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SPECIAL FEATURE: HIGH-ENERGY STORMS

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Abstract. Over the course of 16 d in the fall of 1998, Hurricane Georges made landfall on five Caribbean Island nations, two U.S. states, and two territories. Along its path, it impacted nearly every type of built environment and terrestrial and marine ecosystem found in the Caribbean and the southeastern United States. We reviewed ecological and sociological research related to Georges in order to demonstrate the potential power of regional synoptic networks despite notable gaps that existed at the time. Most studies examined various effects and responses within four years of the storm, though a few reported longer-term results. Reduction in forest stem density was the most reported ecological effect and ranged from 7% to 51% among sites in different forest types. Forests previously impacted by Hurricane Hugo in 1989 showed lower mortality from Georges than forests with longer hurricane-free intervals. Rivers in the storm’s path exported heavy loads of sediment to marine systems. For example, 5–10 million tons of sediment was transported to marine systems from Puerto Rico, and suspended sediments increased tenfold in coastal Louisiana. Economic costs directly related to Hurricane Georges ranged from 5% to 200% of annual GDP in the year after the storm. Sociological research indicated that children and college students exposed to Hurricane Georges experienced elevated effects on mental health such as anxiety and depression for up to 2.5 yr. Established research areas and longitudinal studies were valuable in understanding hurricane effects in the context of long-term trends but fragmented research capacity reduced both local and regional synthetic efforts. Georges provides a template of how future integrated research programs could provide a deeper understanding of how nature, urbanization, human culture, and societal norms interact, respond, and recover from a major hurricane. However, future studies should avoid using the Saffir-Simpson scale as a shorthand indicator or predictor of storm effects because topographic, historical, ecological, political, infrastructural, and societal factors interact to alter storm effects. The breadth of topics addressed in the research produced after Georges shows the potential for transformative, regionally synthetic research that spans whole watersheds and nearshore areas while integrating ecological and social sciences.

Key words: coral reef; disturbance; hurricane; mangrove; mental health; rainforest; seagrass; Special Feature: High-Energy Storms; support systems; synoptic networks; tropical dry forest; tropical montane forest.
INTRODUCTION

Hurricanes and tropical storms are an integral part of the natural environment in most of the Caribbean (except Panama, Costa Rica, and northern South America), the Gulf of Mexico, and U.S. East Coast. This is evident in the NOAA database of mapped storm tracks since 1851 in the North Atlantic (https://coast.noaa.gov/hurricanes/). Average return intervals range from 5 to 50 yr in these regions (spanning various Antillean Islands to Maine), a high enough frequency that natural ecosystems have developed adaptations to high-energy storm disturbances (Lugo 2008). Similarly, from the beginning historic and contemporary human societies in the region have also had to survive and adapt to recurring hurricane disturbance. Indeed, the origin of “hurricane” comes from a pre-Columbian Taíno word, and the earliest European explorers including Columbus and Ponce de León noted hurricanes during their travels (Salvia 1950, Quiñones 1992). Despite the high frequency of hurricanes in various regions of the globe, rigorous research of storm influences on natural systems only began ~70 yr ago when foresters and ecologists first began noting the effects of specific storms at particular locations (Bates 1930, King 1945, Blumenstock 1958, Wadsworth and Englerth 1959, Stoddart 1962). In terms of effects on humans, Salvia noted some commentary about the relationship between storms and human health conditions in the early 1900s in Puerto Rico and many historians have documented effects such as loss of life and infrastructure (e.g., sources used by Salvia [1950] as early as 1788). More recent studies have capitalized on long-term studies to evaluate the impacts of multiple hurricanes at the same sites (Uriarte et al. 2004, 2019, Beard et al. 2005, Imbert and Portecop 2008, Canham et al. 2010).

All hurricane studies confront issues in extrapolating results more broadly, including the following: (1) synoptic issues because hurricanes are short-term events with relatively restricted spatial extent and varying strength along their path; (2) historical issues related to multiple hits on the same location separated in time, between which both human and natural systems changed in response to prior storms; (3) spatiotemporal issues resulting from a single hurricane striking ecosystems under study at different times, resulting in different time zero points; and finally, (4) capacity issues in research infrastructure vary from place to place and time to time, especially the ability for researchers to be physically present to conduct studies without impeding recovery efforts.

Individual hurricanes that strike multiple locations along their path help to illustrate the dynamic nature of storm systems and the apparent variability of responses of similar ecosystems in different locations to the same storm. Hurricane Georges was such a storm par excellence, and we have dubbed it an “island hopper” as a result of its path (Fig. 1). Hurricane Georges demonstrates how the dynamic physical traits of hurricanes interact with the landscape and provide opportunities to assess multiple responses within a similar background set of regional environmental (e.g., drought, El Niño) or economic conditions (e.g., recession) without the confounding factor of elapsed time. In addition to highlighting the highly variable and sometimes surprising effects and responses in natural systems, Hurricane Georges also generated wide-ranging post-storm research efforts, including on forest and marine ecology, infrastructure and disaster response, and mental health. Had post-storm studies been coordinated across a variety of ecosystems, locations, and cultures along Georges’ path, it would have formed a powerful analysis of coupled human–natural systems by offering insights such as how contrasts in land-use patterns between countries influenced the initial impact of Georges and the nature of the post-storm recovery in both ecological and societal systems. As is the case here, integrated ecological studies across sites are uncommon in the tropics more broadly (e.g., Martin and Bellingham 2016). Nevertheless, despite their ad hoc nature, post-Georges studies demonstrate the diverse effects even a single high-energy storm can produce along its path, and demonstrate the breadth of hurricane research and capacity across hurricane-prone areas of the Western Atlantic. This capacity provides a foundation for asking integrated questions in coupled human–natural systems and for responding to current and future hurricanes.

In the effort to draw broader conclusions, hurricane disturbance research can benefit from
studies that either study multiple hits on a particular site (multi-storm, single-site) as some of the other studies in this special issue address (and citations noted above), or the effects of similar strength storms at various sites separated over some period of time (multi-storm, multi-site: such as reviews like Everham and Brokaw 1996, Lugo 2008), or the analysis of a single storm that impacts multiple sites (single-storm, multi-site: island-hoppers), as is the approach used here. Each approach has its strengths and weaknesses related to, for example, storm intensity, spatial extent of storms and research sites, time since previous hurricane disturbance, history of other disturbances, land use, pre-storm data availability, and research capacity, but each approach can highlight various gaps in research coverage and opportunities for better coordination. For our purposes, we consider each location along Hurricane Georges’ path to have essentially the same time zero, allowing us to look at the ecological and sociological responses from the same start point without intervening years as needed using other approaches. The majority of research related to Hurricane Georges covered responses within five years, but we include longer-term results when they are available.

