increases after experiencing one of these events. The trend in the loss of life due to hurricanes increased each century over the last 500 years in the Western Hemisphere (Rappaport and Fernández-Partagás, 1997) but decreased during the 20th century in the USA and Puerto Rico (Jamieson and Drury, 1997). However, loss of property and infrastructure increased significantly everywhere over the same time period. Increases in population density, changes in age structure and population health, sprawl of urban areas, insufficient infrastructure, and human occupation of coastal and flood — and mass wasting — prone areas have all increased the vulnerability of the USA, Puerto Rico, and the Virgin Islands to hurricanes (Pielke and Pielke, 1997; Pulwarty and Riebsame, 1997; Rodríguez, 1997).

Decades are required for both urban and natural systems to recover from the passage of a single category 4 or 5 hurricane. Efforts to suppress hurricanes have failed and there is little that humans can do to prevent the passage of hurricanes. However, because hurricane forecasting is increasingly accurate, people have sufficient time to be prepared for the event. Forecasting contributes to reduced loss of life, but is less effective in avoiding the effects of floods, landslides, storm wave or wind damage on poorly located infrastructure. Strategies to mitigate these effects include enlightened land uses, appropriate building codes, use of proper construction techniques, and development of green infrastructure. Green infrastructure is the use of biotic systems (natural or ecologically engineered) and nonstructural approaches to buffer people from natural hazards and to manage wastes, runoff waters, and other infrastructure corridors in urban and rural areas.

## 5. Impact of climate change on hurricanes

The effects of climate change on hurricanes is not well understood. Global warming may affect the maximum speed of hurricanes but it is uncertain what effects it will have on average speeds or hurricane frequency, and there is no evidence that the area affected by hurricanes will increase (Emanuel, 1997). Some models predict that the frequency and intensity of hurricanes will increase due to the greater heating of the oceans while other models predict significant decreases, particularly in the Southern Hemisphere (Bengtsson et al., 1997). However, Gray et al. (1997) suggest that decadal variation in hurricane intensity and activity is sufficiently wide to mask any changes due to future climate change. Regardless of which model is correct, decadal variation in hurricane frequency and activity is of sufficient magnitude to warrant attention on its own right.

In spite of the uncertainty on what changes in hurricane frequency and intensity will occur as a result of climate change, I propose a series of hypothesis of the potential effects of changes in hurricane frequency and intensity on vegetation and built up lands. Such hypotheses might be useful for anticipating broad scale management alternatives in impacted lands, which cover a large sector of the world. A change in frequency and/or intensity of hurricanes will affect all tropical systems of Caribbean and Pacific islands including human populations and urban systems, coastal systems from the Gulf of Mexico in Texas to the northern coast of Maine, and those along the Pacific coast from California to Oregon. Inland effects can extend several hundred miles within some coastal states. In the east coast alone, some 168 counties with a population of 75 million people and 3.1 trillion dollars of insured property (1993 statistics not including flood insurance) are affected by hurricanes (Pielke and Pielke, 1997; Jamieson and Drury, 1997; Diaz and Pulwarty, 1997b).

## 6. Responses associated with increased hurricane frequency and intensity

Should hurricanes increase in frequency and intensity the following consequences are fairly certain:

- A larger fraction of the natural landscape will be set back in successional stage, i.e. there will be more secondary forests. A modeling study of different hurricane intensities and frequencies showed that a range of forest types are possible ranging from mature forests with large trees in areas of low hurricane frequency to an area in which forest trees are not allowed to mature when hurricane frequencies are high (O'Brien et al., 1992).
- Forest aboveground biomass and height will decrease because vegetation growth will be interrupted more frequently or with greater intensity.
- Familiar species combinations will change as species capable of thriving under disturbance conditions will increase in frequency at the expense of species that require long periods of disturbance-free conditions to mature.
- Human settlements in coastal locations, flood-prone areas, and on slopes prone to mass wasting will become increasingly expensive to sustain.
- Flimsy constructions, such as trailer parks and poorly constructed structures will be affected adversely.
- People's mental states will be impacted by the anxiety caused the increased threat of hurricanes.

## 7. Responses associated with decreased hurricane frequency and intensity

Should hurricanes decrease in frequency and intensity the following consequences are fairly certain:

- a larger fraction of the natural landscape will advance in successional stage, i.e. there will be more mature forests and fewer secondary forests;
- forest aboveground biomass and height will increase because the longer disturbance-free periods allow greater biomass accumulation and tree height;
- species combinations will change as species capable of thriving under disturbance conditions will decrease in frequency and species typical of disturbance-free conditions will increase;
- human settlements in coastal locations, flood-prone areas, and on slopes prone to mass wasting will be less impacted;
- flimsy constructions will thrive; and
- stress associated with fear of hurricanes will decrease in the population.

## 8. Mitigation strategies for hurricane-prone regions

The well being of people in the future with increased levels of disturbance can be optimized by a number of strategies that build resistance to, and survivability after, hurricanes. Some of these include:

- sound land uses so that people know and understand the degree of safety of their dwellings relative to the particular hazards of specific disturbances;
- an increased use of wind- and flood-resistant designs for construction purposes;
- rapid access to reliable forecasts of atmospheric conditions to allow for timely preparations for the disturbance events;
- clear understanding among the population of available escape routes and refuges;
- adequate road and refuge capacity for people to use during periods of catastrophe; and
- a well designed and maintained green infrastructure to assure some level of mitigation of the excessive winds, water, and mass wasting associated with the hurricanes.

To accomplish these mitigation strategies, investments are needed for:

- Hurricane-proofing of infrastructure by use of underground electric and telephone lines, provision for adequate drainage and increased resistance to winds, and more effective escape routes from coastal and lowland to upland areas.
- Improving construction techniques, quality of construction materials, building codes, and enforcement of building codes such that dwellings can survive high velocity winds.
- Improved land use planning, including zoning to avoid locating dwellings in flood and mass wasting prone areas.
- Greater and more effective use of green infrastructure.
- A diverse set of connected natural areas to minimize effects on biodiversity.

In summary, recent research has established the role of large and infrequent disturbances such as hurricanes, in shaping vegetation and influencing species composition and processes of ecological systems. Humans have devised ways for surviving hurricanes, but the infrastructure that supports human activity is still vulnerable to these disturbances. Strategies are needed to improve infrastructure while not harming natural ecosystems nor increasing their vulnerability to disturbances. If these issues are addressed now, human-dominated landscapes will be better prepared to deal with the effects of global climate change, whichever they might be.

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