Our review first describes the main characteristics of Hurricane Georges to provide context of its storm history as it crossed the Caribbean and Gulf of Mexico. We next summarize research findings of post-Hurricane Georges’ effects in both ecological and social sciences. Finally, we describe lessons that are highlighted by the study of Hurricane Georges and the single-storm, multi-site approach. Our intent is not to give a comprehensive analysis of the various studies produced about Hurricane Georges, but rather to...
provide a broad, integrated perspective of this storm by compiling key points from various fields, while introducing the wider literature on the storm. Similarly, we do not systematically compare the effects of Hurricane Georges on any particular site with prior storms that hit that site—such an approach is beyond the scope of this paper and inherently addresses different questions and approaches (e.g., multi-storm, single-site) than our own.

THE GEOGRAPHIC CONTEXT OF HURRICANE GEORGES

The Greater Antilles lie squarely in the Atlantic hurricane belt, with 100s of storms documented since the 1850s (Salvia 1972, McAdie et al. 2009, https://coast.noaa.gov/hurricanes). Hurricane Georges became a tropical storm on 16 September 1998 near 10.6°N, 31.3°W in the middle Atlantic and dissipated 16 d later in the southeastern United States (Guiney 1999). Based on the Saffir-Simpson Hurricane Wind Scale, Hurricane Georges’ strength varied from tropical storm to a major hurricane (Category 3 or stronger) at its various landfalls, and the physical characteristics of the storm varied greatly during its storm span (Table 1). The storm caused nearly $6 billion of damage ($9.4 billion in 2020 USD) and officially caused 604 deaths (Guiney 1999). In the aftermath of the storm, millions of people had damaged homes and were left without electricity and clean drinking water, in some cases for many months.

The storm travelled about 6000 km and made landfall first on 21 September 1998 on Antigua. Subsequently Georges crossed St. Kitts and Nevis, Puerto Rico, Hispaniola, Cuba, near Key West, Florida, and finally entered the United States near Biloxi, Mississippi (Fig. 1). It narrowly missed the islands of Montserrat, Guadeloupe, and the U.S. Virgin Island (USVI) of St. Croix. Prior to 2019, it is one of only two storms in documented history to have hit Cuba, Hispaniola, and Puerto Rico as a Category 1 hurricane or greater and to continue on to hit the U.S. mainland (the other was unnamed in 1876; https://coast.noaa.gov/hurricanes/). Many other storms have had similar tracks that roughly paralleled Georges but further to the north, where they interacted with fewer landmasses. The landmasses along Georges’ path ranged from small islands with low elevation (e.g., Key West: 19 km², 5.5 masl; Anguilla 91 km², 65 masl), to small mountainous islands (St Kitts: 168 km², 1156 m), to the Greater Antillean islands with either high-elevation (3175 m; Hispaniola) or moderate-elevation mountains (1974 m; Cuba),

| Locations          | Windspeed (km/h) at landfall | Storm surge (m) | Rainfall (mm) | Average hurricane return intervals (yr) |
|--------------------|-------------------------------|-----------------|---------------|----------------------------------------|
| Antigua            | 185                           | 190             | 6; 34         |
| St. Kitts and Nevis| 185                           |                 | 6; 56         |
| Guadeloupe         | 250                           | 140             | 7; 34         |
| St. Croix, USVI    | 144                           | 188             | 5; 21         |
| Puerto Rico, Luquillo| 185                         | 3               | 450           | 7; 21                                  |
| Puerto Rico, Guánica| 167                         |                 | 151           | 9; 42                                  |
| Dominican Republic | 194                           | 2               | 530†          | 10–14.4; 19–34                         |
| Haiti              | 120                           |                 | 990†          | 7.5–20; 56                             |
| Cuba               | 65                            | 1.2–1.8         | 620           | 7.5–31.6; 34                           |
| Florida Keys       | 167                           | 1.2–1.8         | 213           | 8; 18                                  |
| US Gulf Coast MS/AL/LA/FL | 167               | 1.6–3.6         | 250–500       | 11; 26                                 |

Notes: Missing cells are unreported data. Sources for wind, storm surge, and rainfall are Guiney (1999) except where noted below. Sources for return interval (since 1851; expressed in years at landfalls) are Blake et al. (2007) for continental US locations, Hopkinson et al. (2008) for PR and USVI, Gannon and Martin (2014) for Greater Antilles, estimates for Lesser Antilles and major hurricane return rate-based NOAA figures derived from McAdie et al. (2009) at https://www.coast.noaa.gov/hurricanes/. Return intervals are expressed as ≥Category 1; ≥Category 3. 
† Geerts et al. (2000). 
‡ Based on satellite inference from NOAA images.
and to generally flat coastal areas in south Florida and Mississippi (elevations from Google Earth). These islands all experience tropical climates, with little seasonal variation in temperature at sea level (Harris et al. 2014). Average annual rainfall on the Caribbean islands along Georges’ path varies from ~800 mm to over 5000 mm, while south Florida is subtropical with 1010 mm/yr of rainfall and coastal Mississippi has a warm temperate climate and averages 1648 mm of rainfall per year.

Hurricane Georges impacted nearly every type of terrestrial and marine ecosystem in the Caribbean, including tropical deciduous and evergreen forests in dry, moist, and wet climates at low elevations; moist, wet forest, and rain forests in lower montane settings; wet forest and cloud forests in upper montane locations; temperate deciduous forests; and temperate and tropical pine forests. Previous land use primarily determined forest structure and age across these ecosystems, and whether these forests were dominated by native or introduced species (Chinea and Helmer 2003, Heartsill-Scalley and Aide 2003, Martin et al. 2004, Uriarte et al. 2004). In addition, the full suite of managed terrestrial systems was also present along the hurricane track—including various types of annual and perennial agricultural systems, and urban, suburban, and exurban built environments. Seagrass, coral reef, and mangrove systems were also impacted by Georges. An in-depth review of the ecology of each of these systems is beyond the scope of this article, but it is worth highlighting that despite the diversity of ecosystem types and ages, the data describing Hurricane Georges’ effects were limited to a small subset of these systems or to a single location of a system along Georges’ path. These are reviewed below.

Historical hurricane data show that the average annual chance of a site along Georges’ path experiencing a hurricane of any size is highest in Key West, the Virgin Islands, the southeast corner of Hispaniola, and the western end of Cuba, and is lowest in Mississippi (Hopkinson et al. 2008, McAdie et al. 2009, Gannon and Martin 2014). Hurricanes are far and away the most common large-scale natural disturbance in each of the locations along Georges’ path, but some of the islands also have active volcanoes or experience natural fires (Sherman et al. 2001) and the region experiences a suite of other disturbances such as droughts related to El Niño cycles and insect outbreaks (Crausby and Martin 2016).

Anthropogenic disturbance is common across the region and includes intentional and accidental fires (Martin and Fahey 2006), and land-use change for agriculture and urban development (Grau et al. 2003, Grau and Aide 2008). Land-use change has increased forest fragmentation and introduced nonnative and invasive species from areas that do not experience hurricanes (e.g., Spatoidea campanulata [African tulip] and various Albizia species; Lugo 2004, Brandeis et al. 2007) or which are heavily favored by storms (e.g., Piptosporum undulatum [Australian cheesewood]; Bellingham et al. 2018). In Caribbean forests along the hurricane path, fire has also been introduced as a management tool for pasture management or as an accidental or malicious disturbance where introduced pasture grasses that have invaded dry forests are burned (Chinea 2002, Thaxton et al. 2012, Wolfe and Bloem 2012).

In less than two weeks from its first landfall, Hurricane Georges crossed every common combination of natural and anthropogenic systems found in the Caribbean and U.S. Gulf Coast. This trajectory provided the potential to assess multiple hurricane effects and responses simultaneously among the diversity of systems regionally. As we show below, this potential was not realized due to variable research capacity in the region. Despite shortcomings in capacity, Georges’ island hopper path allowed various researchers to initiate a wide variety of studies at once.

**Forest Structure and Function: The Most Complete Data Along Georges’ Path**

The effects of hurricanes are most thoroughly studied in forested ecosystems. The strength of these studies comes from networks of long-term research plots and because fallen trees can still be assessed months or years after a storm. Forests
Table 2. Selected ecosystem effects of Hurricane Georges at various locations along its path.

| Location and ecosystem       | Percentage change in Basal area or coverage | Stem density | Litterfall (g m⁻² d⁻¹) | Nutrient return (kg/ha) |
|------------------------------|---------------------------------------------|--------------|-------------------------|-------------------------|
| Puerto Rico                  |                                             |              |                         |                         |
| Moist forest                 | –9.0 [1]                                    |              | 868 (74) [2]            | 309 8.4 [2]             |
| Wet forest                   | –35.5 [3]                                   |              | 477 (55) [2]            | 194 5.7 [2]             |
| Moist and wet secondary forest [4] | –11 (–45 to +25)                           | –49 (–61 to –22) |                         |                         |
| Dry forest [5]               | –22                                         | –12.4        | 748 (160)               | 324 (960) 7.6 (1380)    |
| Dominican Republic           |                                             |              |                         |                         |
| Moist lowland forest [6]     | –68 to –45 (old sites†)                     | +121 to +150† (young successional and cacao) |                         |                         |
| Mangrove [7]                 | –42.4 (–100 to −9)                          | –47.7 (–100 to −14) |                         |                         |
| Montane cloud forest [8]     | –9.7                                        | –7.7         |                         |                         |
| Montane pine forest [8]      | –50.5                                       | –50.9        |                         |                         |

Notes: Missing cells are unreported data. Some locations in Table 1 are not listed here because ecosystem effects were not measured. Percentage change in basal area or coverage and change in stem density are expressed as means with ranges among plots in parentheses. Change in stem density is not exactly equivalent to mortality (except in Dominican mangrove) because some trees resprout from snapped or uprooted stems, so the tree survives while the stem is lost. Also, some studies reported data from up to three years before and two years after Georges, so post-storm estimates can include some pre-storm mortality and ingrowth between samples. Litterfall and nutrient return are expressed as means with percentages of annual in parentheses. Sources in square brackets (if square brackets are next to forest, then all data in row are from that source): Luquillo: [1] Ostertag et al. (2003); [2] Ostertag et al. (2003); [3] Beard et al. (2005); [4] Pascarella et al. (2004); [5] Van Bloem et al. (2005); [6] Uriarte et al. (2004); [7] Sherman et al. (2001); [8] Gannon and Martin (2014).
† Pastures and early successional forests had smaller, non-significant changes in basal area, and other forest types had small, non-significant increases in stem density related to pioneer species recruitment.

provide economic, recreational, and other ecosystem services to humans and therefore have a long history of research; thus, the most promising opportunity to provide a regionally synthetic analysis of the effects of Hurricane Georges on a particular type of ecosystem comes from forest ecology. This section summarizes the effects of Hurricane Georges on forests along its path (Table 2).

On 21–22 September 1998, Hurricane Georges directly impacted the entire island of Puerto Rico and all of its coastal areas, including two long-term research sites, the Luquillo Experimental Forest and Guánica Dry Forest on the southwest coast of the island (Guiney 1999, Ostertag et al. 2003, Beard et al. 2005, Van Bloem et al. 2005). The effects of Hurricane Georges on the forests in these two long-term study sites proved to be distinctive, as contrasting disturbance histories and forest types between the sites led to divergent ecological effects. In particular, time since disturbance played an important role in the susceptibility of each site to the hurricane’s impacts. Forested ecosystems across Puerto Rico are in varying stages of succession depending primarily on land-use history, the time since the last hurricane, and occurrence of landslides. Luquillo was in an early stage of post-storm succession after Hurricane Hugo which had impacted the forest only nine years earlier (Ostertag et al. 2003, Beard et al. 2005, Hogan et al. 2016) when Georges struck. In contrast, Guánica was unaffected by Hurricane Hugo and had not directly experienced a major hurricane since Hurricane San Felipe in 1928 (Miner Solá 1995, Van Bloem et al. 2005).

The immediate impacts of Hurricane Georges (Table 2) and patterns of post-Georges regeneration in these Puerto Rican forests are illustrative of how prior storm history and the life-history characteristics of the dominant species interact to determine disturbance severity. For moist forests in Luquillo, mortality rates were low (7.5% per year) 6 months after Georges, windthrown trees were only 5–17% of stems because susceptible trees (canopy emergent and weak individuals) had been already eliminated by Hugo, and advance regeneration and new seedling establishment—rather than resprouting stems—produced most of the new stems post-Hugo (Ostertag et al. 2003, 2005). Nevertheless, annual mortality rates of trees were still >7 times higher...
than pre-storm mortality rates, and trees damaged by Hugo were more likely to have been killed by Georges. Overall, ~40% of trees snapped and windthrown by Georges died within 21 months of the storm (Ostertag et al. 2005). Windthrow and mortality were even higher in the wet forests of Luquillo (33%) due to a generally more exposed location and larger trees in this forest type increasing susceptibility to windthrow (Beard et al. 2005). In contrast, strong resistance to hurricane disturbance in Guánica, despite its 70-yr hurricane-free interval, was evident in very low tree mortality (~2%) and low windthrow rates (12.4%), and in the rapid production of basal stump and root sprouts in windthrown stems (Van Bloem et al. 2003, 2005). Annual stem mortality rates in Guánica did remain significantly elevated (11 times higher than before the storm) for 7 yr after Hurricane Georges, but absolute rates of tree mortality were low and 17.7% of the dominant sprouts on basal sprouting stems had already reached canopy or subcanopy height by that time (Van Bloem et al. 2007). The root and basal sprouting life-history characteristic of trees in these dry forests confers strong resilience to high-energy storms, as aboveground biomass lost to windthrow rapidly reaccumulates from resprouting stems.

On 22 September, Hurricane Georges made landfall on the island of Hispaniola and caused widespread destruction in human communities, largely resulting from flooding (Office of US Foreign Disaster Assistance 1998; McEntire 1999). In the Dominican Republic (DR), Hurricane Georges affected most of the island and all of its coastal areas, but the most intense impacts were confined to the southern half of the island. The mountainous interior of the country provided some protection from the storm for the northern half of the DR, and the storm weakened as it moved across the landmass (Gannon and Martin 2014). The Cordillera Central, the island’s main mountain range, was the location of the main convective event within the eye (Geerts et al. 2000). Prior to 1998, the DR had not been impacted by a major hurricane since 1979, when the Category 5 Hurricane David directly crossed the DR (Martin et al. 2007). Hence, the patterns of disturbance in the DR caused by Georges reflect the island’s comparatively long hurricane-free interval, not unlike Hurricane Hugo in PR which occurred after an even longer hurricane return period (60 yr; Brokaw and Grear 1991, Scatena and Larsen 1991, Walker 1991, and other studies in the 1991 Special Issue of Biotropica on Hurricanes in the Caribbean, volume 23, Issue 4).

In the lower-elevation karst region of Los Haitises National Park in the northeastern DR, Hurricane Georges substantially decreased the biomass in sites with no recent history of agricultural land use: Basal area decreased by more than 40% in former cacao plantations, 50% in hilltop forests, and by more than 50% in mature moist forest sites, causing a shift to more heliophilic woody species in these communities less than a year after Georges (Uriarte et al. 2004). A permanent study site in nearby mangrove forests in Samaná Bay, DR, also found pronounced yet patchy effects of storm damage from Georges. Mortality of mangrove trees in vegetation plots ranged from 14% to 100% (mean 48%), and basal area was reduced by 9–100% (mean 42%) within 18 months of the storm (Sherman et al. 2001). Interspecific differences in susceptibility to wind damage were the primary factor behind the patchy spatial patterns in mortality, as variation in plot-level mortality was strongly associated with differences in species composition.

Hurricane Georges also had significant and highly stratified impacts on the high-elevation forests of the Dominican Cordillera Central. In contrast to hurricane strikes in topographically flat and low areas like the Gulf and Atlantic coasts in the United States, the patterns and impacts of hurricanes in mountainous terrain, such as the Cordillera Central and across the Greater Antilles, are inherently more complex (Boose et al. 1994). A long-term, landscape-scale study in two adjoining national parks in the Cordillera Central found that effects of Georges on forest structure were concentrated in a small area, with only 11.3% of the study site affected by wind and 4.3% by flooding (Gannon and Martin 2014). Although only a small portion of the landscape, the severe flooding associated with Georges had dramatic impacts on the vegetation in riparian communities in the region, which rapidly regenerated in flood-caused openings (Martin et al. 2004). Wind damage patterns were much more diffuse than flood damage, with hurricane meteorology, landform topography, and vegetation type all contributing to variation in
the patterns of wind disturbance in the Cordillera Central. In particular, 94% of the total disturbed area from wind disturbance was concentrated in high-elevation forest types—12% in cloud forest and 82% in pine forest; these forest types are neighboring on windward slopes but separated by a sharp ecotone controlled by mesoclimatic factors (Martin and Fahey 2014)—as lower elevations were topographically sheltered from direct winds (Gannon and Martin 2014). In these wind-disturbed areas, the degree of tree mortality varied markedly by forest type, with wind-killed trees only 9.8% higher (expressed as a percentage of basal area) in cloud forest but a 50.5% higher in pine forest compared with control plots in areas unaffected by Georges. Furthermore, although much of the montane landscape was undisturbed by Georges, an analysis of the long-term hurricane regime found a 14.4-yr average return interval for the Cordillera Central from 1851 to 2009 (Gannon and Martin 2014), so impacts are likely to accumulate across the landscape as hurricanes repeatedly cross the area. Indeed, using the network of permanent plots in the two parks in the Cordillera Central, a study remeasuring individual trees found notably high rates of above-ground biomass accumulation in the site but also notably high spatial variation in these rates, reflecting the pronounced yet patchy nature of hurricane impacts from Georges and earlier hurricanes on forest dynamics in the site (Sherman et al. 2012).

Hurricanes have pronounced effects on ecosystem process, but to our knowledge post-hurricane nutrient dynamics along Georges’ path were only studied in Guánica and Luquillo, Puerto Rico. In Guánica, the ecosystem processes that govern nutrient cycling showed major deviations from typical years after the hurricane hit the site. In only 24 h, Hurricane Georges deposited 55% of annual leaf litterfall, 160% of total litterfall, and 9 and 14 times more N and P to the forest floor compared with annual levels in non-hurricane years (Van Bloem et al. 2005), leaving a major pulse of C-rich woody necromass and nutrient-rich leaf litter on the forest floor. The leaf litter was more nutrient-rich than normal because translocation of nutrients during seasonal senescence had not yet occurred when the hurricane struck (Lugo and Murphy 1986). Guánica Forest has slow decomposition rates typical of dry forests (7.3 yr for 95% decomposition; Lugo and Murphy 1986), meaning this pool of carbon and nutrients is likely to have a comparatively long residence time in the forest floor. In moist and wet forests in Luquillo, litterfall was also elevated after Georges, with 55–93% of annual litterfall occurring shortly after the storm—with over half of that pulse from leaf litter—and total litter included 60% of the annual N return (Ostertag et al. 2003). These forests have intrinsically rapid decay rates due to wet forest floor conditions (Ostertag et al. 2003), and hence, the majority of hurricane-pulsed litter in Luquillo decomposed within 5–10 months of the storm in the moist forests and 4–5 months in the wet forests, and showed up quickly in the forest’s streams where nitrate concentrations exceeded pre-hurricane levels for 2–10 yr post-storm depending on the lithology of the watershed (McDowell et al. 2013). In contrast, long-term studies in a forest in Taiwan, which experiences very frequent cyclones (0.49 major cyclones/yr), found that stream water ion concentrations rapidly return to pre-storm levels, typically within 1–2 weeks (Lin et al. 2011, Chang et al. 2013). This highlights how the effects of high-energy storms on forest structure and nutrient cycling are closely linked to the historic frequency of storms in the region, decomposition rates, and leaf litter quality. Hurricanes generally cause a greater perturbation in Caribbean ecosystem processes than in parts of the western Pacific where storm frequency is markedly higher.

Using structural data collected after Georges, we can make some general conclusions about the hurricane’s effects on forests in its path and highlight some coverage gaps. Stem density decreased by 5–75% in dry, moist, and wet forests measured in PR and the Dominican Republic, but only moist forests were measured in more than one country. Loss of stems in mangroves ranged from 5% to 100% but was only measured in the DR, despite mangrove forests being present across most of the storm’s path. A larger network of long-term research plots would have also enabled more comprehensive temporal evaluation of storm effects. For example, long-term plots enabled us to determine that ~17 yr of biomass production was lost in the Guánica Forest after Georges, while Hurricane Hugo eliminated 50% of the live above-ground biomass and
damaged 22.4% of stems in Luquillo Experimental Forest (Scatena et al. 1993, Scatena and Lugo 1995), but that Hurricane Georges only resulted in 17.3% of stems damaged 9 yr later. Despite the lower proportion of stem damage from Georges in Luquillo, stem mortality of damaged trees was four times higher than after Hugo as fewer damaged trees survived Georges via leaf reflushing or stump sprouting (Ostertag et al. 2005).

Lugo (2008) noted that many functional and process responses to high-energy storms were invisible effects because they were not readily apparent to the naked eye during or in short periods after a storm. Instead, these effects require long-term research to decipher. Indeed, shifts in short-term patterns reported for canopy animals (highly visible effects) suggest longer-term and less visible patterns underlying these shifts. For example, foraging patterns shifted for Hispaniolan Parrots (Amazona ventralis) in the Dominican Republic, where parrot ranges increased substantially and foraging was concentrated on resource refugia found in undisturbed sinkholes (White Jr. et al. 2005). Likewise, in wet forests in western Puerto Rico, canopy-foraging birds shifted to understory foraging after Hurricane Georges (Tossas 2006). Tossas (2006) also documented a shift in bird species composition for two years after the storm, with some frugivorous species vanishing from hurricane-damaged forests including one of the most abundant pre-storm bird species, the Ruddy Quail-Dove (Geotrygon montana). Patterns in Puerto Rican bat communities in wet and moist forests after Georges indicate that large-bodied, frugivorous, and wide-ranging species were more sensitive to hurricane disturbance (Jones et al. 2001). Finally, Puerto Rican boas (Epicrates inornatus) in wet forests also tended to increase their range and shift their presence into lower levels of the forest after the storm (Wunderle et al. 2004). Considering that all of these species and communities rely on forest canopy for reproduction, roosting, and foraging, it is not surprising to see them respond to high-energy storms; however, the consequences on food webs and forest regrowth of these shifting population and community dynamics will only be evident if studied long-term, preferably over multiple sites to improve the chances of measuring the effects of multiple high-energy storms.

Overall, our ability to comprehensively compare hurricane effects across the Caribbean and coastal United States is limited by a lack of consistency in research locations within each country, systems studied, specific research questions asked, and methods used to evaluate effects and response along portions of Hurricane Georges’ track (e.g., see sites where data are unavailable or absent in Tables 1, 2). We are left to apply broader inferences from the sites that were measured and studies from other storms and locations (Everham and Brokaw 1996). Additionally, some data gaps can be filled using remote sensing approaches and models (Wang et al. 2010, Gannon and Martin 2014, Allen et al. 2017, Holm et al. 2017, Hu and Smith 2018), but these approaches are ideally combined with field studies. For example, Feng et al. (2018) using spectral analysis of non-photosynthetic vegetation estimated mortality or severe damage on 23–31 million trees in Puerto Rico after Hurricane Maria in 2017, but the authors noted that field studies are needed to distinguish between mortality and severe damage, which will determine whether forests recover from the bottom-up via seed or basal sprouts or from the top-down by reflushing and resprouting from remaining crowns.

RIDGE TO REEF

Point-based studies from sites established for other purposes, as noted in the prior section, offered some of our best data on the impacts of Georges but a superior arrangement moving forward would configure hurricane research sites established throughout watersheds, including adjacent offshore areas—a ridge-to-reef approach. With this arrangement, connectivity of effects can be better evaluated. For example, upland processes that increase sedimentation (land use, forest clearing, etc.) interact with storm rainfall, discharge and sedimentation loads, to fundamentally influence riverine dynamics including channel morphology, fish and invertebrate habitat, and flooding (Larsen and Webb 2009, Crowl et al. 2012). In time, upstream conditions and storm interactions will influence reef health as well. A distributed research network through watersheds could pinpoint the role of wetlands in the upper
areas of the watersheds, highlighting their role in decreasing erosion by limiting overland flows and stream floods. Further downstream, the role of well-managed and intact forested buffers, coastal wetlands, mangroves, and seagrass communities in trapping sediment exports from upstream could be quantified. Degraded upland and coastal systems can severely affect reef systems directly by covering reefs with sediment and indirectly by reducing or removing nursery habitats for fish and other aquatic species (Lugo 2008).

With Hurricane Georges affecting the entire surface and coastal areas of many of the Lesser Antillean islands, and Puerto Rico, Hispaniola, and most of Cuba (Fig. 1), a coordinated research network would have been able to assess ridge-to-reef effects on different islands and watersheds. However, the lack of coordinated studies following Georges prevents thorough evaluation of ridge-to-reef connectivity in hurricane effects and responses. The inputs of sediments and nutrients likely exacerbated ongoing declines in reef health in the basin associated with anthropogenically induced nutrient-rich runoff from streams (Larsen and Webb 2009). Numerous slope failures and landslides occurred throughout the Dominican Cordillera Central due to Georges, visible in aerial photographs taken in early 1999 (P. H. Martin, personal observation), and likely moved massive amounts of sediment downstream, threatening the health of aquatic ecosystems and the long-term viability of dams in the DR. The upper watersheds of Dominican Cordillera Central are critical for the nation’s water resources, serving as the island’s largest watershed and providing 25% of the country’s surface waters (Harlan et al. 2002). Even during a period with only one hurricane, deforestation and intensive land use have caused widespread erosion and the resulting siliation has reduced the DR’s largest dam storage capacity by 20% within the first twenty years of operation (Harlan et al. 2002, Nagle 2002). The relative role of land-use change, hurricanes, and road-building as a sediment source is largely unknown, but one study in the DR found that agricultural lands are contributing little to reservoir sedimentation, and suggests road-building and hurricane events—which induce rapid, erosive surface flows—contribute far more to sedimentation rates (Nagle 2002).

Ridge-to-reef assessments of storm effects would enable reports of sediment discharge and offshore effects. Hurricane Georges again illustrates gaps in coordinated monitoring. For example, sediment discharge to the ocean was not measured in the Dominican Republic, but in PR Hurricane Georges produced over $10^9$ m$^3$ of discharge to the ocean (13% of mean annual totals) which contained 5–10 million t of sediment, 1000 t of N and 500 t of P (Larsen and Webb 2009). Suspended sediments in the Atchafalaya-Vermilion Bay system (~240 km W of landfall) of Louisiana increased 10-fold to 750 mg/L (Walker 2001). None of these locations measured offshore effects of sedimentation on coral reefs, seagrass, or fisheries, but some of these systems were measured in St. John, USVI, and off the Florida Keys. In St. John, Rogers and Miller (2001) reported that benthic cover of coral reefs in two offshore locations did not differ before and after Hurricane Georges, but their sites were located in relatively protected areas off a small island with low streamflow runoff. However, in the Florida Keys, density of the three most common seagrass species and calcareous green algae decreased 3–24% after the storm (Fourqurean and Rutten 2004). Transects closer to the path of the storm incurred greater losses with some completely converted to open sand fields in the short term.

Aside from land-use and land cover effects, other ridge-to-reef connections could be evaluated with a more comprehensive approach to hurricane research. For example, freshwater shrimp species play a major role in litter processing in streams in Puerto Rico (Crowl et al. 2001, 2006). These shrimp help return nutrients from streams to forests as prey for birds and other animals, and disperse between rivers during a saltwater phase of their life cycle (March et al. 1998). Long-term studies on stream communities in Luquillo documented effects of hurricanes on shrimp (Crowl et al. 2012). Hurricane Hugo produced numerous dinnerfalls that created debris dams in Luquillo streams that trapped leaf litter and provided sites of high nutrient cycling by detritivorous invertebrates such as shrimp and their predators. Discharge from Hurricane Georges subsequently removed these barriers, simplifying stream structure and exporting organic matter and sediment downstream (Crowl et al. 2012). Overall, Georges impacts on
streams reduced upstream nutrient availability, aquatic invertebrate population sizes, and food-web complexity. Decapod abundance and assemblages explain 32–62% of organic matter storage in streams, and periods where decapod numbers are depleted coincide with higher levels of nutrient and sediment loss downstream (Crowl et al. 2001, 2002, 2006). Larger decapods can migrate upstream to repopulate washed out areas. Shrimp also release larvae after high discharge events (Pérez-Reyes et al. 2016) which mature to post-larval shrimp in coastal saltwater areas after 30–90 d and can help repopulate nearby streams (Bauer 2013). Shrimp in Puerto Rico provide a good example of the connectedness of environments from ridge to reef, and the lack of similar examples from elsewhere demonstrates how fragmented our research efforts are and how little we know about the effects of hurricanes on aquatic species and ecosystems in the region.

SOCIOPHICAL FACTORS

Social and natural systems have coupled feedbacks that can exacerbate or mitigate hurricane effects, but post-hurricane research rarely addresses coupled human and natural systems in a systematic way. The current lack of a synoptic network also impedes comprehensive understanding of hurricane effects on social systems. To our knowledge, Sattler et al. (2002) is the only study that was able to assess similar characteristics of disaster responses in humans across countries (discussed below). Comprehensive analyses of coupled human and natural systems would identify and quantify feedbacks between land use, land cover, and ecosystem management with provision of ecosystem services and stability of human infrastructure and well-being. Understanding those feedbacks would help improve natural and human resource management in hurricane-prone areas.

The social and economic effects of Hurricane Georges depended on the position of a site relative to the path and strength of the hurricane, and infrastructure and agricultural losses were high for locations directly along the path of the hurricane (Table 3 and sources listed therein). However, the amount of economic development and emergency preparedness present prior to the

Table 3. Economic and populations losses immediately after Hurricane Georges at various locations along its path.

| Location       | Population density in 1998 (no./km²) | No. deaths | Customers without electricity; water (%) | GDP 1997 US$ | Total economic losses (million US$) | Agricultural losses |
|----------------|--------------------------------------|------------|------------------------------------------|--------------|-------------------------------------|-------------------|
| Antigua        | 181                                  | 2          | Most                                     | 615M         | 160                                 | 50% sugar         |
| St Kitts and Nevis | 170                                 | 5†         | Most                                     | 236M         | 484                                 | 50% sugar         |
| Puerto Rico    | 415                                  | 7†         | 96; 75                                   | 54B          | 3500                                | 75% coffee; 65% poultry; 95% banana/plantain |
| Dominican Republic | 171                                 | 380–2000†  | 100; NR                                  | 20B          | 2000                                | 40% annual crops; 54% perennial crops |
| Haiti          | 298                                  | 209        | 100; NR                                  | 3.6B         | 179                                 | ≥75% rice; 80% bananas; most other crops |
| Cuba           | 101                                  | 6          | Most in E Cuba, less in central and W Cuba | 18.6B        | 306                                 | 70% plantains     |
| Florida        | 32                                   | 0          | −10%; NR                                 | 401B         | 680                                 | NR                |
| Gulf Coast     | 38                                   | 0/4†/0     | −57%                                     | 298B         | 1630                                | NR                |

Notes: Missing cells are unreported data. Data are from Office of US Foreign Disaster Assistance (1998) and Guiney (1999; updated in 2014) unless noted below. GDP and population density from data reported by the World Bank (countriests/da
ta.worldbank.org) and US Department of Commerce Bureau of Economic Analysis (Florida; https://www.bea.gov/data/gdp/gdp-state) and US Census Bureau for Gulf Coast (Monroe County, Florida; St. Bernard and Plaquemines Parishes, Louisiana; Mobile and Baldwin Counties, Alabama; and 6 southernmost counties in Mississippi).

† Death toll in St. Kitts, Puerto Rico, and Alabama include casualties incurred as a result of Georges, but not directly during the storm (i.e., asphyxia from running generators, electrocution). Deaths directly caused by Georges were 4, 0, and 1, respectively. In the Dominican Republic, death total includes official government and unofficial estimates (Olson et al. 2002). One additional death reported for the Bahamas. NR is not reported.
hurricane also played a role. Consequently, peak losses in terms of dollars were highest in Puerto Rico and the Dominican Republic (Guiney 1999). Haiti, much poorer than Dominican Republic, had lower gross economic losses, in part because the hurricane was less powerful there (Table 1), but also because there was less investment in built infrastructure. Nonetheless, losses in Haiti approximately equaled the same proportion of the GDP as they did in Puerto Rico (Table 3).

Casualty estimates from Hurricane Georges illustrate the linkages between human and natural systems. Heavy rainfall over Hispaniola caused major flooding and dam failures that, combined with poor emergency services, resulted in many casualties and displaced people in Haiti and the Dominican Republic. The large discrepancy in the number of casualties in the Dominican Republic reported by the government’s official death toll (380 people), and the presumed death toll reported by opposition parties (~2000 people) was seen as a move by the Dominican government to hide shortcomings in its hurricane warning and disaster response systems (Olson et al. 2002). Non-governmental agencies estimated an intermediate number of casualties (~600; Office of US Foreign Disaster Assistance 1998). Most of the unreported casualties in the Dominican Republic were probably Haitians who lived near rivers and were in the DR to find work (Olson et al. 2002). These casualties can be ascribed in part to poor economic and ecological conditions (e.g., collapse of agriculture, widespread deforestation, and land degradation) present in Haiti before Hurricane Georges. In contrast, Cuba had a well-developed evacuation plan that saved most of its citizens and cattle from physical harm (García et al. 1999, Guiney 1999). The DR’s poor hurricane warning system (McEntire 1999) was also highlighted by Sattler et al. (2002), who found that college students in the DR were 12–30% less likely to know that Georges was an imminent danger than students in PR, USVI, or the U.S. mainland and about half as likely to begin preparing for the storm 24 h in advance.

While casualty and economic losses were relatively low for the U.S. Gulf Coast, disaster planning was still problematic there. Colossal traffic jams were reported as people tried to evacuate New Orleans prior to Hurricane Georges. After Hurricane Georges (but before Katrina), Gulf Coast states reported that 24–48 h advance notice was needed to adequately evacuate at-risk populations before a category 2 storm, with Louisiana needing the most time. Hence, emergency management officials found that warning systems were inadequate because the U.S. National Hurricane Center could predict landfall within 160 km no earlier than 24 h in advance (Urbina and Wolshon 2003).

Post-hurricane refugia are important to both societal regeneration and ecological regeneration. Patches in the landscape that avoid major disturbance during a hurricane serve as shelters for escape or sources for subsequent dispersal. This phenomenon has been widely documented in ecological systems in tests of island biogeography and metapopulation dynamics and specifically following hurricanes (Wunderle et al. 2004, White Jr. et al. 2005, Turton 2012), but is also illustrated for social systems by Hurricane Georges. Total economic losses in PR were $2.7 billion from Hurricane Georges, $1.9 billion from Hurricane Hugo, and $0.8 billion from Hurricane Hortense (adjusted to 2006 US$; Blake et al. 2007). These costs reflect not just the size of the storms, but also the ability of the island to recuperate using local resources for Hortense and Hugo, as opposed to relying much more on outside resources after Hurricane Georges (and Hurricane Maria). After Georges, the average time that people were without electricity in PR and DR was 13–15 d, water was unavailable for 9–11 d, and people were unable to return to work or school for 2–4 weeks. Living in poor neighborhoods or paycheck-to-paycheck was also associated with greater exposure to hurricane effects (Felix et al. 2011). Yet in the mainland United States where help was able to drive in from other states, utility services were restored within 2–3 d and people returned to work in 4 d (Sattler et al. 2002). As a consequence of island geography and the immense size of Hurricane Georges, Dominicans, Puerto Ricans, and other island residents had no readily accessible area outside the storm’s path to which they could escape, or from which to get easy reinforcements.

Though few people reported major damage to their object resources (homes, belongings), a much higher fraction of island residents than
U.S. mainland residents reported suffering from depression, anxiety, or family disruption as a result of prolonged loss of services and disruptions in daily routines caused by Hurricane Georges (Sattler et al. 2002). Furthermore, children aged 4–17 who experienced Hurricane Georges in Puerto Rico showed short-term declines in mental health. At 1.5 yr post-Georges, 18.5% of hurricane-exposed children exhibited psychiatric disorders (such as disruptive disorders, ADHD, substance abuse, post-traumatic stress disorder, separation anxiety, depression, or panic disorders) while only 13% of non-exposed children showed the same disorders. By 2.5 yr, the rates of disorders had returned to the same levels for exposed and non-exposed children (Felix et al. 2011). Mental health was conserved when children had support from non-violent peers, good quality relationships with parents, and stability in support systems such as neighborhoods and schools (Felix et al. 2013a, b, Rubens et al. 2013).

Human practices also influence natural systems’ responses to hurricanes. One example is increased sedimentation as described above. Another example is the interaction between forest fragmentation and hurricane effects. Van Bloem et al. (2005) found that, taken as a whole, 19 dry forest fragments in SW PR experienced the same rates of stem breakage and mortality as the 4500-ha Guánica Forest. However, the age of the fragment, the type of edge (abrupt, as a road side, or diffuse, as a forest encroaching on an old field), and prior land use of the forest all explained significant amounts of variability within the fragment data (Van Bloem et al. 2005). Finally, high human population density and low availability of cooking fuel have resulted in massive deforestation of Haiti. This in turn leads to unstable slopes and exacerbates floods that damage crops and kill humans (Brandimarte et al. 2009).

**Lessons from Hurricane Georges Research**

A clear lesson of Hurricane Georges research is that the Saffir-Simpson Hurricane Wind Scale is only a partial predictor of ecological or social effects, a conclusion previously stated (Lugo 2008), but worth emphasizing again here. The ecological and social impacts and responses to many hurricanes are poorly tied to windspeed. Hurricane Georges provides an especially good example because it impacted so many locations in only two weeks. Hurricanes have obvious effects such as toppling trees and damaging infrastructure, and Saffir-Simpson categories are described using examples of damage (Marshall 2009, Saffir-Simpson Team 2012). However, even when areas experience the same strength winds, the effects are not uniform. The USVI, Puerto Rico, parts of the Dominican Republic, the Florida Keys, and Mississippi were all impacted by Category 3 winds from Georges, yet structural and economic effects were quite different in each location (Tables 2, 3). Similarly, 35% of the 20 costliest U.S. hurricanes (adjusted for inflation) were low on the Saffir-Simpson scale, classified between Tropical Storms and Category 2, while the strongest storm, Hurricane Andrew (1992), only ranks sixth (Blake et al. 2007). Of course, the Saffir-Simpson scale was not produced with the intention of quantifying ecological effects. Its purpose is to quantify wind speed and help people determine the potential threat that a storm poses (Saffir-Simpson Team 2012). In practice, however, it is used as a shorthand method to describe storm intensity and to compare strength of various storms in the ecological literature. In a local context, this use is probably fair with the caveats that return interval, local topography, and landcover patterns still strongly interact with wind speed to determine effects (Van Bloem et al. 2003, Uriarte et al. 2019), and the understanding that kinetic energy increases with the cube of wind velocity, so distance between field sites and meteorological stations must be considered when assessing hurricane strength.

A main limitation in using the Saffir-Simpson scale to compare high-energy storms is that the size (diameter) of a storm is not incorporated into the scale, but clearly plays a key role in the scale of potential impacts. Georges’ hurricane-force winds had a radius of 250 km and tropical storm-force winds up to 490 km from the eye of the storm (Guiney 1999), among the largest hurricanes recorded. Size of the storm determines how much area will be impacted, and thus, the distance species must go to access undisturbed refugia, the distance new propagules will disperse to colonize disturbed patches, and the distance to sources of relief supplies for human
communities. Large storms like Hurricane Georges also have the potential to reset the disturbance return interval over a much larger area than small storms. The interval between major hurricanes along Georges’ path varied widely, ranging from 9 to 70 yr, but were reset to zero across most of the Caribbean and portions of U.S. coastal areas. Studies from other storms and locations suggest that a second storm relatively soon after a previous storm will have fewer effects on ecosystems as weakened components of the system were eliminated by the previous storm (Everham and Brokaw 1996).

Likewise, the Saffir-Simpson scale does not incorporate the magnitude and effects of rainfall, flooding, and storm surge, which can be more important than wind in impacting human and natural communities in upland, riverine, and coastal areas alike. Previously, the Saffir-Simpson Hurricane Scale attempted to incorporate storm surge, but issues related to trajectory, bathymetry, and storm extent made this attempt confusing and highly variable (Saffir-Simpson Team 2012), so storm surge is no longer part of the Saffir-Simpson Hurricane Wind Scale (note addition of “wind” in the name). Floods are central to hurricane impacts, and Georges was one of many storms where flooding was a significant source of impacts to natural systems, built infrastructure, and human life. Sites along Georges’ path received from 140 to 990 mm of rainfall, and flooding was responsible for the vast majority of human deaths and crop destruction along the path, which exacerbated crop losses from the El Niño-triggered drought the previous year (FAO 1998). Other examples of hurricanes with substantial flooding impacts include lower category storms such as Florence (2018) and Sandy (2012) and stronger storms like Harvey in 2017. Quantifying ecological extremes in flooding or rainfall is highly context dependent, as a location’s long-term average precipitation regime is important to a storm’s impact. For example, precipitation during Georges was about 20% of the average annual rainfall in Guánica and 13% of the average annual rainfall in Luquillo, yet total rainfall in Luquillo during Georges was three times higher than in Guánica (Table 1). In addition, various components of ecosystems respond differently to flooding. In Guánica, for example, positive effects of flooding included an unusually high flush of tree seed germination (S. J. Van Bloem, personal observation) and the first reproductive event for the endangered Puerto Rican crested toad (Peltophryne lemur) in many years (Miguel Canals, Guánica Forest Manager, personal communication). Both provide critical pulses in recruitment to long-term population dynamics. Conversely, flooding created landslides, increased sediment loads in streams, reorganized rivers, and washed out refuge sites for aquatic biota, as detailed above for multiple sites on Georges’ track.

Interacting with both wind and flood effects is topography, which is also not incorporated in the Saffir-Simpson scale. Landmasses along Georges’ path varied from mountainous to relatively flat, influencing the storm’s effects. Windward locations in mountainous terrains exacerbate wind effects and create more force in flash floods. Windward areas also tend to amass more storm surge. Leeward areas minimize the effects of wind, flooding, and coastal storm surge. Thus, a better approach than using the Saffir-Simpson Hurricane Wind Scale to indicate storm strength would be to estimate the amount of energy present at a research site based on topography and windspeed or storm surge corrected for distance from measurement source, along with rainfall and flooding. Post-storm modeling efforts have combined windspeed and topography to quantify force across landscapes in Puerto Rico and New England states for selected storms (Boose et al. 1994) and a wider application of that approach would help standardize intensity reporting among storms and sites.

The island-hopping path of Hurricane Georges provided a body of research on hurricane effects and responses in a wide variety of natural systems and human societies that was quite comprehensive if considered as a whole. Forests of various types, streams, seagrass beds, and reefs are all represented in the post-hurricane research. Unfortunately, most of these studies occurred in disjunct locations, so linking ridge-to-reef effects was not possible, with the exception of Luquillo Forest in NE Puerto Rico, and therefore requires extrapolation between sites or storms. Studies in social systems included the effectiveness of emergency response and psychological and sociological studies of the effects of social and infrastructure support on stress and mental health but
these studies were, for the most part, not replicated across locations or linked to ecological studies. Natural resource management which expressly integrates the effects of hurricanes could result in more resilient coupled human–natural systems whereby infrastructure is designed or sited to avoid or absorb hurricane effects, leading to more stable food, water, and utility systems. This in turn would mitigate hurricane effects, leading to more stable food, water, and utility systems. This in turn would mitigate hurricane effects on mental health (Felix et al. 2011, Rubens et al. 2013) as, for most people, the truism holds: Most of the pain is not so much from the storm as the aftermath.

What would a more robust hurricane research network look like? Hopkinson et al. (2008) called for a series of instrumented sites in hurricane-prone areas along a latitudinal gradient. These sites would build from existing long-term research locations to increase watershed coverage, allowing analyses that link ridge to reef. Ideally, these sites would include replication of major ecosystems and representative land uses across the region. Baseline data taken with the express intent of evaluating future hurricane effects (Lugo 2008) would be collected in these sites, using a combination of field sampling, instrumentation, and remote sensing before, during, and after high-energy storms. Instrumentation, if not fixed at the site, could be moved into place when a storm is approaching. The use of automated and remote data collection techniques would reduce the intrusion of data collection campaigns on the post-hurricane recovery efforts in affected areas, an important consideration for research that the authors have faced both during their research and as residents of hurricane-impacted locations. Data collection should focus on quantifying the hurricane itself and the key ecosystem attributes and processes impacted, for example, salinity, flow, water level, carbon balance, nutrient balance, change in structure and species composition, dispersal patterns, and tree species regeneration. Considering the role climate change may play in changing hurricane regimes and the susceptibility of human and natural systems, data that can help explain how natural processes and human responses are affected by the combination of storms and climate change should take precedence. Other important effects of hurricanes, such as shifts in water quality or quantity and the potential increases in invasive species, should also be considered. Concurrent with ecological data, baseline data on human communities (demographics, economic characteristics, attitudes toward natural systems, mental health indicators, etc.) surrounding study sites would provide an important avenue to link ecological and societal effects. Additional hypotheses and approaches for a hurricane network are addressed in greater detail in Lugo (2008) and Hopkinson et al. (2008).

Hurricane Maria, and to a lesser extent Hurricane Irma (September 2017), followed similar paths to Hurricane Georges through the eastern Caribbean but turned north sooner and so had much less impact on Hispaniola and other locations on the western part of Georges’ track. A thorough review of their impacts and human and natural responses to these more recent storms is beyond the scope here and still await data reporting and analysis. However, some patterns from Georges seem to have been repeated. First, natural systems along these storms’ tracks have been relatively resilient. Despite widespread defoliation and crown thinning in Puerto Rico from Maria (Feng et al. 2018), crown recovery is underway and by May 2018 most of the forests had recovered from a brown, defoliated state. Basal sprouting in Guánica forest has again been reinitiated despite lower peak wind speed from Maria (114 km/hr) creating less windthrow (S. J. Van Bloem, personal observation). Hurricane Maria demonstrated again that the effects of rainfall and flooding are major reorganizing events in aquatic, coastal, and human systems and that fragile and infirm individuals (whether human, plant, or animal) or systems were more likely to experience catastrophic effects. Applying mental health studies done after Hurricane Georges, we would predict that stress, anxiety, insecurity, and other symptoms of declines in mental health to remain high after Hurricane Maria, perhaps for a period even longer than after Georges because the recovery of infrastructure has been much slower. Indeed, the departure of many Puerto Ricans from the island to the U.S. mainland to escape the aftermath of Maria was widely reported (Gamboa 2017). Similarly, there were media reports of Puerto Rican parrots and other fauna species seen well beyond their normal foraging range in response to the storm. Whether these shifts are permanent or not remains to be seen. As with
Hurricane Georges, the lack of a coordinated synoptic and coupled human–natural research network limits the research produced after Hurricanes Maria and Irma. However, building on the foundation of research from Georges and other hurricanes, we predict that this new research will deepen our understanding of hurricane impacts and how social and ecological systems interact to shape the recovery.

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